Evolution of Air Interface Towards 5G
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Lecture – 27
Waveforms Beyond 5G

Welcome to the lectures on Evolution of Air Interface Towards 5G. So, till now we have been discussing about the various wave forms which have evolved since the second generation and we have seen a basic structure based on which one can develop all the different kinds of wave forms that have existed till now. And, in the previous few lectures we have also seen how the numerology issue has started and how the numerology solutions have to be picked; that means, the particular solution set in terms of subcarrier spacing and in terms of guard interval.

We have also seen how if one aggregates the resource block the different kinds of benefit that one can get. So, today our objective is to briefly go through some of the earlier things as well as most importantly look into wave forms which have been contending waveforms for 5G. So, there has been lot of work on different wave forms which have competed towards the 5th generation, but because of one primary reason that is backward compatibility.

These wave forms could not find an opportunity, but the flexible numerology which we discussed earlier fits into the framework very nicely while supporting all the new requirements. Whereas, given their capabilities it is very very important that we understand them and with the new flexible framework that has evolved and been accepted in the 5th generation, we firmly believe that there would be lot of opportunity for these new wave forms to possibly getting accepted as the next generation wave forms in the upcoming releases of 3 gpp or maybe upcoming version of the mobile radio communication systems.

So, with this brief we get into the wave forms beyond 5G because as of now they are not part of 5G although they were designed and people are trying to make them being part of 5G and as we have said earlier that it is possible that in the next few years. So that it gets so it is getting a window before it’s again becomes part of contending technology.

So, in that period we believe these wave forms will become mature and they would be able to bring in more capabilities and adjust themselves within the framework. So, that they provide all the benefits while maintaining backward compatibility.

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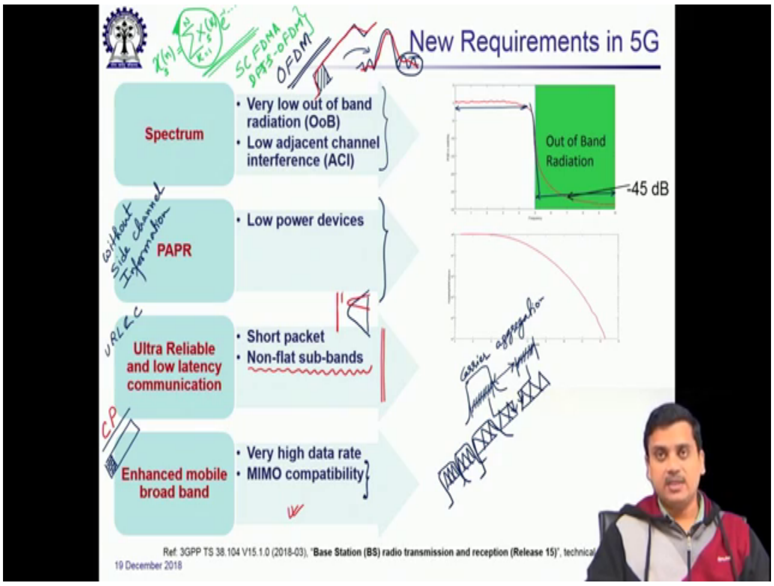

So, one of the important requirements of 5G had been low out of band radiation so; that means, within the band of transmission it should be good signal and beyond the out of band the emission should be as low as possible with as narrow transition band as possible.

So, that is one of the key requirements and if we look at what are the problems with existing systems. So if there is a high out of band adjacent channel interference would be high and with the low out of band adjacent channel interference would; obviously, below and this is very very important because what we have kind of not discussed in very great details, but what we have seen is that separate band widths can be allocated and there is very important part which is called carrier aggregation which we are not discussing.

So, in carrier aggregation suppose there is a certain band of frequencies available and a particular service is operating in that and another band of frequency and is available and the service is operating in that, these two bands could be aggregated to provide the same kind of service this is one thing, but now look at this that the other side of the same picture is there are some bands which remain in between, this is very very critical.

So, if one has to utilize all the bands in the most efficient manner one should have spectrum properties of multi carrier signals which are expected to be as close to Nyquist filter characteristics as possible that is what is desired, in that case one can utilize things better. Also if we look at the in our framework we have seen that different numerologists can coexist simultaneously right so; that means, there could be narrow bands, there could be mid band and there could be wider bands. So, they will have different amounts of interference against each other.

So, again if these bands have narrow transition band or they have a sharp transition band and there is very less amount of power going into the adjacent channels; obviously, the performance would be excellent. The second very important property that is desired is that the peak to average power ratio must be low and we have also discussed the influence of having low peak to average power ratio.

It helps us getting a better battery life at the user equipment side or providing more range, so over all there is lot of benefit. And why are these two important considerations and why have different waveforms being considered? If we look at OFDM the primary mode with which OFDM is usually discussed in public is that it has a rectangular pulse ship, which gives rise to a sinc spectrum which we have been drawing also right.

So, in a sinc spectrum the outer band radiation is pretty high it is not desired; however, I would like to mention an important point which is mostly absent in publications academic publications is that this we have slightly mentioned earlier that there is a cyclic prefix in front of the OFDM symbol and when the symbol goes out usually there is up shaping that happens without pulse shipping no signal is going to go out that is for sure.

So, this pulse shipping that happens this is able to reduce this and; obviously, it is not a true rectangular and hence one can expect a lower out of band compared to the idealistic rectangular pulse that; obviously, happens but still better performance is desired. The other aspect which one can think of is the PAPR because we have discussed heavily when we were discussing OFDM that the signal xn is composed of sum over X of k where k is the subcarrier index s is the OFDM symbol index e to the power of something something.

So, as many numbers that we add up the peak to average power ratio grows right. So, peak to average power ratio grows all the disadvantages that we have mentioned comes in. So, one desires a multi carrier method, the moment you have multi carrier you cannot live without peak to average power ratio by default. So, what it says is that if we can have no PAPR and yet have multi carrier then things would be wonderful.

So, this is the kind of requirement and we will see some solutions which do really provide some great advantage. One of them we have already seen that is SCFDMA which is nothing but DFT spread OFDM and hence there is already a mechanism by which things can be reduced there could be other mechanisms also and all these without any additional information being sent over the channel. So, what is very very critical without side channel information that is also important. Because if you are sending side channel information there is a huge increase in extra bandwidth or in other words reduction in spectral efficiency ok.

Ultra Reliable Low Latency Communication we have seen that ULRCC is the requirement URLLC rather yeah and we have already seen how this is supported and what we mentioned at that time is also included over here that as your subcarrier bandwidth increases right initially it was something small, initially subcarrier bandwidth was small.

So, hence the frequency fluctuation which was restricted to smaller band it is now desired that the frequency fluctuation is remaining constant over a larger band, but that may not be true because of the propagation characteristics of the channel. So, non flat sub bands may come in so one should find better mechanisms to cope with such a system any such facility. So, it may not be possible to allow OFDM to do that.

So; that means, this non flat sub bands is a requirement, so if we have mechanisms which can handle this at the different that would be wonderful. So, next is enhanced mobile broadband of course, we require very high data rate, so one of the problems that OFDM has is the cyclic period now looking at cyclic prefix from the other side. Cyclic prefix has helped us in overcome I sigh, but look at this every OFDM symbol there is a cyclic prefix in front of it which is a necessary evil its an overhead.

So, now since we are happy with some techniques which can address some of the earlier problems, next stage would be to go beyond whatever is the is already provided and come up with even better mechanisms. So, as you may know that there are other mechanism solutions against CP in OFDM, but we may explore mechanisms which can reduce this CP overhead.

Along with that there should be MIMO compatibility also so if we come up with schemes, but they are not compatible with MIMO then again they are pointless. So, these are some of the important considerations when waveforms are usually design, usually from the earlier generation to the next generation and this was especially valid for the 5th generation system and since things have not been in favor of the new wave forms, but since it is very important to understand them because the next level of activity should be around these so we should take a look at all these requirements.

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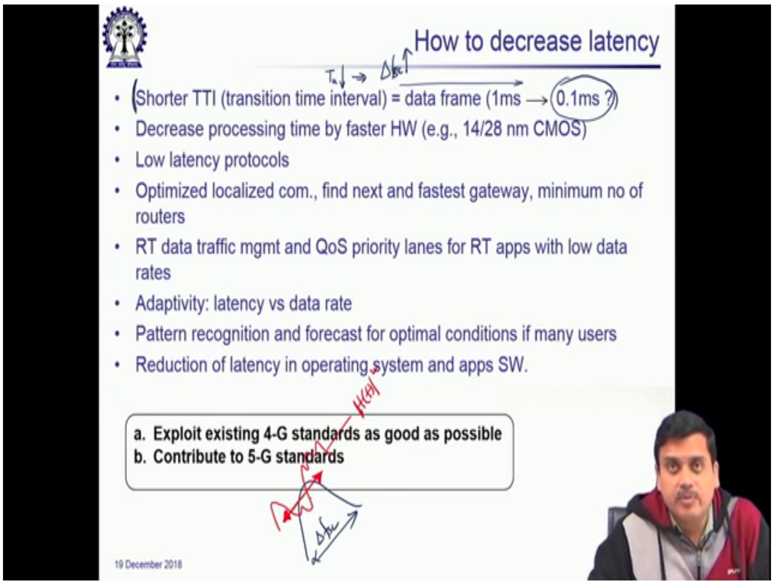

So, we have already established that that low latency is a very important case and we have also discussed like how things have happened and amongst the various things what has played a very important role is the short TTI; that means, transition time interval which is reduced right and then the next question is can it be made even smaller.

So, the moment you reduce the transition transmission time interval what we find is that OFDM symbol duration decreases, as a result of which this subcarrier spacing increases, if subcarrier spacing increases then what happens is suppose your subcarrier spacing is like this it’s some imaginary picture, this is delta fsc and the channel fluctuations are like this this is the channel so mod of H f squared let us say all right.

So, under this situation addressing the frequency selective channel within the subcarrier spacing becomes a problem because originally OFDM was designed to handle flat fading and there was a single tap equalizer. So, now if one has to get back and use multi tap equalizer then all the advantages of OFDM are gone. So, one would like to have some better mechanisms to address this.

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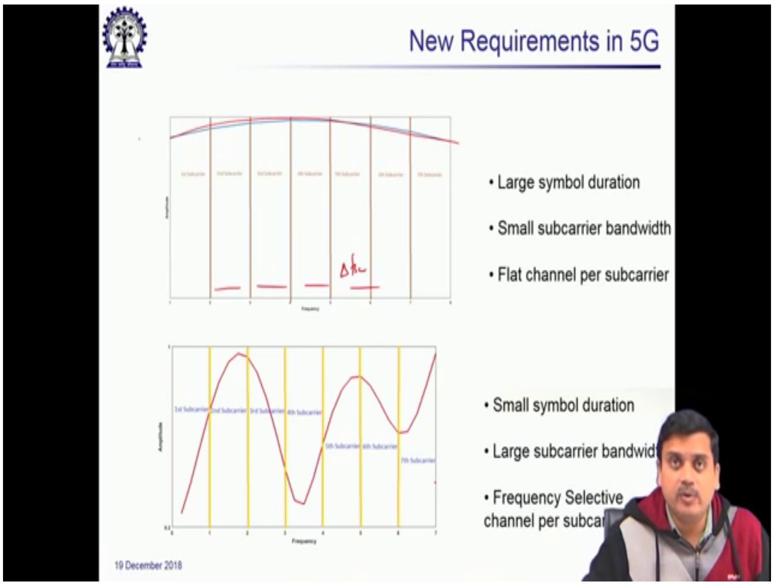

So, effectively it's boiled down to earlier more or less all the subcarrier so these were subcarrier spacing and the fluctuation was more or less flat across each of the sub carriers whereas, you have a situation like this and hence some solution is required to address this.

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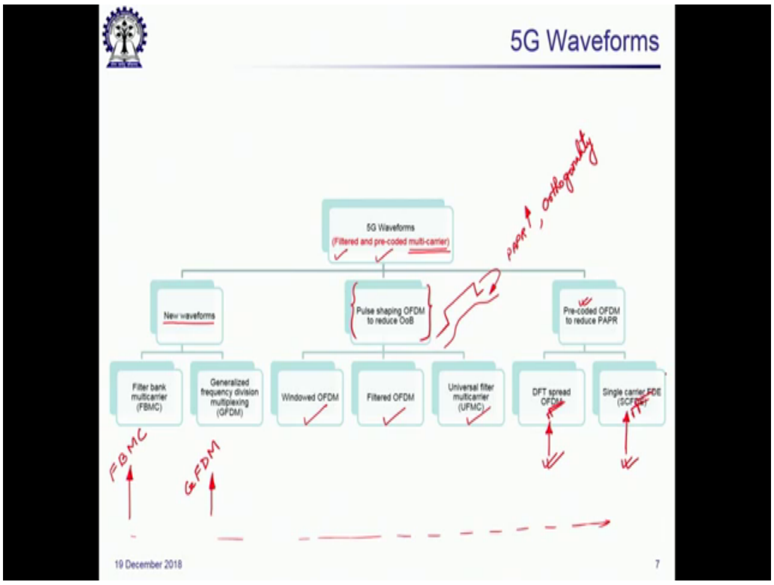

So, the different waveforms that were under consideration or that are still under consideration for the next generation are some forms of multi carrier, there are some form of multi carrier communication and they could be filtered there could be pre coded so various forms have evolved. So, what we find is that one set is coming under the pulse shaped OFDM.

So, this is pulse shaped which simply means that earlier we were talking about rectangular pulse and now probably you can think of some other pulse shape which could be of value. Now the moment you go for any other pulse shaping in multi carrier what happens is that peak to average power ratio increases if nothing else changed nothing else changes, but only the pulse shaping changes another factor that happens is the orthogonality also is lost right.

So, these are some important issues that come into play and if one has to allow this to happen then there has to be done in a very specific way. So, windowed OFDM is one of the mechanism, filtered OFDM is another mechanism and universal filtered multi carrier is another mechanism which is very similar to OFDM. Some other forms which are not just pulse shaped OFDM are new wave forms amongst the new wave forms so this is the set of new wave forms, one is the Filter Bank Multi Carrier FBMC. Then there is another one generalized frequency division multiplexing.

So, these are the two waveform people have been working upon, so one set of people in working on FDMC another set of people have been working on GFDM to improve upon their raw baseline architecture and make them acceptable towards a practical transmission mechanism. While on the precoded side this is the new waveforms we find DFT spread OFDM is already available this is already present no issues about it and single carrier FDE is also an extreme case of DFT spread OFDM in that case this is also available in some sense.

So, we will in this lecture and probably on the next lecture also depending upon how well we progress. We intend to cut across these different waveforms architectures, we have already seen this particular waveform we have already seen, this particular waveform also we have seen a basic OFDM structure we have seen. So, we are remaining to see the rest of them.

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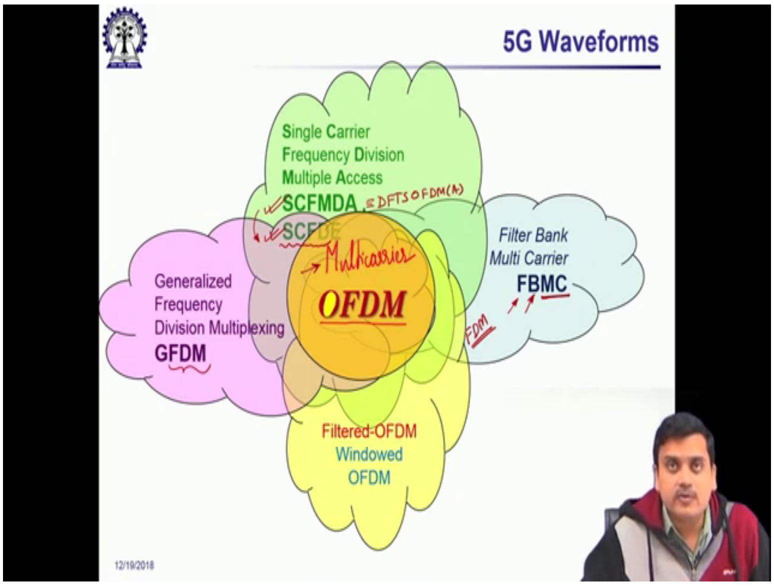

So, all these waveforms what we consider is they are variants of OFDM one can also think of them in variants of some basic multi carrier. So, thinking them as variants of OFDM may not be very well accepted by everybody, so OFDM as if we call it one of the critical factors is the orthogonality factor right. So, this orthogonality factor is not carried across when we go to different waveforms.

So, although we claim that or we say we do not claim we actually say that it can be viewed as variants of OFDM one may not accept that and one can even go by their own thinking and case a that know let it let there be some multi carrier structure which is a fundamental and which can be used, but what we are simply saying is that since OFDM is very easy to understand and it has very simple architecture one can think that there is a baseline and there is a variation so there is no conflict in these; in these thoughts as such ok.

So, directly from OFDM we will find that single carrier FDMA fits in we have already discussed this through DFT spread, this is also DFT spread OFDM and single carrier FDE is a direct consequence of making DFT size being equal to the IDFT size. So, there is not really much difference although SCFD is a true single carrier system that is that is the pure difference.

The next set is the filter bank multi carrier so what we see is there is this multi carrier business in it and the difference is that each of the carriers are filtered. So, that is why you have a filter and you have a bank indicating there is a whole set of filters each one for each of the carriers so that way it is kind of a variant ok, but this process destroys some of the properties of OFDM, but brings in certain other advantages.

The next set is the generalized frequency division multiplexing, so the frequency division multiplexing nature is maintained, this is also a kind of frequency division multiplexing, but here this is not a frequency division multiplexing this particular method, but one can handle it in the receiver from frequency domain perspective and then we have filtered OFDM and windowed OFDM. So, since there is lot of similarity we think OFDM is at the core of it and one can think of variations about it ok.

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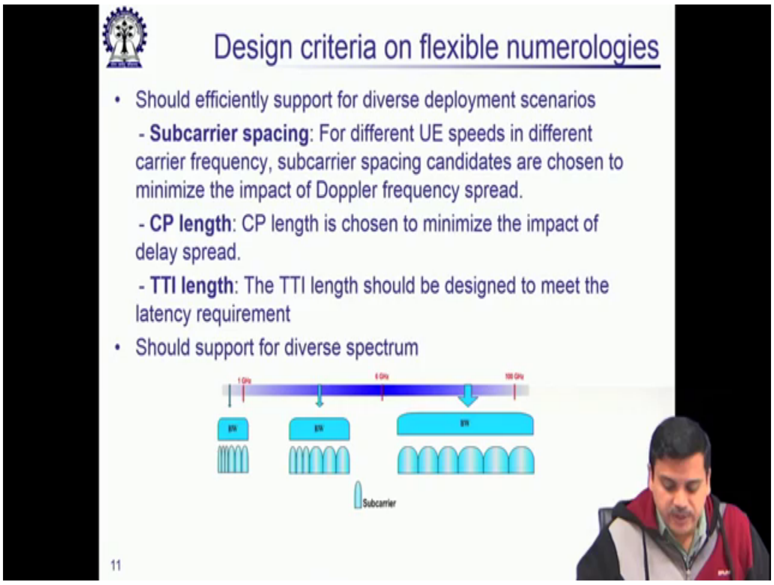

So, we have already discussed about the 5th generation waveform structure so we will not discuss the details of it, these pictures simply explain whatever we have talked before; that means, different subcarrier spacing can be used and they can coexist there is no problem in coexistence also.

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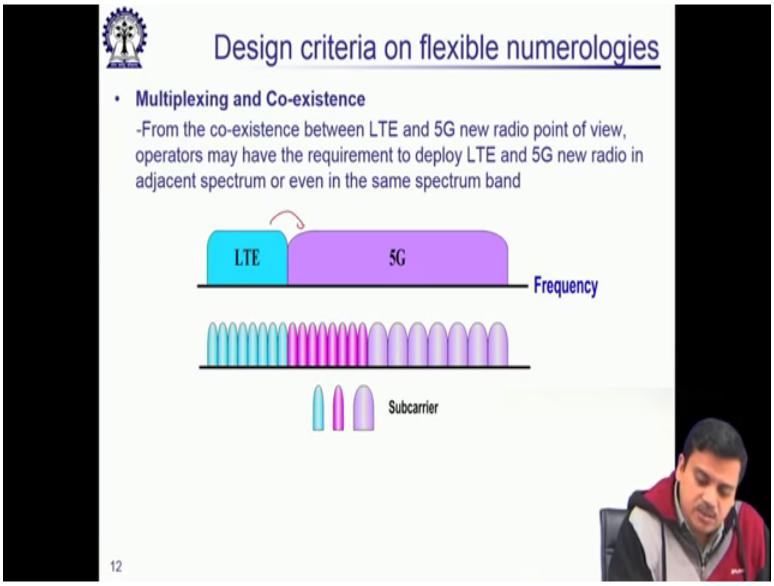

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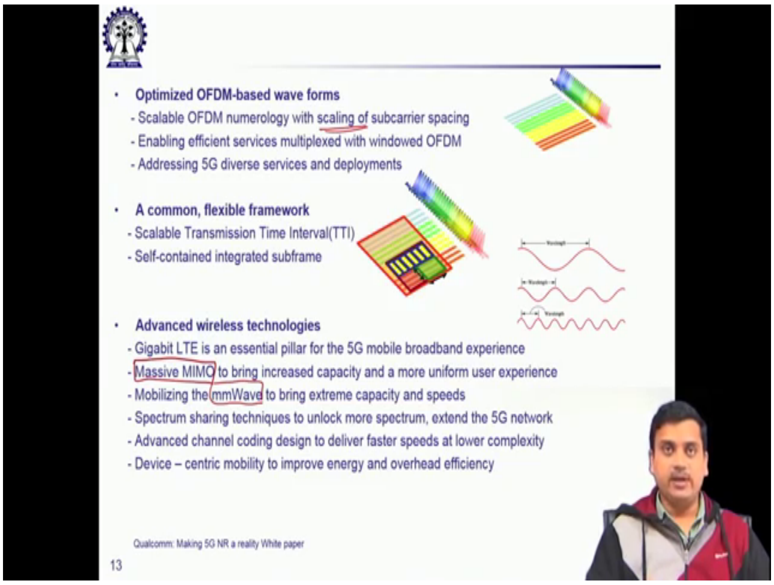

And the other important facts that we have also stated is that these are optimized version of OFDM with scaling, we have already talked about this there is a common flexible frame structure as indicated by this particular picture as well as one important thing that has come into play is the use of newer bands and newer techniques amongst which the millimeter wave and massive MIMO are two very importantly distinct things which have come in and we will get an opportunity to see them and I would also like to mention although this has not been explored much.

But the waveform structure for these specific set of things are also very important to be looked into, very specifically if one things of millimeter wave communication single carrier till now has very good properties in this particular situation; however, making multi carrier work effectively and efficiently needs to be investigated probably better solutions can be found under these conditions ok.

So, we have already discussed about the various structures in the previous lecture so we need not explain them any further it’s just a quick view. So, that you can remember some of the things and we have also pointed out a whole set of references so will move beyond that.

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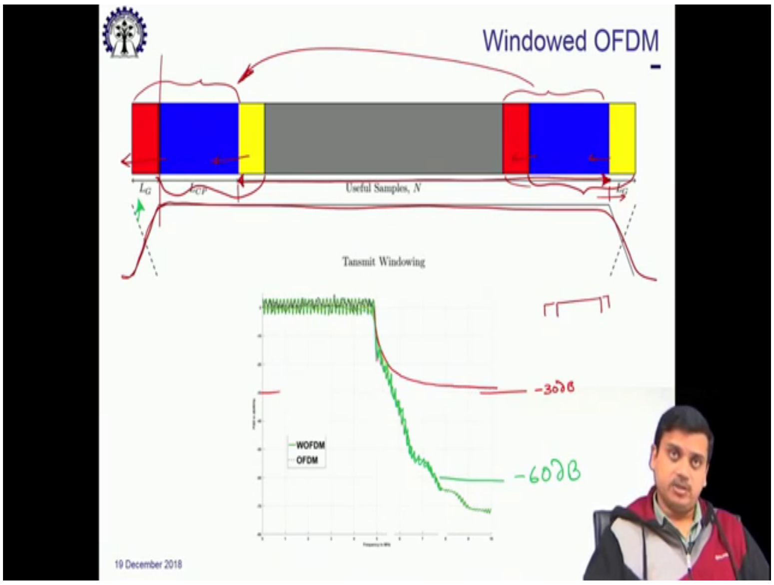

So, now, we take a look at the windowed OFDM architecture. So, in windowed OFDM this is the useful part. So, from here to here is the useful part of OFDM signal and there is a section which is copied as you can clearly see it is copied into the front. So, when it is copied into the front it is copied as the cyclic prefix, but then within that one would designate a guard section ok.

While one would also recognize that this portion is a copy of this portion rather this entire section is a copy, but what we find is that the useful section is this from here the useful section starts from here goes up till here right. So, there is a certain extension and the both front and well as well as at the backside; that means, if this is the original useful signal part we extend the signal on the front as well as on the back in a circular fashion.

So, what you see is that the circular symmetricity is maintained so if you stretch on this side you will find that you are back from here you will find that you are back into this section right that is something which is interesting as well as if you go from the other direction then you are again back in the front part. So that means, when you are stretching on that on the on the on this side you will find that you have this section and this section coming in as we have already discussed in the cyclic prefix part all right.

So, now on top of this there is some kind of windowing is done in time domain. So, winding operation means if there is a multiplication of this kind of a window, so when you have windowing it would result in a change in the spectral occupancy of the signal.

So, otherwise if the spectral occupancy of OFDM signal were here right. So, this what I have drawn is slightly higher let me clean it and trace the exact line.

So, this is the one for OFDM this particular point is minus 30 dB what we find is that the windowed OFDM as has been depicted and has been calculated falls much faster and in the in the sideband it can easily obtain a minus 60 dB of adjacent channel interference. So, by this mechanism one can reduce the adjacent channel interference significantly and with an appropriate trade off; that means, one is wasting a certain amount of bandwidth, but one is obtaining a significant fact significant amount of adjacent channel reduction in adjacent channel interference.

So, this is a traditional method only thing is that it's it matters whether its being to be used or not. So, there is I would say there is not a hugely new thing only the structure there is slight change in OFDM and it can be having a lot of backward compatible compatibility with other systems. So, at least one of the properties can be improved because of this mechanism.

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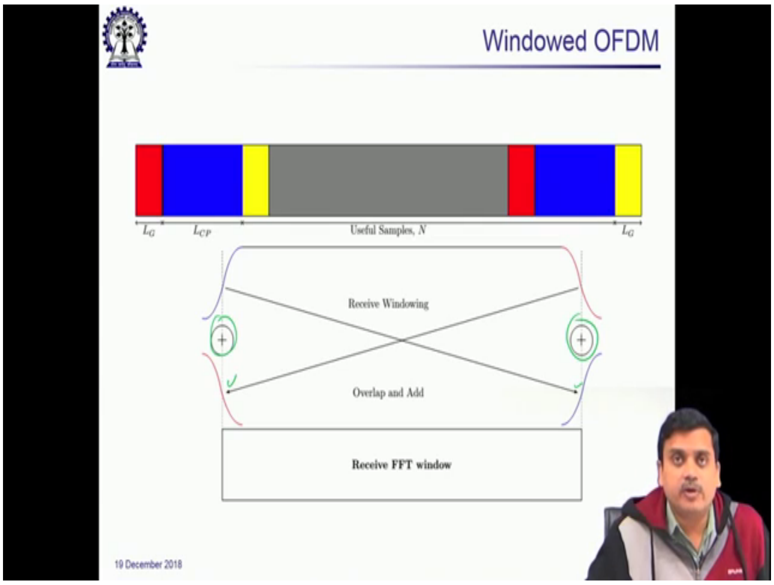

So, in windowed OFDM there is a particular mechanism that is suggested for receiver operation so; that means, and on the receiver side one has to window the received signal and one has to change over; that means, one has to bring the receiver part, one has to bring the opposite part; that means, from the front to the back and from the back to the front add these parts in order to reduce the interference between the multiple users and process the signal.

So, this way one can improve the performance by reducing the adjacent channel interference with such a windowing mechanism.

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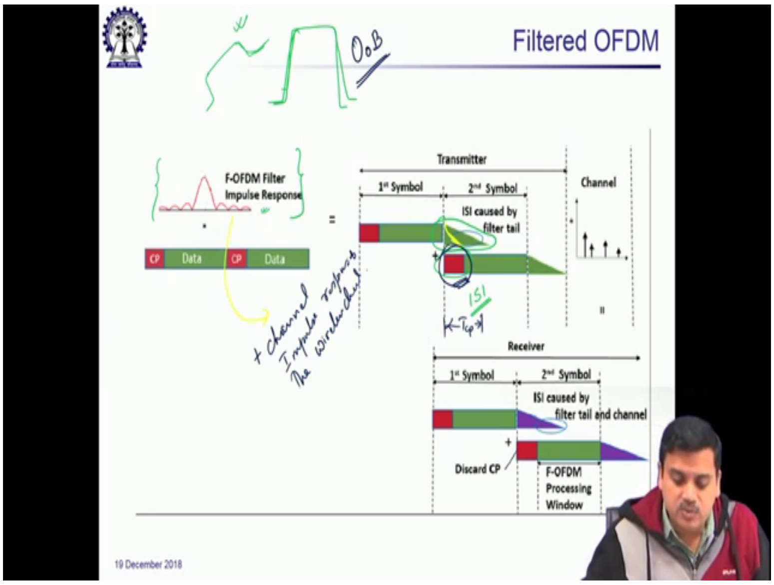

The next particular structure we can look at is a filtered OFDM so since we understand OFDM this is a this is not a very very huge modification from OFDM. So, in filtered OFDM instead of windowing one can use a filter impulse response to filter the OFDM. So, both can be thought of as kind of duels of each other.

So, when we do a windowing in frequency domain one can think of kind of doing a convolution in the time domain because windowing in frequency domain is multiplication in frequency domain convolution in time domain is the dual of that. So, if one does windowing in time it is convolution in frequency, if one does windowing in frequency it is convolution in time.

So, whenever we are talking about the impulse response in time domain one would indicate that there is some kind of windowing in the frequency domain. So, the advantage of windowing in the frequency domain is that you can actually create a spectrum of the desired characteristics, but of course, with within the limitation of practical constraints.

So, now, if one intends if one is interested to have very very sharp cut offs then what happens is that the impulse response becomes long and if the impulse response becomes long, then it stretches quite a bit into the next OFDM symbol and it can be even larger than the cyclic prefix of the next OFDM symbol it can result in ISI.

Now if so; that means, if one has to avoid ISI, one has to restrict the channel impulse response length to a certain maximum value which would be useful because beyond this channel impulse they is also the channel impulse plus one should also consider the channel impulse response of the channel of the of the wireless channel. So, together if it is less than the cyclic prefix one can control ISI otherwise is I will come into play.

So, one has to decide how which one is more important is out of band more important for the particular application or ISI is more important, if one is having worse isi then one has to put extra length of cyclic prefix or guard interval and has to handle it. In either of these two cases what we find is there is a trade off with bandwidth and out of band radiation and this is again standard methods being applied to OFDM.

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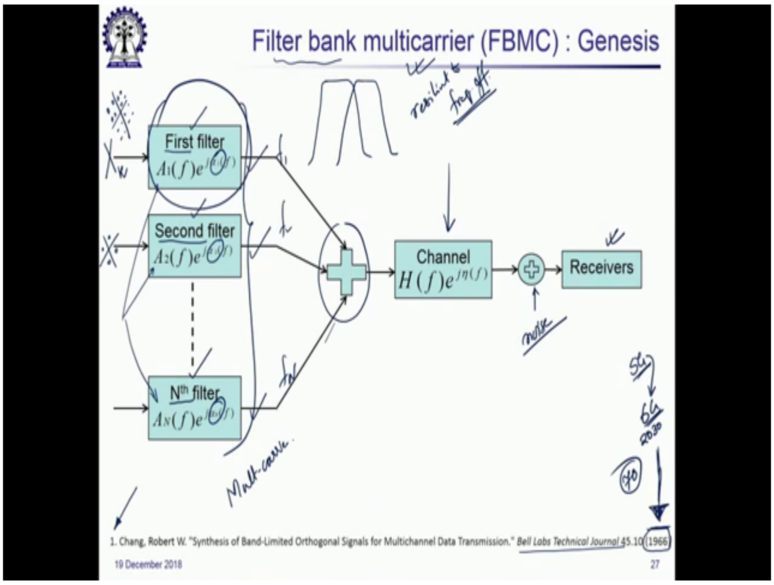

The next important class is the filter bank multi carrier. So, we have almost reached the time line for this particular lecture, but will briefly introduce that before stopping over and we will continue this in the next lecture. So, in the filter bank multi carrier the first most important thing I would like to point out is the reference which has been given here.

So, as we have been doing in the earlier case especially for the numerology scenario we are provided with the earliest reference work which has which we have been doing since 2004, 2005 onwards and we asked you to look at the reference, here also in the same manner we asked you to look at the genesis or the reference because usually what we find as researchers in such institutions that there is a general tendency of looking at very recently literatures and not even going beyond that.

But you will often find that lot of work which we are doing today has its roots back to much longer time in history. So, this particular work you can find it dating back to 1966 right, so this work is from nineteen sixty six it can be found in bell labs technical journal. So, so what I am trying to point out is although this is fighting for its place in 5th G and probably it will keep fighting for its place in the 6th generation hopefully around 2030 or maybe sooner than that original things had happened around 1960's.

So; that means, the it's around let us say 70 years from the time that these things have been investigated thoroughly we are these things are becoming going to be practical. So, so this has a lot of advantages and disadvantages also the reason things have been delayed because of the disadvantages and the reason why this has been attractive is because of its advantage. So, let us look at the basic structure before we close today's lecture.

So, there are different filters for the different carriers. So, as you can see first filter second filter Nth filter. So, as if there are n parallel transmissions which are similar to the multi carrier right. So, in each of the multi carriers what you will find that there is also e to the power of j alpha 1, e to the power of j alpha 2, e to the power of j alpha n indicating the change over in the different frequencies and these A 1 and A 2 and A N indicate the amplitude gain factor of this particular filters right.

And they all add together so overall we do not see any difference with the basic structure as in OFDM; that means, there are parallel sub carriers coming in, each subcarrier choosing a particular constellation point from the constellation which is to be used right and there is no such restriction that all the constellations have to be the same they can be different constellations, then there is a channel and finally, there is addition of noise one can think of at the receiver and the reverse processing has to happen at the receiver.

So, the fundamental difference with OFDM is that there are filters on each of the carriers and there is a whole bank of filters and hence it is a filter bank and they appear as multiple carriers operating at different frequencies. So, there is a multi carrier system and the advantage is that one can design these filters in such a manner that this transition band is very sharp and yet one has this multi carrier structure.

So, although there is multi carrier structure overall one can be having a very tight spectral characteristics by virtue of which and highly efficient system can be realized, not only that one can also shape the characteristics of each of these sub carriers such that they can made more resilient to frequency offsets which we find is one of the critical constraints of orthogonal frequency division multiplexing system. So, with this we bring this particular lecture to a stop and we will continue on filter bank multi carrier in one of in the next upcoming lecture.

Thank you.