Optical Wireless Communications for Beyond 5G Networks and IoT
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Lecture - 14
Part - 2
OFDM in VLC, DCO-OFDM

Hello everyone. So, now we will discuss about use of visible OFDM in Visible Light Communication system.

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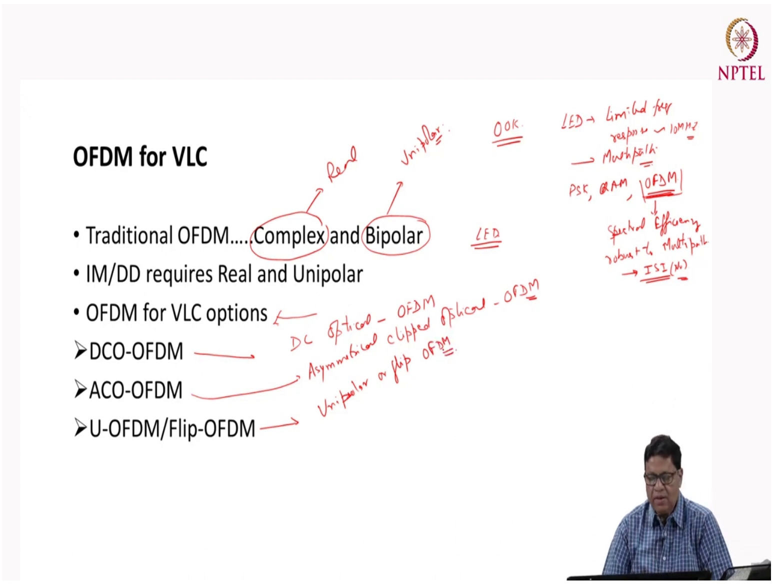

So, having understood the theory of OFDM, let us try to understand how it can be used in optical wireless communication particularly for indoor communication. So, if I do not use

OFDM, I use normal on off keying, my data rate is limited because the devices for example, the LED, they have limited data rate, or limited frequency response say about 10 megahertz.

So, on off keying may not give you know high data rate and also there is an issue of multipath. This we had discussed the delay spread because of the multipath which limits the data rate. So, basically, we need to, for high data rate we need to have some different modulation scheme. So, one can use PSK or one can use QAM or OFDM, which will increase the data rate because they are all spectral efficient modulation schemes.

So, one of the most common technique is using OFDM and we have already discussed the theory of OFDM and OFDM we know has high spectral efficiency. And it is robust to multipath distortion or multipath. Robust of multipath and it may not result into ISI, no ISI. If you, OFDM. So, we will use, try to use OFDM and VLC, but there are challenges.

The challenges are if you see the traditional OFDM, it is complex and it is bipolar. It has both negative as well as positive magnitude or voltage levels. So, whereas, for your devices LED they will not respond to complex signals and they will not, so not respond to negative signals. So, I first job before giving to optical transmitter is to convert this complex and bipolar into a real and unipolar signals.

So, we will try to understand how to convert this real to unipolar and then what value of you know SNR or performance we get after we have converted or what happens to the spectral efficiency of the overall system and what happens to the power efficiency of the overall system, this we will try to understand.

So, first job is to convert the complex and bipolar signal to real and unipolar and then give it to the optical transmitter. So, some of the techniques which are very common which we will explain discuss in detail is called as DCO OFDM, which is DC optical OFDM that is orthogonal frequency division multiplexing.

The other technique is ACO which is asymmetrical, clipped optical OFDM. So, we will discuss in detail these two techniques and third technique is which is also used is unipolar OFDM or flip OFDM so, unipolar or flip.

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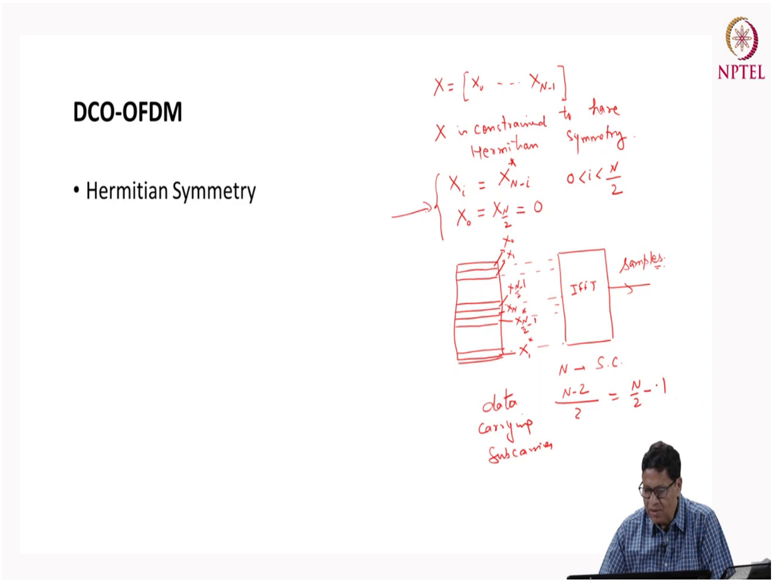

So, now let us start discussing about the first part DCO OFDM. So, for making a OFDM signal which is bipolar and complex I need to invoke Hermitian symmetry to make it real. So, suppose my data signal is given by X, X 0, these are data symbols x minus N. So, let us invoke Hermitian symmetry and then we will see that the signal which you get OFDM is actually now become real.

So, an X is constrained to have Hermitian symmetry, X is constrained to have Hermitian. Hermitian that is X i is equal to X N minus i, this is conjugate here and this is 0 to i to N by 2.

So, I have invoked Hermitian symmetry that is first half of the symbol are carrying data, the other half is actually conjugate of this.

So, and also, I put a condition that X 0 that is the 0, the corresponding to N is equal to 0, subcarrier X is equal to 0 and X N by 2, they are equal to 0. So, if I have these two conditions then I will find, I will see that the signal, the OFDM signal which was complex has become real. Now, so what we do here is. So, basically if I perform IFFT operation here, let me first draw, and this is say I do the IFFT operation here because remember that we do IFFT and the transmitter when we generate OFDM signal.

So, this is say X 0 and this is X 1, so on and so forth and then we will have this as X half N by 2 minus 1 and then we have this is X N and the next one can be X N by 2 plus 1, for this will be minus 1, X N by 2, let me rewrite this. So, this will be, we start from here, this is the conjugate X 1 conjugate and this will be X N by 2 minus 1 conjugate and this goes to IFFT. And we will see these samples in the time domain, they will all be real, if you have you know these two conditions satisfied.

So, basically there are n subcarriers, two subcarriers are carrying 0 signal that is X 0 is equal to X N by 2th subcarrier that is 0. So, two subcarriers are gone. So, this becomes n minus 2. So, the data carrying subcarriers will be half of it because the other half is conjugate of it. So, the data carrying subcarriers, this is data carrying subcarriers, this is nothing but N by 2 minus 1. So, now let us see how these samples are unipolar.

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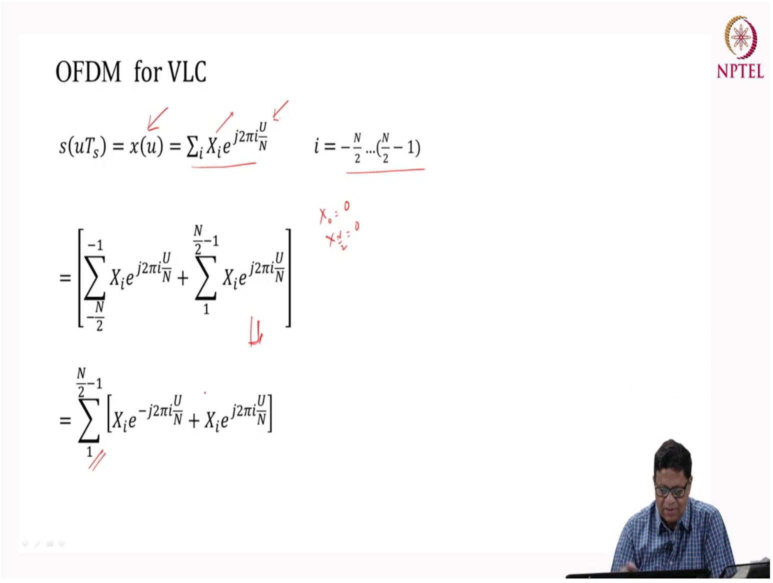

So, if you see the samples, the uth sample or at the time stand uT s is given by x u summation over i and this is the data on the ith subcarrier e raise to the power j 2 pi i U by N. This you will have to recall from our earlier OFDM discussion. So, I am breaking this into two parts and this i goes from minus N by 2 to minus N by 2 minus 1.

So, I am breaking these two parts, noting the fact that X 0 is equal to 0. So, there is no X 0 term here and X N by 2 is also 0. And because of this Hermitian symmetry, using Hermitian symmetry, this can be written as summation from 1 to N by 2 minus 1 into X i, this is the Hermitian symmetry that is why you see the negative here e raise to minus j 2 pi i by U N.

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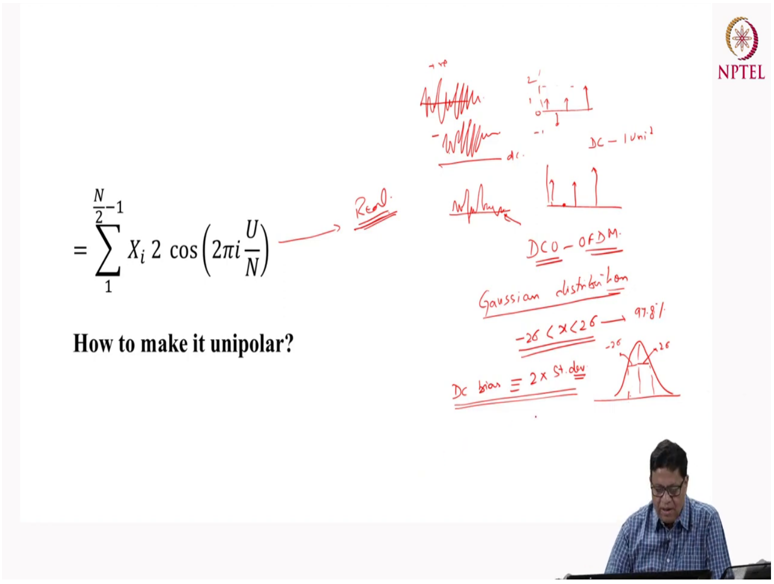

So, this reduces to this and if I use expression for e raise to power minus j theta in terms of sin and cos, then what I get is X i 2 cos 2 pi i U by N. So, this has become a real value. So, these samples have become now real. So, by invoking Hermitian symmetry and X 0 is equal to X N by 2 is equal to 0, we have made it real. So, right now the singularity is real, but it is bipolar. So, we need to again do some trick to make it unipolar. Then we are all set to give it to optical transmitter having LED or laser.

So, how to make it unipolar? So, unipolar, actually now you have made the samples real and then suppose these are the samples. So, if I, this is say 0 and this is some say minus 1, this is say plus 1, this is say 2. Then if I give a DC shift to all these samples, give it DC shift of for example; say minus 1 volt, DC shift of say 1 unit, then this will become. So, this, this will become 2 actually, this will become 2 and this will become 0 and this will again become 2 and this will become 3.

So, by giving a DC shift, I have made the samples all positive. So, this is how a DC OFDM, DC OFDM that is DC optical - OFDM works. So, you give a DC signal. So, if you see the OFDM signal, it is something like this and it may have some negative peaks or positive peaks.

So, if you give DC shift to these signals, basically you are making it power inefficient, you have to give more power to the signal. So, and if I shift too high, I basically shift all the, even the most negative signal to positive value, but then it results into power inefficient system.

And if I do not do that, then you know there may be some clipping. For example, the one case could be I shift the whole signal, so that so that nothing is below the DC, but this is inefficient because you require high amount of power. The second option would be, I do not give too much DC, but give some DC, but there will be some peaks, which will be below minus 1. So, I will introduce some sort of clipping distortion.

So, there has to be compromise between how much DC shift you are giving because you are making it more power inefficient. And if you are not doing it, then you are adding clipping distortion. So, there has to be some balance here. So, how do you decide that value of DC shift? So, for DC shift, for DC shift, because if you see the amplitude of these signals, they follow a Gaussian distribution.

And we know from Gaussian distribution that if x is between 2 sigma n minus 2 sigma, that is where sigma is a standard deviation then we have 97.8 percent of the signal which is close to 1. So, this is a 2 sigma, this is minus 2 sigma. So, 97.8 percent of value of the amplitude will lie within this range. So, which means I need to shift the signal at least twice the power of the signal.

So, if I shift the DC, give the DC bias which is twice the standard deviation, the DC bias is equal to twice 2 times the standard deviation. Then it is a good compromise between the power efficiency and the clipping distortion. So, this is a rough, but you know one can change the value of DC bias and depending on the application, you can you know optimize the value of DC bias.

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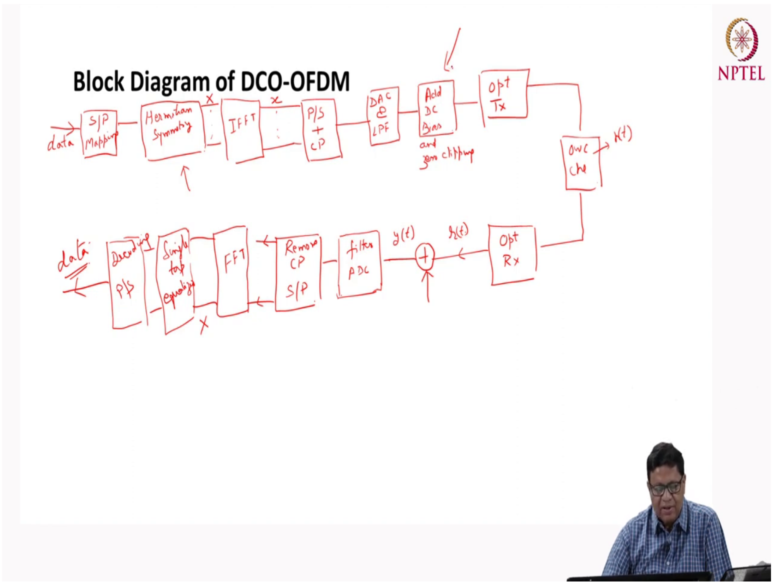

So, now let us understand the total block diagram of DCO - OFDM. How we will generate DCO - OFDM which can be useful for indoor optical wireless communication system. So, this is the input part which is the cell data. And then we have first step as serial to parallel and also, we do some mapping that is some modulation technique here.

There is M qam, 4 qam or 16 qam or 256 or whatever. And then we invoke Hermitian symmetry because ultimately, we want to make the signal real Hermitian symmetry. And then what we get is data X and this will go from 1 to n n and then this is given to IFFT block, which will convert into time domain signal that is samples which is denoted by x from earlier discussion on OFDM.

And then once you have got the samples, then you do parallel to serial converter and also add cyclic prefix this we had discussed. We have to add cyclic, some part of the portion of the symbol has to be appended before the symbol. So, cyclic prefix, actually the cyclic prefix makes the channel look like a flat fading channel. So, once you have appended the cyclic prefix and then this serial data stream is given to make it analog is given to digital to analog converter and some sort of LPF Low Pass Filtering.

And after that to make it positive or unipolar you have to add DC to the signal, add DC bias. And also do some zero clipping because there may be some signal, negative signal left because if your DC bias is not sufficient, then there will be some negative signal left which you have to clip. So, you have to do additional function if the DC bias is not enough to you know push all the negative signals to the positive side.

So, zero clipping and zero clipping and then this signal is given to the optical transmitter. And then you have the channel optical wireless channel, which is characterized by impulse response a h t. And then you have optical receiver which would be a PIN no photo diode. Then you get the received signal which is r t and this is the noise which is get which got gets added because of the optical receiver, the thermal noise there is a short noise and if you are using a p d excess noise as well.

So, what you get is y t. So, that is the signal which you receive which is corrupted by noise. And then you do the reverse operation that is a filter convert that into some log to digital signals ADC Analog to Digital Converter ADC. And then we need to remove CP which you had added earlier, remove cyclic prefix and also do serial to parallel conversion.

So, you got the time samples here and then you do the reverse of IFFT. There is FFT operation here and what you get is signal in the frequency domain x. And then you need to use a single tap equalizer. And whatever mapping you have done earlier you have to demap or decoding and parallel to serial. So, this is any signals here.

What you get is data. So, this is the total block diagram of DCO-OFDM. So, what we have done? The important things to see in to be seen here is this Hermitian symmetry block to make the signal unipolar and also adding you know DC bias. So, that there is no negative signal left in the OFDM stream and then doing this operation. So, this will give a DCO-OFDM signal.

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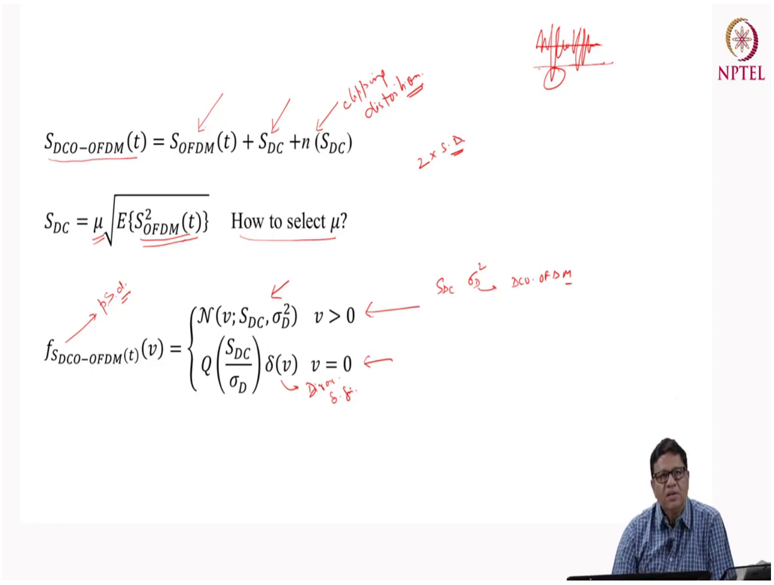

Now, let us try to find out the SNR for such a case or how we will calculate the SNR. So, if you see the DCO OFDM signal which I represented as S it will consist of that OFDM signal, then giving DC to it to make it you know positive. And this is the noise which is coming because of the clipping. If you have DC because this again, I am repeating this the this the

OFDM signal is something like this, so you may not give full DC to include the most negative peak.

So, maybe in the interest of power or make it more power vision you give some DC and you know you do away with these parts. So, this will introduce some sort of distortion. So, this is I am denoting this as NSDC, so this is clipping distortion. And the DC which I have discussed earlier that it has to be it depends on the power of the OFDM signal.

And it is scaled down by a factor mu and we also discussed how this mu is to be selected which came out to be twice the standard deviation because you will have 97.8 percent of signal within this range. So, this value is typically you know 2. So, it will be 2 into the expected value of the power of the signal.

So, this is the DC which is added. And then if you see the amplitude the DC shifted signal and if you will try to find out the power spectral density for a such a signal. As I mentioned this the amplitude variation, they follow a Gaussian distribution. So, this first part is basically because of the Gaussian distribution. So, this is characterized by mu which is the average is SDC and you know variance is sigma d square d stands for you know DC of DM.

So, this follows a Gaussian distribution here for you know for this variable v greater than 0. And then because of the clipping this is the you know distribution here, which is v is equal to 0 because you are clipping it. So, this is Q given by Q SDC by you know rho D and this is Dirac delta function. So, this is the power spectral density of the DC shifted OFDM signal.

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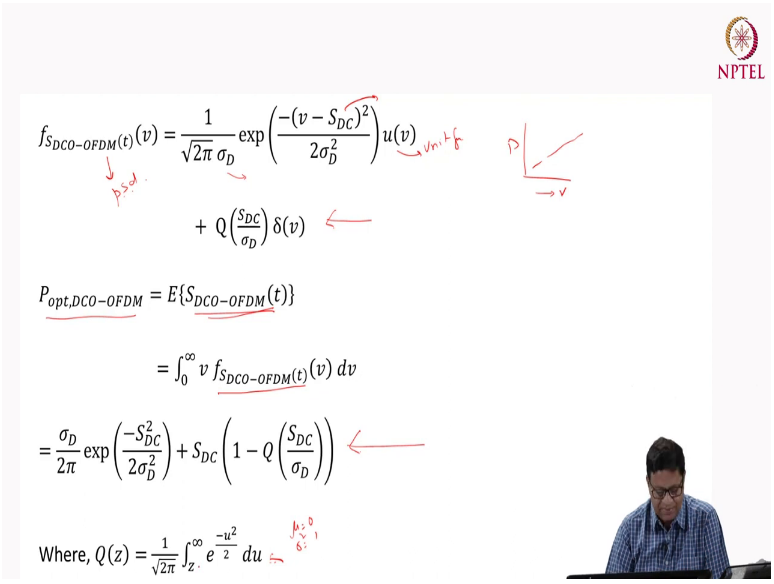

And this can be written as the first part is as is told you is a Gaussian distribution which can be written as 1 by the standard Gaussian distribution 1 by root 2 pi standard deviation. And this is the average value mu divided by 2 sigma D squared and this is a unit function. And plus this is because of the clipping Q SDC by sigma d into Dirac delta function.

So, if I want to calculate the power optical power because if you give this signal to LED depending on the amplitude it is the LED will give you optical output which is directly proportional to the amplitude of the signal. Because recall our characteristic of LED this is say v this is P, so this is some sort of linear.

So, you have to take the expected value of this signal which will give you the P optical power of the DCO OFDM. So, this is expected value of DCO OFDM. So, for calculating x you know the power spectral density this is the psd and to calculate the expected value of this

DCO signal you have to you know integrate from 0 to infinity v into the power spectral density into dv.

So, if I put the value of this psd here and then try to calculate this integral what I get is this expression. So, this is the power output in the OFDM signal which is you know sigma D divided by 2 pi exponential minus S squared DC divided by 2 sigma D square plus S DC this is coming because of the clipping part 1 minus Q S DC by sigma D.

So, this is the optical power and the Q is the standard definition for a normal distribution 1 by root 2 pi z to infinity where, mu is 0 and variance is 1. So, it is given by this. So, this expression is in the form of Q and in order to calculate Q there are standard Q tables or one can evaluate this integral if it is possible to do.

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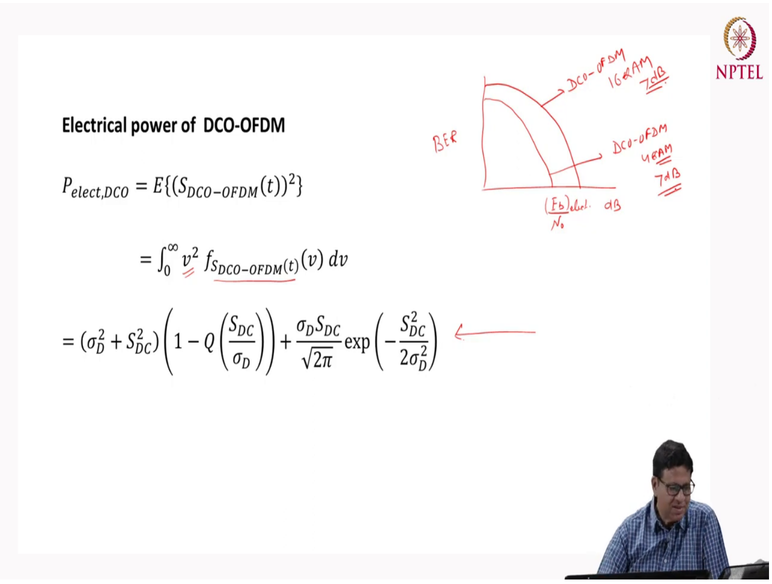

And if I calculate earlier was the optical power and if I calculate the electrical power of DCO OFDM this will be given by the DCO OFDM signal square expected value of square of OFDM signal DCO OFDM signal and this for evaluating this, so this will be v square into the power spectral density into dv.

So, if I evaluate this integral by after putting this power spectral density for the DCO OFDM signal, I get this expression. So, this is the electrical power of the DCO OFDM. So, now you have calculated the power and then one can calculate the noise also which is coming from the detection process.

And then using these expressions one can plot Eb by N naught this could be in dB and this is electrical. And this can be plotted again BER. So, you will get something like this or for different QAM. So, this is for example, this is for DCO OFDM and this is 4 QAM as the mapping which is used and the DC shift which is given is a 7 dB.

And this could be for a higher order Qam which is a DCO OFDM 16 QAM and again you have given it 7 dB or DC value is 7 dB. So, one can calculate the performance of OFDM signal for different values of for different modulation formats and also giving you know different values of DC. So, here I have used 7 dB one can plot for 7 dB or 10 dB or even lesser dB and then you will see that higher the DC better is the BER performance.

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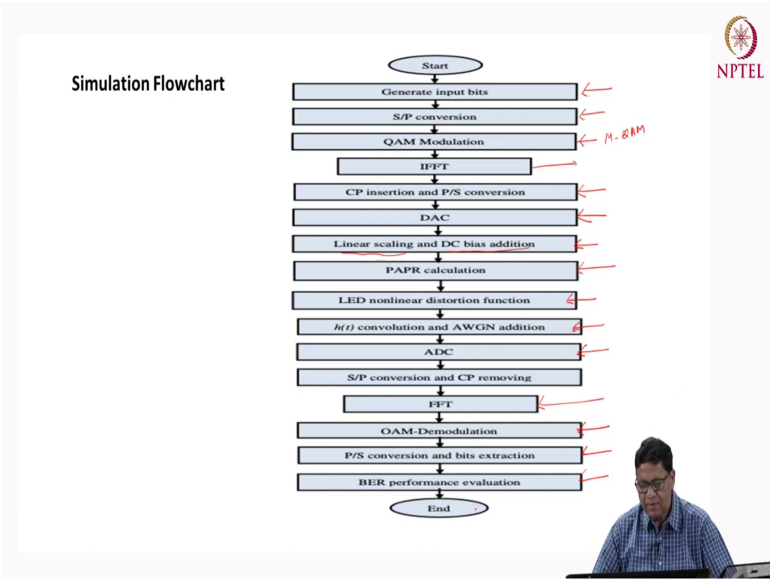

So, how you do the simulation part? So, in this course also towards the end there are some simulation exercises where you know how to simulate a DCO OFDM or ACO OFDM that will be explained, but I am just giving you a brief idea what are the what is a flow chart what are the things which are involved in the simulation for a DCO OFDM.

So, you basically first is generate input bits then the next process is serial to parallel conversion and then you use higher order modulation QAM modulation this is basically M QAM and then you do the IFFT operation converting into time samples or time domain and then once you have done the IFFT you have to introduce or add CP and also do parallel to serial conversion and then as discussed earlier you do digital to analog converter and then you add DC to the signals. So, that you get positive signal.

So, this is DC bias addition and also do some sort of linear scaling if required and then you want to study for different PAPR. So, PAPR calculation the effect of PAPR on the BER that can be done here PAPR calculation at this stage and then the signal is given to the LED which has some non-linear distortion it is not perfectly linear device. So, you have to take care of that non-linearity in the device.

And then this is the channel response H2 we have to convolve with the Ht channel impulse response and addition of additive white Gaussian noise and after that you have to convert back to digital converter and then you remove the CP and do the signal to power conversion and then you do the reverse operation that is IFFT and then you are required to do QAM demodulation.

And then after QAM demodulation it is parallel to serial conversion and bits extraction and then one can do the BER analysis. So, these are the different steps which are involved in simulating DCO OFDM network I mean it is true for any OFDM network the other type of you know technique which is ACO OFDM which I will be discussing now is valid here or flip OFDM or unipolar OFDM. So, these are the different steps involved in the simulation.

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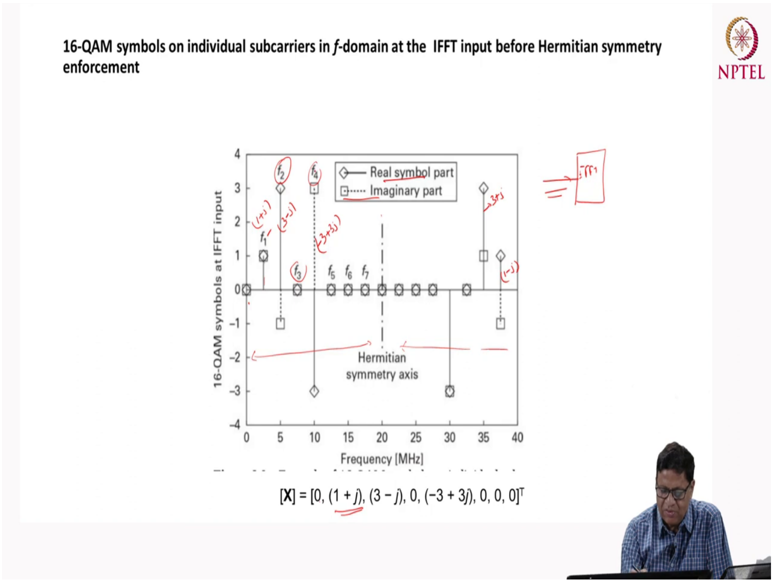

So, just to give a flavour of you know signals at different points. So, this I have taken as 16 QAM signals. So, basically you see you know 8 here and this is the you know Hermitian symmetry axis because we have to recall that the first half and the second half they are related the they are conjugate the second half is conjugate of the first half and X 0 and X N by 2 they are 0.

So, this is X N by 2 this point which is Hermitian symmetry axis and this is X 0 and these are you know 16 QAM symbols at the input of IFFT this is the IFFT. So, this is at the input of the IFFT. So, for example, the data symbols are 0 1 plus j 3 minus j 0 minus 3 plus 3 j 0 0 0. So, this 0 correspond to this. So, you have the real part and the imaginary part 0 this is 1 plus j.

So, this will be 1 real part and 1 imaginary part. So, both are coinciding this is 1 plus j and this is 3 minus j. So, this particular thing is 3 the real part and minus 1 is the. So, this is 3 minus j and then you have 0 here and then minus 3 plus 3j. So, this is minus 3 plus 3j and then you have 0 here 0 here and the rest are 0.

And similarly on the other part you have to take the conjugate. So, this is for example, this 1 f 1 is 1 plus j it will be 1 minus j here and so you have to take the conjugate part here. So, this 0 will become like this and 1 minus j will be for example, this is 1 this is 1 minus j and then the next one is 3 minus j.

So, this will be 3 plus j, so this is 3 plus j so on and so forth. So, these are the 16 QAM symbols on individual subcarriers in frequency domain at the input of IFFT before Hermitian symmetry. So, once I pass it through the IFFT, then you know Hermitian symmetry is invoked and then you get the signal you get the real signal.

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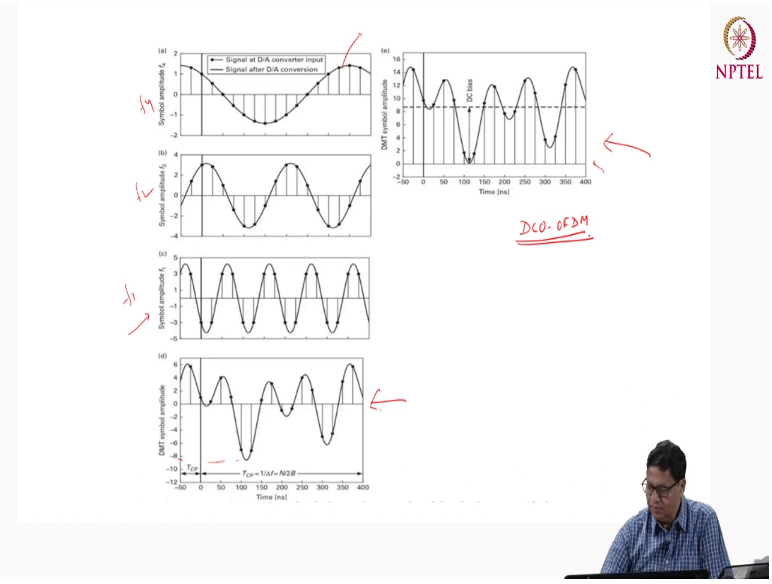

So, this is given for different components. So, this is for f 1 if you see from the earlier this is f 1 this is f 2 this is f 3 this is f 4. So, let us see f 3 is anyway 0, so we need to see f 1, f 2 and f 4. So, these are the symbol amplitude this is for f 4 this is for f 2 this is for f 1. So, these are the different frequencies and these are the you know samples after digital to analog conversion.

So, you get a something like this and if you add all these things, you get a DMT symbol amplitude or the OFDM signal which is of this form which is given here. Now, it has negative components also minus here for example, so I need to give a DC shift to make it positive. So, my DC shifted optical OFDM system will something look like this for the example which I had taken in the last slide.

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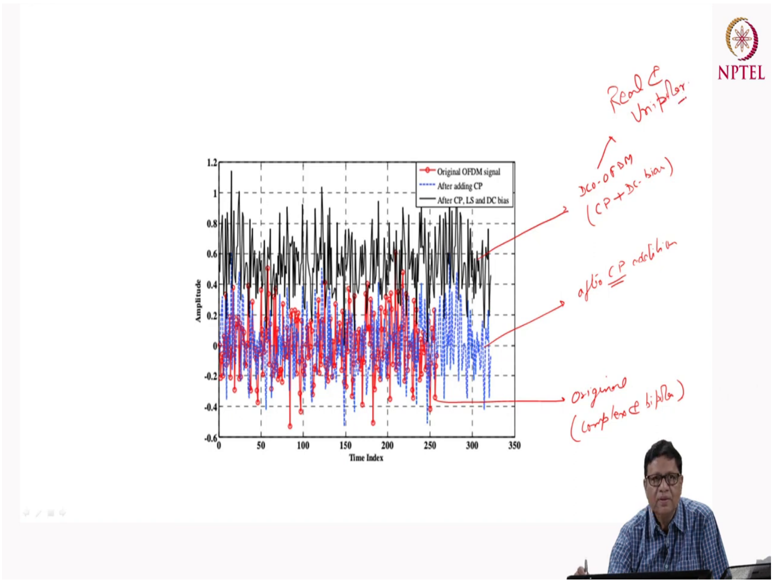

So, this is DCO OFDM signal this is actually how the signal looks like if you happen to see a OFDM signal in a CRO. So, the original signal is the red this is the original signal notice here it is complex and bipolar original complex and bipolar and this blue is actually after adding cyclic prefix.

So, some part of the portion is upended here. So, so this has the overall symbol length has increased. So, this is after adding CP, after CP addition and this black signal which you see here actually it has CP it has some linear scaling which has been done and some in the DC bias added to it.

So, that all the total signal is above this DC line and this is all positive. So, this black color thing which you see is actually a DCO OFDM signal, which means you have added CP which anyway was added earlier plus DC bias to make it possible. So, the signal which you get here is actually real and unipolar.

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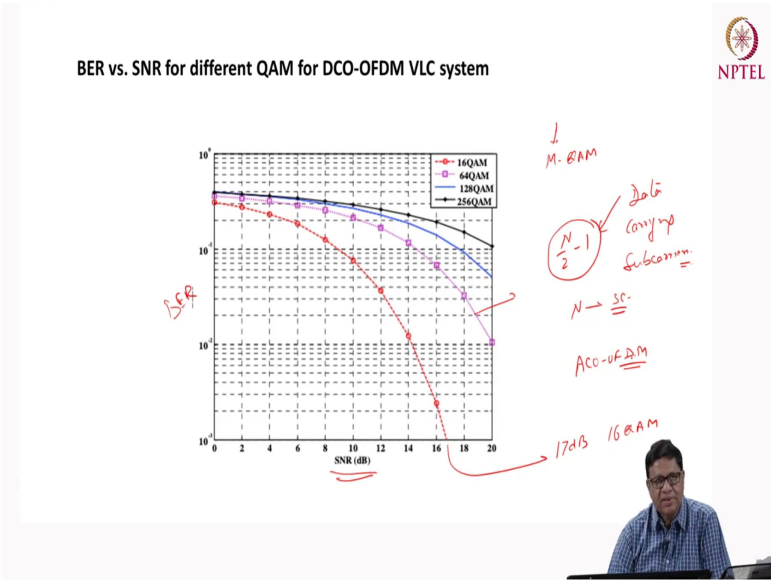

And if I see a curve between BER this is say BER and this is my SNR and I use different levels of modulation M QAM where m is 16 or 64 or 128 or 256. So, this is what I get here. So, if I see at 10 raise to power minus 3 I require about 17 dB for case of 16. So, this is 17 dB for approximately for 16 QAM and for next value of QAM that is 64 I may require you know higher value.

So, it is not shown in the graph, but as I increase the value of m here, I require to get same BER I require more signal to noise ratio. So, this is has been plotted you know using the simulation in the flow chart which I had discussed earlier. So, this is about the DCO OFDM and then we will also do study another technique which is the ACO OFDM and also notice that DCO OFDM data carrying subcarriers are N by 2 minus 1.

So, the spectral efficiency has gone actually I have got total of N subcarriers, but the data is only carried on N by 2 minus 1 subcarriers. So, the spectral efficiency has gone. But if I want to make the system you know compatible with VLC scenario, I need to make the signal you know real and unipolar. So, that is why I did Hermitian symmetry. So, because of the Hermitian symmetry I lost some subcarriers. So, the data subcarriers this is the data carrying subcarriers.

So, next now we will study about another technique which is called as asymmetrical clipped asymmetrical clipped optical OFDM or ACO OFDM. So, this is what we will study now. So, we will end the discussion of DCO OFDM at this stage.

Thank you.