Evolution of Air Interface towards 5G
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Lecture – 28
Waveforms Beyond 5G (Filter Bank Multicarrier)

Welcome to the lectures on Evolution of Air Interface towards 5G. So, we have been discussing several Waveform technologies and we have presented the one of the earliest forms of the 5th generation waveform which is called the 5 GNR and we described it in terms of variable subcarrier bandwidth or redaptive subcarrier bandwidth which we discussed earlier, as seen in this particular picture.

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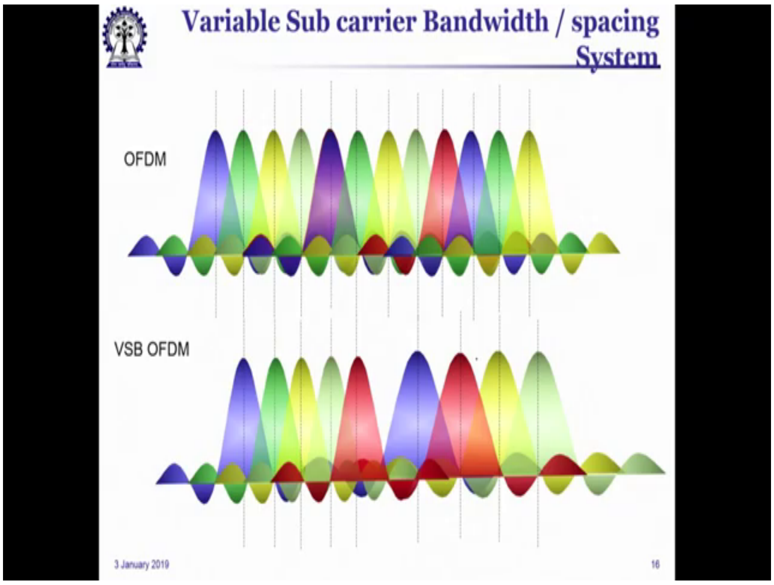

We have described various forms of it and then we moved across to the different architectures of realizations thereafter we would shown the different gains.

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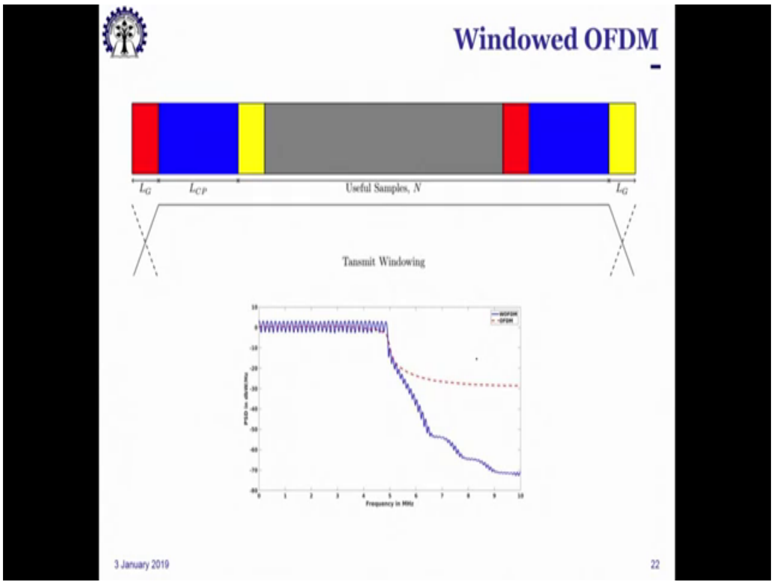

And we also started discussing about the various other forms of OFDM which are not typically yet part of standards, but as the course requires that we also discuss things which go beyond the existing set of things.

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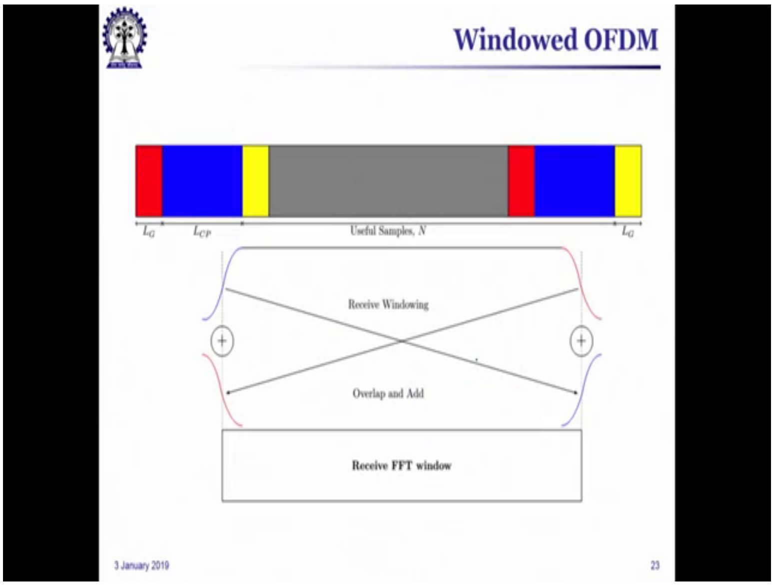

So, we discussed window OFDM as one of them and we described how it is done in the previous lectures this is just a summary.

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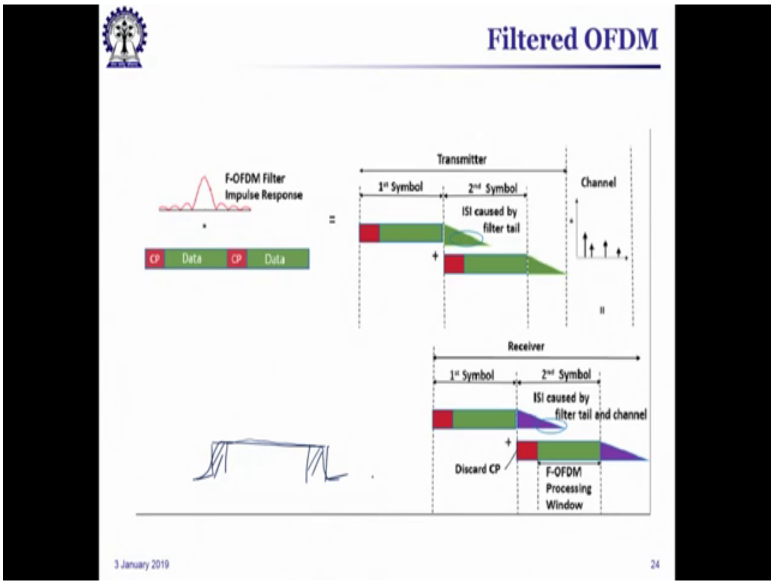

We have also talked about filtered OFDM and we have also described the issues and associated factors with it. And primarily these are all variants of OFDM and these filtered OFDM if we look at it or the windowed OFDM whatever was there one may consider the fact that that typically any OFDM system. I mean probably this I had mentioned earlier also is one where one considers a rectangular pulse shape. But if you take any commercial OFDM system and you look into the standards you will find that of course, this is the CP, that there a is some kind of a windowing which naturally happens without which you cannot generally send out the signal.

So, although these have been proposed in literature as separate techniques, but these those are all pretty similar to OFDM and minor variations or probably more realistic implementations of things especially the window OFDM, but when we talked about filtered OFDM this is a again a slight variation where you do time domain filtering which is equivalent to having a window in the in the frequency domain. So, these are duals of each other in one case you do windowing in time and which appears as filtering in frequency the other case is filtering in time which appears has windowing in frequency.

So, then after this we move on to the next set of waveforms as we had said earlier, that these waveforms as we will be discussing now onwards are future generation waveforms and that these waveforms have not yet been accepted, but they have a high chance of getting accepted in future generations and one strong reason is that they were contenders for 5G they many people worked on it and they were discussed heavily. And for some various reasons it was decided that these waveforms probably require even more maturity, especially with respect to backward compatibility and hardware complexity and realization factors.

So, variant of OFDM which is the adaptive subcarrier bandwidth or variable subcarrier bandwidth is accepted one prime reason was it’s prime resemblance with OFDM and it could be controlled or realized by simply changing of parameters and hence the new name was assigned numerology. So, now, we move on to other waveforms which are important to be learnt to be to be looked at as future generation versions of multi carrier systems.

So, what we have here is a multi carrier structure we described earlier how these different schemes do come under overall group of multi carrier combinations for multi carrier communications and we are talking about filtering then there is a bank of filters. So, let us look into the details of it.

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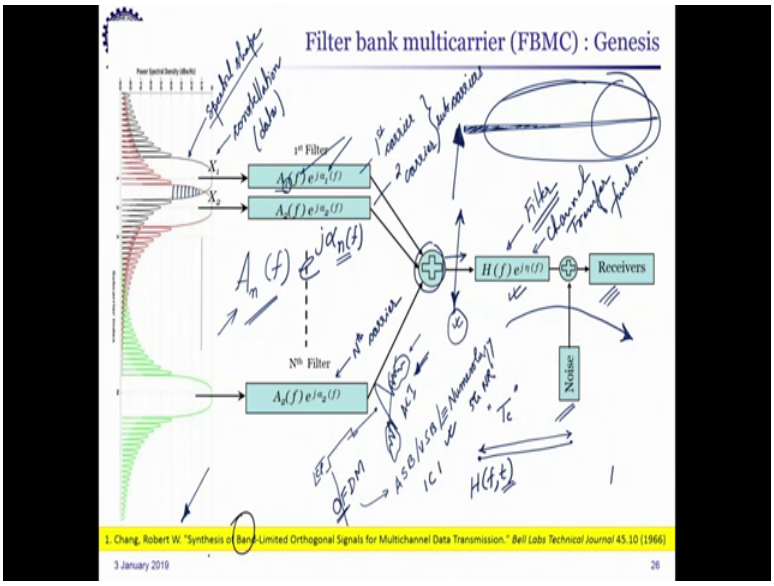

So, in case of filter bank multi carrier what we see is that there are different carriers. So, this could be first carrier, this is the second carrier rather these are sub carriers if you put the name sub carriers, then it makes more sense and this is the Nth carrier. So, these are all a typical like the frequency division multiplexing systems and in case of OFDM we have said that there is a orthogonality factor which comes in, here things are slightly different.

And in case of OFDM we have also said one of the factors which contribute to orthogonality is the rectangular pulse shape along with a CP in front of it but here things are going to be different then what we had discussed earlier. So, amongst several reasons why these are considered are the OFDM because of it's rectangular pulse shape in time domain, in frequency domain generates a sinc which also we had mentioned and sinc as you know the sinc function has pretty high side lobes. So, there is adjacent channel interference which is pretty strong, but the good part is there is orthogonality, but again the reverse side of things is that if you lose orthogonality then there is a big problem.

And that is one reason which gave rise to adaptive subcarrier bandwidth or variable subcarrier bandwidth and with got the name numerology in or 5G NR right. Now those are all good, but still they have their own issues with respect to this adjacent channel interference which is still not addressed although the ICI is addressed in this mechanism, but this still remains to be addressed.

So, one of the competing waveforms the filter bank multi carrier as it is known what we see is that, each of these carriers that we have identified carries these complex constellation points or real constellation points these are basically constellation points or data right picking from the constellation and each of them are filtered. So, what you see is that this is the spectral shape of each of the carrier's right.

So, each carrier is spectrally shaped and sent out and they are next to each other there is overlap as you can see there is overlap between the sub carriers and each carriers filter is designated as A with a sub index and there is f indicating the frequency domain and there is a phase component associated with it e to the power of j alpha sub 1 f. So, in general it is A n you can say it's the Nth one f e to the power of j alpha n of f right that is the general form, but this is the amplitude response and this is the phase response and all of these get added together and they get added together and then they are sent out into the channel, when it goes into the channel the channel is also represented as a filter.

So, channel can be represented as a filter this is the frequency domain representation of the channel noise gets added at the receiver end or AWGN is also present with that and then you have the receiver processing. So, this is a generic structure in case of OFDM you can think of the filters as the ones which have a kind of sinc structure, but here it's a more general one and one needs to find about these things.

So, although these are contending techniques for the 5th generation we have pointed out or have identified the literature which is the starting point of these things this is the 1966 paper were by Robert Chang and the title is synthesis of band limited orthogonal signal for multi channel data transmission. So, again we are trying to point out the fact that although there are newly termed as filter banks and their 5G and they will get new names it's very very important to go back to the starting point to the genesis of where these things started. So, that you get a sound foundation of how to build such systems.

So, we have highlighted the earliest paper it is in bell labs technical journal 1966 you can download the paper and have a look into the details of it we will present a summary of what is given there. So, in all of these now the question that remains to be addressed is what should be the filter design? So that the received signals remain orthogonal; so now, the whole problem or the question gets framed.

In OFDM it is made orthogonal by virtue of rectangular pulse shapes and cyclic prefix and integer multiple of wave forms. But here the question is in terms of the filter design. So, that the overall structure remains orthogonal.

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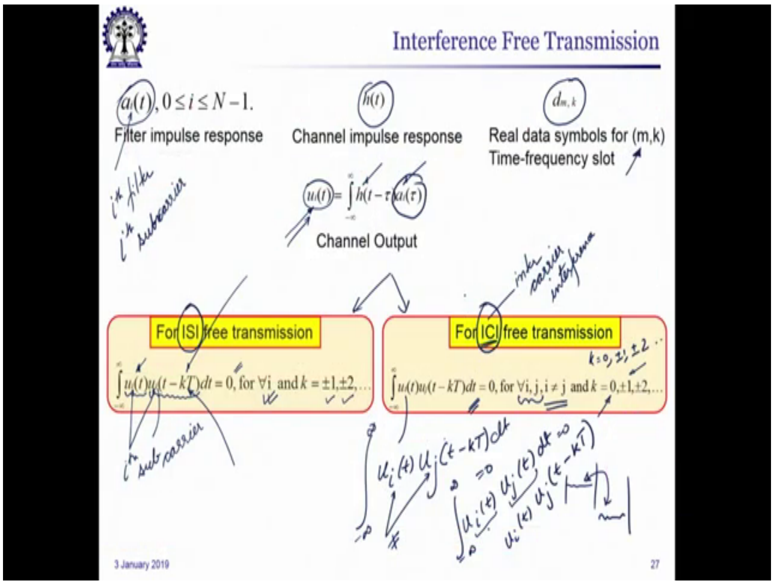

So, what we see is that the impulse response is given by a i t for each of the filter and the channel impulse response is given by h t and real data symbols are indicated by d m k for the time frequency slot indexed by m comma k right. So, the channel output in time domain can be given as u i of t that is the ith sub carrier here using the ith filter or the ith sub carrier and that is a convolution of the filter impulse response and the channel impulse response.

Now the conditions that are thrust into this by virtue of the requirement to find signals the filter design so that the signals remain orthogonal is translated to expression. So, for the ISI free transmission we see that the output which is u i of t u i of t what we have over here and u i of t minus kT. So, remember k indicates the frequency index sorry k indicate indicates the time shift and i is the subcarrier index.

So, what we find is that this should entire thing should go to 0 for ISI free transmission right and; that means, two symbols on the same subcarrier both are i ith subcarrier shifted in time; that means, two neighbouring symbols or any other symbols when it's integrated turns out to be 0; that means, no one has a component on the other one and this is true for every i and for values of k equal to plus minus 1 plus minus 2, k cannot take a value of 0 because then it would mean this thing and that makes no sense. So, k takes plus minus 1 on the either side of the signal so there is no inter symbol interference at all. So, that is one criteria for orthogonality.

The other criteria for orthogonality as we see over here is the one for ISI free transmission. So, yeah so that is for ISI free transmission just a second, yeah for ICI; that means, Inter Carrier Interference free transmission, so; that means, you do not want interference in time domain, you do not want interference in frequency domain and hence you are you require the whole thing to be orthogonal.

So, here when we translate these requirements of having orthogonal orthogonality, we have already translated one in the time domain if we look at the frequency domain, we find we have used over here u i of t right that is the output from the ith channel that is over here and u j which is the neighbouring or any other value of the subcarrier index t minus kT right.

So, this is the setup that we have taken integrate from minus infinity to infinity dt should be equal to 0 that is what is written over here for all i and j and i not equal to j this is important; that means, I and j should not be equal; that means, you are not taking the same subcarrier, hence you are talking about inter carrier interference right and for values of k this includes 0 as well and so for values of k equals to 0 plus minus 1 plus minus 2 and so on.

So, if you take the value of k equals to 0 you will be getting u i of t and u j of t integrate minus infinity to infinity dt being equals to 0. So, this is ICI on the same time domain symbol block, but if you take another value of k plus minus 1 you are taking the ith subcarrier and jth subcarrier of different symbols. So, u I of t and u j of t minus kT, so; that means, two different symbol.

So, that means, there is one carrier here in this time block another carrier in another time block, so there is no inter carrier interference between them as well. So, that encapsulate s the overall orthogonality requirement criteria for this particular system. So, now, we have stated the problem the rest of the part is to find out these filters.

So, once these filters have been identified which meet this criteria then you have actually solved this particular problem. So, this is the overall structure for filter bank multi carrier communication system, it’s a more generic than OFDM and that would also satisfy the requirements as it’s given over here.

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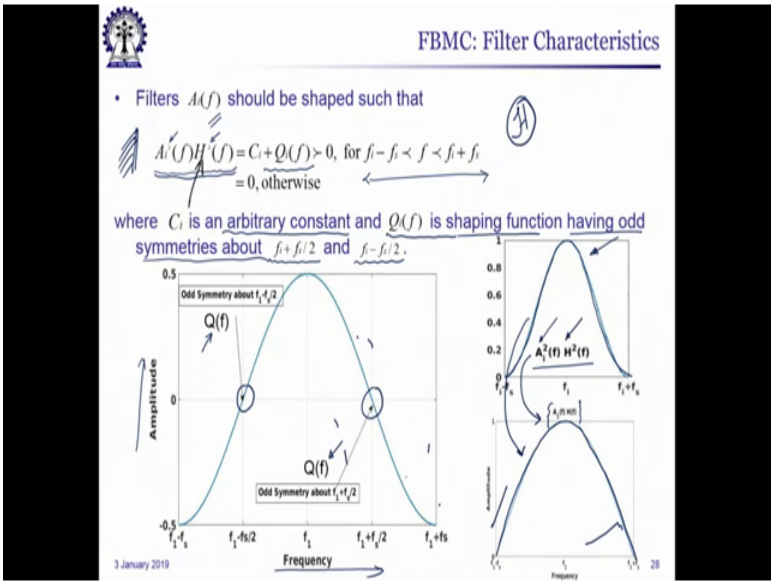

So, what we find is we are not solving it we are just simply taking it from that particular paper and for the sake of description and understanding the things. So, Ai of f which is the amplitude response of the filter, so what we see here is that A i of f is the amplitude response right this a n indicating the nth filter.

So, the solution that has been brought out in that particular paper is that A i f squared times H f squared and H f is the channel transfer function should be equal to C i which is some arbitrary constant and plus Q i of f which is greater than greater than 0 because these are all squared terms right, for a range of f which lies between f i plus minus f s as indicated over here and it is 0 otherwise; that means, outside this range it should be equal to 0.

Now C i is an arbitrary constant, but what defines this particular product is Q i of f which is the shaping function and it is said that it should have odd symmetries about f i plus f s by 2 and f i minus f s by 2, it's an outcome and we are going to use the outcome and we are going to see how does it look like.

So, if we look at the amplitude, so the amplitude versus frequency plot this is the frequency plot this is the amplitude plot. So, at f s plus f by 2 and f s minus f s by 2, we find that Q of f has odd symmetry right. So, this is what is the requirement and accordingly A i H f A i squared H f squared, where A i is the filter transfer function of the transmitter for the ith subcarrier and H f is the transfer function from the channel.

So, the product squared would have to look like the shape as given in this particular picture right, so it has to take the shape and then you get the orthogonality criteria. From this if you take the square root of this then you are going to get the product A i of f H f A I times H f; H f would be translating to the expression or to the to the filter whose amplitude versus frequency response would look like this right.

So, this overall summarizes the characteristics that are required, so if you design your filters with such characteristics then one can get orthogonality. Now one should keep in mind that this requires the knowledge of H; that means, the channel ok. So, if we go back and look at this whole setup we want the received signals to be orthogonal this is a criteria which one has to pay attention whereas, we are not restricting ourselves to orthogonality criteria over here. If we had restricted ourselves to orthogonality criteria over here, then we would not have taken the channel into account and we could not have commented on what would happen when the signal would go through such a channel.

So, this is a more generic one which says that given a particular channel now can you design the signal such that they are orthogonal at the receiver end. Now if one wants to get back to the situation where wants to find the orthogonality over here, then one can simply set the channel to be an ideal filter and one would get the criteria required at the transmitting end right that is that simple. So, this is more general and it is useful if I know the channel characteristics and it is especially useful, if the channel is going to remain constant over a certain duration of time.

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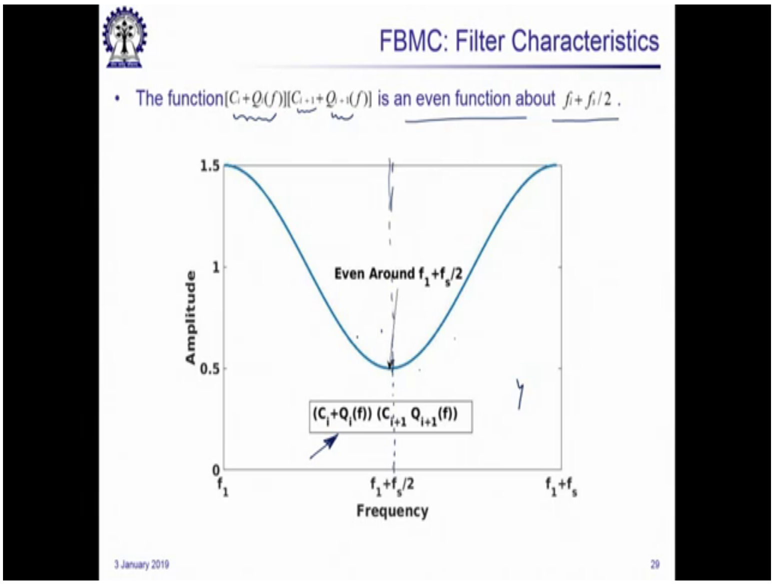

So, there are some more criteria that that comes up it also says that C i plus Q i of f which is basically here as you can see over here C i plus Q i of f which defines the amplitude function, amplitude squared of the filter as well as of that of the channel and the product of that multiplied by C i plus 1. So, this is C i plus 1 and Q i plus 1; that means, the neighboring one is an even function about f i plus f s by 2 right.

So, what we see over here is the response of Q C i plus Q i of f; that means, it is given over here it’s written over here the product function is described above has to be a even function around f i plus f s by 2. So, around this it is an even function so that is another condition.

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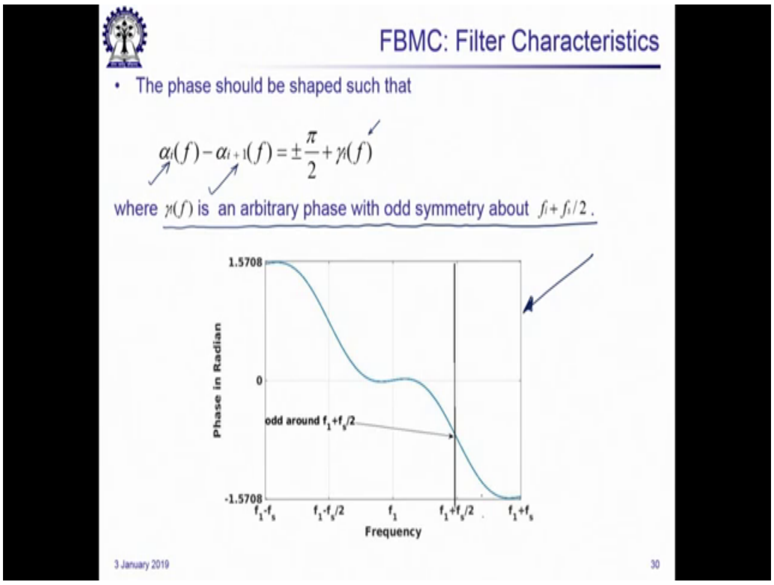

And finally, we get to see that the phase should be shaped such that alpha i which is the phase of the ith filter minus alpha i plus 1 that is the phase of the neighbouring one is plus minus pi by 2 plus gamma i of f where gamma i is an arbitrary phase with odd symmetry about f i plus f s by 2 right. So, now, if you look at the phase then the phase will have a structure which is represented by this picture graphically it would look something similar to this and you can have other phases also depending upon the values of gamma i and over all these criteria or these conditions if they are met successfully then one can satisfy the ICI free and ISI free transmission schemes.

Such that, the received signal at the receiver remains orthogonal for a particular given channel transfer function right. So, now this clearly means that if we have a wire line channel the channel remains constant for the entire duration of the communication link provided we are having a circuit switch connection or if we think of point to point connection one point to another point for the entire duration of the communication this channel transfer function should remain typically constant, in that case this is easily realized.

In case of wireless links there is a problem because this H of f should ideally be written as H of f comma t which indicates that the channel transfer function fluctuates with time and hence these schemes to be realized in it’s exactness as described just now is valid as long as we maintain the coherence time constraint we had seen such a constraint earlier, when we talked about the link adaptation mechanisms that are typically used.

So, now if we add this kind of adaptivity into the system this can also be considered as one more dimension of link adaptation, whereby you would like to get a signals which are orthogonal at the receiver for a given communication channel. So, which satisfies both ISI free as well as ICI free communication, ICI and ISI free transmission requirements.

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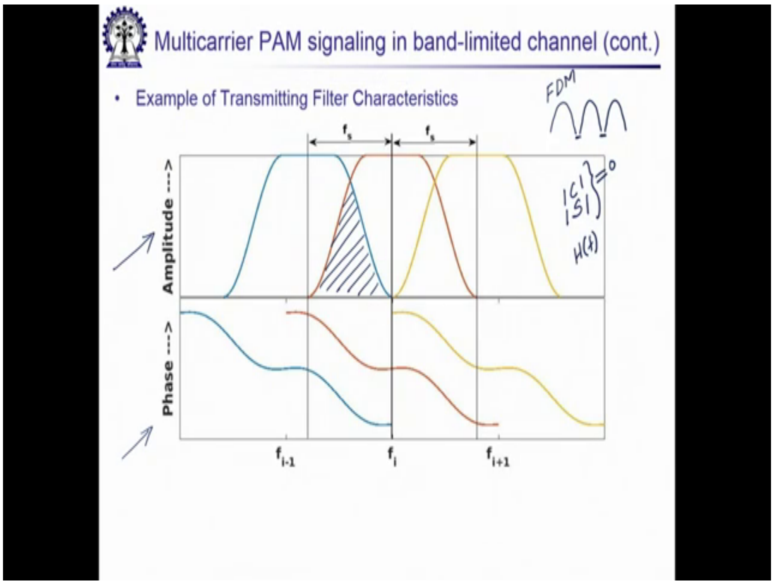

So, now typically if we put everything together the amplitude response would look like as we have given over here and the phase response would look like this for the difference of carriers, what we see is that although we described initially it is a frequency division multiplexing mechanism typically in a frequency division multiplexing mechanism we had said quite some time back that one would have to put some kind of a guard interval between them a guard band which is a wastage which is not used for anything other than reduction of inter channel or adjacent channel interference.

Here we find that there is overlap which is allowed between the neighbouring channels, but the filter coefficients are designed in such a manner that there is ICI orthogonality ensured as well as ISI both go to 0, if we use appropriately designed filter coefficients. Of course, points to remember that H f is supposed to be known, if H f is not known and one is using ideal then the transmitted signal would be orthogonal, but once it passes through an unknown channel there is no guarantee of such orthogonality criteria and results could be quite a way from expected values.

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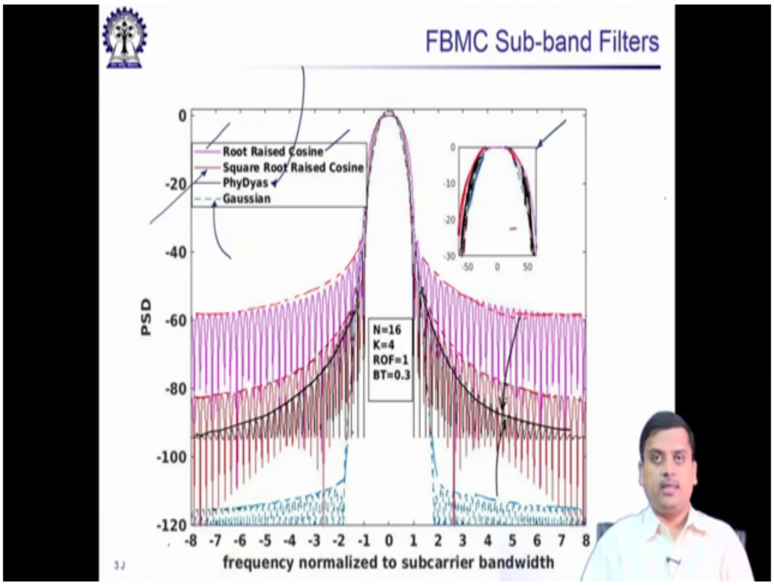

So, then we move on to see certain transfer functions of the filters or the gain versus frequency plot for different pulse shapes or different filter structures and what we have seen, what we are seeing over here are the route rest cosine which is a standard thing which we all know pretty well sorry this yeah this is a route rest cosine which is pinkish color, which is slightly difficult over here to distinguish, but I will trace that.

Ah Then we have the square root raised cosine right which is again common thing which we get. Then we also have the Gaussian which is dashed line and we also have another one which is known as the phydyas filter. So, this phydyas filter is an outcome of one of the European funded research projects and they have come up with filter characteristics which are very much likely to be used in such systems which have a lot of good properties.

So, we briefly discuss this what we find is that the root raised cosine which is a little bit pinkish as we can see over here, the out of band I mean if we look focus in this picture the inset picture if you look at the insert picture and let us take the appropriate color to help us yeah let us let us take this red color instead and we trace it. So, this is this particular one is the one for the raised cosine, this is for the raised cosine right and what we can also see is that the raised cosine envelope for out of band is as per this right, so which is significantly high or the highest amongst the related ones that we have considered.

Then as we move to the root raised cosine I will use the brownish dark red color and what we see over here is the root raised cosine is there as we follow with the marker right which is very much close with the raised cosine for the main lobe part, but we can identify the distinction, so here is the root raised cosine and here is the raised cosine. So, there is a gap in that and if you look at the adjacent channel or out of band the envelope would be here which is better then that of the raised cosine as we can see over here.

Then we go to the Gaussian so for the Gaussian we again see that the out of band is the best and in fact, it is the best filter that one can think of with a pretty narrow the main band, as you can see the main band is here right the main band is here. So, it is one of the best possible filters, but it’s one of the ones which is pretty large time domain impulse response, so it’s usually not preferred from that perspective.

Whereas, if you look at phydyas it is a tradeoff between all of these and again if we try to trace it, what we will find is that the phydyas which is a black one is here which is lying in between them the phydyas filter characteristics is lying between them and here the envelope goes there the out of band. So, which is worse than Gaussian, but it is better than the raised cosine and root raised cosine as we can clearly see right. So, this is this is how you can pick the filters design your filters if they satisfy the previous criteria you are done.

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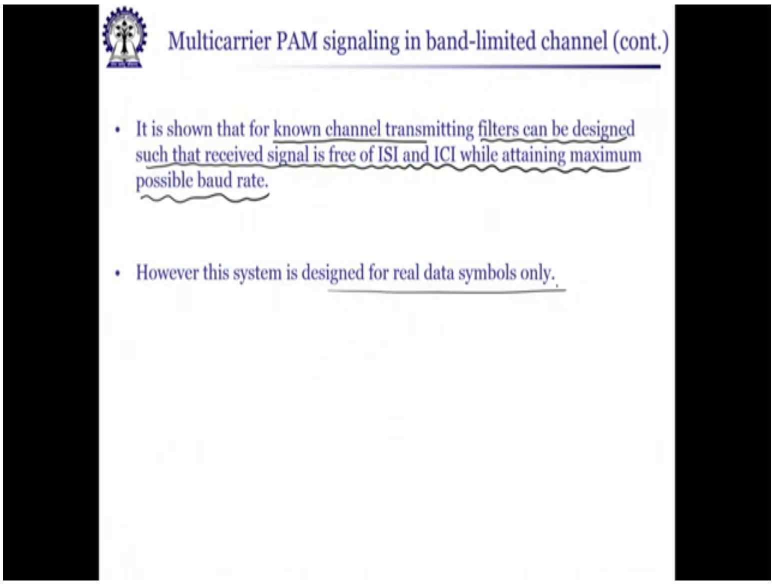

So, what we see over here or what we summarized is that it is shown that for known channel; that means, if the channel is known transmitting filters can be designed such that the received signal is free of ISI and ICI while attaining maximum possible baud rate signaling rate; however, the system is designed for real data symbols only right of course, you can change it for complex data symbols and what is one of the things that we are going to see next, in the next lecture.

So, what we summarized is that if we want mechanisms which are multi carrier mechanisms, but they are not OFDM, but they have there some other ones and the special properties that we want in them or the ones where we have good out of band signals; that means, less adjacent channel interference then we have to go for structures which is usually termed as the filter bank multi carrier, the genesis is given in this particular reference where each subcarrier is filtered and there is criteria for designing the filter coefficient which provides no ISI no ICI given a channel, such that there is odd symmetry about a certain frequency position f i plus f s by 2 minus f s by 2 with the product of the channel transfer function included with that of the filter.

And there is even symmetricity again with the product of the channel and the filter and as well as there is criteria on the face which completely defines the filter and hence one can attain structures which look like this. So, as to attain orthogonality even under transmission through a channel provided the channel coefficients are known. So, this technique one of the problems of this technique is the receivers are pretty complex people have been working on low complexity receivers, in enough technique have to be developed on low complexity MIMO mechanisms which can comfortably work with them.

But the biggest advantage is that you can really shape the filters such a way that you can use really narrow bands of available channel spectrum. So, that the desired signal can be sent through such narrow bands of channel, you can also group larger sub carriers together and they can be sent through and under all conditions you can maintain orthogonality at the receiver. So, we bring this discussion to an end over here in the next lecture we will start talking about another transmission mechanism which was also a contender to 5G and the remains enough work to be done in order to make it mature and potentially a candidate technology for the next generation.

Thank you.