Evolution of Air Interface towards 5G
Prof. Suvra Sekhar Das
Department of Electrical Engineering
Indian Institute of Technology, Kharagpur

Lecture – 24
Frame Structure of 5G air Interface

Welcome, to the lectures on Evolution of Air Interface towards 5G. So, till now we have discussed all the previous waveforms, the base line structure, we have also discussed the waveform which is used for the fourth generation as well as the fifth generation which is the primary. We have also discussed the variation that is presented in the fifth generation wave from with respect to the fourth generation. We have said primarily they are the same wave form, but it is parameterized and it is called OFDM numerology.

So, after understanding whatever is the required for the basic elemental structure today we will look into the frame structure frame format that is present in 5G and as we said will also look at the genesis and also how these things are evolved and what is the reason behind designing such a system?

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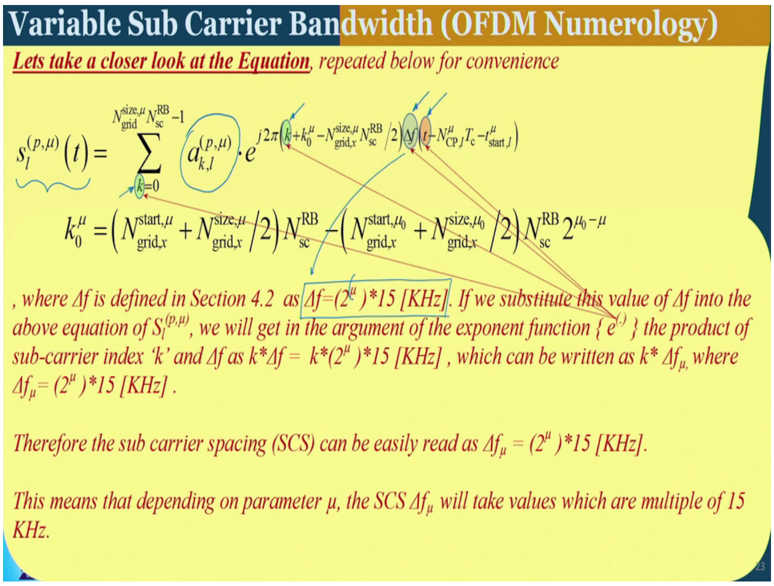

So, what we have discussed in the previous lecture is the expression for the OFDM symbol generation and where we have identified that the time domain signal, the OFDM signal is generated like a standard OFDM generation where we have the symbol constellation in case of OFDM otherwise, it will be the combination of the DFT spread signal. It is summed over k that is the subcarrier index and e to the power of k comes in like a typical IDFT expression and frequency domain subcarrier spacing and time. So, these are the three important factors.

We have also identified that this delta f which is present there is essentially this factor delta f is equal to 2 to the power of mu multiplied by 15 kilohertz. So, it is a multiple of the basic structure that is used in the fourth generation system and what we find it is a variable OFDM system and this variability is controlled through the choice of values of this parameter mu which we have also described in the previous lecture. And hence it is termed numerology that is what we have given over here it is called OFDM numerology because this number changes the values of the subcarrier spacing as well as that of the cyclic prefix.

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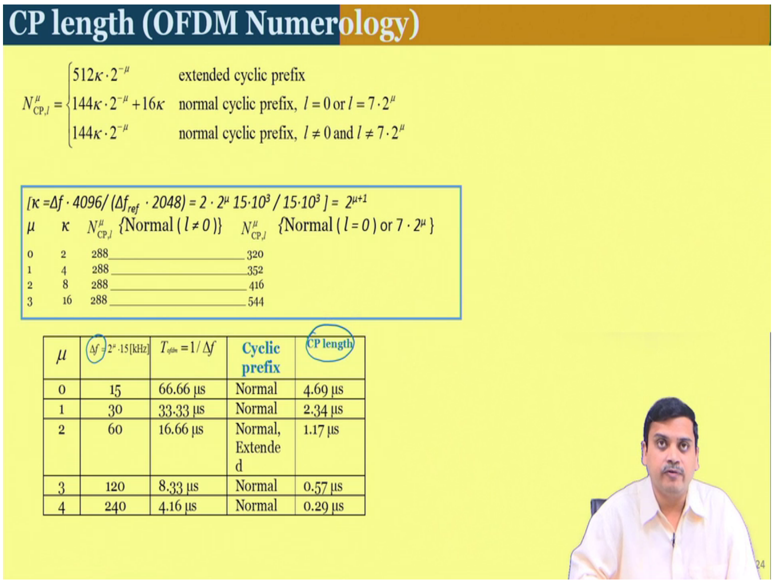

So, that is the only difference. So, we have also discussed the various lengths of cyclic prefix that come along with the different parameters of mu and hence the combination of delta f and the CP length together defines the numerology and this combination comes from higher layer information. So, higher layer information will convey to the lower layer what is the values to be used and it goes on accordingly.

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So, what we have summarized is that numerology essentially talks about variable subcarrier spacing or variable subcarrier bandwidth along with variable guard interval or cyclic prefix.

So, cyclic prefix and subcarrier spacing together they define numerology that is what we have over there, alright.

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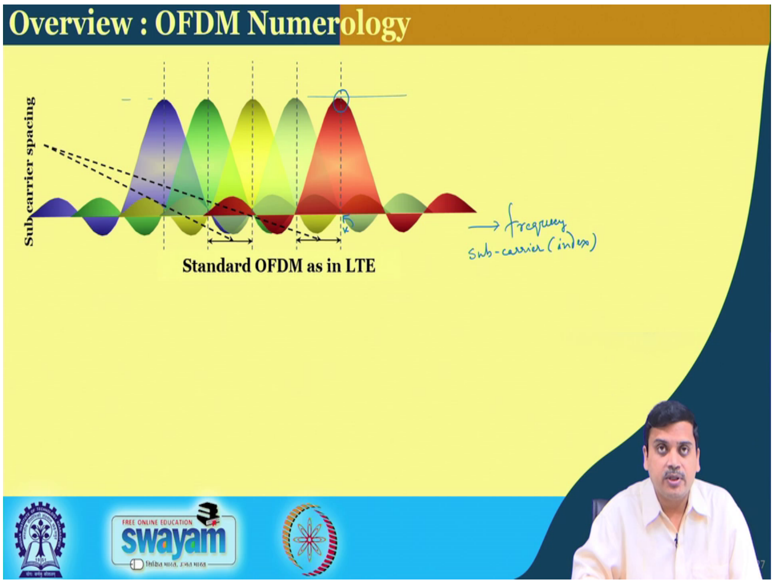

So, what we will discuss is how does it look like. So, in a standard OFDM system like in LTE we have the subcarrier spacing which is constant which is uniform and this is the frequency domain view. So, this is this is the f-axis or subcarrier index you can call it as index also if we want to put it as k values if these are different values of k and these are the different amplitudes.

So, one may remember that these amplitudes will change depending upon the modulation that is used. So, in this picture all the values have remained the same indicating they are carrying the same constellation or even they are carrying the same amplitude of the constellation. So, if it is QPSK this picture matches very well. Further one should also remember that even in QPSK in the same amplitude one could be of reverse phase that is also possible.

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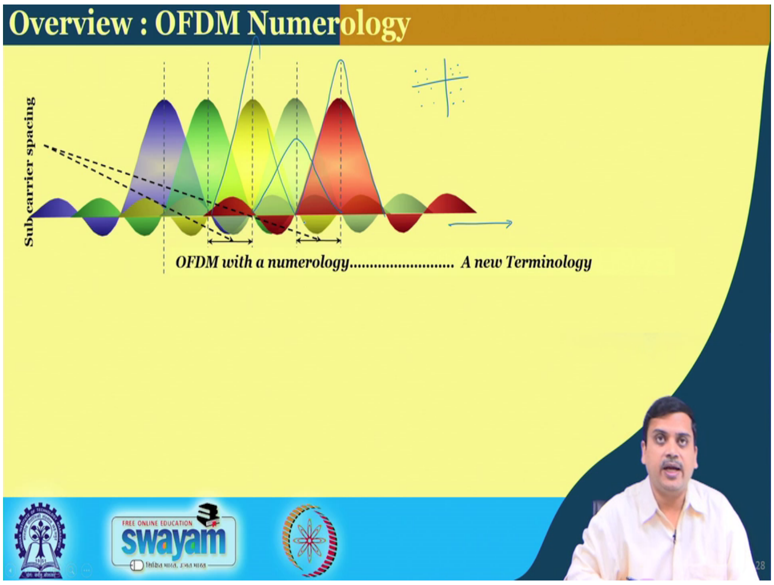

And, if one uses a 16 com like constellations so, in that case different once will be a different levels. So, one could be like this and one could be like this, but the 0 crossing would essentially remain at the same point. So, that fluctuation will remain ok.

So, now in case of 5G, instead of calling it standard OFDM, they are simply changing the name to numerology and it is a new terminology. So, if we just look at this particular figure there is not much distinction.

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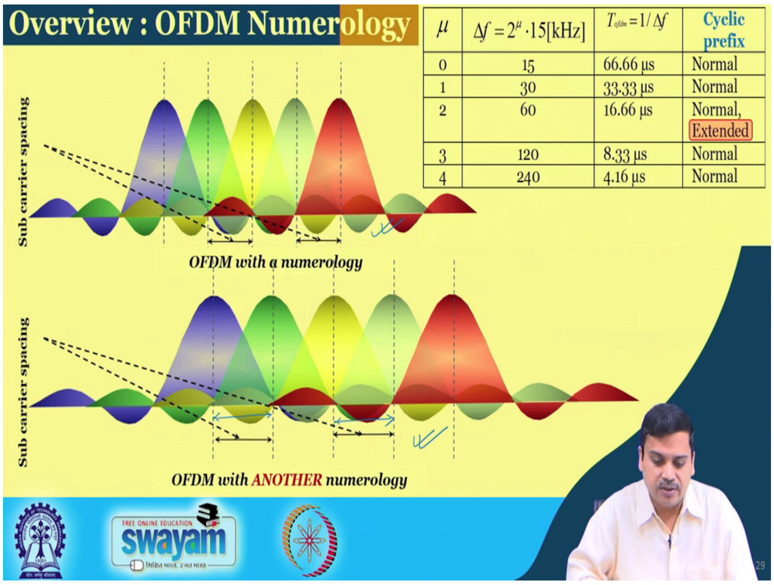

But, what happens is that because of the concept of numerology one can change the subcarrier spacing to a different value as we have been discussing. So, while this is possible in fifth generation another combination is also possible and they could simultaneously exist at the same time. So, with this picture it gives a clearer picture of what exactly happens with the set of equations that we have showed in the previous few lectures.

So, the description of a cyclic prefix and it is calculation we have already discussed and we have presented it here just for a review.

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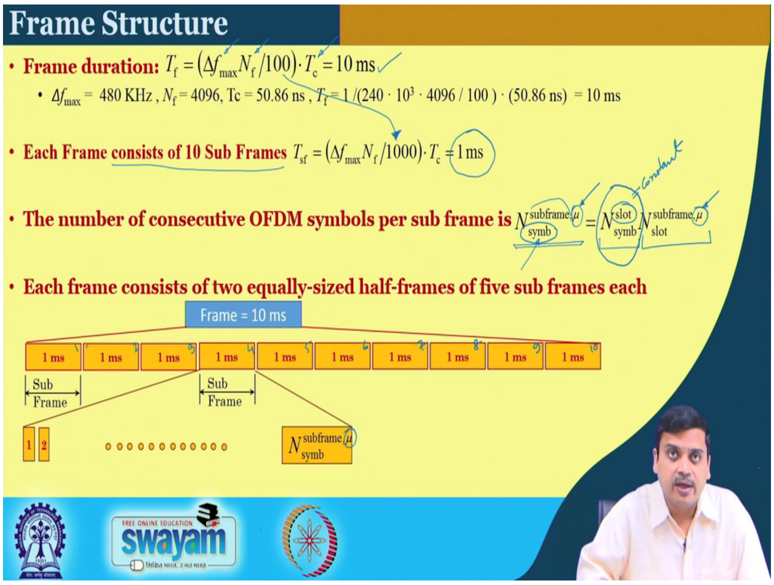

So, when we look at the frame structure this is the next important thing that we are suppose to discuss. So, the frame duration is defined as 10 millisecond, we have said this earlier the frame duration is a 10 millisecond duration. In an earlier slide we are summarized everything in one slide and now we are getting into details of it. And if you do the calculations of putting in a delta f max and N f with the values we have given in previous slide and you multiplied by T c which we have defined earlier you get this particular value.

The next important thing to consider is that each frame consists of 10 sub frames; each of 10 of 1 millisecond duration. So, here what you see the changes instead of divided by 100 it is getting divided by 1000 naturally it is one tenth of the value and 10 such values together combined to produce 1 millisecond.

Number of consecutive OFDM symbols per frame is defined by this parameter, at some point we said that yes we will we are going to use these parameters we said in appropriate context will be defining them. So, now, we have it. So, number of symbols per sub frame. So, what we have over here is per sub frame, for a configuration mu is equal to number of symbols per slot; so, here we have something called as slot which we will define and multiplied by number of slots per sub frame for a combination or a numerology mu.

So, what is clearly means is that the number of symbols per sub frame is a factor which depends upon mu, as well as the number of slots per sub frame depends upon mu. We are just trying to look at the expression and trying to understand what is derivable from the equations whereas, what we see over here this particular expression it tells us that number of symbols per slot is not parameterized by mu, right. So, that means, that number of symbols per slot is a constant value which we will see ok, but number of slots per sub frame changes and thereby it will produce different results. So, what we see here is that we are given a pictorial representation of the description whatever we have given on top.

So, each frame consists of 10 such sub frames; 10 such sub frames each of 1 millisecond duration and this is called the sub frame as we have defined and each sub frame if we look deeper into a sub frame we will find consists of several OFDM symbols up to N symbol per sub frame parameterized by mu right. So, this pictorially explains the particular picture that one can generate and this obviously, helps in a easier understanding of how things are set up.

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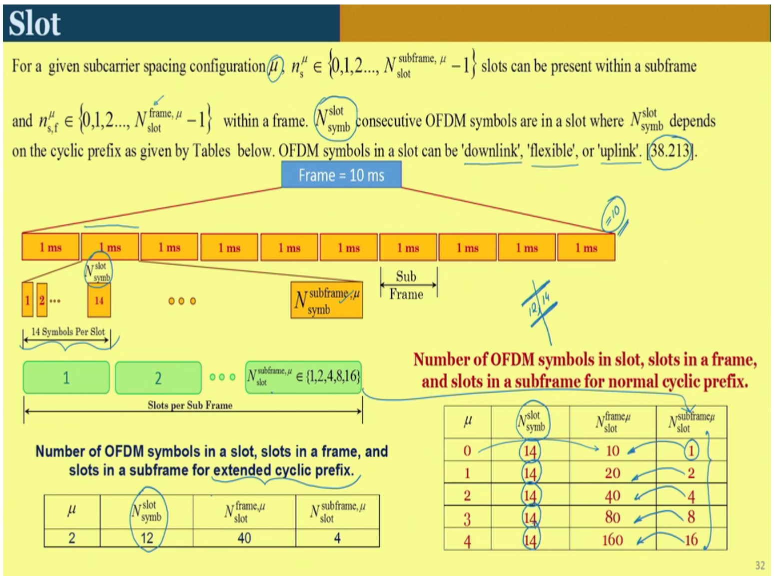

μ	N_{symb}^{slot}	$N_{slot}^{frame,\mu}$	$N_{slot}^{subframe,\mu}$
2	12	40	4

μ	N_{symb}^{slot}	$N_{slot}^{frame,\mu}$	$N_{slot}^{subframe,\mu}$
0	14	10	1
1	14	20	2
2	14	40	4
3	14	80	8
4	14	160	16

So, now what we see over here is that for a given subcarrier configuration mu, right, n s mu can take such values; that means, it is indicating number of slots per sub frame, right within sub frame and n s f mu is basically number of slots per sub frame which is simply multiplied by 10 because there are 10 sub frames in a frame. So, that is what we can remember that is 10 sub frames in a frame is constant and number of symbols in a slot is also constant. So, these two things are constant, that is what one can remembered.

Now, these slots as we will see can be defined as down link slot they can be defined as uplink slot and they can also be flexible slots. So, accordingly one can choose to distribute between downlink and uplink and detailed description one will find in the document 38 dot 213. So, we have described this different documents earlier and if one has to go into details of them one should go into those documents and find out.

So, let us look at the picture once again. So, we have the different OFDM symbols coming up and we have already seen that there are N symbols per sub frame and we have also identified that number of symbols per slot is basically constant which is 14 independent of the different numerologist that one is concerned with. So, this number is similar to the one in the fourth generation system. In the fourth generation system you could had 12 or 14 depending upon the length of cyclic prefix which would be dependent upon the operation situation.

Number of slots per frame would change according to mu, right. Now, why this would happen? We would obviously, get to see that and number of sorry number of slots per sub frame would also change for the same reason that is what we are going to discuss, but number of slots per frame is a 10 times the number of slots per sub frame for all cases that you are seeing, simply by virtue of this number 10 that is present in all the cases for all values of mu right.

So, that means, we also have another situation where one can use and extended cyclic prefix which is nothing, but a larger value of the cyclic prefix there the number should be different. So, there you have number of symbols for slot is 12 and as we said in the earlier generation that facility was also available. So, which is matching and there is no reason to be surprised with this because whatever technology 3GPP comes up with they have a basic agenda that there should be backward compatibility with the previous technologies. So, this essentially helps to maintain compatibility with the previous generation.

So, what we see now is we are getting a deeper picture into the frame structure or sub frame structure and what we have is that there are 14 symbols per slot that comes into play and the number or the variable is depicted over here so that, a more or less completes the picture of a frame with its sub frame and symbols per slot. Not only that so, now, what we have is that since there are 14 symbols per slot ok; however, this duration has remained constant over 1 millisecond. Obviously, they would be more number of slots or they will be multiple slots per subfra me. So, that is what is indicated over here multiple slots per sub frame. So, that is what is indicated in this particular chat as well as reflected in the image next to it.

So, we go ahead further. So, this is indicating the slots per sub frame and these numbers are depicted over here which matches with the number as you are seeing over here right this number matches with this number over here. So, they exactly fit into the jigsaw and we are able to setup the expressions.

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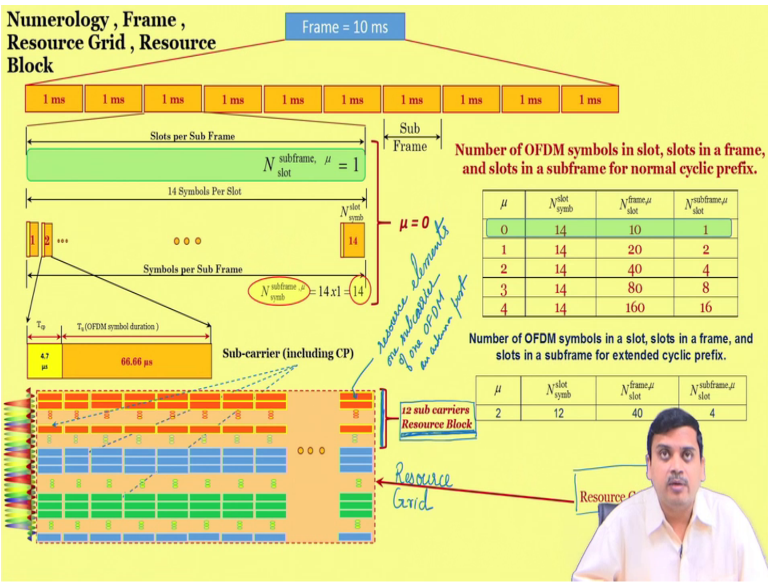

But, now again we will take a look at the same picture, but we will rearrange the view compared to what we have seen earlier, so that we get a proper hierarchy of the symbols and the frames from the bigger to the smaller number.

So, we have a frame of 10 milliseconds, in the frame of 10 milliseconds we have 10 such 1 millisecond sub frames. In each such 1 millisecond sub frame we have multiple slots that is the next level of hierarchy. In each slot we have 14 such symbols which present one particular slot and that remains constant and hence we will have multiple such symbols in one such sub frame. And that overall represents the entire structure that we need to look at when we consider the frame structure.

And again for the sake of reference we have pointed out the different parameter values that one needs to use and one should be careful if extended cyclic prefix is used if you are using a longer cyclic prefix and earlier we have described how they extended cyclic prefix calculation happens. So, if the cyclic prefix length increases then the number of symbols that can fit into this would obviously, going to be different. Accordingly you get different number of symbols per slot and the numbers are so calculated that it matches with the earlier generation right.

So, now, we take a look at the symbol that we are talking about. Each symbol carries a cyclic prefix that is what we have indicated over here in each of them we have indicated a cyclic prefix and that cyclic prefix depends upon whether you are going to have a normal cyclic prefix or an extended cyclic prefix most of the calculations that we have shown over here are with respect to the normal cyclic prefix. With the extended cyclic prefix one can change the calculations accordingly.

So, when we take a deeper look into each of the OFDM symbols; so, that means, we are looking into final and final granularity. We have started with 10 millisecond, then we have moved to 1 millisecond, then we have moved to slots, from slots we have moved to symbols. Now, we are going inside the symbol and we trying to see how does it match.

So, each symbol consist of a cyclic prefix as well as there is this OFDM symbol duration and this is the basic structure and when we move beyond that what we find is that in one of the numerologies the number of sub frame is equal to 1, that is what we have said and that matches with the case when mu is equal to 0 and this is what is the base line structure matches with whatever is present in the earlier generation system.

So, in that case number of symbols per sub frame would be equal to 14 because you have only one slot in the sub frame. So, if you see the changeover of the picture that we have drawn from the previous, this is the generic picture. Now, we changeover there is only one slot, but since number of symbols per slot is constant to 14, so, the entire OFDM symbols stretch to 14.

So, for obvious reasons the duration of this OFDM symbol as to be longer and what we see is that the duration of OFDM symbol is 66.66 or 6666 or 67 micro seconds and that corresponds to the 15 kilohertz sub carrier bandwidth. What we have given over here is the cyclic prefix length 4.7 micro seconds for a normal C P, right and so that it fix into the picture very well and this is the frame structure for mu is equal to 0.

So, when we move further what we find is that on the frequency axis; so, this is the frequency axis because remember we are talking about time access horizontally. So, this is the time axis, this is the time or OFDM symbol index l, time index one can say OFDM symbol index and this access is the f access or one can also think as sub carrier index k going in this direction. So, each of the these a different sub carriers whose detailed picture or zoomed picture we had seen earlier right.

So, that means, in one sub frame duration they would be several such OFDM symbols, right because here we are saying in one numerology there are 14 OFDM symbols there is only one slot present. So, which will be several such OFDM symbols and each OFDM symbol is consisting of several sub carriers depending upon the size of the bandwidth that is available, this is very very important to note.

So, this entire resource grid we called it the resource grid; so, this entire resource grid is available. So, this also called probably not visible so let me write it here instead of. So, the entire resource grid is available for allocation or doing modulation and coding scheme allocation towards having higher and higher throughput. And group of 12 sub carriers this is also important to note group of 12 sub carriers forms a resource block this is important. So, this is the minimum unit that is addressable. Each of this elements are called resource elements which we have defined earlier alright.

So, each of these are resource element each resource element is one sub carrier of one OFDM symbol for an antenna port. So, if there are multiple layer transmission will be having them on stacked on top of each other. So, if there is a single antenna system then you have only one layer and then it is basically the smallest unit which can carry information. Now, for all reasons we have also discussed this thing that you cannot address every single resource element. Then the overhead will be so high there is you will actually the system is going to breakdown it is to going to actually some benefit in terms of transmission of data. So, they are grouped together, 12 sub carriers are grouped together.

And as you can see that the slots keep on varying. So, the total number of OFDM symbols that are part of or resource element that are part of the resource block keep on varying because of the numerology right. As we move beyond that to the second numerology that is mu goes from 0 to 1, we will find that there are 2 slots per OFDM symbol. So, that is what we get over here from 1 we get 2. So, there was 1 and from this 1 this changes to 2, right and we get 2 such slots and hence in each of the slots we are going to get 14 OFDM symbols.

So, that means, 28 symbols in all in case of normal cyclic prefix, but if there is extended cyclic prefix the value would be different and what we have going to find is that since there are more OFDM symbols in the same duration right; that means, it is now 1 millisecond, but the total number of OFDM symbols has become; total number of OFDM symbols has now become 28 from 14, right; we had 14 that has become 28. So, the symbol duration of each OFDM symbol must decrease right. So, earlier it was 66 it will become 33 because it has to be half of that and cyclic prefix length also reduces because that is a combination we have said.

So, now because of which because you have reduce the OFDM symbol duration if you look at the transition that happens in this the frequency domain effect because of time domain we know this thing when we shrink the pulse the bandwidth of the system increases. So, that is what is depicted over here, for ease of understanding the sub carrier bandwidth increases. The resource elements which were longer if you look at this resource element which was longer and narrower in bandwidth will become shorter in time and wider in bandwidth.

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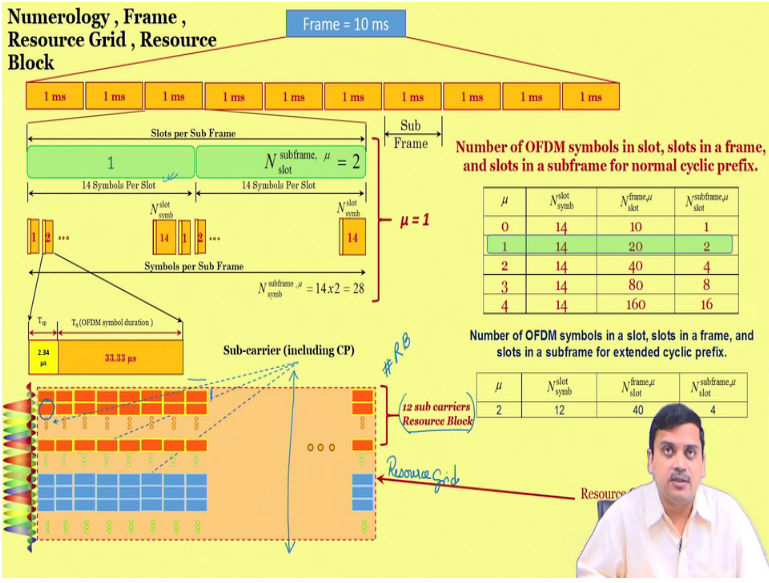

The resource grid definition remains the same. So, this again and 12 sub carriers forming a resource block that remains the same. Only thing that changes in number of elements in this in a slot remains the same there is not variation, but number of such resource blocks available changes because, if the total system bandwidth remains the same and one chooses two different numerologies then the number of sub carriers supported would obviously, to be different.

So, number of resource blocks RBs would change as per mu and bandwidth allocation and these are said by higher layer parameters and they can accordingly be chosen based on the appropriate operation. So, here again this is the resource element. So, the resource element definition remains the same resource block definition remains the same resource grid is the total number of resource elements that aware that are available for scheduling and hence the entire structure keeps on modifying based on the condition.

So, now what we have is that there are more number of symbols in the time domain which we have already seen and depicted graphically in this picture to give a proper view of things. So, then we move to the next numerology we find that there are 4 such slots; that is how the picture is going to happened and hence since there are 4 such slots the symbol duration OFDM symbol duration which was stretched still here will now reduce much further right; if the OFDM symbol duration reduces much further then as depicted in the picture below it the sub carrier bandwidth increases further right. Resource elements which were longer will become shorter in duration and they will wider in bandwidth and they will be more number of resource elements in the time duration to be allocated.

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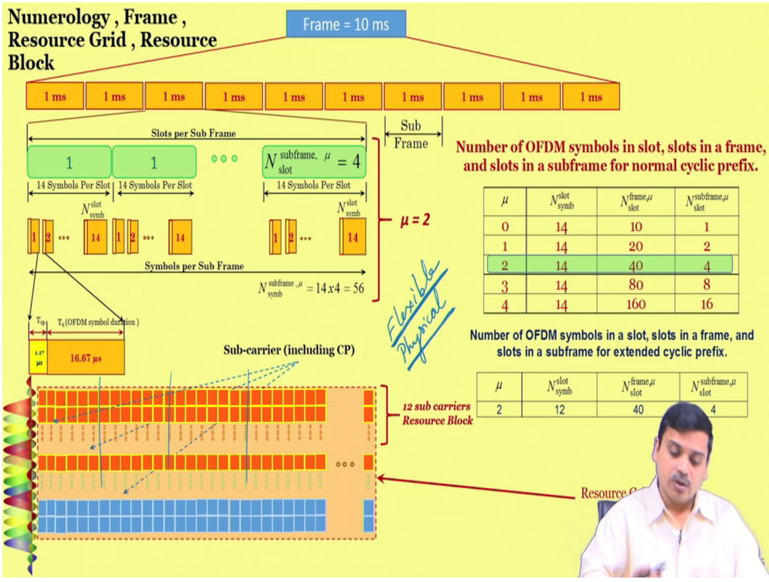

So, again depending upon how one wants the use the particular setup one has to one will set parameters accordingly the structure changes. The definition of resource block remains the same, 12 sub carriers. But, now one can have multiple such slots within that time frame to allocate. So, depending upon the different types of services that are being addressed by 5G, one can do this different type of service multiplexing or service multiple access through such a flexible mechanism.

So, this provides a very beautiful flexible, physical layer which was much needed for a long time and only now time has come that people have agreed to this common frame work that this is being allowed. Now, we will discuss in the next lecture that why this flexible structure is necessary and the how this all started and probably took longer time to come on to this consensus, but one can easily understand that if one as this flexibility one can do a lot of things in terms of providing support to various kind of services not only that there are various different other reasons also to have this basic thing in to the picture.

So, if one goes to the next higher level that is the third one the fourth one would get 8 slots as we transition from the 4 to 8 we find that the number of OFDM symbols increase, that is point number – 1. The symbol duration shrinks further. So, to help the picture being readable we did not reduce the picture over here, but we are changed the notion or the values of it and one can clearly see that the sub carrier bandwidth increases even further, symbol duration becomes shorter, but the sub carriers become wider and hence one can support more number of such symbols in the time duration. So, there are various advantages and disadvantages of each combination one has to appropriately choose.

Now, one thing I would like to point out at this instant of time is that if we trace back the sequence of events that we are we have been looking at and. So, what we are trying to see here is the transition and is very important to look at one very important issues we had said earlier that the sub carrier bandwidths indicated over here should be narrow enough, so that they experience nearly flat fading, right if this is the channel gain, right.

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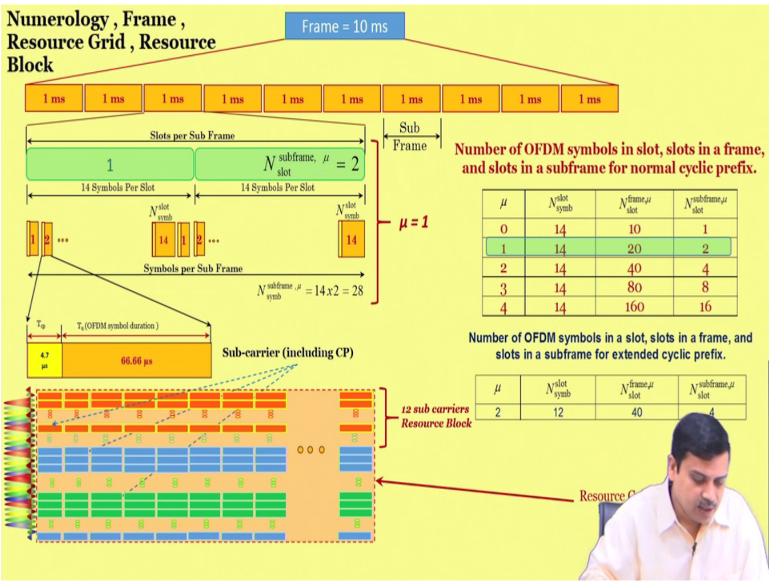

And, then when we transition from one numerology to another numerology , then the sub carrier band width increases.

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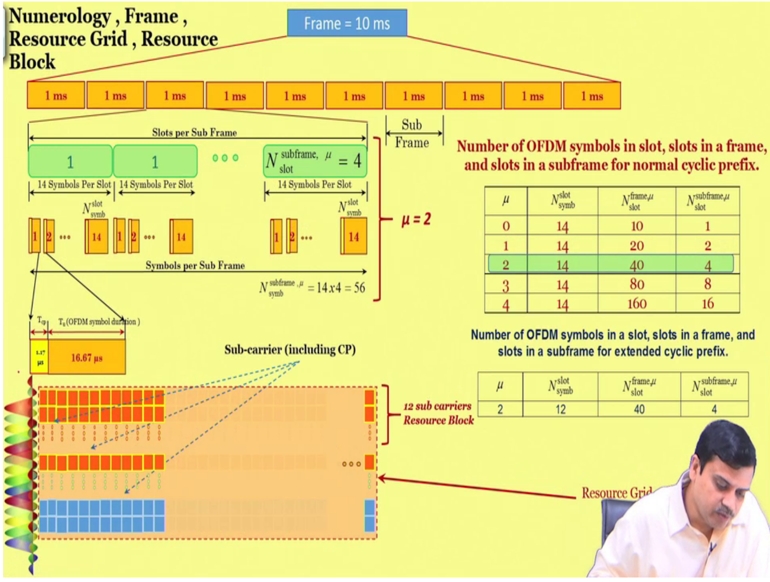

So, as we transition from one numerology to another numerology and we keep focusing on this particular section which is about the sub carrier band width what will find is that the bandwidth becoming larger and larger.

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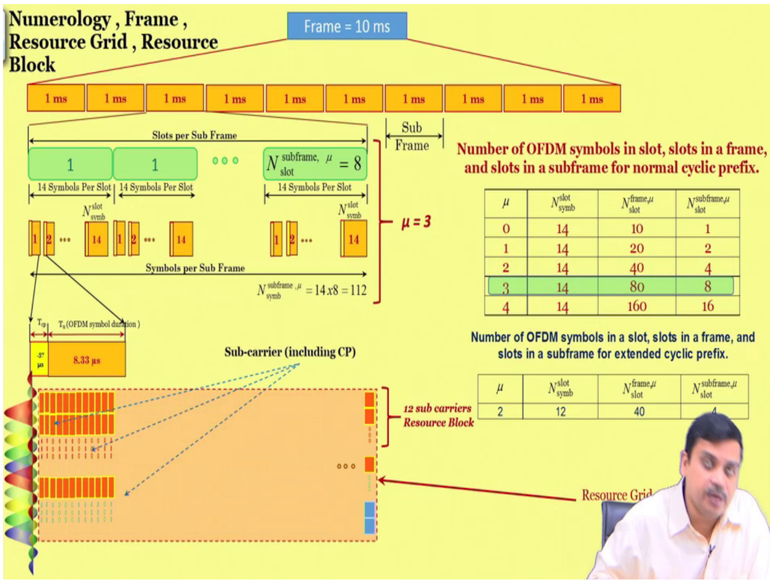

So, if the bandwidth becomes larger and larger this fluctuation in the channels strength would appear in some cases such that this sub carriers are no longer experience in flat fading. So, this is something one as to understand and carefully choose the numerology of choice. Further, we will also see later that the cyclic prefix length becoming smaller and smaller as one changes from one numerology to another.

So, what we have started of discussing is the numerology where the sub carrier spacing was 4.7 micro second in this particular picture, right we had 4.7 micro second and from that number this number is changing to the level of 0.57 and even 0.29 even if you go one level further it will be 0.29 instead of 0.57. So, in that case one will find that the channel in pulse response might be long enough and one is not able to use that particular numerology. So, one has to see this different effects and choose an appropriate numerology of choice one actually implement this particular system.

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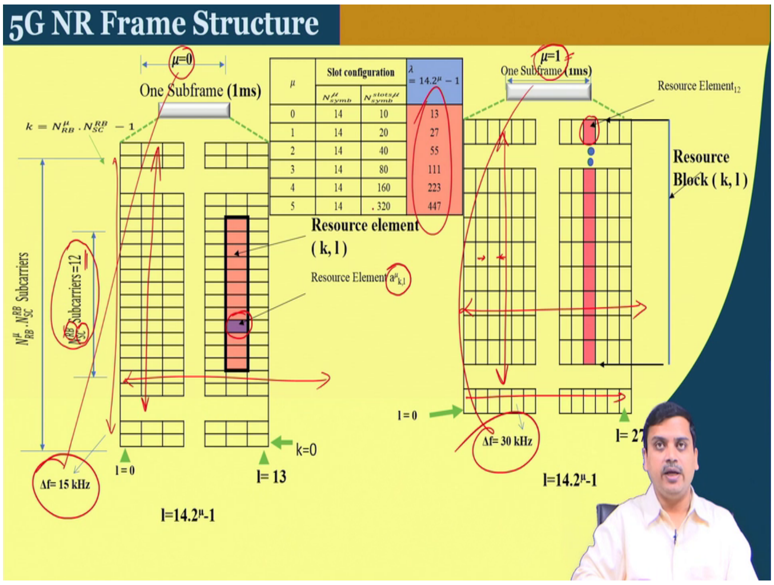

So, moving further in this particular slide we have combined the information in a little bit abstract manner where we you have removed the sub carrier picture to see only grids structure. So, this is easier to look at.

So, what we have is, for mu equals to 1, we have the sub frame structure and what we have over here is for a mu equals to 0 the sub frame structure and the total number of OFDM symbols is on this access and the total number of sub carriers is on this axis. So, over all we see that in both cases number of sub carriers per resource block number of sub carriers per resource block is 12 here again we see that number of sub carriers per resource block will again remain as 12.

And, here the resource element is 1 sub carrier here again the resource element is 1 sub carrier. Along with this these complex modulations will go in case of mu equals to 0, your sub carrier spacing is 15 kilohertz; in case of mu equals to 1 your sub carrier spacing is 30 kilohertz. Here what you see is that more number of sub carrier available, here lesser number of sub carriers are available within the same duration of time that here there are more symbols are available, right whereas, sorry here there are lesser symbols available, here there are more symbols available because mu equals to 1 thus symbol duration decreases. So, more number of symbols would fit in.

So, this is how the structure is going to change and this indicates the number of OFDM symbols that are present in the entire structure.

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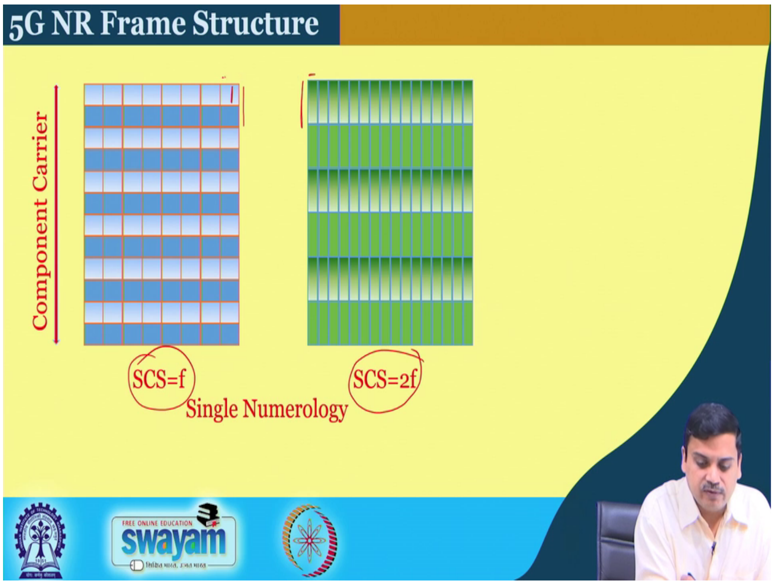

So, here again we simply show what would structure look like in a simplistic picture when the sub carriers spacing is a certain value and here the sub carriers spacing is of larger value. So, when it is larger value as you can see this width is equal to this width. Here the sub carriers spacing is half compare to the sub carrier spacing over here, but here the symbol duration is half compare to the symbol duration over here. So, these are just different pictures to show you the complete story.

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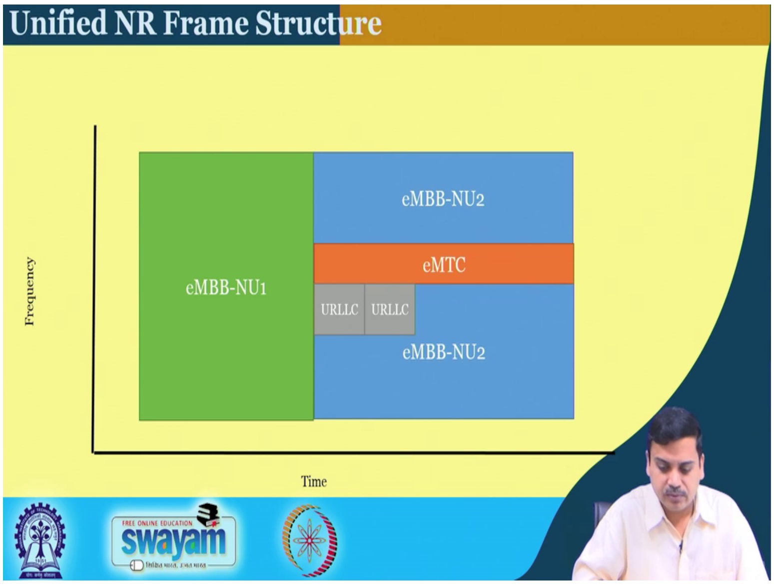

Further, because this frame structures are flexible it provides as an opportunity to provide multiple different services within the same frame. They can all be put in depending upon the requirements. So, one of them what we see is that URLLCC which is the Ultra Reliable Low Latency Communication service. So, when we talk about a low latency, we note that the symbol durations should be small, so that one can have shorter duration of transit time. If the shorter duration of transition time is there then the overall round trip time will be reduced and one can address lower latency applications.

So, we stop this particular lecture here. We will continue on this in the next lecture.