Evolution of Air Interface towards 5G
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Lecture – 26
Numerology OFDM – Cyclic Prefix & Link Adaptation by Slot & RB Aggregation

Welcome to the lectures on Evolution of Air Interface towards 5G. So, we are discussing the main unit of waveform in the 5th generation and that is the numerology. We have explained the frame structure earlier and in the previous lecture we have described how the numerology is subcarrier spacing is to be designed and why it is decided in such a manner. And, when all did this work start and what is the genesis and the original source of work which you may find useful towards understanding more details or even coming up with better designs which can be useful in future generation communication systems.

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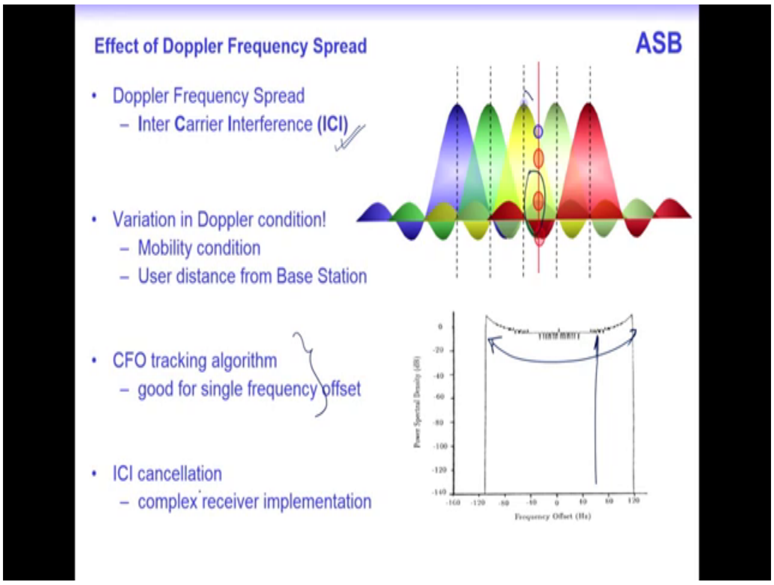

So, briefly very very quickly look into the background we simply stated that there is variability of Doppler conditions and beyond that we also stated that Doppler spread leads to inter carrier interference. We had explained the orthogonality loss, where signal power decreases, interference power increases and we said that since the mobility conditions are different.

And in case of Doppler instead of a single frequency shift there is an entire range of frequency which comes in. So, even if there is good CFO tracking algorithms its limited in its effectiveness and ICI cancellation mechanisms are also very very complex and especially when there is a whole lot of Doppler frequencies the effect of such mechanisms are no longer useful.

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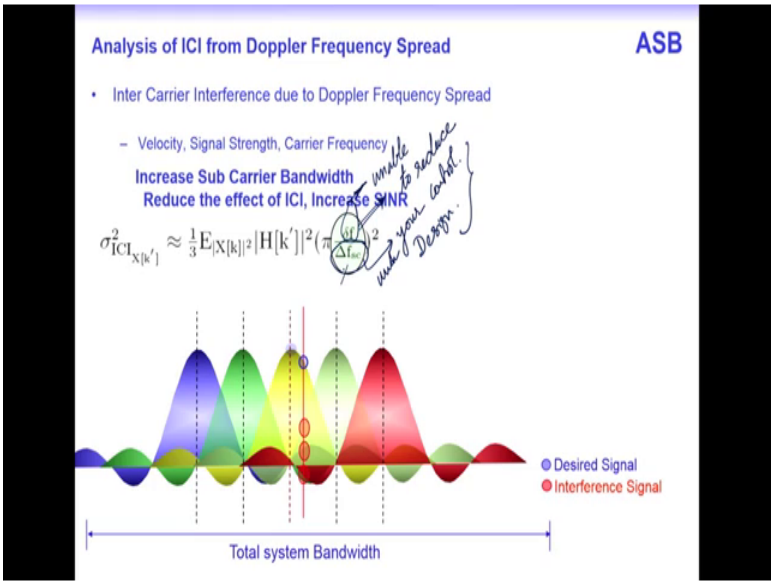

We also identified that the inter carrier interference power which is due to the Doppler frequency spread or frays noise is affected by parameter which is the ratio of the offset or maximum offset with respect to the subcarrier spacing. So, if there are situations where we are unable to reduce this; that means, we are unable to control this because there is a natural phenomena you are unable to control and one would not like to do ICI cancellation then the denominator parameter is under your control and becomes a design parameter.

And we are proposed that this could be used flexibility as per the situation and what we find happily is that the 5th generation system is actually using such a mechanism which can provide very simple way of accepting this broad Doppler spread or phase noise related issues which can give rise to ICI, we have also explained how the system works visually. So, when there is offset there is reduction in the signal power increase in interference power, but if we make the denominator larger we find that things can be improved significantly.

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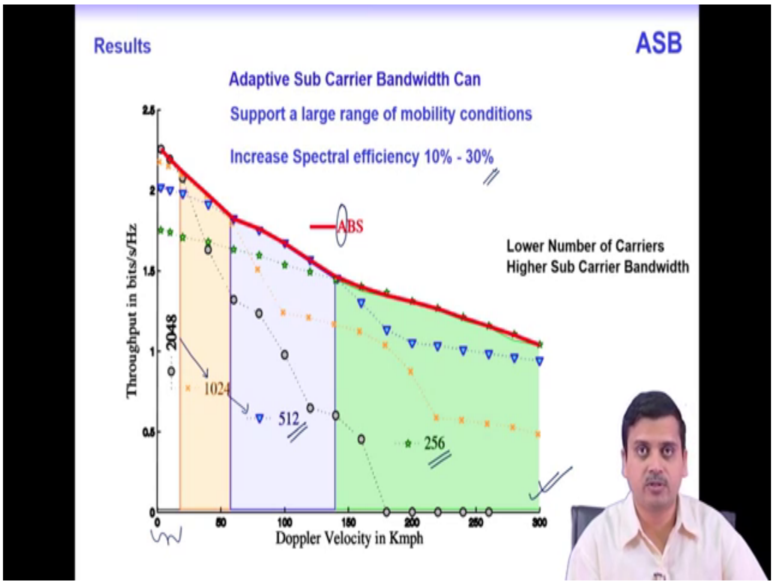

And we have also presented some of the results by which we have shown that as the subcarrier spacing increases; that means, as the FFT size decrease as the FFT size decrease as the FFT size decrease and the subcarrier spacing increases, we find that the wider subcarrier spacing are useful for more velocity or larger velocity. Or in other words situations where phase noise is larger whereas, they are not good under situations where Doppler is less or phase noise is less.

So, what we find is that if we have a combination of different subcarrier spacing which can be brought about by choosing the number of or the size of FFT one can effectively cover the entire set of Doppler or phase noise or effectively the frequency offset or frequency spread by adaptively choosing the subcarrier spacing and there you get a huge amount of benefit up to 30 percent benefit in spectral efficiency can be found based on the investigation that we have done; based on newer settings even one can find more precise numbers which are available for the 5th.

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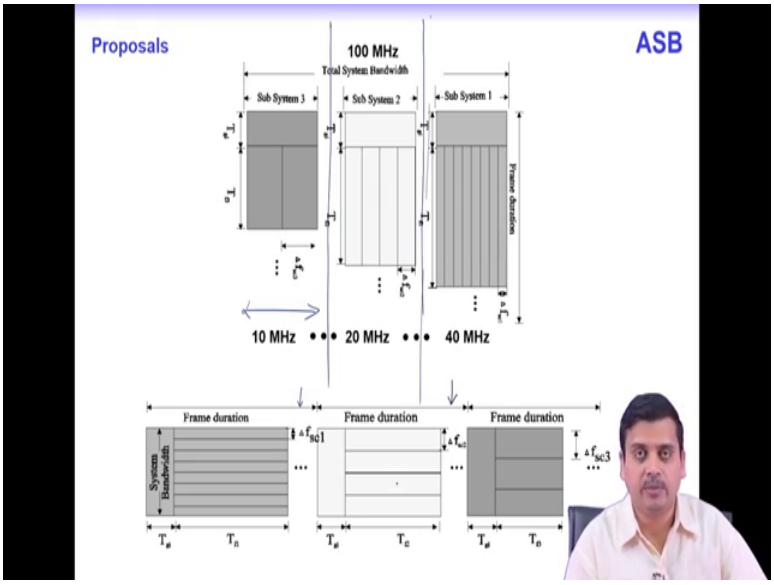

We also iterated that such systems can be implemented in the frequency division manner in a way that a large bandwidth can be split into smaller sections each having let us say 20 megahertz or 10 megahertz or 40 megahertz as per availability and they can use different subcarrier spacing and the detailed ways of how this assignment can be done are also mentioned in the references which we are pointed out. We also had said that such mechanism may be implemented in time division manner depending upon the implementation strategy and similar benefits can also be fetched.

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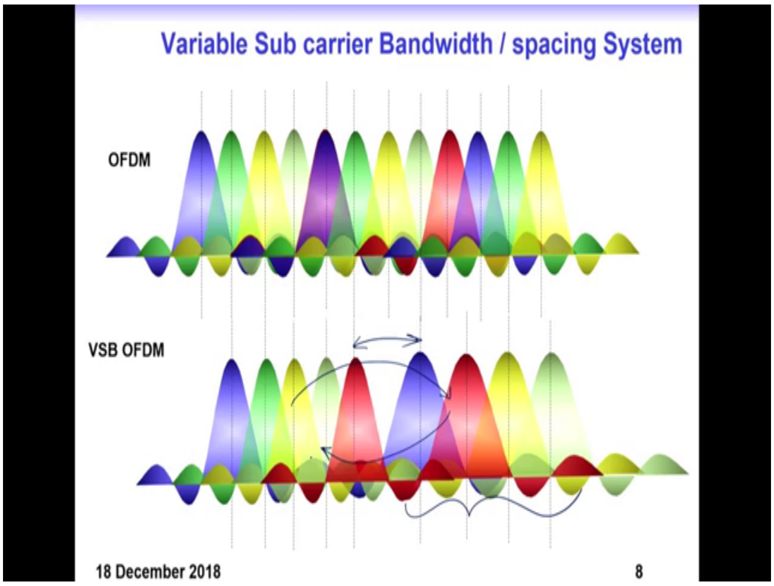

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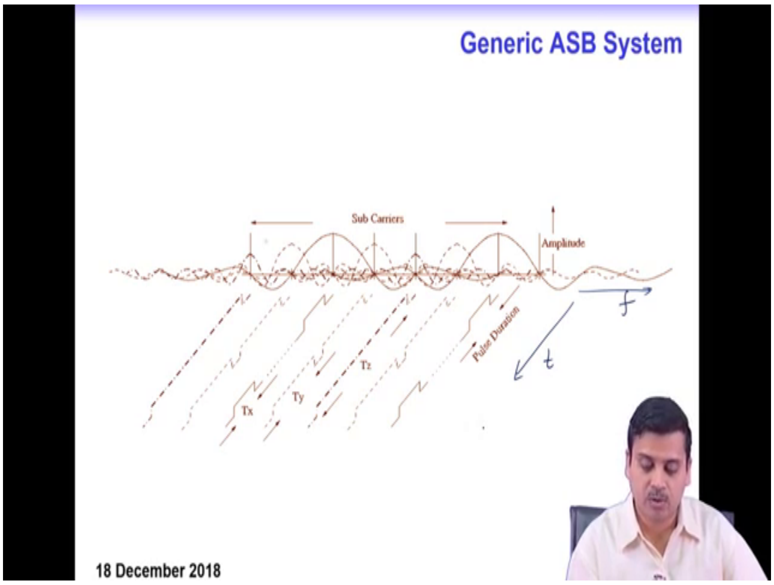

So, this particular picture we had shown where we said that mixed strategy can be used and the worse condition or the extreme cases where an absolute mix of different spectrum, difference subcarrier bandwidth can come into play where this picture particularly gives the time frequency diagram is the time and this is the frequency axis how it would look like and what would happen because of the interference? So, some kind of orthogonality loss is introduced because not all sub carriers are orthogonal, but you can choose a set of sub carriers which will be maintaining some kind of orthogonality amongst them.

So, when we have a group of sub carriers they will be orthogonal to each other; however, one set may be orthogonal to another, but it is not in the reverse direction. So, there is some kind of orthogonality loss and we have found that the edge sub carriers which are at the edge of interference would be suffering the most, but still you can benefit a lot. We have also shown implementation mechanisms which are also very vital.

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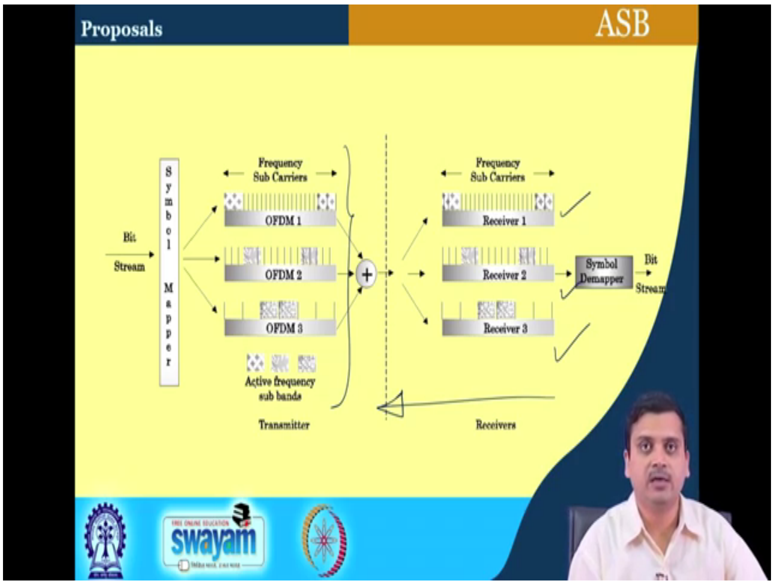

And we had also shown how at the base station side the various things can be, various subcarrier spacing can be introduced while they can be decoded at the user end independently and the reverse direction they can be generated independently and combined at the base station receiver side.

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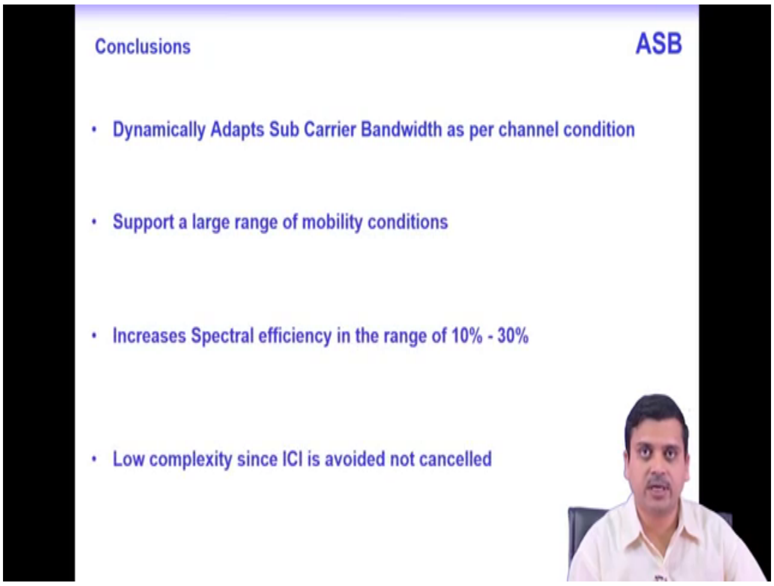

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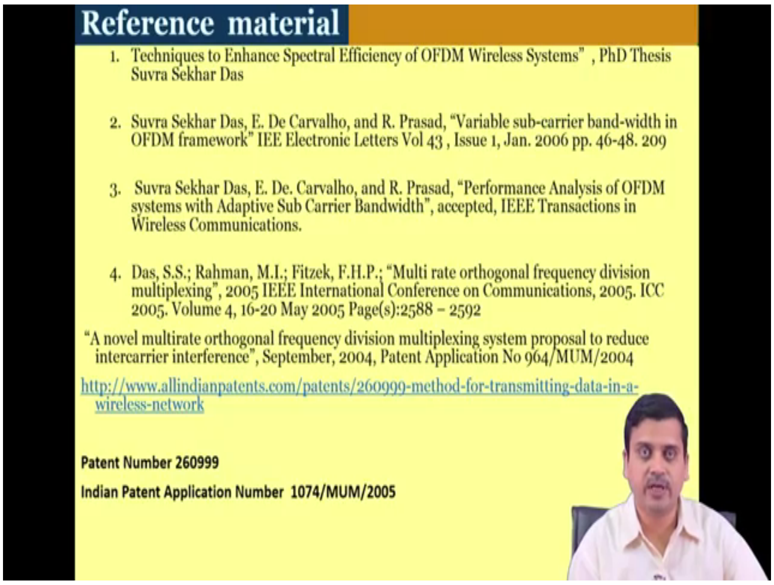

So, we have also presented different architectures and we have provided the benefit. We have also given you the references which we find are important which you can go through for finding more details.

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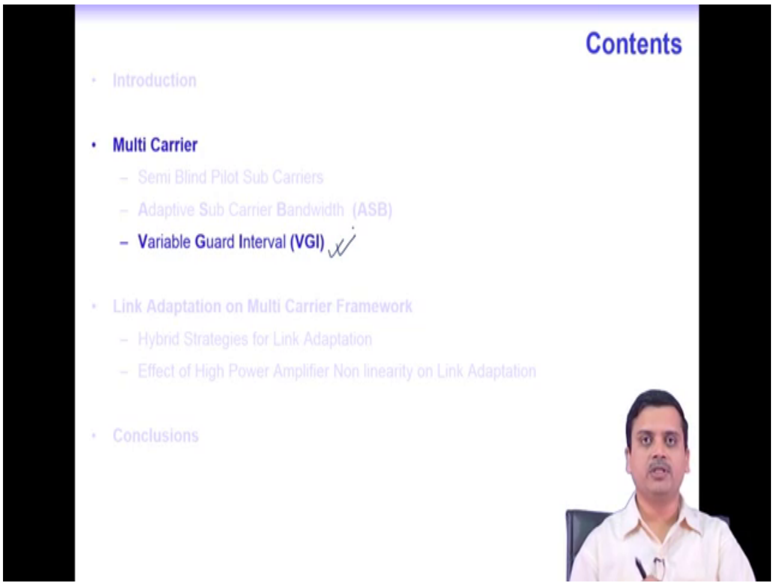

Now, we move on to the other aspect of the numerology that is the guard interval or the cyclic prefix and we will discuss how this is to be chosen. So, that together one can find ways to select both the subcarrier spacing and the guard interval. So, that one gets where appropriate combination of choice to in during deployment.

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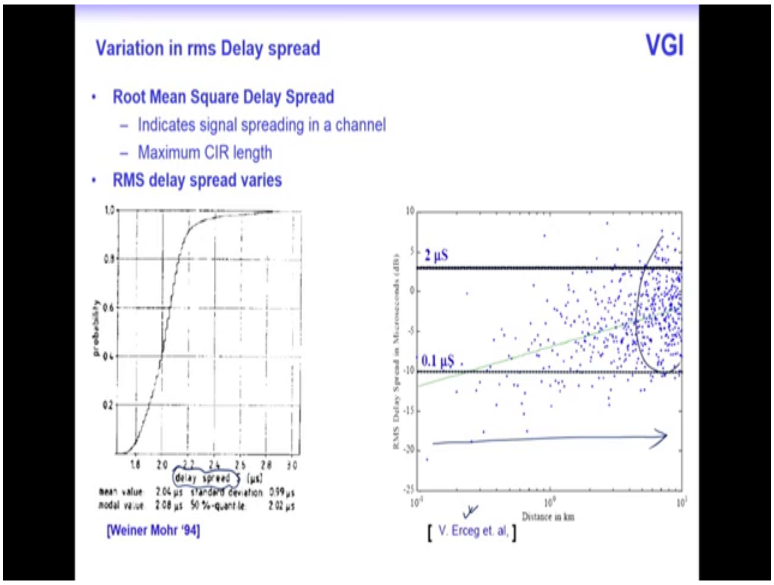

So, in this particular picture although it's from some papers we have taken it only for academic reference, you can always find reference to these particular papers. It is shown that the delay spread has a certain distribution and in this picture which is again from one of the works by Vinka Erceg we have shown or we have actually taken it from there which shows that as the distance increases the delay spread also increases following certain distribution.

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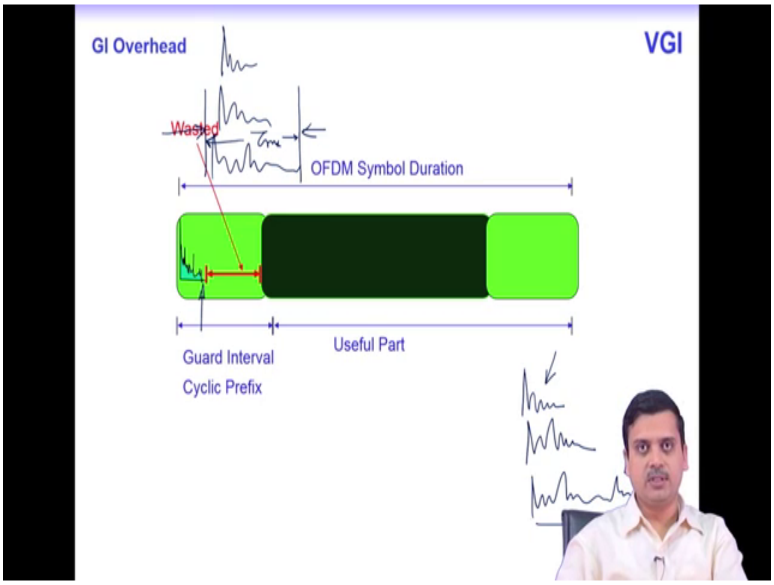

So, effectively what we mean is that when you instead of looking at a situation where delay spread is constant, rather one should take delay spread as the characteristic of a particular environment. Now when we look at the deployment scenarios what we have described earlier is that there are various deployment scenarios like indoor scenarios, urban micro cells, small cells, rural large cells. So, if we look at these different conditions the amount of echoes and multi paths and their characteristics will be different.

So, if they are different then we naturally expect in some environment the delay spread to be maybe symbolically in this manner, in another situation it might be symbolically like this and in another situation which is like this. So, it effectively means that there are larger echoes coming at longer duration of time whereas, in other cases this is smaller one, so the same air interface has to handle multiple situations.

So, what happens is one would design an air interface so I will redraw it here a small a medium and a large. So, if one has to define an appropriate air interface then the cyclic prefix interval should be chosen as large as this because this is tau max over all possible deployment conditions, but what we find is that if the channel impulse response is small in certain cases there is a huge loss in spectral efficiency. So, all we have trying to do is find out mechanisms by which this can be improved.

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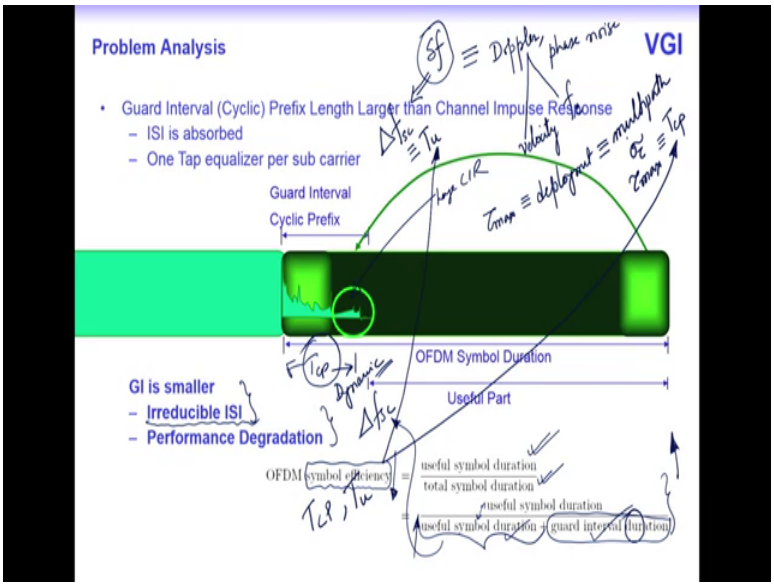

So, we can actually reduce the cyclic prefix length that is what is the proposal. So, what we find is that in case you reduce the cyclic prefix where as you encounter a situation where the channel impulse response is large in that case you would encounter irreducible interest interference and there is significant degradation in performance.

So, effectively one has to find an appropriate balance between the two conditions; that means, neither one can use a very large cyclic prefix that would reduce the spectral efficiency. And, if one uses a small cyclic prefix then one would end up in a situation that where cyclic prefix is large there would be ISI and this kind of ISI is irreducible you cannot reduce it by simply increasing this signal power.

So, this leads to the obvious choice that can one make the cyclic prefix dynamic can this be made dynamic, the answer naturally is yes one can make it dynamic because the cyclic prefix is not connected to this subcarrier spacing right cyclic prefix is not connected to the useful duration of OFDM symbol. It is only connected through the spectral efficiency because the spectral efficiency would be the ratio of useful symbol duration divided by total OFDM symbol duration; total OFDM symbol duration is useful symbol duration plus guard interval.

Now if we find cases where guard interval becomes pretty large then whereas, the useful symbol duration has not been modified then the OFDM symbol efficiency decreases. So, one way to improve the OFDM symbol efficiency is to increase the useful symbol duration part. So, if you increase the useful symbol duration part then the entire fraction becomes larger and the efficiency increases right. So, if I increase the OFDM symbol duration then in other words I am affecting the subcarrier spacing.

So, the only way it is connected not through the characteristics of the channel, but because of this efficiency factor one can think of associating T cP with Tu not otherwise. So, summarizing we find that the frequency spread which is indicated by del f one can think of putting a sub suffix c indicating with respect to carrier is largely due to Doppler or phase noise.

And Doppler is largely due to velocity or mobility or due to the carrier frequency whereas, the tau max is with respect to deployment conditions; that means, it is dependent upon the multipath scenario; that means, sigma tau or tau max and this affects your T cp whereas, this affects your capital delta f sc which in turn affects your Tu. So, there are two different things which affect these two important parameters of numerology, but if we take OFDM symbol efficiency then we can connect these two.

So, we can connect these two via OFDM symbol efficiency. So, if the OFDM symbol duration is becoming small because of the because of this Doppler or the phase noise then one can only reduce the guard interval, but up to that much only where tau max is still captured within the guard interval. So, we will see further some of the important outcomes of this.

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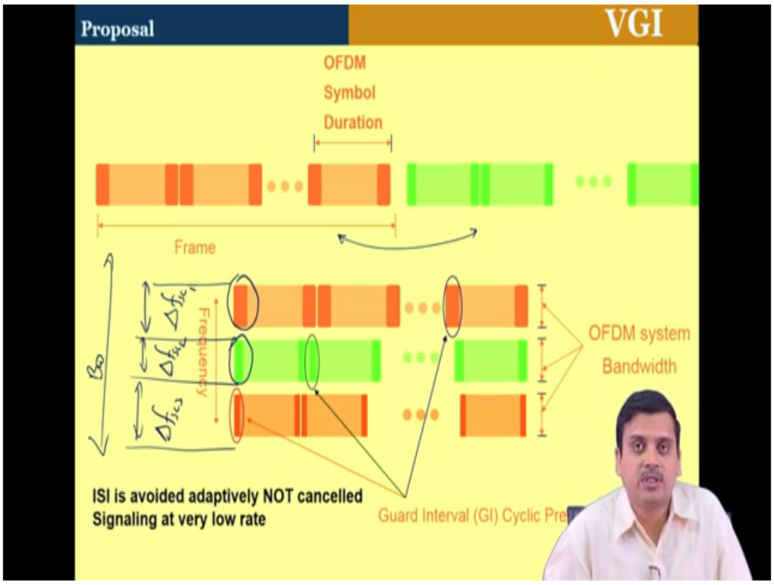

So, in this particular picture we had depicted earlier that what are the different deployment scenarios. So, as we have shown earlier that in the frequency domain one can divide the entire available bandwidth into smaller chunks and in each chunk one can operate an OFDM system and each can be of different subcarrier spacing and in each one correspondingly a different amount of cyclic prefix may also be used.

So, this is in frequency division and this is precisely the way the 5th generation NR is operating and we had also talked about doing it in time domain which is open for implementation. So, this way one can appropriately handle the different variations and vagaries of the wireless channel in a very; very effective manner and use very low complexity signal processing at the transmitter maintain the simplicity of OFDM. So, to do this one has to choose the appropriate value of cyclic prefix.

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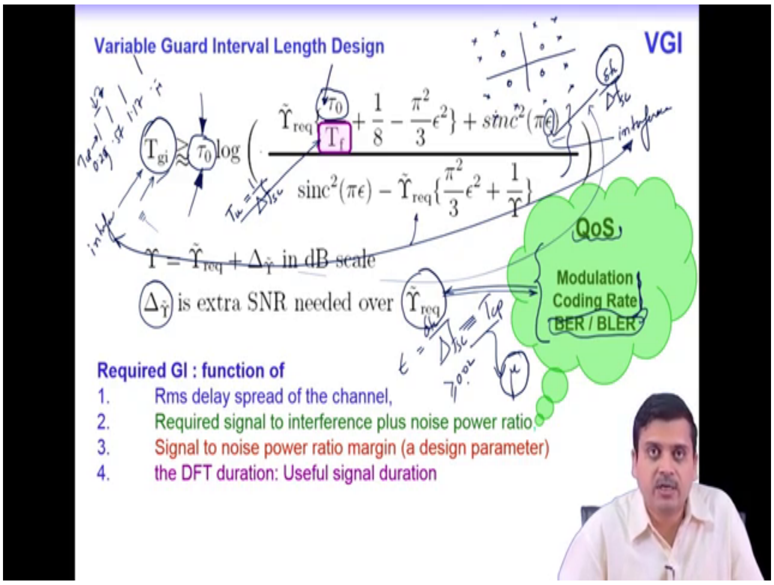

So, what we had presented over here is that the choice of cyclic prefix or guard interval can be done in an approximate way in some manner although this is open for improvements is that this particular guard interval should be greater than in some complicated function which involves the rms delay spread of the channel. Now, rms delay spread of the channel is something which one can measure or pre estimate. So, this is one single parameter which characterizes the delay properties of the channel we will see it again.

It is also dependent on the signal to noise ratio required or SNR required which is from the QoS conditions. And which decides the modulation code rate and BER. So, it is interconnected to this parameters which is connected to quality of service. So, or a particular BLER or BER for a given modulation and code rate is connected to the SNR requirement. So, it is also a function of SNR required and we had also introduced a delta SNR indicating some margin which is a bit different from standard thinking; that means, one can partially trade off the cyclic prefix with respect to extra amount of signal to noise ratio because it may be possible that the user end or the base station has some spare amount of power.

So, we just try to figure out that if that extra amount of power could be utilized was trading of some amount of ISI that may be present. For example, if one is choosing QPSK constellation, in that case since there is only phase to be identified and not amplitude there is certain margin what one can use, but if one extends to 16 qualms then probably the margin that is available would be less. So, depending upon particular situations certain amount of extra margin may be available to take care of the extra benefit by a which can be achieved by using a different or variable amount of guard interval. So, these are all the parameters that we had identified along with this T f which is nothing, but our T u it is not the T frame as per the 3 gbb descriptions.

And which is equal to one upon delta f subcarrier spacing is also one of the important parameters while taking a decision of the guard interval. So, if one computes such an expression and one may scale this rms delay spread depending upon the particular power delay profile, one can scale this value instead of using it just like that to find an exact or more appropriate choice, but; however, this will give you certain numbers and since the cp is quantized since only fixed values as you have seen 0.29, 0.57, 1.17 and so on microseconds are there.

So, any value in between that this result can throw up one can always go to the next immediate higher value of cyclic prefix that one is allowed in the standard. So, in this manner one can also choose an appropriate value of guard interval, one can even simplify this and what we have also shown over here there is a parameter epsilon which is again the ratio of delta f c by delta f subcarrier spacing.

So, if one has information or prior information then one can also introduce into this expression to get an appropriate value of guard interval because this causes certain amount of interference while the small guard interval if it is used also brings in certain amount of interference. So, there is a certain tradeoff between the interference or exchange that one can think of how much one wants to distribute here how much one was distribute there and to find an appropriate size of guard interval.

Although not entire thing can be exchanged, but partially it can be handled because any ISI that is resulting over here would also result in additional amount of inter carrier interference. So, there is a complicated relationship amongst these parameters and we have been able to find one particular expression through which one may be able to choose the appropriate choice of cp. Using the choice of delta f sc we had earlier mentioned that the ratio epsilon is usually desired to be kept at more than 0.02 it should be kept greater than 0.02 to maintain 20 db of SNR accordingly one can fix up all the set of parameters for an operation.

So, a choice of this together with Tcp and that has to map to an appropriate value of mu one would get a numerology; that means, to be deployed in the operational conditions. So, with this we summarize or we conclude the discussion on choice of parameters for numerology although will present a few results immediately following this.

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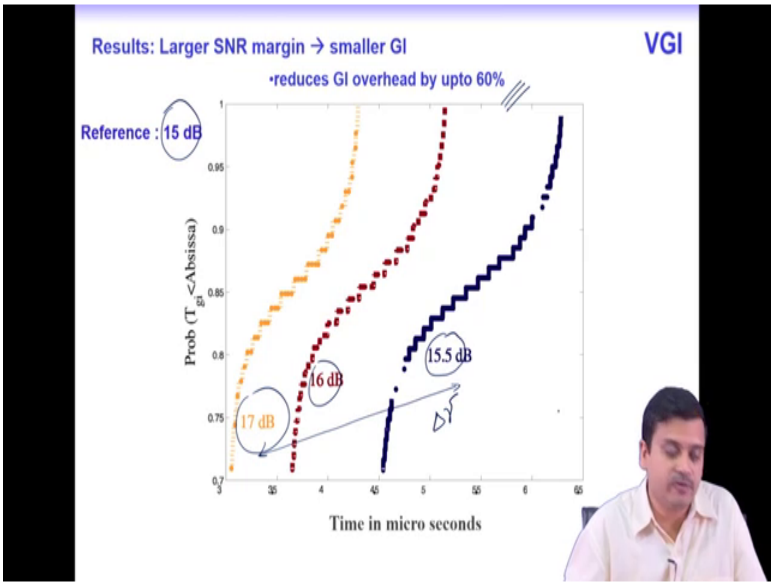

So, this particular result shows the overhead reduction by changing guard interval by allowing certain amount of extra SNR. So, what we see is that if a certain amount of extra SNR is allowed. So, here reference is 15 dB whereas, point 5 dB.

If extra SNR is used or 1 dB or 17 dB then we find that up to 60 percent of reduction in guard interval is possible. So, these particular set of results are with specific set of conditions which we have described in the references one is encouraged to going into the references.

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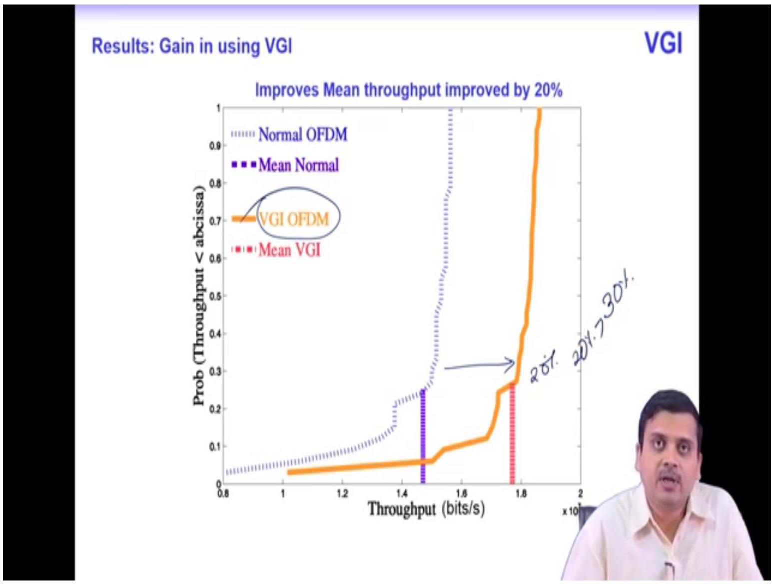

And here what we have shown is the distribution of throughput so what we show is that the variable guard interval or variable CPU OFDM it can enhance the throughput by twenty pursuant or so or one can get even better depending upon the operational conditions. So, by both the mechanisms the cyclic prefix can give you around 20 percent increase and the subcarrier spacing can give you around 30 percent increase.

Now together they may not add up to 50 percent they may also depending upon situation, but that is the different amount of gains that can be benefitted by using variability in these two parameters ok.

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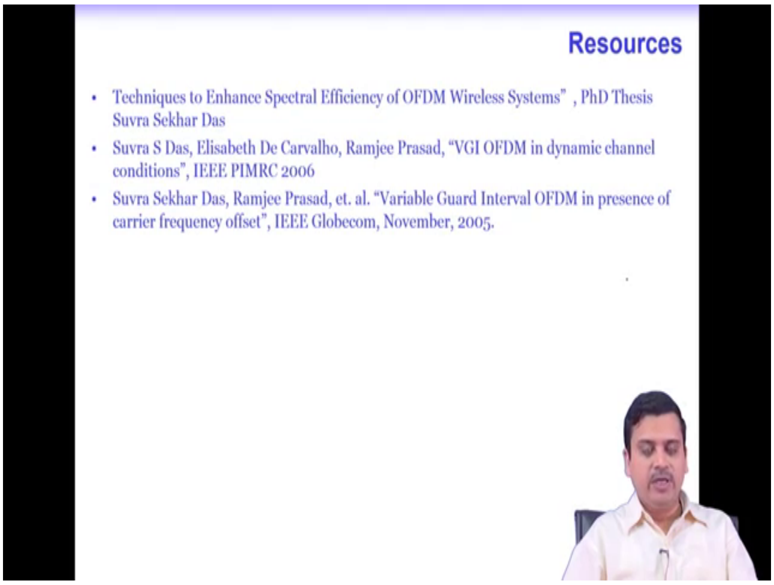

So, these are the certain set of references which are very very critical in this context. So, one again can find all details as discussed over here to understand how these different choices are made.

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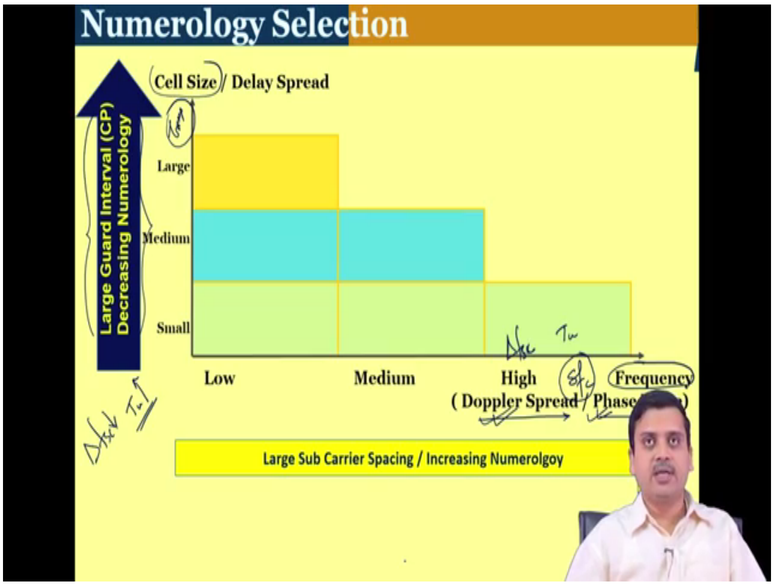

So, here this particular picture essentially summarizes this can also be found in one reference from Eriksson also they have given a similar picture. So, we have taken reference from that and recreated this where we summarized the entire situation where we say that on one side as the frequency increases the operation frequency increases phase noise increases so does Doppler spread increase.

So, one can think of this axis as the Doppler spread axis or phase noise axis or delta f c axis and this one; one can think of as the tau max axis and as we have said from earlier results because of other measurement campaigns that this happens when the cell size also increases right. So, when your cell size increases tau max increases and hence the guard interval required would increase and to maintain the efficiency of the OFDM system the numerology has to decrease because decreasing numerology means subcarrier spacing decreasing and T u duration increasing, T u duration increasing means OFDM symbol efficiency increasing.

Whereas, on this side we find that as the offset increases this subcarrier spacing has to increase and hence T u has to decrease right. So, this is the reverse trend. So, one has to choose a combination this is a reflection of different combinations than who that one can get appropriately with methods as has been described in the earlier slides.

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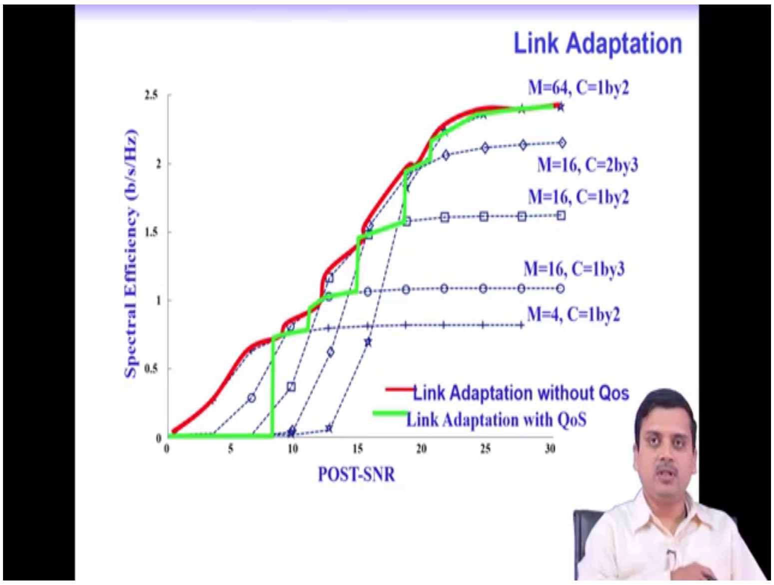

Now, we quickly look at another important aspect this link adaptation thing we had explained in an earlier lecture which we do not want to discuss much now, but we just have it here. So, that you can take it as a reference and recall the earlier discussions that we had had and continue on the next part of the discussion that we are going to have now.

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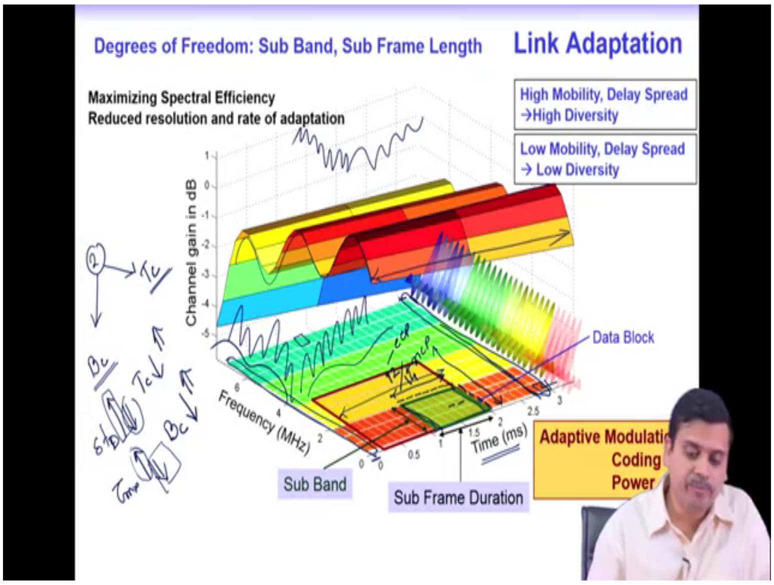

So, we had said earlier that the OFDM communication system in both the 4G and the 5th generation they do not allocate one subcarrier so this is the subcarrier unit, this is the resource element any one tiny box is the resource element, this is a subcarrier width, this is the time width and this forms one OFDM symbol ok.

So, this forms one OFDM symbol all sub carriers one unit of time and we had also explained that these different OFDM symbols consecutive symbols and different subcarriers forms a resource block which we had also described when we talked about the frame structure. So now, we also mentioned that in this resource block the modulation coding scheme and the power controls power is kept constant and that is the unit of allocation of a particular data block or a particular user allocation.

We had also mentioned that in the 5th generation this size remains constant in terms of number of OFDM symbols which is also same as in the 4th generation that is 12 or 14 depending upon whether extended cyclic prefix or normal cyclic prefix, but because in 5th generation and what we have explained in the just previous slides that the duration of the OFDM symbol would be different that can become smaller or larger hence the tile size is going to be different.

Now, what we need to look at is a detailed understanding of the propagation characteristics. So, we had talked about the propagation characteristics that the signal strength fluctuates significantly in the time domain as well as it fluctuates in the frequency domain we can clearly see how the frequents how in the frequency domain the signal strength fluctuates and how in the time domain the signal strength fluctuates right.

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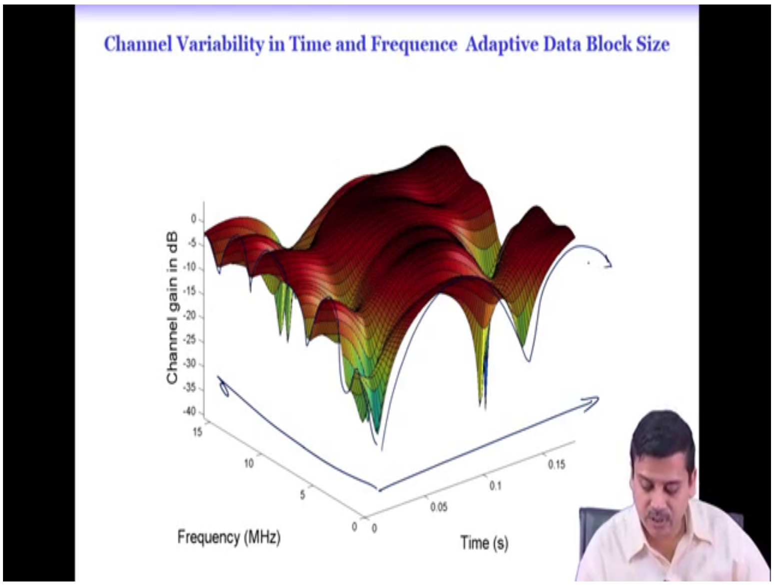

And we had also stated that this was in seconds this is a larger window in frequency whereas, if we zoom in to that particular picture and see a much smaller window what we will find? That when time is given in milliseconds that will be zoom into it, there is much smaller variation in time it is nearly flat you can clearly see there is slight variation, where indicated colors indicate the signal strength whereas, still in the frequency domain we have a certain amount of fluctuation.

Now these fluctuations are dependent on two important parameters; one is the coherence bandwidth and another is the coherence time. Coherence time tells us the time duration over which the signal strength would remain more or less constant and coherence bandwidth would give us the bandwidth over which the signal strength would remain constant in the frequency domain. So, now, if the channel is having very high Doppler condition then T c is low.

So, if del f D is high then T c is low, similarly if tau max is high then B c is low and vice versa and reverse. So, if it is low then it is high and if tau max is low then this is high and there can be other combinations also; that means, there can be cross combination; that means, this is high and this is low and the other; that means, it is tau max is low and f D is high. They can also be such conduct conditions because of the propagation scenario.

So, now, when you have this if coherence time is small the signal would fluctuate faster in time and if coherence bandwidth is small signal would fluctuate faster in frequency. So, in frequency there will be much faster fluctuations, in time there will be much faster fluctuations and if the coherence time is large in time domain it will fluctuate slowly, if coherence bandwidth is large in frequency domain it would fluctuate slowly so that is what is going to happen.

So, now, what we will discuss is if what is the effect of such a thing on different tile size? So, one can increase the tile slice or number of slots for allocation in time domain or one can do the same in frequency domain or one can do the same in both the domains. So, basically what we are talking about how much of time window and how much of frequency window are to be grouped together to form a resource block in order to get the best benefit in terms of spectral efficiency.

So, we will see such an effect, we first show the result when if you allocate a larger window in the frequency domain; that means, more number of resource block and do modulation coding scheme and power on that window.

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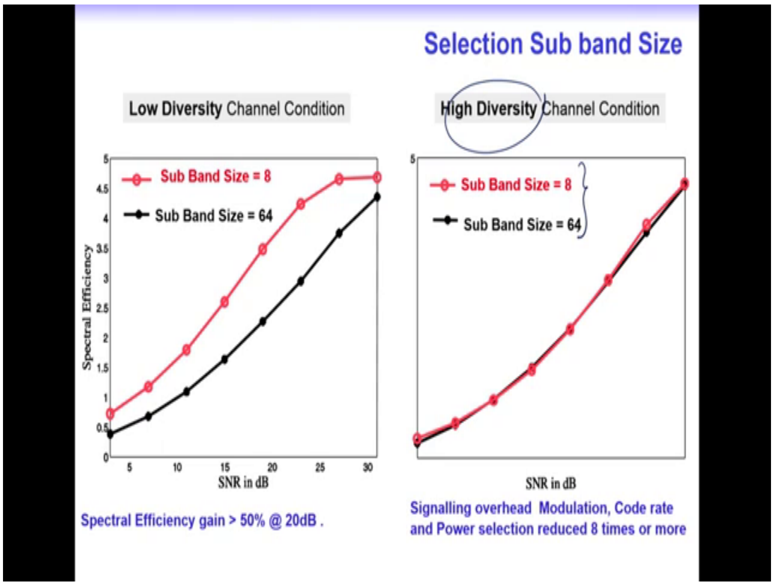

So, here what we say is suppose we group 64 sub carriers together ok, we get a certain spectral efficiency versus SNR curve. If we reduce the sub band size to 8; that means, smaller window then we find that the spectral efficiency increases much beyond that of 64. Now this is the case when there is low diversity condition, low diversity condition means that the signal strength remains flat over a certain window in frequency and over a certain window in time; that means, one can do link adaptation over smaller chunks of our concern and chunks you cannot make lesser than certain numbers.

So, we have said that this number is twelve in case of l t and in case of ah5th generation we had done the study for the entire range from 8 to 64 we have presenting here only two extreme results. So, all other results would come in between we are showing only two results for the sake of ease of seeing these things right. Now if we compare this particular scenario with another situation, where the diversity is high what we find is that there is not much effect of changing the block size in the frequency domain.

Now why does it happen in this manner? If we go back and try to discuss and look into this if there is lot of fluctuation in time domain and lot of fluctuation in frequency domain in this small size; that means, this window is already getting the effect of averaging the time and frequency fluctuations and one calculates the modulation and code rate to be used as per this fluctuation. If you increase this size the average over this entire size has not changed and hence there is not much of a benefit whereas, on the contrary if one would look at a situation where one would see that over this window.

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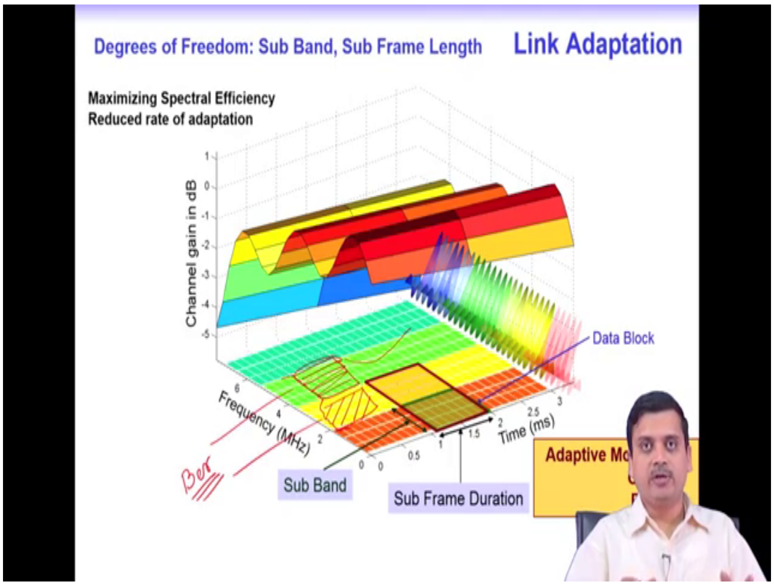

There is a certain signal strength and over this window there is a certain signal strength; that means, a signal is fluctuating slowly in frequency as well as it is fluctuating slowly in time let us say so; that means, over such a window we find that there is some flatness a particular modulation recording rate to be chosen.

Whereas the other window one can choose a different modulation and code rate while satisfying the individual BER constraint, this is very very important. So, this falls directly in whatever we have discussed when we talked about link adaptation; that means, each block is to be adapted so that the BER threshold is met you can go back to the discussion on link adaptation as we had discussed earlier and refer to that particular discussion for clarity on this particular part.

So, what we find is that when there is high diversity condition there is no benefit. So, if we understand the channel well then we can adaptively choose the slot that we can aggregate in time domain and the slot size that we want to put in frequency domain or number of resource blocks that we want to allocate. So, this the immediate next result in the time domain; that means, if we extend it in time is what we are going to show over here.

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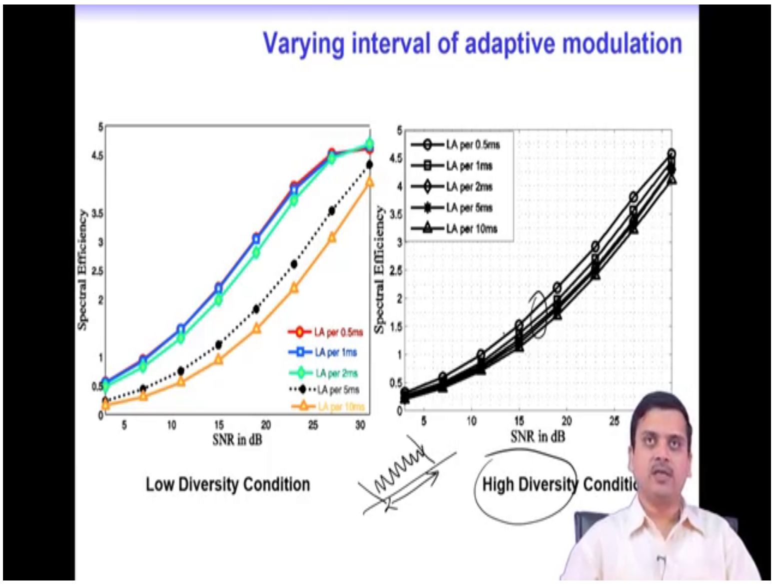

So, this is link adaptation per 0.5 millisecond and this is link adaptation for 1 millisecond for 2 millisecond and so on and so forth. So, as you increase the interval over which you are able to adapt what you find is that the throughput is decreasing or reverse way as I do it faster I am able to get a much more benefit in spectral efficiency whereas, when we are doing it in a high diversity condition; that means, within the duration of time for the smallest unit of block size there is sufficient fluctuation in time domain the averaging effect is already captured.

So, the gain or change is not significant whereas, the overhead that will come in signaling the smaller units of tiles will be significantly large. So, here again what we see is that under low diversity condition smaller chunks of tiles are going to give you benefit under high diversity condition larger chunks of tiles are give you going to give you the same benefit without much modification.

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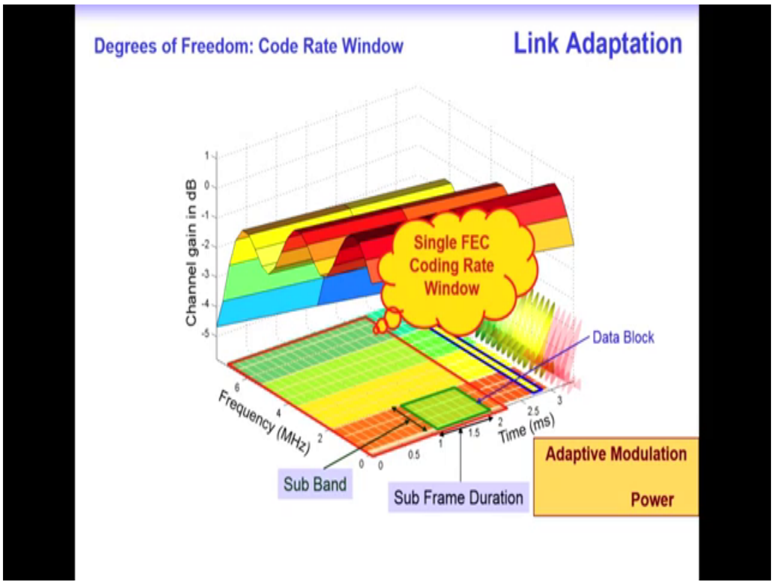

The last piece of result which we want to show is that one can think of even having very large code block size and putting different modulations in them.

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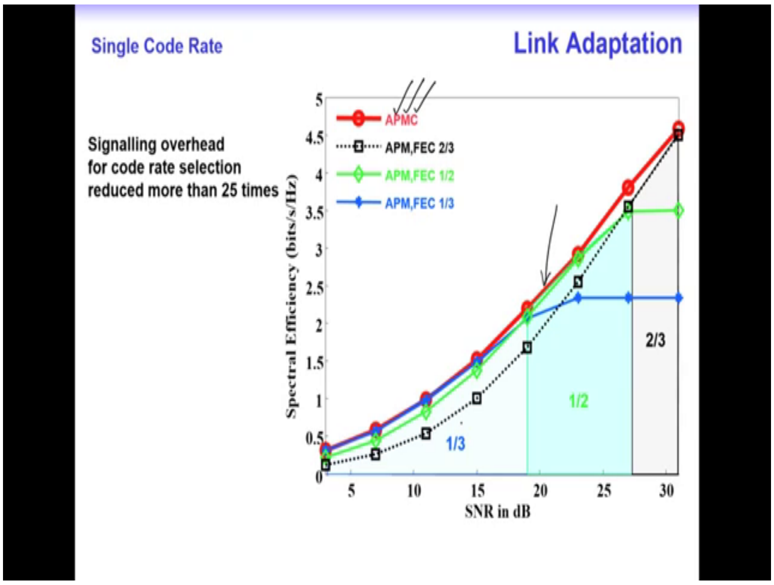

So; that means, we are suggesting that one can think of keeping the code rate fixed, but one can take chunks of data within that code block and vary the modulation index, instead of choosing coding and modulation scheme for each block which is different from another block. So, this will save a huge amount of complexity at the transmitter and receiver side while it's going to give you some benefit the benefit is what we will see.

So, this red one is where you adapt the power, the modulation and code rate for each particular chunk that we are doing the link adaptation, but this result is the case where we have a certain code rate and you are varying only the modulation. So, what we see is that, one can get a much more benefit by using even a single code rate without much of an effect. So, what we see is that if one chooses only a single code rate, but varies the modulation one can still get sufficient benefit.

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So, overall what we see is that there are different combinations of schemes that to be use and which are also supported in the 5th generation and these are some of the references which describe all the details of these different mechanisms by which one can actually get this get all the benefits of get all the benefits of having various adaptation. In terms of subcarrier spacing adaptation, in terms of cyclic prefix together called the numerology as well as one can get all the benefits of link adaptation by appropriately clubbing a number of resource block or by clubbing a number of slots together to get the most benefit in order to maximize the spectral efficiency.

In all this context we have identified the resources which are primary in this kind of work which have been one of the earliest kind of work and which describes all details that are presented in these different technologies and which are of use in the 5th generation communication techniques.

Thank you.