Evolution of Air Interface towards 5G
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Lecture – 25
Numerology in 5G and Adaptive Subcarrier Bandwidth

Welcome, to the lectures on evolution of Air Interface towards 5G. So, we have seen the frame structure for the fifth generation mobile communication system, especially the series which comes from the house of 3GPP and we were discussing how the slot size remains constant in terms of number of OFDM symbol, but when it comes to the time duration for the slot it changes because OFDM symbol changes. So, the entire frame structure now becomes flexible with different amounts of resources available for different services.

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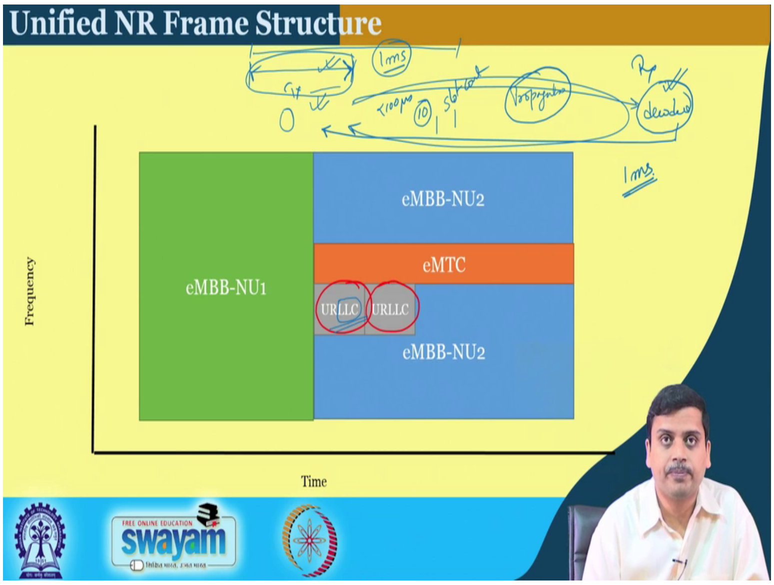

And, as a result of which what we see over here is a combination of several different services which could be multiplexed together to provide various different services over the same air interface. Now, this is very very important which has happened over the earlier generation system which did not provide such kind of flexibilities.

And, we have identified that for example; in this case the URLCC which is the Ultra Reliable Low Latency especially will talk about the low latency part which becomes very very critical. So, in a typical communication system a slot is the unit which gets addressed. So, in the earlier generation there was a sub frame which was getting addressed 1 millisecond duration; now, you can address a slot, that is point number 1. But, look at the flow of things when it goes from T x to R x an entire transmission unit has to be decoded at the receiver. So, it has to be generated at the transmitter going from transmitter to receiver through propagation ok. At the receiver it has to be decoded and then it has to be sent back to the transmitter, right.

So, the basic unit which constraints this entire flow is this unit which is the slot unit which is not addressable. Earlier it was the sub frame unit plus there is this processing delay at the receiver side as well as at the transmitter side. Now, why we are talking about this round trip, because there is constraint on latency on the round trip. If this duration is 1 millisecond then there is by no means by which one should be able to respond within 1 millisecond from one node to another node with the shortest possible inter node connection. However, the only way one can do it is to reduce this duration.

So, first and foremost with mu equals to 0 what we find that this duration becomes 1 millisecond, the duration of a sub frame which is the one for the fourth generation system. But, here with different mu configurations one can change the slot duration to a much smaller value.

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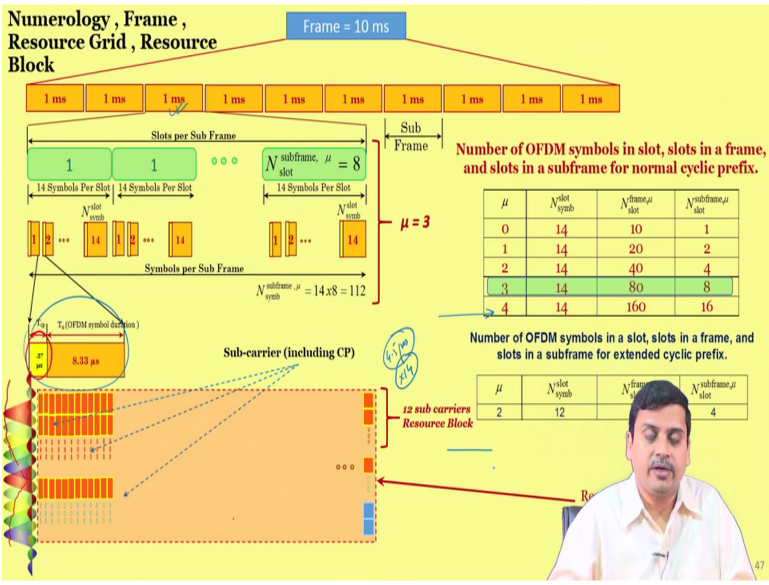

And, you have seen in the previous lecture that the sub frame size, the sub frame size remains constant, but the OFDM symbol duration can become it is very very small. So, there is another mode where it can become even smaller than this. So, when it becomes even smaller; that means, the symbol duration becomes around 4.5 microsecond including a cyclic prefix roughly speaking that is the value. So, that means, if we take 14 OFDM symbols in one slot, then the number is not very high right it is it is within around 70 microseconds and so on.

So, that means, you have a huge amount of time. So, if this particular duration is within 100 microseconds let us say so; that means, one should be able to do a round trip transmission; if this is let us say less than 100 microseconds, so, then you have 10 such slots available for transmission. So, that means, there is sufficient interval in terms of slot count that can be used and hence one should be able to transmit the slot the propagation delay is not much if the distance between the transmitter and receiver is small. If the packet duration is small then the decoding time would also be small and hence it will it will help respond to a total of 1 millisecond of response time.

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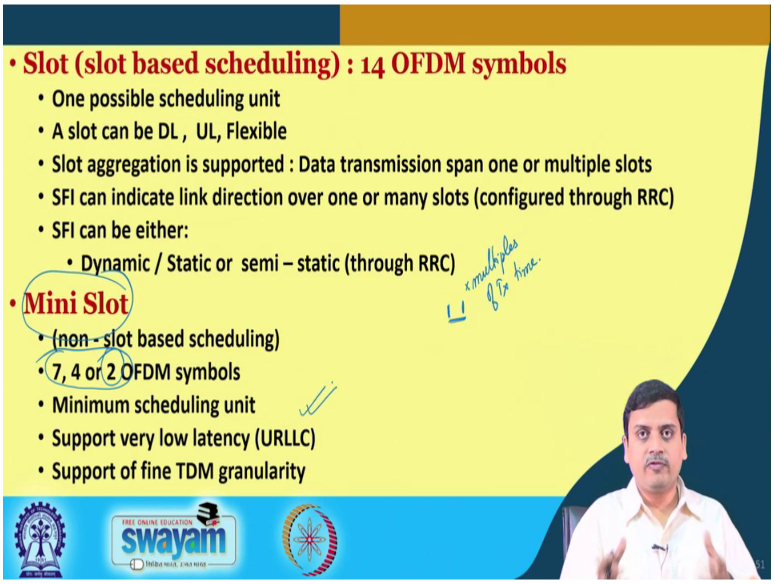

Further, we will also see that when we go to this new generation system there is a provision for mini slot compared to only sub frame or the slot duration for mu equals to 0 which can also be addressed. And, this slots mini slots can be of 7, 4 or 2 OFDM symbols, meaning that within a very short burst within a very short burst one can see this is the entire transmission unit. So, if the burst rate short, decoding time is also short, response time become short because the total response time is counted in terms of multiples of this transmission time of a slot of a particular slot.

So, this smallest slot duration can provide you a lot of flexibility and capability towards meeting this URLCC. So, what we see is that because there was a requirement to support such things, such different services this particular flexible structure can provide a lot of support towards meeting the multiple different services within one particular frame structure.

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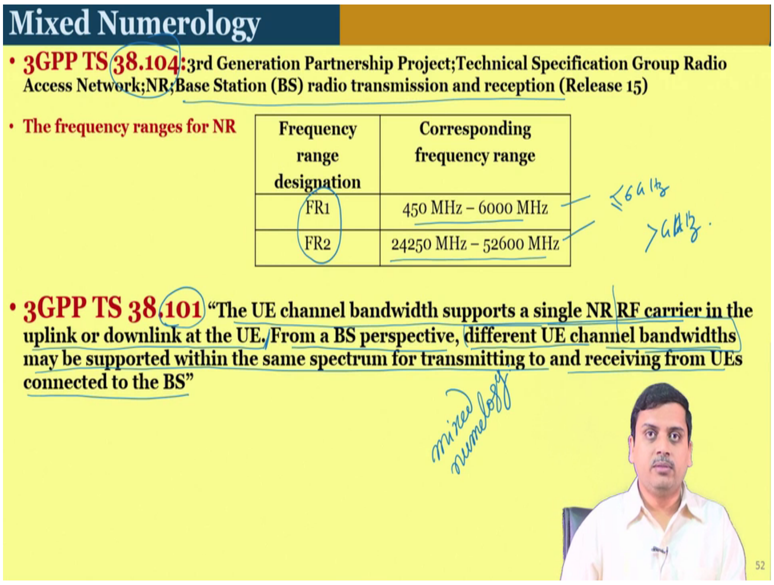

Now, we move on to understand the numerology even in a better sense or complete the understanding one has to go for 38 dot 104 that is the next part which talks about the base station radio transmission and reception.

So, in that there are two sets of frequency ranges that are defined: frequency range 1 is from 450 megahertz to 6 gigahertz and the next one is from 24 gigahertz to 52 gigahertz. So, that means, there is two different ranges over which things are going to happen. So, usually this is referred to as less than 6 gigahertz and the other set which is greater than 6 gigahertz frequency, ok.

So, we also have 38 dot 101. So, if we take out one particular statement from that what we find is that the UE channel bandwidth supports a single NR RF carrier; NR is new radio, radio frequency carrier in the uplink or downlink at the UE that is one part. From the BS perspective different UE channel bandwidths maybe supported within the same spectrum for transmission to and receiving from UEs connected to the base station. So, what it effectively means is the different user equipments will be connected to the base stations and different UE channel bandwidths should be supported.

So, not only that since each UE can choose a different numerology, the base station may be simultaneously supporting different numerologist together and one would encounter a situation where one is going towards a mixed numerology. So, we will see the particular structure how it fits in.

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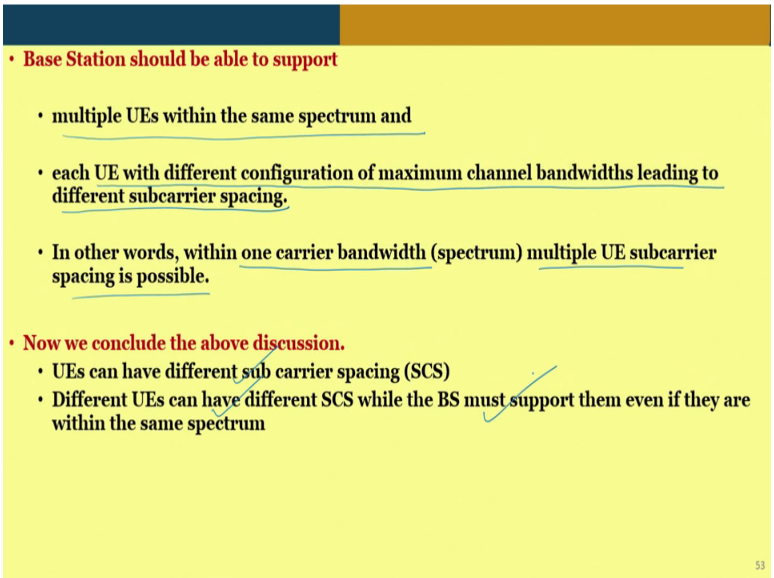

The base station should be able to support multiple users within the same spectrum. So, that is what it means, it also means that each UE with different configuration of maximum channel bandwidth leading to different subcarrier spacing right. In other words within one carrier bandwidth from the base stations perspective multiple UE subcarrier spacing is possible. So, what we conclude overall is that UEs can have different subcarrier spacing and different UEs can have different subcarrier spacing while the base station must support them even if there within the same spectrum. So, that is what we get.

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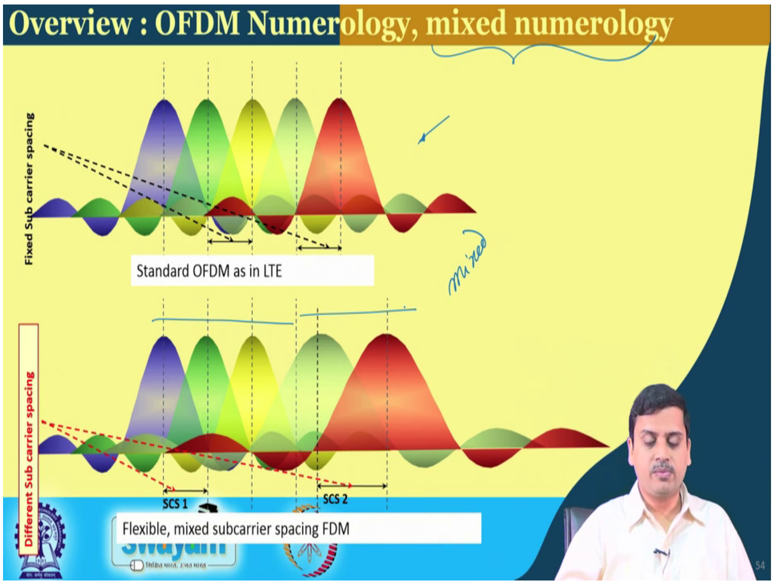

So, overall picture that we get is in standard LTE this is the kind of figure which we have referred to earlier and which we will see where the subcarrier spacing is constant, but now under mixed numerology situation. So, we have the mixed numerology mentioned over here different subcarrier spacing should be supportable from the base station. So, this is a very different thing compared to what has been encountered in the earlier generation system and this would lead to many different questions and many different issues many different aspects. So, we will get into the discussion of that particular aspect. So, let us look into that.

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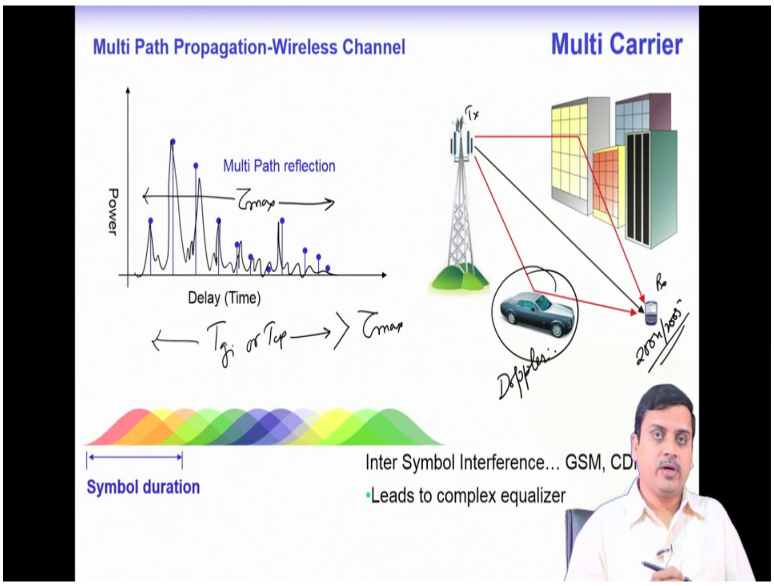

So, we will now discuss about what is the genesis and how things have come. So, primarily I would like to point out over here that this particular work that we are referring to is not a very new work it actually started at least 10 years from now. So, in the year around 2004 to 2005 we will find that there is reference for these works 2004, 2005 we will point out such references and one such reference that will talk about is one particular material which will actually give the details about it later on. So, let us get into how things are and why things are in that format.

So, we have seen this particular picture earlier, where we said that between the transmitter and the receiver there are multiple paths. So, multiple paths would give rise to a channel impulse response as depicted in this particular picture and we said that they are needs to be a guard interval or T cp which should be greater than the tau max. So, this is the tau max of the channel, correct. Along with this there is also mobility which gives rise to Doppler, ok.

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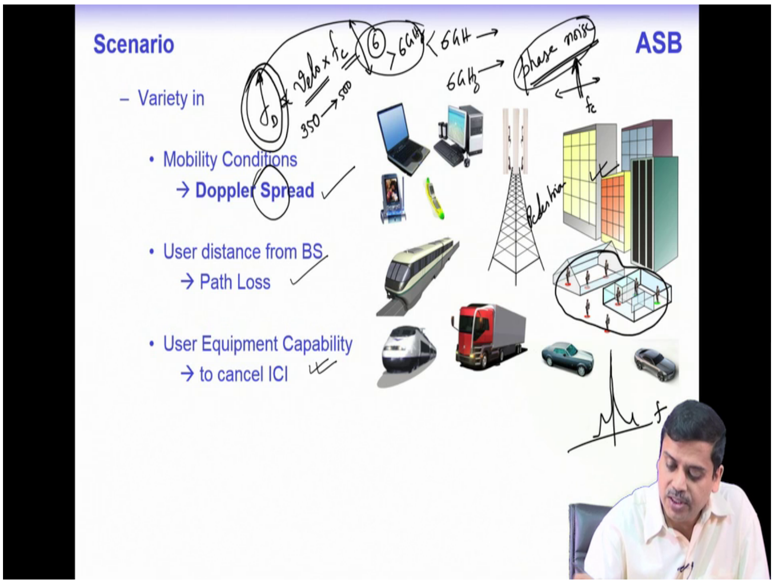

So, there we will find that in a particular situation you will be having different Doppler conditions coexisting. If different Doppler conditions coexist then each of the users would going to experience the different kind of channel. So, mobility gives rise to Doppler, user distance gives rise to path loss and user equipment capability gives rise to various ICI problems, various ICI capability.

Further, what we have seen in the earlier discussion is that there are different frequency ranges of operation. So, if one things of below 6 gigahertz and the another set above 6 gigahertz these different frequencies if you look at and look at the components or devices that would be useful to making them, as you increase and go towards higher and higher frequency one of the important factors that comes into play is phase noise.

The effect of phase noise becomes larger. Phase noise effectively means that the oscillator frequency that is generated is wearing about f c; if this is the f c beyond just being a delta function. So, in the frequency domain it is no longer a delta function, rather in frequency domain you will find that there is a certain amount of spread in the frequency and there are certain other spurious frequencies that also coming.

So, as you increase the carrier frequency this particular effect dominates. Further, as you increase Doppler what we find is that the Doppler frequency f D is proportional to the velocity of the vehicle multiplied by the carrier frequency. So, simply if the velocity increases then Doppler frequency increases or if the carrier frequency increases Doppler frequency also increases further.

So, if we go from the 4G to 5G first and foremost the maximum frequency supported increases from 350 kilometers per hour to 500 kilometers per hour and the frequency of operation not only goes up to 6 gigahertz, but it also goes beyond 6 gigahertz. So, over all these conditions indicate that your Doppler frequency Doppler experienced increases, also the phase noise increases. But, at the same time you will find that stationary uses would also to their; that means, pedestrian users would also be there, there would be indoor conditions, there will be multihued of various outdoor conditions which needs go exists at the same time.

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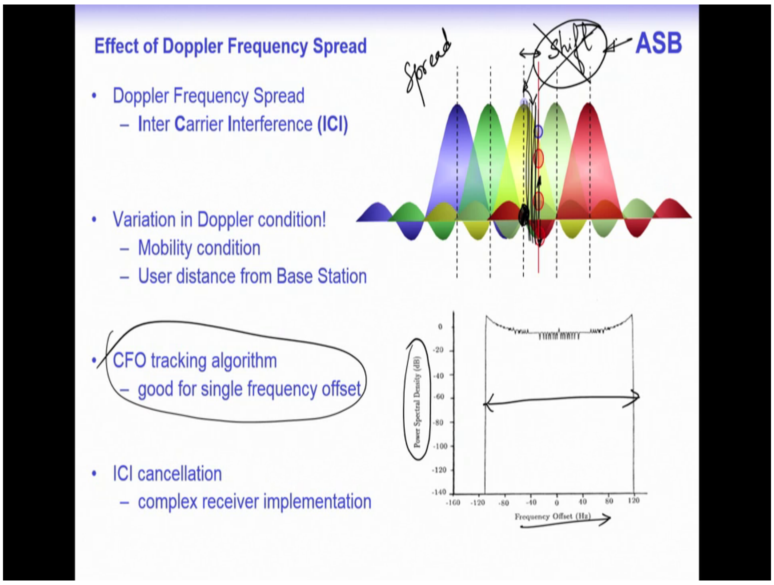

So, if we look at what is the effect of Doppler so, or let us say phase noise or carrier frequency offset. So, we said that in OFDM the sub carrier spacings are such that they are orthogonal; that means, the peak of the desired carrier coincides with the null of all other carriers; that means, there is no interference. But, if there is shift in carrier the desired signal strength reduces and there is huge amount of interference that comes into play.

So, if this interference comes into play there is heavy reduction of signal to interference ratio, if you have Doppler then the problem is there is no one single frequency shift. So, if we call it a shift then it can be handled. That means, one can be track the frequency of set one can do it, but because of multipath the shift does not happen and instead what you get is basically a Doppler's spread condition, right.

So, what is depicted in this picture is this powers spectral density verses frequency and we see one particular spectrum which imitates the (Refer Time: 14:13) spectrum; that means, there is a whole bunch of frequencies. What it means that the receiver would perceive that there are several such multitude of frequencies which is come in and there is a smearing of the signal in the frequency domain, they just overlapping the multiple values.

So, in that case this CFO tracking algorithm is not going to be much useful under that situation, if there is only a frequency shift then that kind of algorithm are useful, right.

And, if you have complex ICI cancellation algorithms that would also increases the complexity of the entire system.

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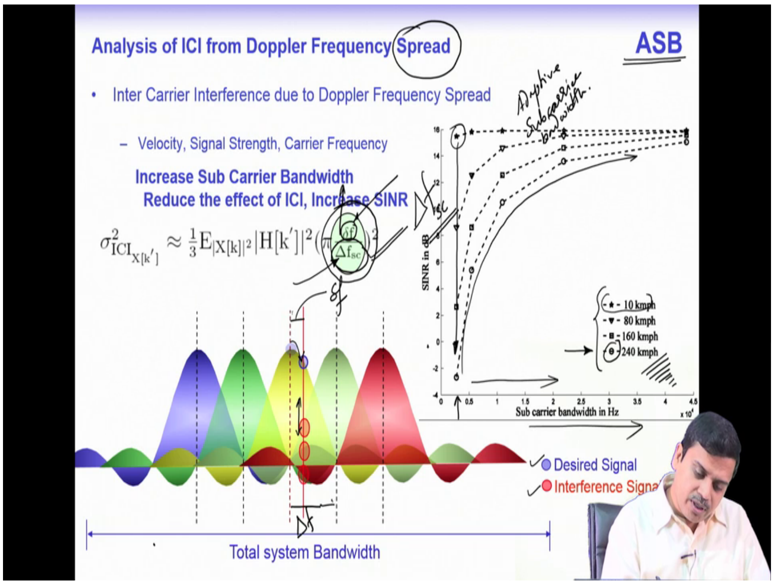

So, if you look at how does the Doppler effects the inter carrier interference we will find that in the inter carrier interference power term; this is the power for inter carrier interference there is a ratio of frequency offset with respect to the sub carrier spacing. So, this delta f sc is a sub carrier spacing.

So, what do see as this numerator increases the ICI power increases, right as you increase that the ICI power increases. So, one way which we as designers or transmitters can reduce the effect of ICI is by changing the denominator term which is in our control and as you can clearly see this denominator term which is delta f sc indicating sub carries spacing it can be varied. So, this way one can easily implement a method by which one can take care of such Doppler spreads and this exactly has been adopted in the fifth generation system. And, originally it was proposed in the by the name of adaptive sub carrier band width by us when you were working on this particular issue way back in 2004 – 2005 and as well as we have proposed various mechanisms to handle this in the sub sequent years. So, will get into all the details of how this kind of thing works.

So, going further we just look at this how does this pictorially represent. So, typically because of frequency offset one gets a reduction in signal strength as well as increase interference values, but then this particular variation is delta f that is a small delta f and this is the capital delta f. So, as you increase the sub carrier spacing simply you can improve the signal condition at the receiver. So, these indexes indicate the desired and interference terms and thereby you can improve the overall condition.

So, what you get is that as you keep increasing the subcarriers spacing in this axis and these different curves are for different mobility conditions that we are tested long time back, we have we are not introducing a newer set of values because this is an earlier work that we have done. So, what do you see is that at 10 kilometers per hour you get a certain signal to interference ratio. As your Doppler increases at a particular value of sub carrier spacing your signal to interference ratio becomes smaller and smaller. This is something very critical to note simply by virtue of this particular case, As you increase the sub carrier spacing the signal to interference ratio increases beautifully a specially for the once where you have higher Doppler condition, right.

So, this clearly indicates that to handle higher Doppler conditions having higher sub carrier bandwidth is a much better solution than implementing advanced interference cancellations techniques which also get limited when you have multiple paths coming to play and there is a spread.

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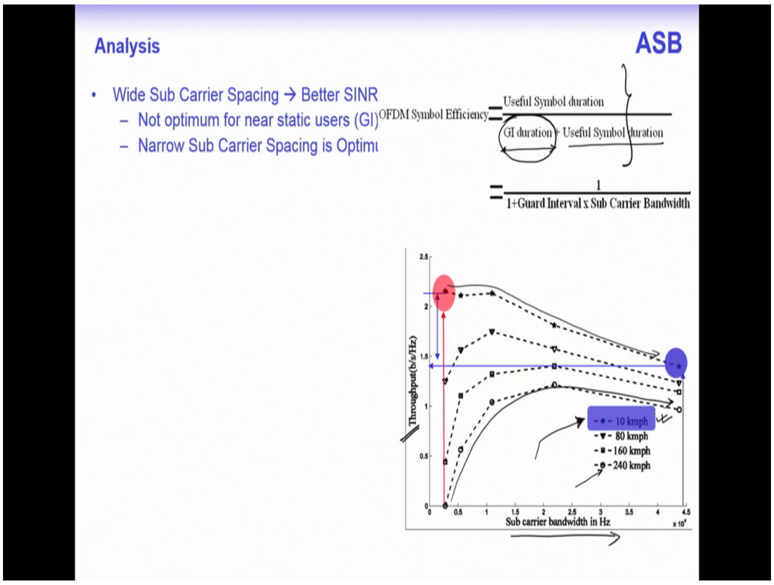

So, with this we have we have discussed that we have also analyzed the throughput condition; that means, when you increase the sub carrier band width what happens for different throughput conditions. What we find that as you increase the sub carrier bandwidth or as you decrease the sub carrier bandwidth we have discuss this when you talk about the frame structure for longer OFDM symbol durations the guard interval duration is also longer. Sorry, I mean guard interval duration is correspondingly longer.

Now, if you have a certain channel impulse response and you cannot do much with a guard interval part; that means you are restricted then the overall system efficiency decreases, right. So, that is what we find that if you are maintaining certain subcarrier spacing and you are changing and you are simply studying the effect on different mobility conditions will find whether throughput would decrease as one increases a sub carrier spacing, but one maintains a certain mobility conditions, ok. Whereas in another situation it initially increases then more or less it is remains the same up to a certain point.

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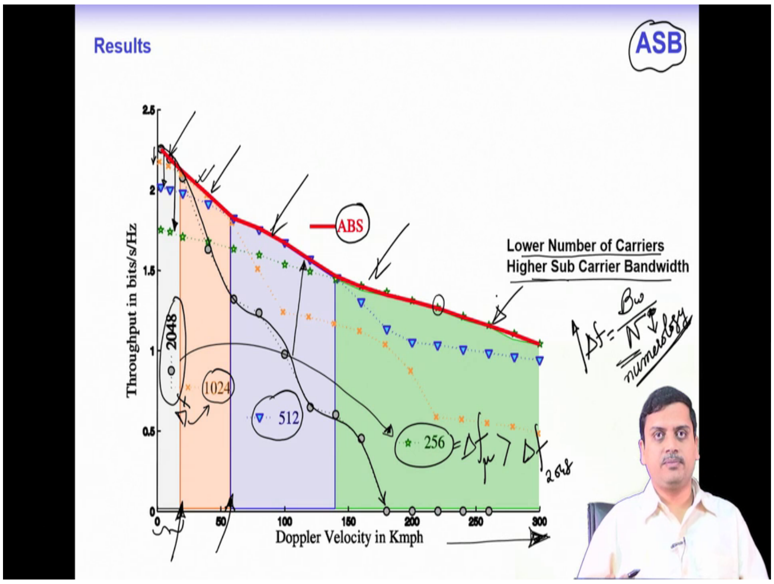

So, we go beyond this and we look at the overall structure. So, here what we have plotted is on the x-axis we have given the velocity, and higher number of sub carries or reverse lower number of sub carries indicate higher sub carrier bandwidth because we have a bandwidth divided by N. So, as N increases delta f decreases or vice versa.

So, as N decreases delta f increases right. So, 2048 has a certain value of delta f with 20 megahertz bandwidth as we increase to 1024 the delta f increases, as we go to 512 delta f increases further. So, what we see is being depicted in this particular picture is that if you are maintaining certain narrow sub carrier bandwidth, this is very very critical. The throughput decreases heavily with increase in mobility, right. After a certain point you simply cannot support the throughput because yours interference is very very high. If you are using a little bit wider then you can support a higher throughput, but there is a decrease in throughput for low mobility conditions.

Similarly, if we increase the subcarrier spacing further we find that the throughput as improved in higher mobility conditions, but it has decreased in the low mobility condition. As we go on increasing, so, this green set is for 256 which is several times wider than the 2048, just remember this. So, this directly corresponds to the new name of numerology that we are using for few generation, but the original name that was propose was adoptive sub category bandwidth. So, what we have shown is this different shaded portions indicate the range of mobility which causes a certain Doppler, which can also be connected with corresponding phase noise in terms of delta f which gives the highest throughput.

So, if we clear this things up so, will find that is the each particular section represents the corresponding throughput for that sub carriers spacing. So, if you have this delta f mu this delta f mu is much larger than delta f of 2048 and hence it can support a larger throughput over here, but there is a significant reduction in the throughput in the lower mobility condition. So, what is suggested or proposed is that one can adaptively change the bandwidth of the sub carrier and depending upon the mobility condition or channel condition one can flexibly allocate the sub carrier spacing. Thereby one can get the best throughput under all conditions of sub carrier spacing or phase noise or whatever is the situation.

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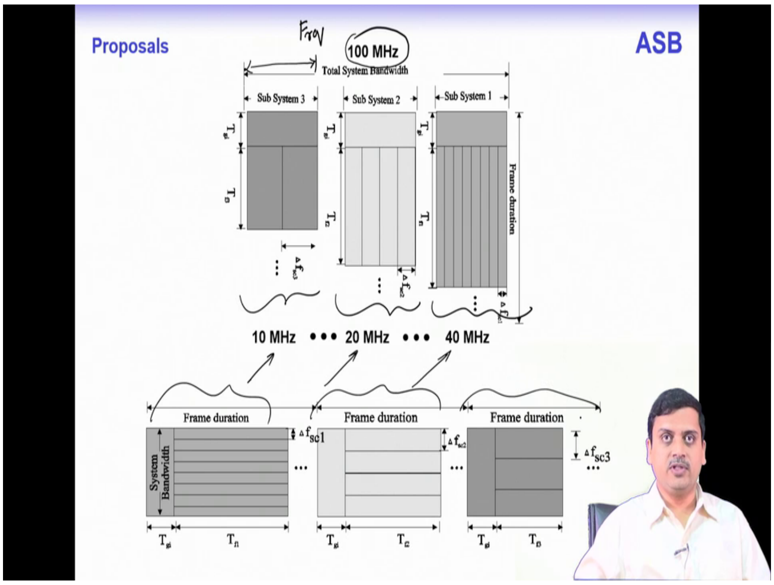

So, if we look at the structure what we had proposed is we had consider that let us say there would be a much wider bandwidth in that case one would limit a sub part of the band width to let us say 20 megahertz because as you increase the bandwidth your processing complexity also increases. So, we had assumed that let there will be smaller parts and smaller parts can be a various bandwidths depending upon the particular realization. So, this is in frequency domain you can have several chunks which run in parallel. One could also think of doing this in tedium fashion depending upon the implementation technically it is feasible, but this is the approach which is now adopted in the fifth generation system.

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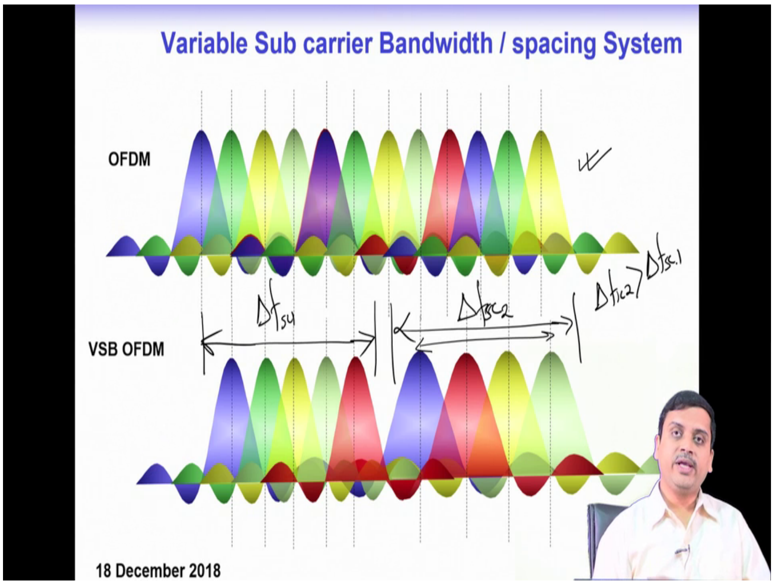

And, the picture that would look like is in a standard LTE is would look like this. In a variable sub carrier bandwidth we have certain fractions having narrow bandwidth, certain fraction having wider bandwidth this work that we are representing over here is an extreme case of the picture over here.

In this case, we had a group of sub carriers which are next to each other whereas in this case we have a allocated, a consecutive group of sub carriers who have a wider sub carrier spacing. Let us say this is 2 and this is delta f sc 1, we have delta f sc 2 greater than delta f sc 1, right.

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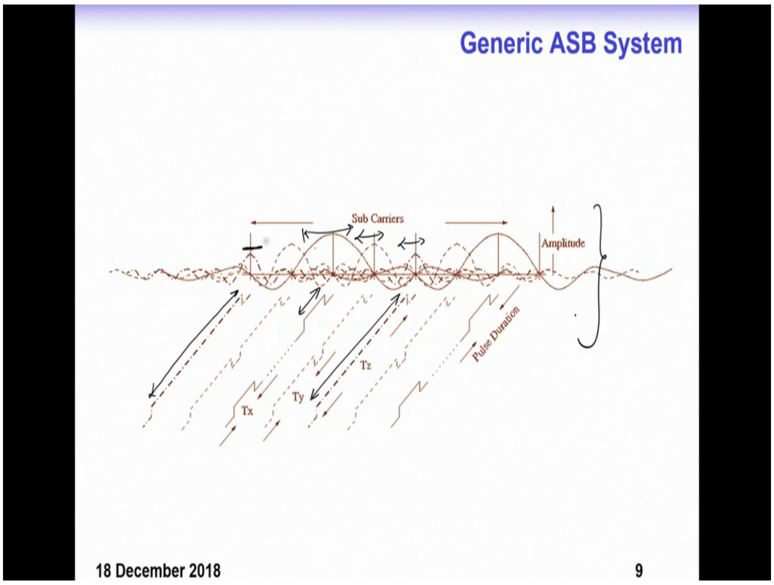

Whereas, we can think of an extreme multiplexing of things where we will find that different bandwidths are multiplexed simultaneously and correspondingly the different time domain pulsed this would also exists simultaneously. So, what we see is that the narrow band sub carriers have a longer pulse duration and the wider band sub carriers have a shorter pulse duration.

So, with this also the detailed analysis of signal to interference plus ratio noise ratio and the throughput calculations have been done and as I had shown earlier this particular reference which we will give you in details including the cover page which contains this particular image, one can find all details about the performance analysis that one needs to do.

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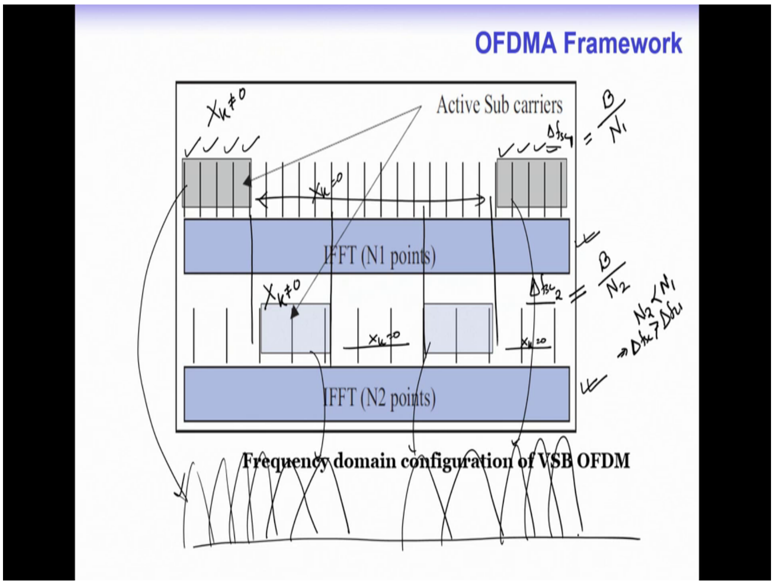

So, here we have also proposed the structure in which this can be worked out; that means, one can think of different FFT sizes; that means, they are all operating on the same bandwidth, but the sub carriers spacing is simply different. So, that means, if the total bandwidth is B, sub carrier spacing 1 should be equal to B divided by N 1 and this sub carrier spacing 2 is the same bandwidth divided by N 2.

So, in this case N 2 is less than N 1 leading to delta f sc greater than delta f sc 1 and here what we indicate is that in one set of FFT, IFFT operations one would activate few sub carriers; that means, send them non zero signals with X k not equal to 0 and it would let the other sub carriers having X k equal to 0 while in the other FFT, one can have the X ks not equal to 0 in the portion which is not overlapping in the frequency domain of the other system. Whereas, here you can have X k equals to 0, X k are the consolation points.

So, by virtue of which if you look at the final frequency domain picture we will find that these sub carriers are present because of this. In the next portion we will find wider sub carriers present because of this. So, here we will find wider sub carriers spacing, here we will find narrower sub carrier spacing.

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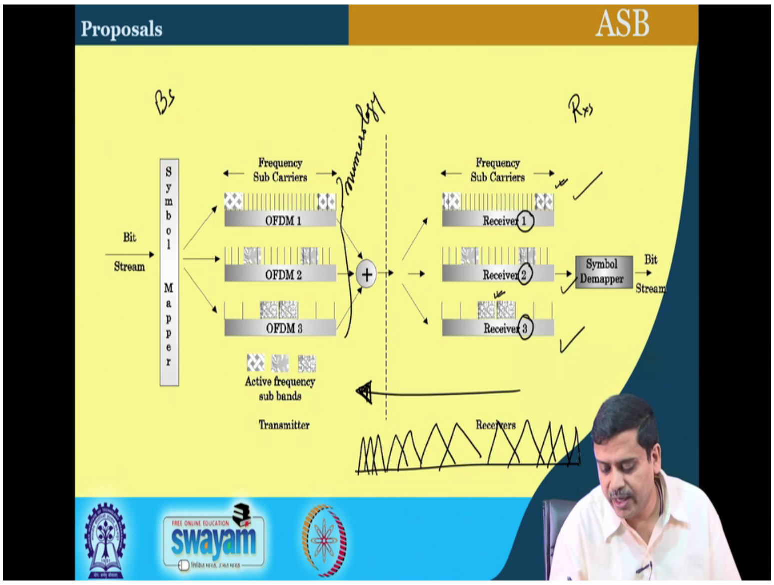

So, implementing this is also not a problem and this particular picture generalizes the entire thing where we can have different sub carrier spacing. So, this you can connect to different numerologies and it can be decoded by different receivers simultaneously. So, as if this is the base station and these are the different receivers as have been indicated here receiver 1, receiver 2, receiver 3. They can decode independently. And, one can also think of a reverse direction transmission; that means, each trans these becomes transmitter would activate only these few sub carriers out of the entire set of sub carriers this receive. This transmitter would activate only this set of sub carrier.

So, when the signal arise at the base station one would find that corresponding to this there is some narrow band sub carriers, then there will be a little bit wider band sub carriers and they will be even wider band sub carriers next to each other. So, then this way one can have a mixed numerology architecture.

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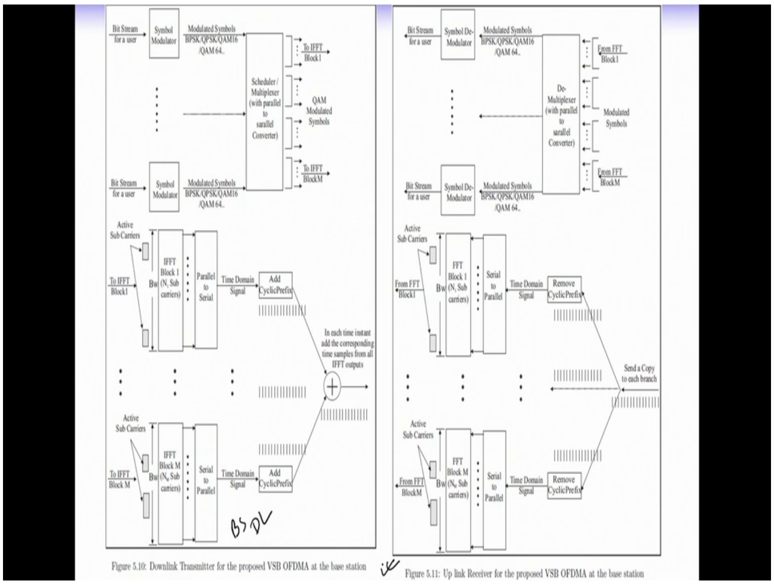

In this figure we have given a detailed block diagram of how the transmitter and receiver would look like. So, this one is the BS or the down link transmitter, here we have the uplink receiver structure. So, all this details have been proposed and you can find them in the different in the different material.

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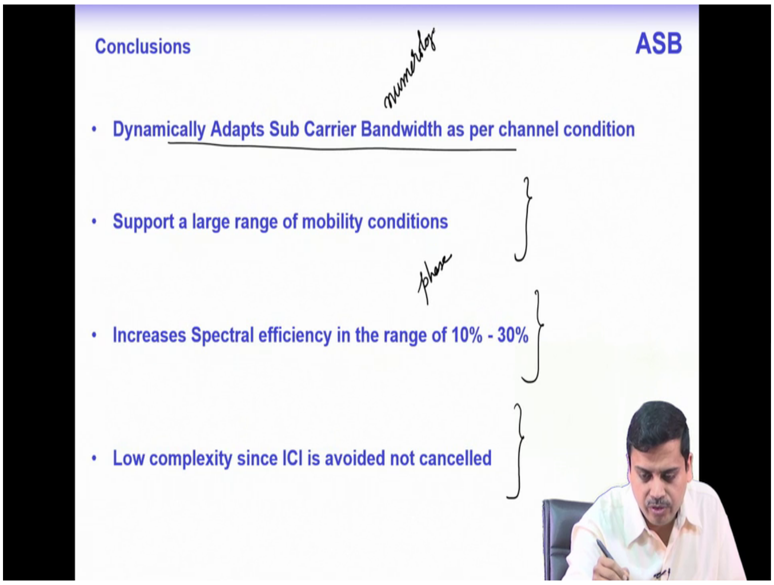

In this we have verified that the spectral efficiency improvement from 10 to 30 percent can be had. It can support different mobility conditions and different phase noise conditions. As well as low complexity, ICI management can be done we need not cancel the ICI, right. Only thing you need to do is the dynamically adapts this sub carrier bandwidth and which you will now term as numerology.

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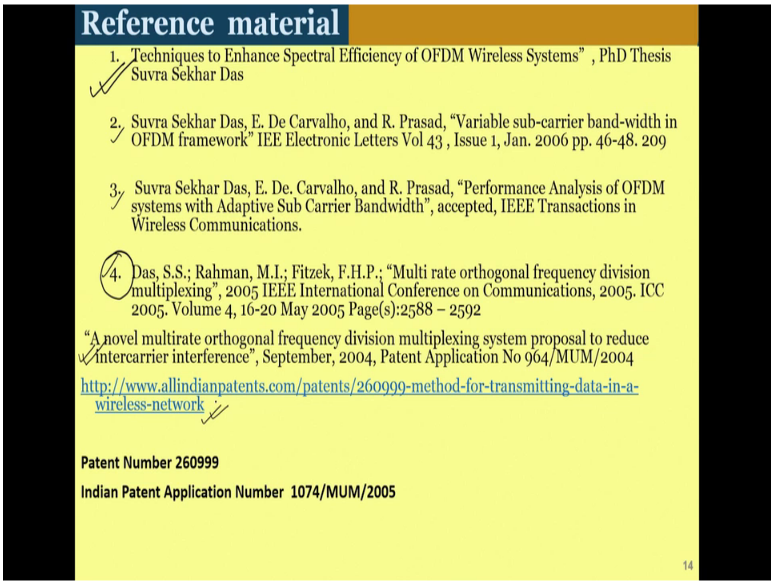

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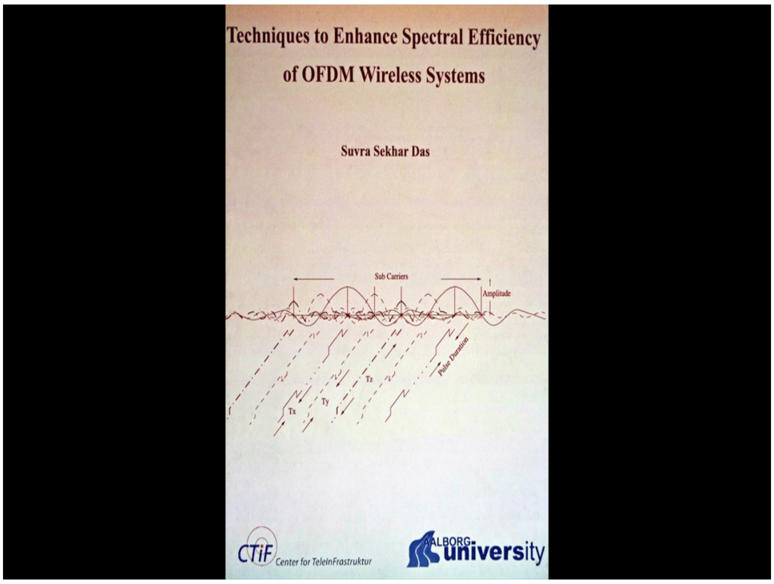

The references which we would point out is the first worth here which contains all details of the things that were that are presented in this particular discussion and relevant for the fifth generation air interference and there are different publications which also point out to the same. This is the earliest worth in this particular direction and there you can also refer to a patent which can be at easily accessed from this particular website which divide gives all details of the adopting sub carrier spacing, you call it variable sub carrier spacing or whether you call it numerology as per the new statement.

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I would also point out at this point that yeah. So, this particular thesis that you are saying in front of you can also refer to this particular work which can describe the hardware realization of such a thing. So, as you can see from the picture which is depicted on top of the particular PhD thesis by Christian Blumm which is maximizing OFDM performance real time adaptivity and you go into the details you will also find that they have also referred to the work that I just presented to being one of the first kind of work in this domain.

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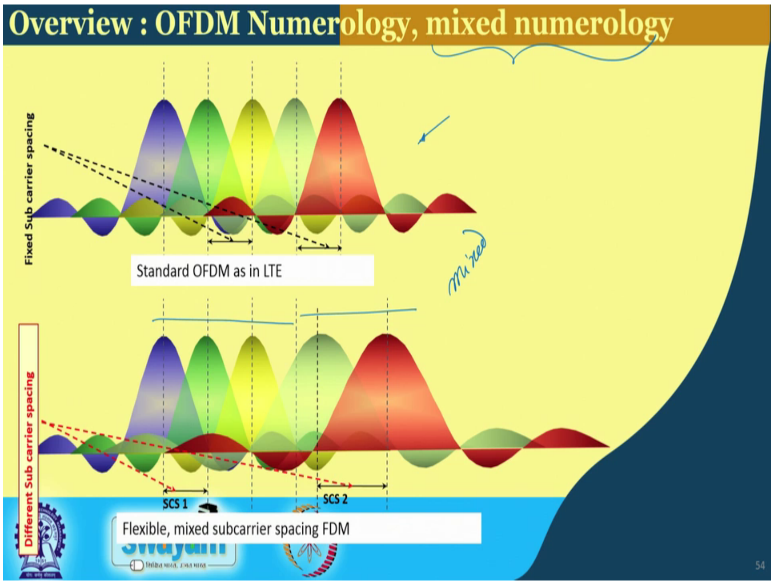

And we are all really extremely happy that finally, these kind of proposals which we thought is pertinent is finally, being used in the fifth generation system where the terminology that is used is numerology and we have the most complicated situation which is the mix numerology and if you want detailed analysis of this numerology please refer to all the details that we have pointed out over here to find detailed analytical expressions, performance analysis, how to do the simulations and all other details available.

So, we stop this particular lecture here ah. We will continue to discuss some more things related to the choice of cyclic prefix, how does effect and what are the uses, so that it can also provide you with more tools and methods by which you can improve the systems even beyond what is available today also give you information about the problem that is associated with coupling the cyclic prefix along with the sub carrier spacing. Further we will go beyond and discuss about the slot aggregation which is also one of the important characteristics which have been investigated earlier.

Thank you.