Evolution of Air Interface Towards 5G

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Lecture – 29
Waveforms Beyond 5G (OF set QAM DFDM & UFMC)

Welcome to the lectures on Evolution of Air Interface Towards 5G. So, we have been discussing the Waveforms which Goes Beyond 5G which are expected to be in the next generation standards.

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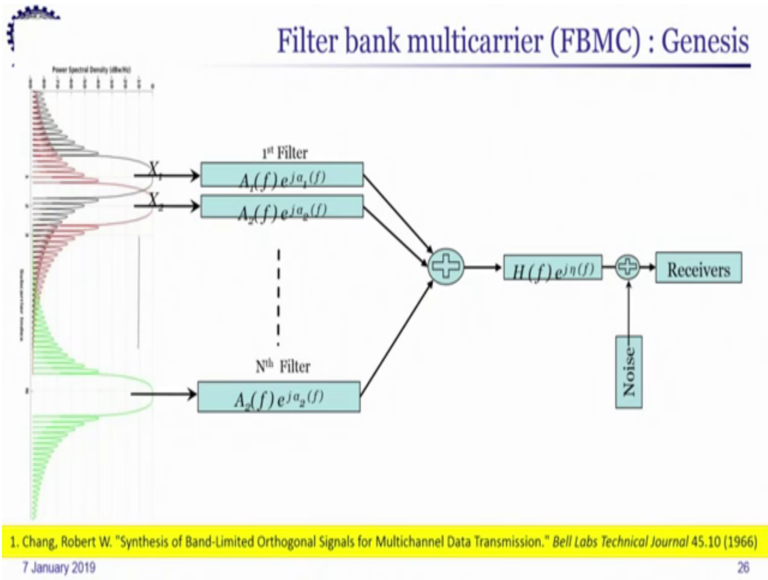

So, we have discussed filter bank multier air in the previous lecture, briefly speaking we talked about filtering each of the sub carriers.

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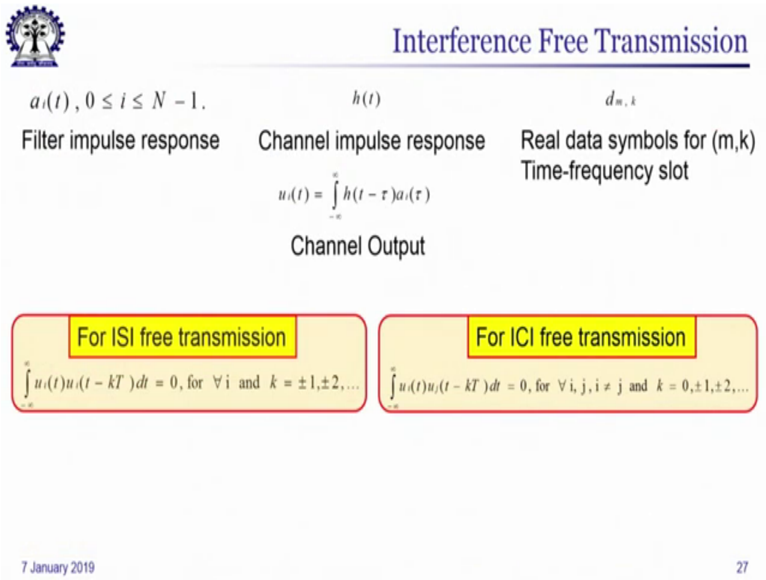

And we discussed the conditions under which one could design the filters and there were two conditions which were identified ISI free and ICI free.

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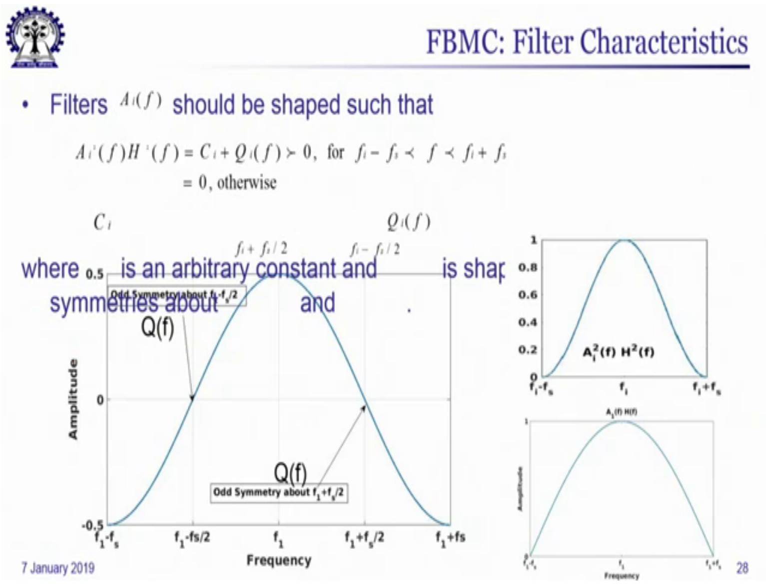

And it was also shown about the different conditions that come up to meet these two different requirements.

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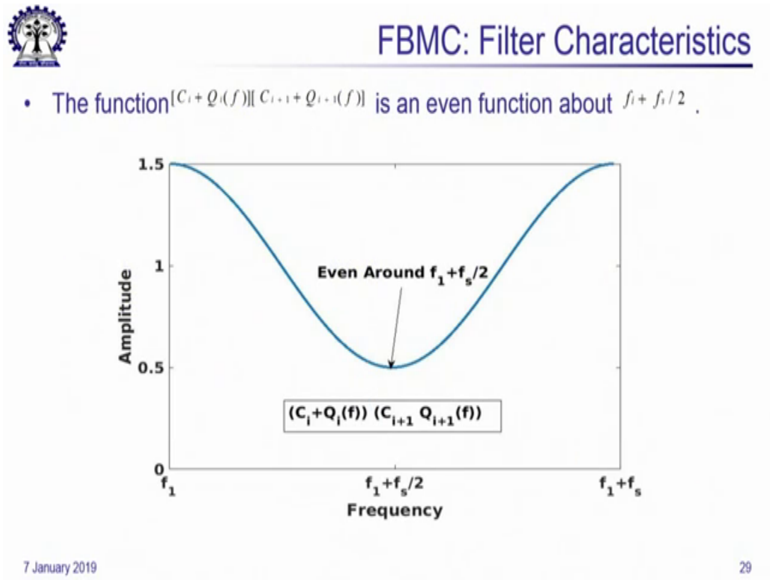

And there was some kind of symmetry which was brought out as the necessary properties of the filters.

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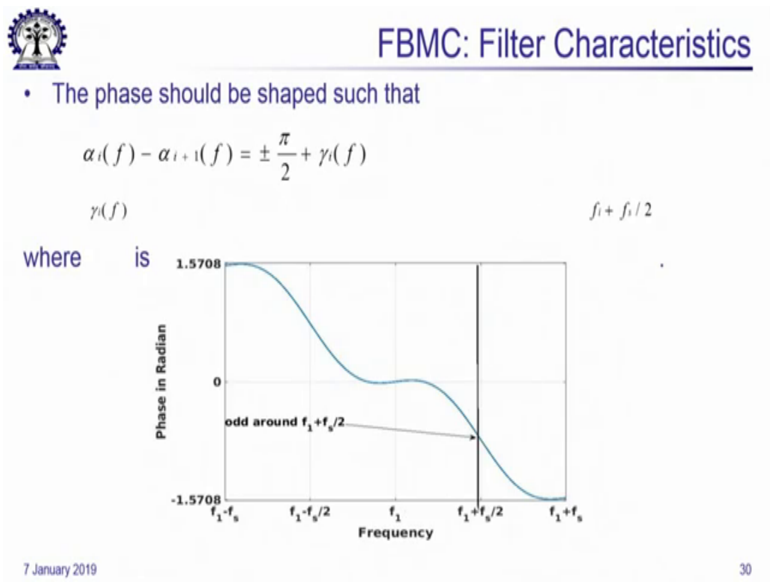

As well as there was some kind of shape structure for the phase difference between the neighbouring sub carriers is also pointed out.

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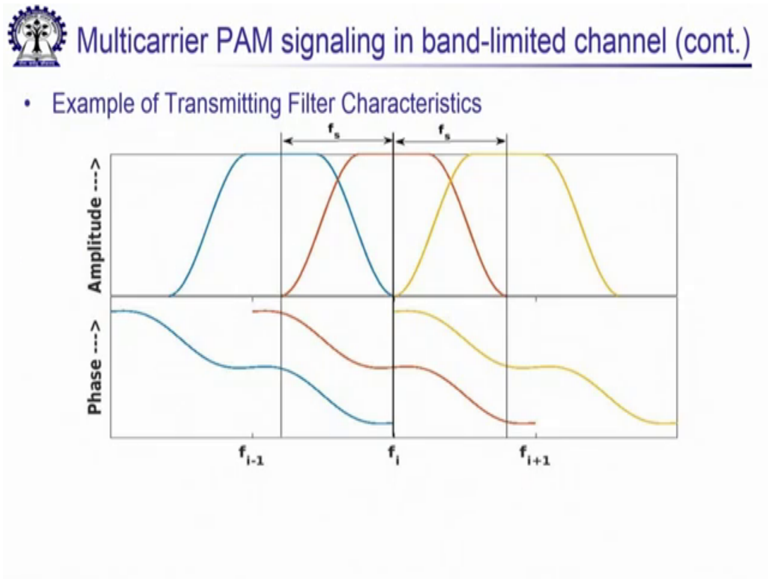

And typically what would be the amplitude and phase response would look like for a filter bank multi-carrier was discussed.

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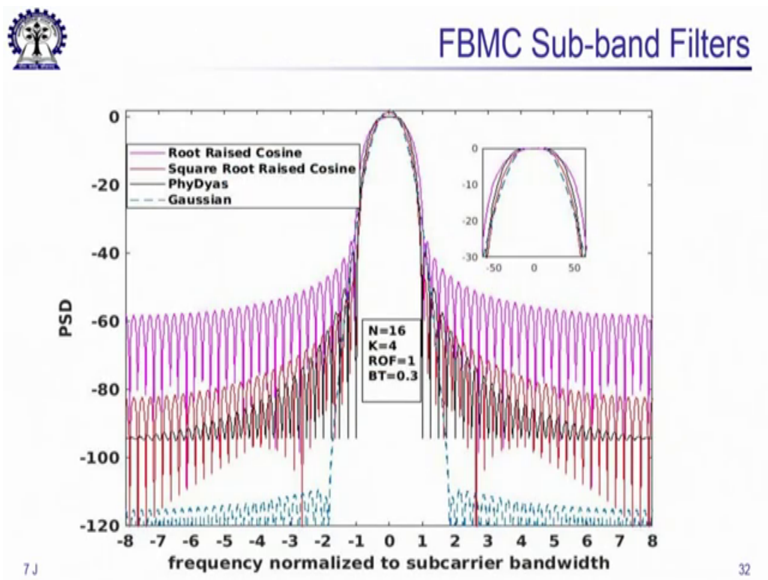

And finally, the different pulse shape or the filter characteristics that are to be used were also described and how they compare against each other was discussed.

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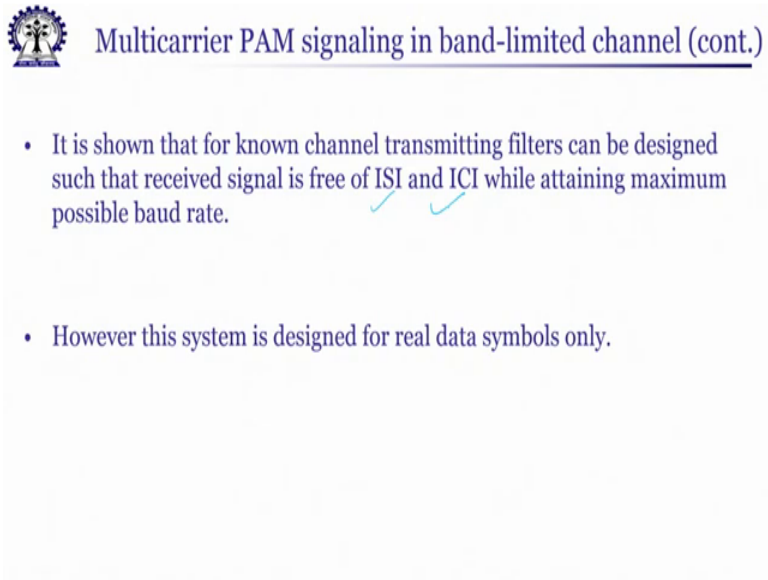

And in the conclusion, it was shown that by means of the different methods it is possible to have ICI free and ISI free communication system if one appropriately designs the filter based on the conditions which have been arrived in this particular session.

So, then we said that we move beyond the FBMC and see some of the other structures which exist.

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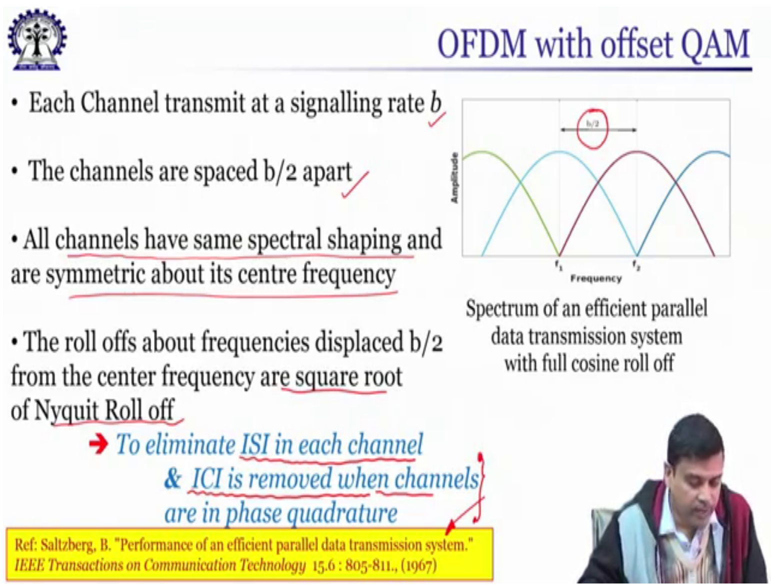

So, one of them what we look at is OFDM with offset QAM. So, for OFDM with offset QAM we would start off with the paper or we would mainly look at the work which was due to Saltzberg and that was again from 1967 and again we are pointing out that these may be very old classics, but they contain the foundation for the work that is being still done or that invokes interest in the new generation communication system. So, in this setup what was proposed is that the channel transmission signalling rate if it is defined as b and the channels are spaced at b by 2 apart. So, that is what you can see that b by 2 apart ok. So, that is what is pointed out and all channels have the same spectral shaping. So, this was variant and symmetric about its centre frequency.

So, variant in the sense that we will see certain structures where one could go beyond this and we will see what are the outcomes, but as of now this remains with the structure that they all have the same shaping that is not a problem that is kind of pretty fine and the role of about the frequency displaced b by 2 from the centre frequency is square root Nyquit's Roll off right. So, this is these are some of the conditions and these give rise to eliminate ISI in each channel; that means, each subcarrier and inter carrier interference is also removed when the channels when the channels are in phase quadrature. So, this is another part which is critical for us to review. So, this gives us a different structure and finally, this also satisfies the earlier criteria and let us see what do they mean finally.

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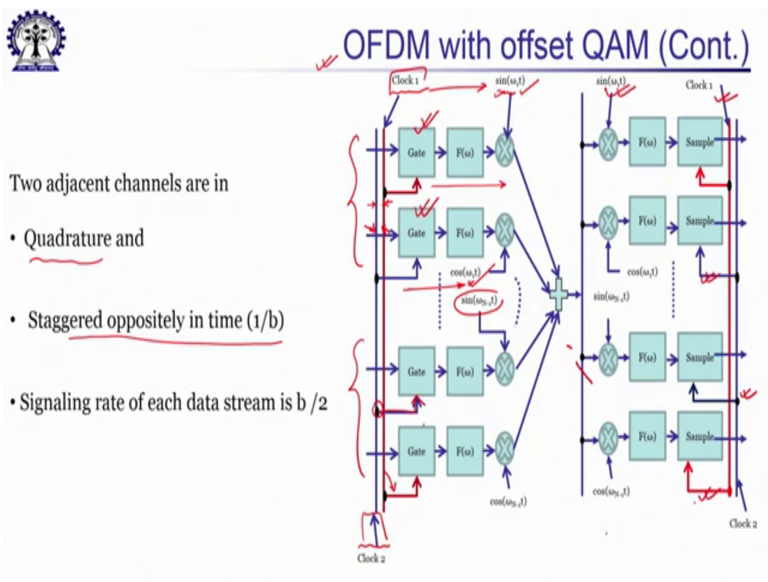

So, what we see over here is that there would be two adjacent carriers which are in quadrature right, so we have a sine and we have a cosine. So, these are the two adjacent carriers in quadrature and they are staggered oppositely in time with 1 by b. So, what you see over here is clock 1 in the crimson or reddish colour that is given over there and clock 2 is driving the other line and the first line is going to one of the carriers which is at which is in sinusoid and the other one is triggering the quadrature carrier. So, basically they are staggered oppositely with 1 by b difference. So, what you see is that one of them is sine, the other is cosine which are quadrature, but they are staggered and the difference is 1 by b and the sampling rate of each of the data stream is b by 2 because it is similar to offset QPSK if you have studied offset QPSK only thing is that it is extended to multicarrier right.

So, what we also find is that there is an oppositeness in it; so; that means, in one series you will find the sine being triggered by clock 1 as over there, but in the next one you will find that the carrier with sinusoid is being triggered with clock 2 as you can see over here. So, this line is triggering this one right with sinusoid and hence the corresponding cosine will be triggered by clock 1 right. So, this is kind of alternate whatever happens over here alters over here, and the sine and cosine are at offset with each other and the neighbouring carriers are with sine and cosine.

So, then the gating pulse is of course, used as typical gating pulse. So, this way one would be able to realize the offset QAM and all the advantages of offset transmission techniques we have discussed quite earlier would apply to this. So, this only helps us in extending the offset QAM transmission methods to OFDM and hence one can try to get the benefits of offset coming offset QAM communication on multi carrier systems.

The receiver as we can see is the exact opposite of it. So, what whatever is happening at the transmitter it has to follow in the same structure, but in the reverse order. So, basically sine goes with clock 1 in the first channel and cosine goes with the clock 2 and in the next one it is the reverse; that means, sine goes with clock 1 and the cosine goes with clock 2, right. So, that is the standard processing that has to happen at the receiver and one would be able to decode the signals.

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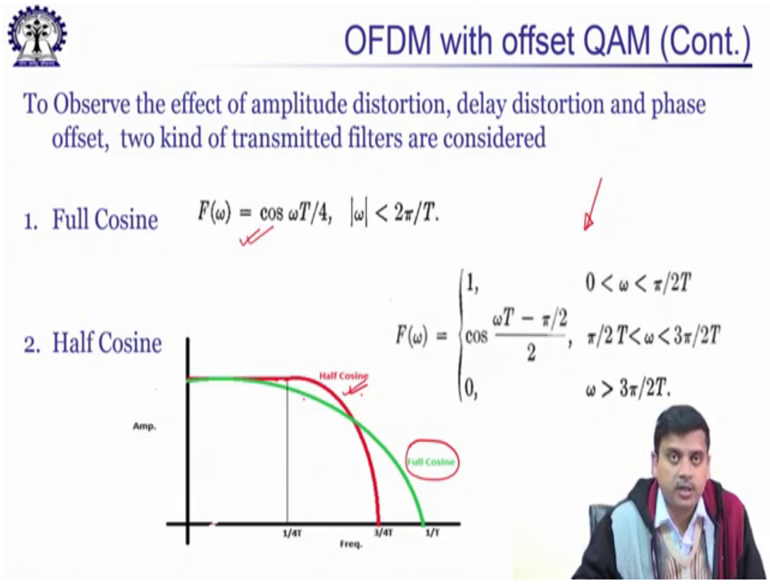

So, to observe the effect of amplitude distortion, delay distortion and phase distortion on or phase offset two kinds of transmit filters were conceived in the work; one is the full cosine as described over here. So, this is the full cosine curve that is the green in colour and the other one is the half cosine which is described over here in the frequency domain and that is as per the red coloured curve in this picture which describes the frequency characteristics of the two filters.

So, let us study or see the impact which has already been analyzed and accordingly one can choose, the different filter structures or the filter shapes as per the need.

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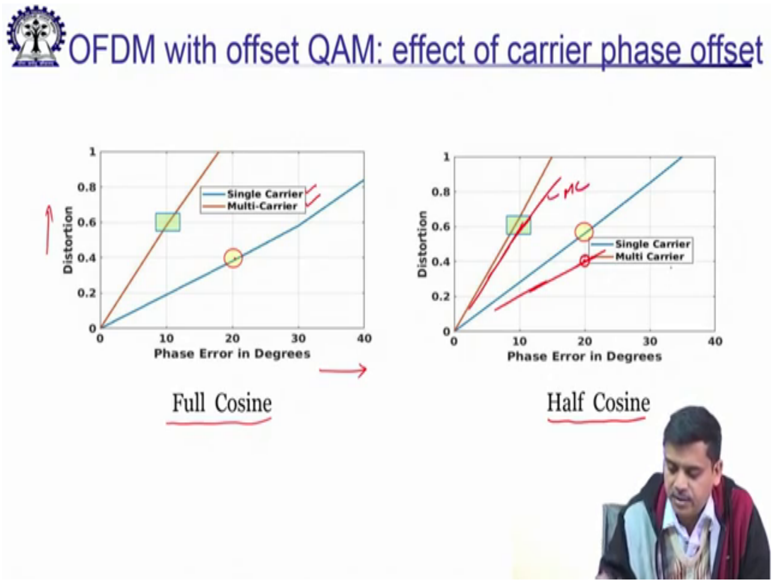

So, what we find over here is there is a comparison which is made between a single carrier and a multi carrier system and in this it is the phase error and this side it is the distortion and two curves have the same x axis and y axis as you can see, but on the right hand side it is the half cosine and the left hand side it is the full cosine. So, if we try to compare the effect on the single carrier system what we find is that this point which is corresponding to this point over here, the half cosine has a worse distortion for the effect of carriers phase offset on single carrier system.

Now if you look at the multi carrier system there is a slight better performance in the full cosine, because full cosine would be somewhere here right. So, the full cosine curve would follow this line somewhere like this if we compare against each other right. So, that is a somewhat better in that sense right. So, full cosine is going like this for single carrier this is for multi carrier right as given in the index.

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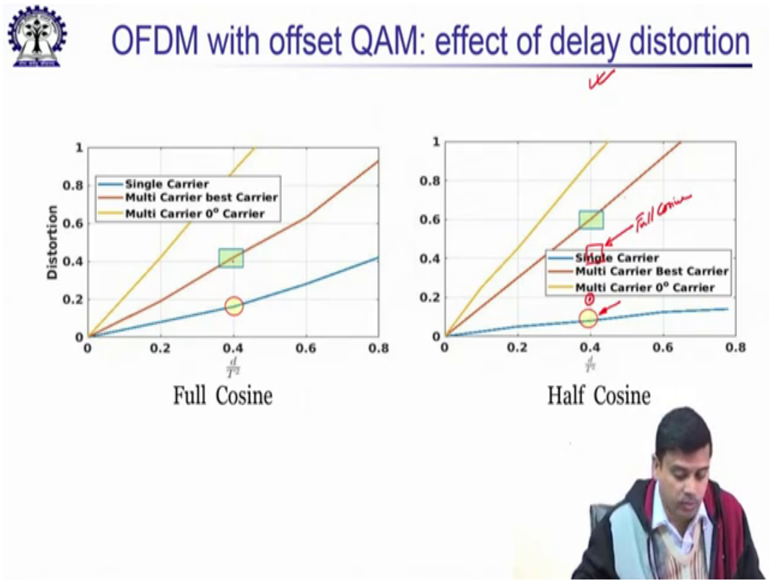

So, now if we move ahead further and see the effect of delay distortion again we will compare the full cosine and half cosine. Filter characteristics, what we find is that the half cosine has a better performance on the single carrier system right. So, we have the single carrier performance over here. So, if we bring the full cosine performance, the full cosine performance would be somewhere there. Now if we compared the multi carrier, the best carrier case, so, the full cosine is somewhere there; that means, it would be somewhere around this point ok.

So, here what we see is that the full cosine is better for multi carrier and half cosine is better for single carrier under the delay distortion case. So, depending upon the application one has to choose the appropriate one and this is of course, for the best carrier. For the 0 degree carrier again the performance there is a performance difference. So, one has to see what criteria one chooses and accordingly one has to choose the pulse shape for this system.

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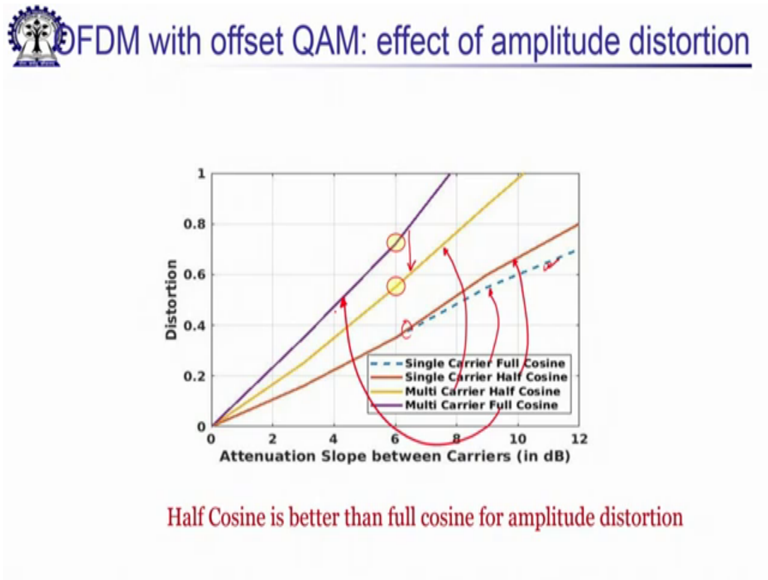

Finally what we see over here is the amplitude distortion. In the amplitude distortion we have the single carrier full cosine which is given by this and the single carrier half cosine is given by this. So, up to a certain amount of attenuation there is not much difference, but beyond that what we find is that for single carrier system the full cosine performs better. Now if we compare the multi carrier systems what we will find is that the half carrier has a distinct advantage over the full carrier in terms of distortion this is the half cosine and this is the full cosine. So, the full cosine has more distortions. So, depending upon what is important one has to choose the appropriate filter shape in order to get the right performance ok.

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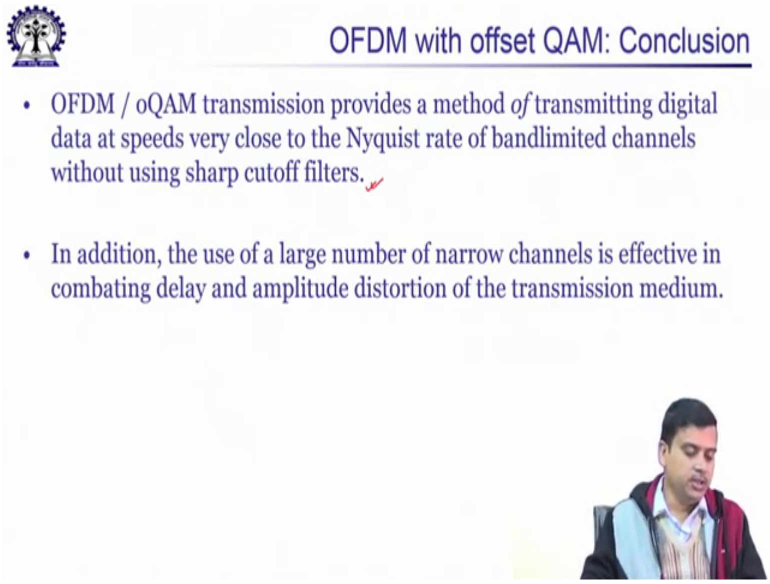

So, what we find in this particular study is that OFDM with offset QAM transmissions provide a method of transmitting digital data at speeds very close to Nyquist data rate of band limited channels without using sharp cut off filters. So, we find another method of doing the same and in addition the use of large number of narrowband channels is effective in combating delay and amplitude distortion of the transmission medium.

So, these are some of the requirements and they also meet the criteria provided by the other work that we are studied before. So, we have at least two different ways of realizing a multi carrier system which has good characteristics in terms of out of band and most of the works beyond this build on the platform which have been developed a with these particular works.

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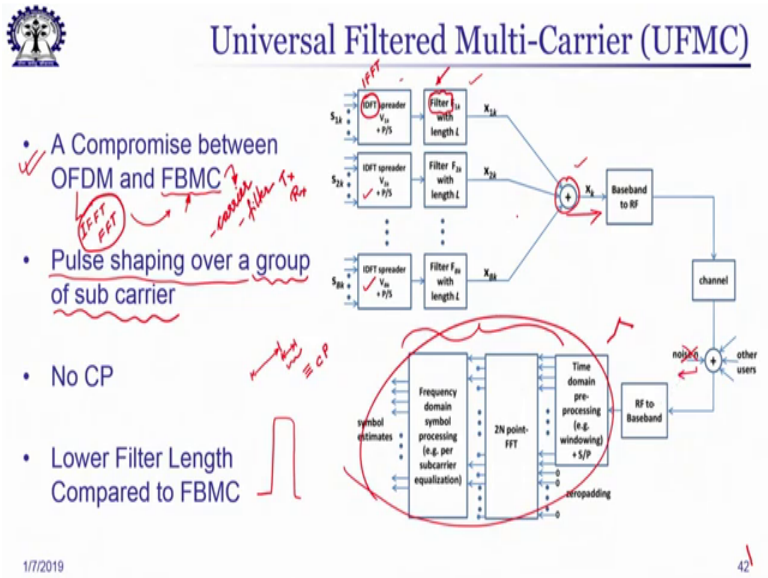

So, with this we move on to the next important architecture that was also studied as a contending wave form in fifth generation system and they were being selected and they also have very good characteristics and as said we do expect that they would still carry on to evolve or mature and they may be replacing the existing numerology or the adaptive subcarrier bandwidth based OFDM system which is currently accepted as the standard for 5th generation.

So, what we see in the universal filtered multi carrier structure it is a compromise between OFDM and FBMC. So, that is one of the things. Now if you look at OFDM and FBMC essentially has a large number of carriers and each carrier has a filter associated with it and this operation is to be done at the transmitter as well as at the receiver, whereas, OFDM replaces the entire set of operations with FFT structure with IFFT at the receiver and IFFT at the transmitter and FFT at the receiver.

So, the order of complexity of OFDM is significantly lower than that of FBMC although both can maintain orthogonality criteria. The advantage of OFDM sorry, the advantage of FBMC is that it maintains a pretty narrow out of band or low out of band signal leakage compared to OFDM. So, this unified universal filtered multi carrier is an attempt which reduces complexity to some extent and brings in performance of out of band which is better than that of OFDM system. So, it is somewhere between OFDM and FBMC both in terms of complexity as well as in terms of performance.

So, the characteristics are the pulse shaping is done over a group of subcarriers. Remember here in FBMC we talked about each subcarrier undergoing pulse shaping here it is reduced unlike OFDMCP is not there because OFD; FBMCCP is not there and typically when you do filtering your length of the signal increases. So, whatever is the length of your original signal it would increase by the length of the filter and hence, one has to accommodate this extra length. So, this can be comparable to the extra length of CP as is used in OFDM and hence no additional CP are usually encouraged, but if one wants one can do it, but that will obviously, reduce the spectral efficiency.

Now, the filter length usually selected is usually lower compared to FBMC because in FBMC you have per subcarrier and you have really narrow band filters whereas, here you have a compromise. So, essentially the filter length is smaller and hence you would also expect naturally that the out of band radiation or outer band leakage would not be as good as in FBMC. It will be a little bit worse, but maybe better than OFDM because you are pulse shaping over a group of subcarriers. Now in OFDM, you essentially do pulse shaping, but that is over the entire set of sub carriers. So, it is again coming in between.

So, let us see what do we have over here. So, there is IDFT operation which is corresponding to the IFFT operation right. So, that is like the OFDM system and then there is a filtering. So, this filtering operation is the one which actually does this pulse shaping over a group of sub carriers right. And you do them over multiple such bands or blocks and the entire thing add up together and send for transmission. The receiver side is of course, the reverse operation, but there is slight change because there is a speciality processing which reduces the signal processing complexity and we will see that in the lecture now.

So, moving further we need to remember this architecture that we have drawn over here there is IDFT or IFFT followed by filtering and then there is addition.

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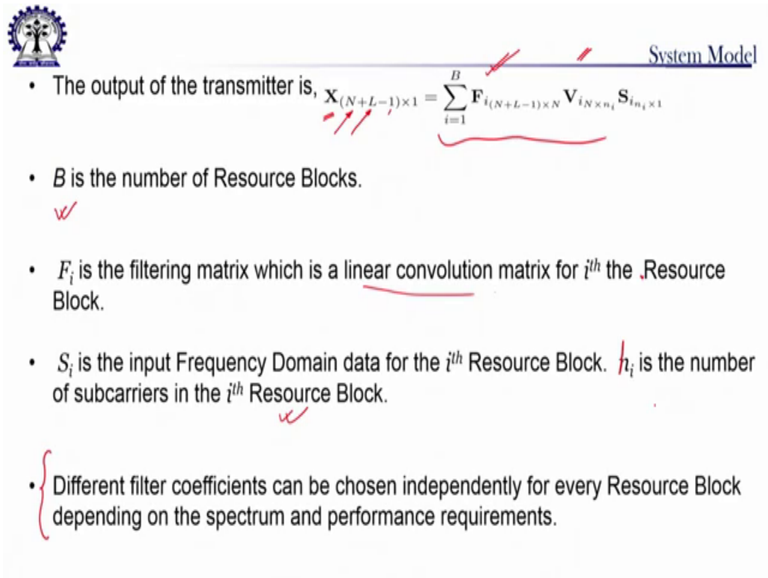

And what we see is that the output of the transmitter can be written as X of length N plus L minus 1. N is the size of number of subcarriers, L is the filter length and minus 1 because after convolution you have one unit less and Fi is the filtering matrix. So, you can operate it as a matrix and Si is the set of sub carriers that are to be used in the blocks and then we have the data part. So, we have together the entire set of signals that needs to be processed and B is the number of resource blocks ok. So, F is the linear convolution matrix as we can clearly see. S i is the input frequency domain data and n i is the number of subcarriers for the ith resource block.

So, that is how this whole thing is structured that you can clearly see as compared to this particular picture all right. So, then the different filter coefficients can be chosen independently for every resource block. So, this is different compared to what we have in the previous structure.

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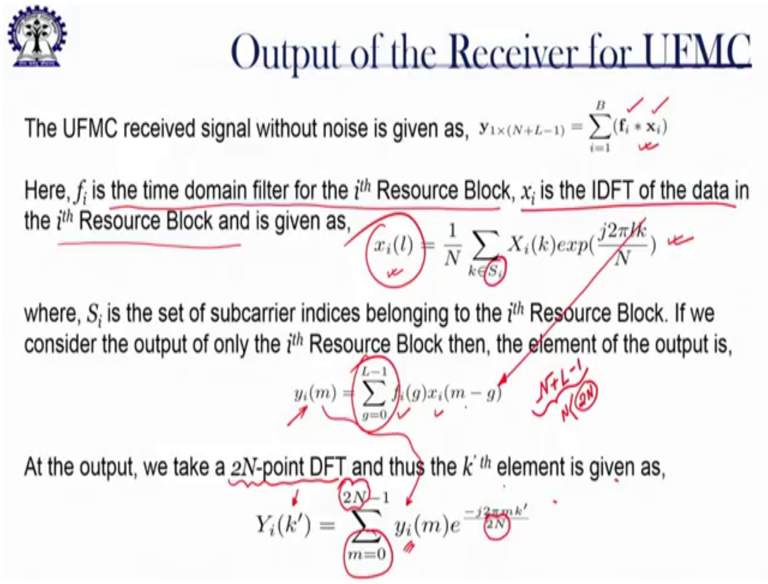

So, now moving further what we see is that the UFMC received signal without noise is basically f i convolved with the signal x i and x i is the time domain filter for the ith resource block and x i is the IDFT of the data in the ith resource block. So, this is the time domain representation in a linear convolution form whereas, previous it was in the matrix notation form all right. So, what we have x i is given as since it is the IDFT you can clearly see the IDFT expression that is over here and s i is the set of subcarriers, subcarrier indices belonging to the ith resource block.

So, each block has a certain set of subcarriers and if we consider the output of the ith resource block then the element of the output would be f i x i and this is this convolution operation that you are seeing. This convolution operation is simply expanded over here, nothing else that same operation and at the output. So, now, this is at the receiver noiseless receiver. So, we are talking about the noiseless receiver structure. So, forget noise because we want to establish the receiver structure and once we establish it whatever noise would come in has to be accepted.

So, what we see is at the output you take a 2N point DFT instead of taking a standard N point DFT. One way to look at this is that instead of having N point you now have N plus L minus 1, so many points. Since we have N plus L minus 1, we need to have 2 N which is greater than N to take care of all the points that is one of the ways of looking at it. So, if you take a 2N point DFT and then the k prime-th element because we need to look at how this is helping us would be y i whatever signal you are getting and e to the power of minus j 2 pi m k prime because we are talking about the k prime-th element and you are seeing the 2N in the denominator indicating a 2N point DFT and of course, you have a 2N in the summation also indicating a 2N point DFT operation right.

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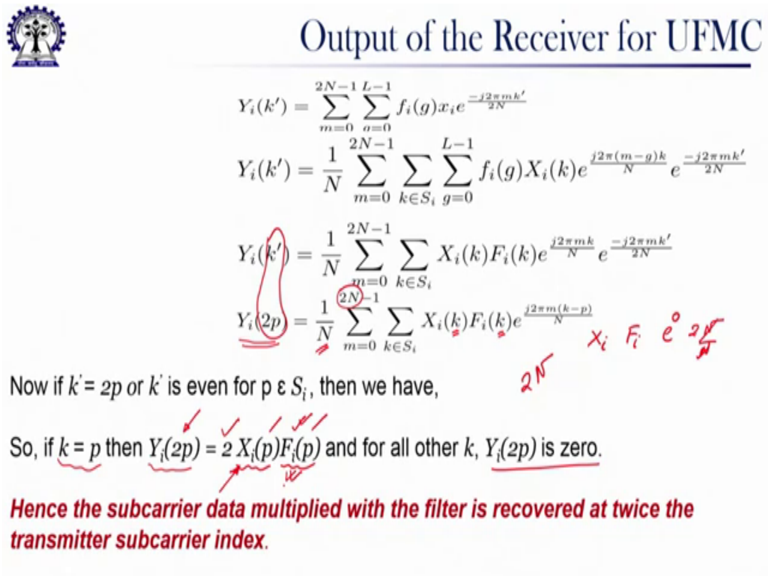

So, then as we as we see this expression y i, so, you can expand y i in terms of the equation here ok. So, you are going to replace y i which is here in terms of f i and x i and then you have this summation of g equals to 0 to L minus 1 which comes in additionally in this particular expression right. So, whatever is here is now included in this particular equation and then what we have over here is x i is getting replaced by the IDFT of capital Xi that is also available over here. See whatever is x i present in this particular expression you are using that expression over here and you are having this summation over the particular set of sub carriers which are of your interest, and summation over m is continuing. So, this summation over m is here this summation over m is here and this is the summation over g. So, all the components are now in place.

So, now you could also replace this f i of g with this particular operation that you are seeing here along with g over here that you are seeing by its corresponding Fourier transform or DFT operation which indicates capital F i of k right. So, basically you have a X i F i and then you have rest of the terms m k term over here and m prime m k prime term over here and this particular operation leading to the DFT of F i which is the filter transfer function. And then by manipulating this or working on with the terms what you find is that what you get over here is X i F i and all the terms accumulated here, you can bring it over here and instead of putting k prime you are using the variable p over here to make the terms appear better. So, we will see what do we get for p.

So, what we have over here is k prime is equal to 2p. So, if k prime is equal to 2p then you get it if you put 2p over here 2 and 2 cancels. So, you have the denominator as N which is matching over here as the denominator of N and then k comes over here and p comes over here right. So, that is how we get the expression. So, for, so, our k prime is even for p belonging to this sub carrier set. So, this is to be remembered.

So, if k is equal to p; that means, if you have k is equal to p in that case Y i 2 p k prime is equal to 2p ok, that is what is there. So, if k is equal to p Y i 2p that is Y i 2p that is what we have over here, what we get is if you put over here k is equal to p these whole terms cancel out because just let us look at this remove these terms and you take the pen. So, if k is equal to p you are going to get X i F i e to the power of k is equal to p this is 0 ok, and the summation. So, when you have the summation you see the summation is over 2N right.

So, basically you are going to get 2N terms denominator there is 1 N term. So, basically you get this 2 term. So, that is why you have this 2 factor and k is equal to p, k is equal to p. So, k is equal to p k is equal to p; so, X i p and F i p right. So, that is what you get.

So, what we see is that in the even indices you get X i p times F i p; F i p is known. So therefore, we can easily decode X i p which is the transmitted data and for all other k, Y i 2p should be equal to 0. So that means, in order to decode we must do a 2N point DFT at the receiver that is what you see 2N point DFT at the receiver and one must decode at the even subcarriers. See if one decodes that even subcarrier then one gets the desired signal with the corresponding filter coefficient since the filter coefficient is known one would be able to recover the data signal as it is.

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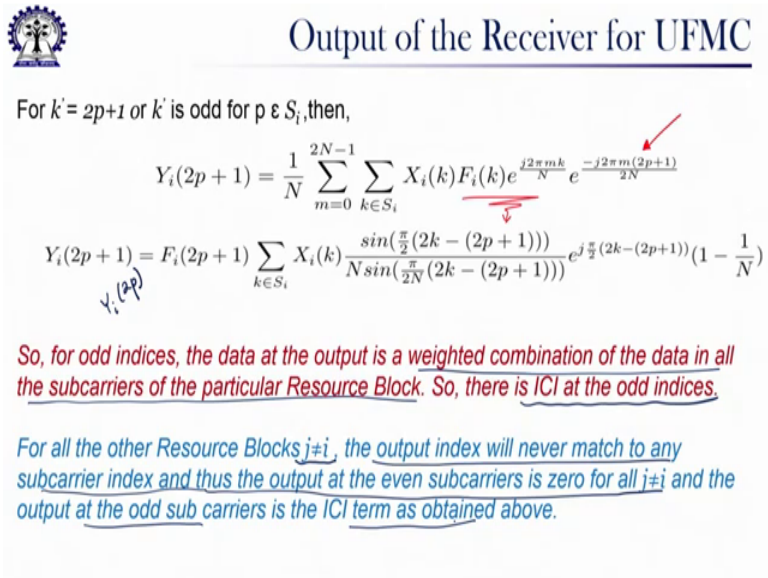

So, for k prime equals to 2p plus 1 or k prime equals to odd for p being element of these sub carriers what we see is that Y i 2p plus 1 is has an expression where you would put over here 2p plus 1, earlier we had put 2p and that 2 and these 2 had cancelled, but now that is not going to happen right. So, that is not going to happen now and you are going to evaluate these terms. If you evaluate these terms and get into some things what we will find is that it becomes a weighted combination, the weighted combination of all data in all the sub carriers of the particular resource blocks. So, there is ICI at odd indices right. So, since there is ICI at odd indices this is of not much use for us and we are only concerned with Yi 2p and we will decode our data.

So, what we see is that for all other resource block j not equal to i, the output index will never match to any of the subcarrier index and thus the output of the even sub carriers is 0 for j not equal to i. So, this way one can decode the UFMC signal and at the output of the odd sub carriers one finds the ICI terms as obtained above right. So, if one follows through the step 1 would be able to regenerate all the things.

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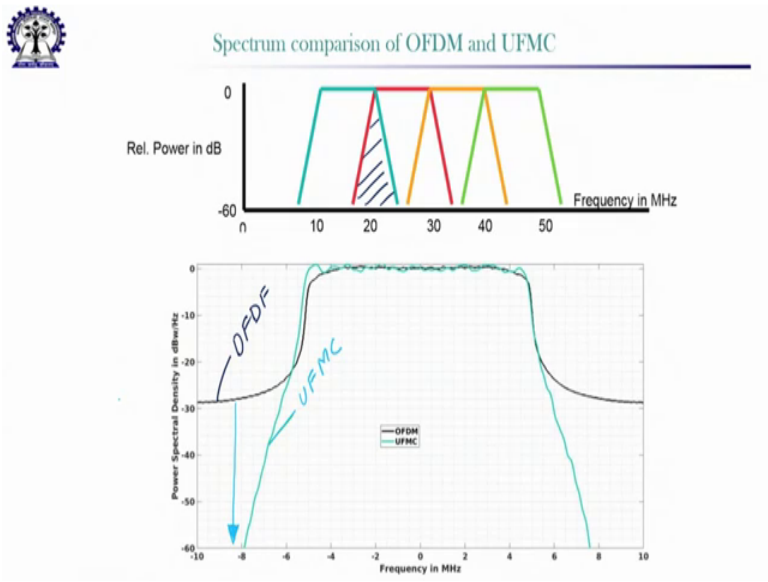

And then what we find is that the spectrum, one could be able to generate the spectrum with out of band characteristics as shown in this figure. So, once again what we find is that there could be overlap that is possible; so that means, efficient spectrum usage is possible and in this line and in this figure this black one is for OFDM and the slightly greenish bluish colour this one is for UFMC is for UFMC. So, what we find is that because we are kind of filtering and filtering a group of subcarriers, therefore, we are able to reduce the out of band leakage by a significant margin when compared with OFDM.

The complexity is also not very high as compared to OFDM and the performance is going closer towards FBMC and this is somewhat realizable in all terms and hence this makes a good candidate. The only problem that we have over here is there is no CP. So, managing the inter symbol interference is one of the factors and that needs to be addressed appropriately ok.

So, with this we bring this particular lecture to an end where we have come considered at least two signalling mechanisms. One is UFMC which is a universal filtered multi carrier and we have also seen offset QAM OFDM which is an extension of the earlier version of filter bank multi carrier and essentially what we are focusing on is waveforms which have characteristics especially in terms of out of band leakage we are much superior to OFDM, but the constraint that we found in FBMC is that the complexity is becomes very high because you have to have N number of filters and N number of paths at the transmitters, similarly N number of paths at the receiver and trade off between these two would be UFMC which has complexity somewhere between OFDM and FBMC and out of band leakage performance again between OFDM and FBMC to a desired performance limit.

In the next lecture we will discuss the generalized frequency division multiplexing which is again another contending waveform for the 5th generation as well as we hope it continues to remain and become mature even better because lot of work is still going on with GFDM. So, that it is able to provide all the facilities and bring in all the features which are required in the next generation system. So, in the next lecture we will talk in more details about the GFDM or generalized frequency division multiplexing.

Thank you.