Optical Wireless Communications for Beyond 5G Networks and IoT

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Lecture - 13
Part - 3
OFDM Basics

Hello everyone. So, we have already discussed basement modulation techniques. Now, we are going to start another topic which is based on multi-carrier modulation. And under this multi-carrier modulation, we will study about Orthogonal Frequency Division Multiplexing which is OFDM. And we will see that it is more efficient than basement.

So, what are the VLC challenges if I want to use OFDM technology or multi-carrier modulation technique. So, why to go for OFDM? Because, basement can give you a limited data rate.

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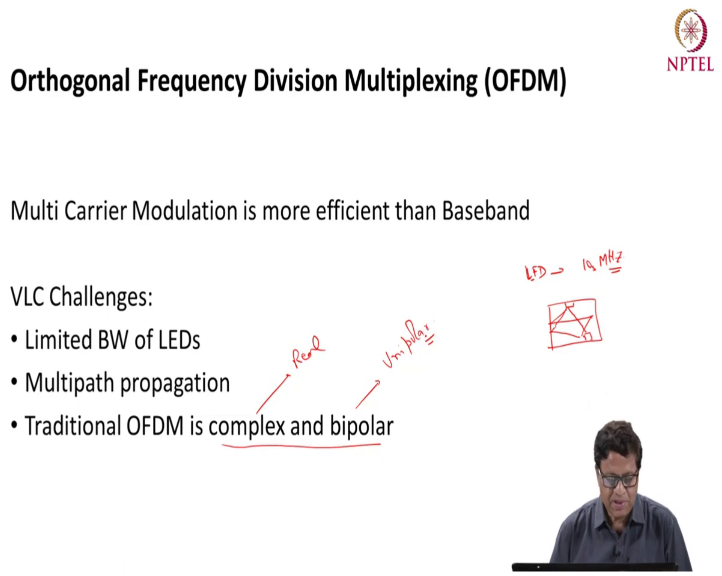

And if you want to have high data rate, then one has to use some advanced modulation techniques. And we already know that be the LEDs, they have very limited bandwidth, the commercial LEDs which are generally used for elimination. They have very limited bandwidth, of the order of 10s of megahertz. And in order to get high data rate, we need to have advanced modulation techniques.

So, OFDM is one option. And the other issue is that there is multipath propagation. If for example, inside the room, this is your transmitter, this is your receiver, although the room is very small. So, you can have line of side component, you can have non-line of a component, you can have components after multiple reflections. So, this results into some sort of delay spread which limits your data rate.

So, because of this multipath propagation, there may be some compromise on the data rate. And also, VLC, we cannot use OFDM directly because OFDM signal is generally complex and bipolar. Whereas, if you want to give signal to a LED, it has to be a real signal. And it has to be a unipolar signal. So, some changes have to be done in the conventional OFDM systems in order to make it compatible with optical wireless communication systems.

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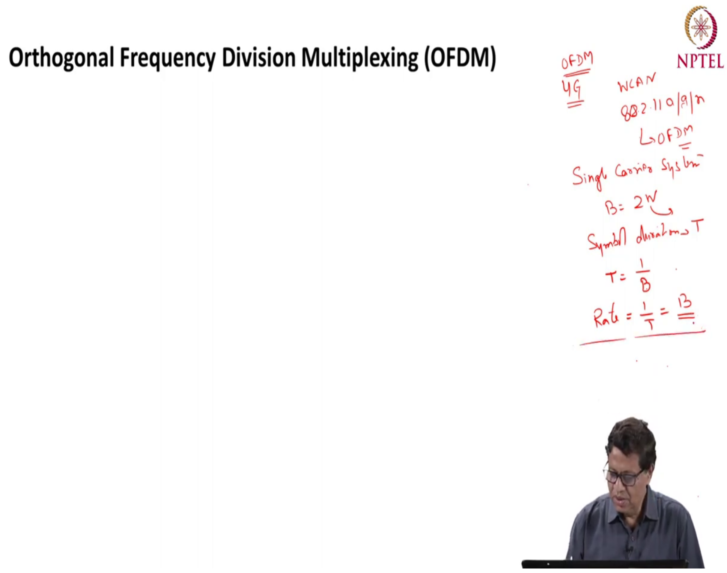

So, let us let us discuss first about the single carrier systems and what is the data rate we get in a single carrier system. So, single carrier system, just to give you some more applications of OFDM, we have been used. We are you we normally, you know, standards promotes in OFDM, in 4G systems and also in wireless local area networks, that is 802.11 a or g or n. They also use OFDM. So, OFDM is quite popular in 4G applications and in, you know, wireless local area networks.

So, let us now go back to our single carrier system. Suppose, I have a single carrier system and the bandwidth is say B, which is equal to 2W, which is W is one sided bandwidth. So, the and the symbol duration, symbol duration is s T. And for a for a single carrier system, T is equal to 1 by B. So, you have you transmit one symbol, one symbol every T second. So, transmission of one symbol every T seconds, which means the rate is 1 by T or B. So, for a single carrier system, the transmission rate is B.

Now, let us do this now differently. Let us break the whole bandwidth into n equal parts and examine what happens.

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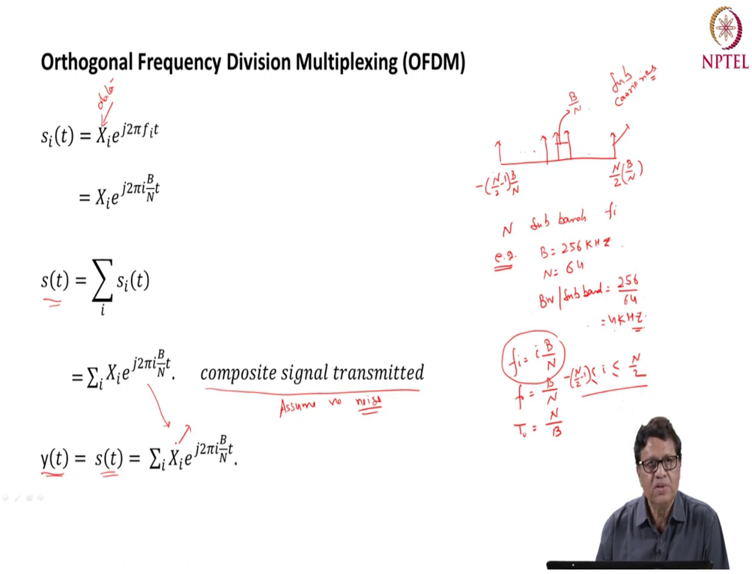

So, if my total bandwidth is this is the total bandwidth B and I have I break into this is middle so on and so forth. This is the last one and let us this is say N by 2 into B N B by N. The spacing between two carriers, these are all carriers with different frequencies f i's and the spacing or the spacing between two carriers or sub-band is B by N. And the last is N by 2 into B by N and this one will be minus. So, totally there are N sub-carriers. This is B by N.

So, there are N sub-bands, each corresponds to some carrier f i and the bandwidth between two adjacent frequencies is B B by N. So, let us take some example. If B is say 256 kilohertz and there are N sub-carriers or N N is equal to 64 frequencies, then B by n the spacing will be. Then bandwidth per, sub band bandwidth per sub-band is 250, this is over 64 is 4 kilohertz.

So, this B by N is 4 kilohertz and the frequencies, different frequencies which are there is f i i into B by N. So, these are the frequencies here and the fundamental frequencies is f 0 B by N and so, the T 0 will be 1 by f 0 that is N by B, alright. So, now what I do? Now, there are f i sub-carriers and i is actually going from i goes from the limits of i r N by 2 N minus N by 2 minus 1. So, that is the limit of i. Now, I transmit data, this is X i is data, this is data. Use f i as the sub-carrier frequency and these are called as sub-carriers.

So, X i data is on f i sub-carrier. So, s i t will be x i into e raise to power j 2 pi f i t and I can write f i as B by N. This is i f i is equal to i B by N, i B by N T and that and similarly all the datas X i where i changes from you know N by 2 to N total N sub sub-carriers, the data is X i X i plus 1 X i minus 1 and so on and so forth.

So, the total data, the composite signal, the combined signal carrying different data on different sub-carriers is given by s t summation over i s i t which can be written as X i e j 2 pi i B by N T. This is the composite signal which is transmitted. And now let us assume that there is no noise assume no noise. Ultimately, we will consider noise, but right now just to understand about OFDM concepts, assume there is no noise in the system.

So, the whatever is transmitted is received. So, y t is same as s t which is given by X i e raise to power j 2 pi i B by N T, where X i is the data which is writing on ith sub-carrier. And similarly for other sub-carriers and i goes in the total number of N sub-carriers and the range of i is between N by 2 and minus N by 2 minus 1.

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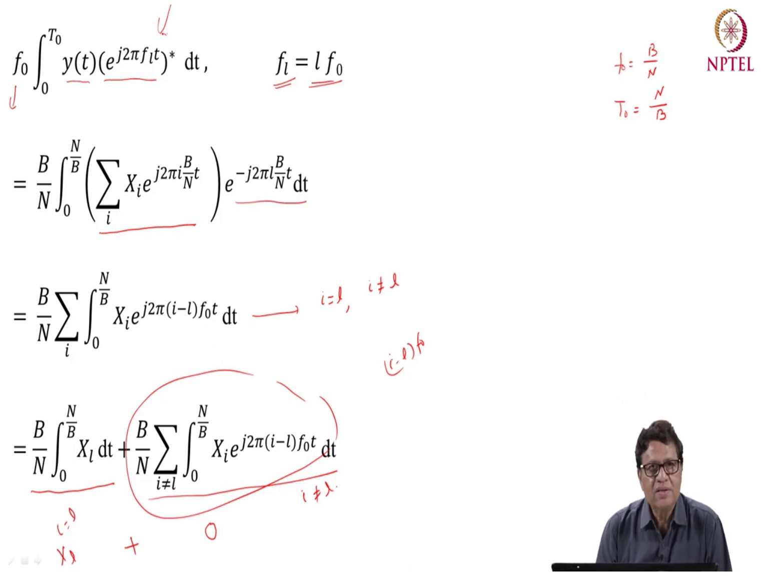

So, now let us do try to do this operation f 0 is the fundamental frequency and take y t and take some frequency sub sub-carrier f l which is actually lth time the fundamental frequency l f naught. And multiply y t by the conjugate of conjugate of this e raise to the power j 2 pi f l t. Let us see what this operation does.

So, I have taken the fundamental frequency f naught and y t is a received signal and I multiply this by the conjugate of a e j 2 pi f l t and y t has signal corresponding to lth sub-carrier. So, f 0 is as we know is given by B by N and T 0 we had calculated. So, f 0 the fundamental frequency is B by N and T 0 is N by B. So, this is the limit and this is the composite signal y t and this multiplied by the conjugate. So, this minus sign has come e raise to the power minus j 2 pi l b by N Dt.

Now, this has become I have taken this factor inside. So, this has become X i e raise to the power j 2 pi i minus l f naught t I have replaced B by N by f f naught. So, now this has various components and there will be a component which is i is equal to l and the other component in the summation will be actually i not equal to l.

So, let us separate these two components i equal to l will give me this. This is i equal to l and i not equal to l will give me this i not equal to l. Now, if I calculate this integral this is nothing but X L because this will be N by B and B by N will get cancel and l get X l. So, this will give me X l plus this component the circled one is actually 0 because if you see this i minus l f naught is some multiple of fundamental frequency f f naught.

So, basically an i and l they are all integers. So, if you integrate over these multiple sub multiples different multiples of f naught the integral will give you 0. So, and also it amounts to saying that all the frequencies which are where i is not equal to l they are orthogonal to each other. So, this integral will be 0 because of orthogonality. So, what I get is actually X l plus naught.

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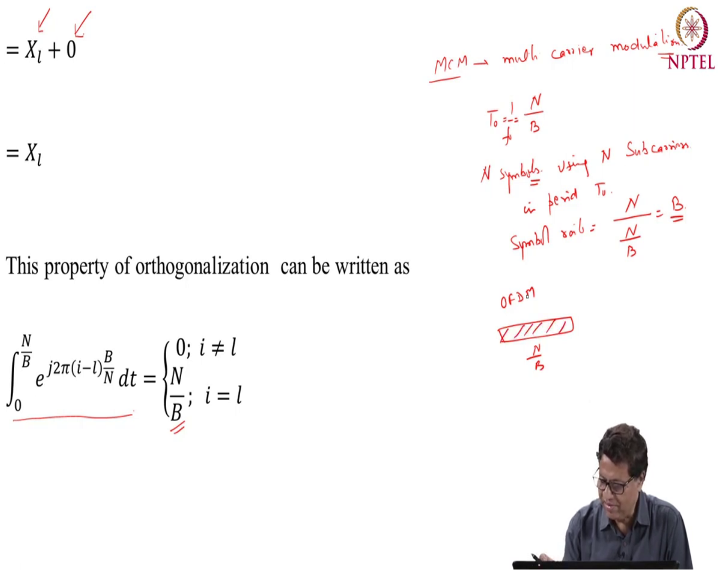

So, this is what I have written X l the second integral is 0 X l is the data which is writing on the lth carrier. So, and this is possible because of this property where this is 0 if i is not equal to l if i is equal to l this is equal to N by B. So, actually what we have done earlier we have multiplied this by the conjugate. So, basically, I have done a coherent demodulation.

That means, I have taken a frequency f l and I have coherently demodulated the composite signal and I am able to recover X l same thing I can do for other sub carriers f i or f 1 f 2 f 3 a and up to f n. So, I can basically demodulate all the data which is there on those sub carriers by doing this simple demodulation coherent demodulation. So, in MCM that is in the multi carrier modulation that is multi which I did just now the integration time is actually T naught which is 1 by f naught and which is nothing but N by B.

So, there are N symbols they use N sub carriers in period T naught. So, if I find out the symbol rate in MCM it will be N divided by N by B which is actually T naught. So, this gives you B. So, the symbol rate symbol rate is B here as well. So, in the single carrier also we saw the symbol rate is B and here also it is symbol rate B in B. So, the only difference is in OFDM this whole is N by B. Let us not call it OFDM is still it is MCM.

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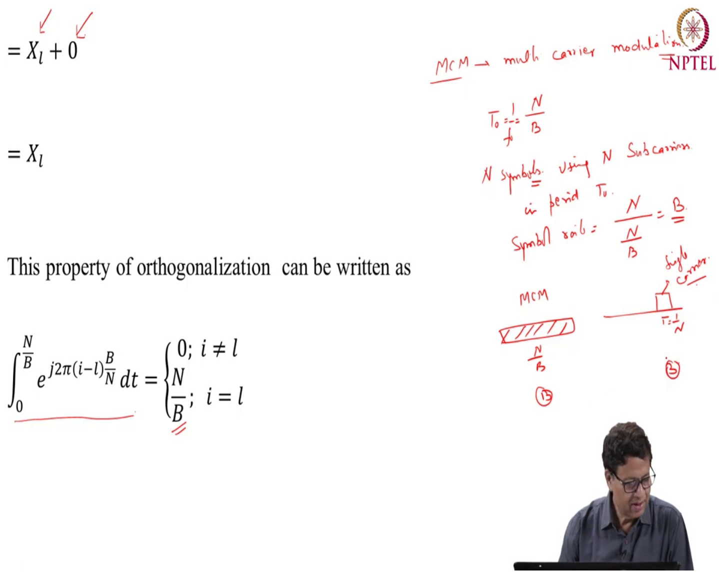

And in single carrier you know this was this was T this is one symbol single carrier single carrier and this is 1 by N or T is 1 by N. So, this is the difference, but both in both the cases the symbol rate is B.

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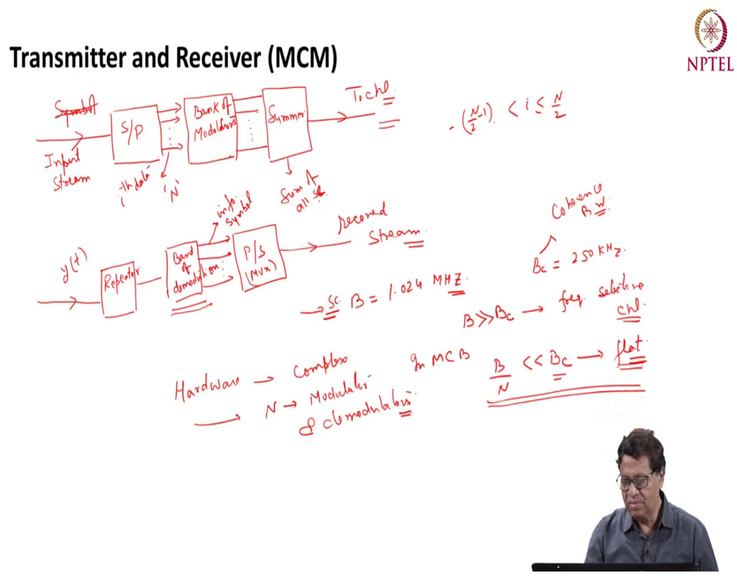

Now, let us draw a diagram for this multi carrier modulation what does it look like. So, this is your symbol. The first operation you do is yours do the serial to parallel conversion and then you get different outputs that is the different data different data for example, this is you know serial data x i x i plus 1 and so on so forth.

When you do the single on top you will have x i x i plus 1 and so on and so forth and after this you will have a bank of modulators where you whatever data is there on the ith sub-carrier this is let us write this is ith data and then we use bank of modulators.

So, there are different modulators and each is modulating ith data is getting modulated by f 5th subscriber lth data is getting modulated by lth subscriber so and so forth and there are N sub sub-carriers the total number is N sub-carriers or these total number is N. So, each modulator is modulating the corresponding data and then we use some sort of summer here and this is sum of all sub-carriers sum of all sub-carrier data and this goes to the channel.

So, this is a transmitter for a multi-carrier modulation technique and then whatever data is received let us write this i is between N by 2 and this is N by 2 minus 1 minus. So, these you require N modulators for each sub-carrier. Now on the receiver you are you receiving say y t right.

Now, let us assume that there is no noise added in the channel then maybe you have some sort of repeater. So, that the attenuation which has happened in the channel is taken care of and then you have this goes to a bank of demodulators these are coherent demodulation because we saw that by coherently demodulating, we are able to recover the data.

So, this goes here and then you get the information symbol after demodulation information symbol on each sub-carrier which was there on the each sub-carrier. So, information symbols and then once you have got all the information symbols you have parallel to serial converter and this is your recovered data. Recovered.

So, this was a recovered stream or this we can call it input stream this is a recovered stream. So, this is how typical block diagram of a transmitter and receiver of MCM you have input stream you divide into N parts and each has you know data which goes to a bank of modulators and after modulating it is summed you sum them up and it is transmitted over the channel and the channel then again you from the combined signal we have seen in earlier slide that by coherently demodulating you are able to recover the data.

So, this is a set of set of demodulators where you are able to recover the data information symbols and then you combine them or parallel to serial or some sort of MUX to recover the original stream. So, let us see some example to understand some numbers. So, suppose your B is 1.024 megahertz and B c which is a coherence bandwidth in a wireless channel is of the order of say 250 kilohertz.

I mean I am talking about right now wireless channel not right now I am not introduced the optical part because currently I am giving the fundamentals of OFDM; once we understand the OFDM as it is used in RF then we will try to map it to our VLC applications. But right now, it is for as it is used in you know RF applications.

So, the coherence this is the coherence bandwidth. So, as we see here B is much greater than B c; that means, its a frequency selective channel because the coherence bandwidth is much less than the bandwidth of the channel. So, you say frequency selective channel. So, in MCM this was the case with single carrier for example, in MCM now you have divided the bandwidth into N parts B by N.

So, B by N is now much smaller than B c the channel becomes actually flat. So, that is the advantage of having multi carrier the channel is behaves like a flat channel because the sub channel bandwidth if you see B by N is much less than B c which you can calculate divide by 64 depending on how many sub carriers are using or 256 it is much less than B c channel is flat.

So, MCM this problem is resolved which was there in single carrier system. But the main problem is that one has to use so many modulators and demodulators. So, the hardware becomes very complex the hardware becomes very complex because it uses N modulators and demodulators and if N is high 256 then becomes very very complex. So, that is the issue with multi carrier although the channel has become a flat channel.

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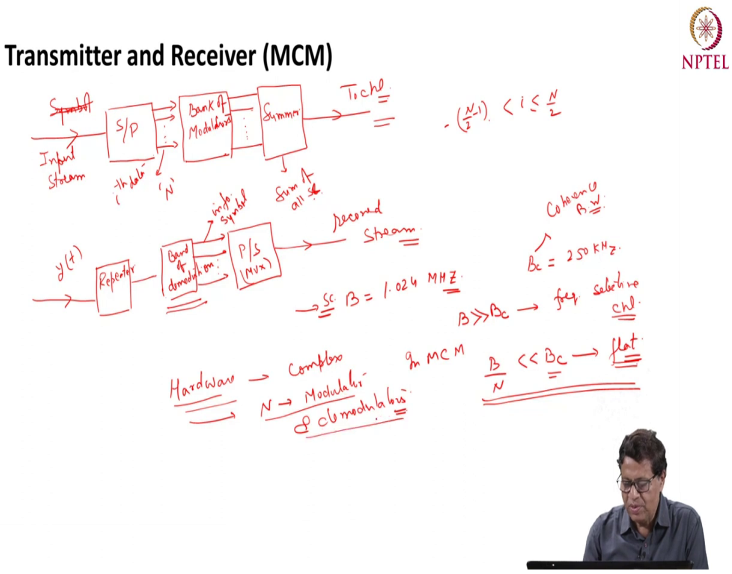

Because the bandwidth B by N the sub band bandwidth is much less than the B c and so, you are able to recover your data signal. So, how to solve this problem of hardware complex hardware how to get rid of this so many modulators and demodulators which makes your circuit very complex.

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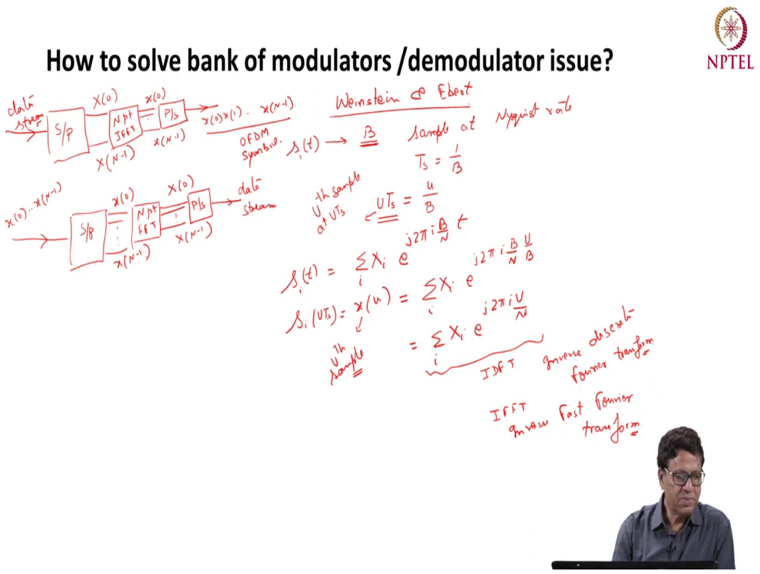

So, let us try to understand this and this was solved by two engineers Weinstein and Ebert. So, what they did that your s t signal has bandwidth B. Now, if I sample this this system this signal at Nyquist rate sample at Nyquist rate which is say t s given by 1 by B that is a radii simple sample at. So, I get a Uth sample which is at instant UT s this is the Uth sample at UT s this is a s i T.

So, that the signal with the combined signal if I sample at an Nyquist rate the bandwidth is B. So, the Nyquist rate will be t s is equal to 1 by B I will get series of samples and let me call that as UT s which is actually the Uth sample at time instant UT s and UT s is equal to u by B.

So, the s t or the combined signal s t actually it is summation of summation over all sub-carriers xi these are the data e raised to power j 2 pi i B N by T this is my s i T. Now, I sample. So, so the sample UT s call this as x u this is the uth sample. I will be denoting the sample with a lower case. So, this x u is the uth sample. So, this will be i x i e raised to power j 2 pi i B by N U by B. So, this becomes i x i e raised to power j 2 pi i U by M.

So, if you notice this carefully this is actually IDFT inverse digital Fourier transform and x i are the coefficients. So, I can recover this x i from this IDFT from the samples. So, this becomes very very easy I do not have to have you know bank of modulators and demodulators simply I recover the coefficients of the signal and they are the actually x i's.

So, this becomes little simpler now and in OFDM this IDFT is actually IFFT inverse first Fourier transform. This is discrete I am sorry inverse discrete Fourier transform and in the OFDM context it is inverse fast Fourier transform. So, the problem of bank of modulators and demodulators is resolved by simply taking IFFT or IDFT and the coefficients are actually give you will give you the data symbols.

So, let us make the block diagram of the block diagram will get slightly modified and maybe we can make the block diagram here. So, this is your data stream and then you do signals serial to parallel and these are the symbols N minus 1 or the constellation points in the signal and then you have the IFFT this is N point IFFT.

Still, it is not complete OFDM, but we will see we will add some more thing to make it complete OFDM. So, this is N point IFFT and then you get these samples. So, these small cases denoted as samples this is x and minus 1. So, these are the samples after sampling it using Nyquist rate and then you have parallel to c l converter and then a series of samples which is x 0, x 1 so on and so forth up to x and minus 1. So, this whole thing is a OFDM symbol.

So, actually that c p l is also added that cyclic prefix right now I am not adding it, but first I have to explain why c p is added then actually the whole signal when you have the cyclic prefix and this whole symbol that becomes a OFDM symbol. Now, these samples this is x 0 to x N minus 1 they go to serial to parallel. So, these are the samples.

And then you do the reverse operation in the transmitter you had an N point FFT now you will do N point FFT and then you are able to recover the coefficients of IFFT is the coefficients are nothing but the data symbols. So, this is x 0 and this will be capital X N minus 1 and then you have parallel to serial converter and you get your data stream out this is your data stream this is input data stream.

So, by doing this IFFT FFT operation we are able to get rid of the bank of modulators and demodulators. So, it becomes quite simple.