Evolution of Air Interface Towards 5G
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Lecture - 21
Waveform for 4G & 5G OFDM (A),
SC – FDMA, DFT Spread OFDM (A) Contd.

Welcome to the lectures on Evolution of Air Interface towards 5 G. So we are discussing currently OFDM that is Orthogonal Frequency Division Multiplexing. And, I have been iterating that it is very important to understand the details of OFDM, how the principle layout structure is, how the things work and most importantly: what are the different parameters which affect the performance and how the parameters are to be chosen.

What are the channel effects or what are the environmental effects which influence the choice of parameters. Because, when we go to 5G air interface which is primarily OFDM but, the difference is choice of set of parameters which is essentially driven by the different conditions under which it has to operate. So, going forward from where we had discussed the things in the previous lecture.

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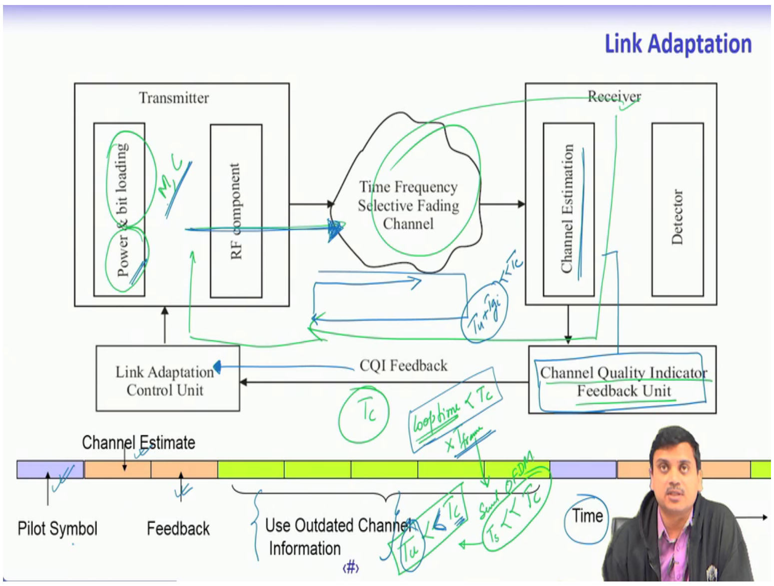

So, we had been talking about the link adaptation procedure in OFDM and we had explained how the channel fluctuations are utilised.

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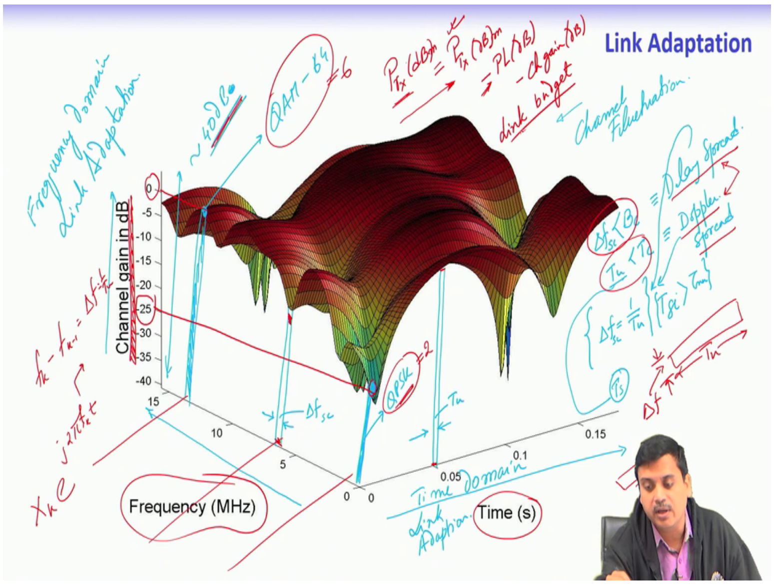

So, what we have discussed I will briefly talk about it that the signal strength fluctuates in all directions in time as well as in frequency, so in both these directions signals keep on fluctuating. And, we had discussed through this particular diagram is that the subcarrier spacing has to be maintained in a manner that it experiences flat feeding for every sub carrier. And we had also mentioned that in the time domain the time has to be decided in a manner that it experiences near constant channel; that means, each sub carrier width and the corresponding symbol duration this is Tu.

So, if you draw it over here it might be visible. So, if this is Tu for us and this corresponding to that is the delta f ok. So, these are to be maintained in a manner as has been discussed several times like this is one of the criteria and on the other side on the Tu side this is another criteria. So, this comes from delay spread this comes from Doppler spread which are two different characteristics of the channel and they are on two different dimensions; one is because of the excess path length and one is because of the mobility. And then we said further that since this fluctuates that there is around 40 dB of fluctuations of signal strength since these sub carriers are different sub carriers they are all orthogonal.

So, we remember that they are all orthogonal subcarriers e to the power of j 2 pi fk t and fks are chosen such that fk minus fk minus 1 is equal to delta f is equal to 1 by Tu this is the condition we have been using. So one can choose to use different modulations on each of the sub carriers and clearly from this picture we had explained that whichever subcarrier experiences a low signal to noise ratio can be given lower order modulation. Whereas, the subcarrier which experiences a higher signal to noise ratio will require a higher order modulation it can support higher order modulation effectively this can support 6 bits as an example this is going to support only 2 bits.

So, overall instead of doing an single modulation across the entire set of frequencies one can actually fluctuate, one can vary the different different data rates and thereby overall increase in throughput or spectral efficiency can be achieved. So, this is one of the biggest advantage that the OFD OFDM brings it brings in along with other different advantages which we have been discussing and one issue about this particular picture the y axis is channel gain in dB. So, this is to be taken into account.

So, when we take the received signal strength, the received signal strength is to be taken along with this. So, if you are doing in dB so, P received signal strength in dB should be set equal to P Tx that is the transmit power in dB sorry in dBm or may be in dB watt dBm, then you take away the path loss in dB and you also take away the channel gain. So, what you see over here is the maximum channel gain is usually set to one that is normalised. So, whereas, what one has to do is the average small scale channel gain is set to be equal to 1. So, instantaneous fluctuations will be there dB and this is your received signal strength. So, to translate this picture to received signal strength one must be given the transmit power and one should also consider the path loss associated with it then one will get the received signal strength.

So, one should not get confused that a minus 25 dB how one will support a QPSK modulation and at 0 dB how one will support a QAM modulation this is not the complete picture, so the complete picture has to be taken into account by taking the transmit power as well as the path loss. So, as to take the complete link analysis and there you are basically taking into account the link budget in total.

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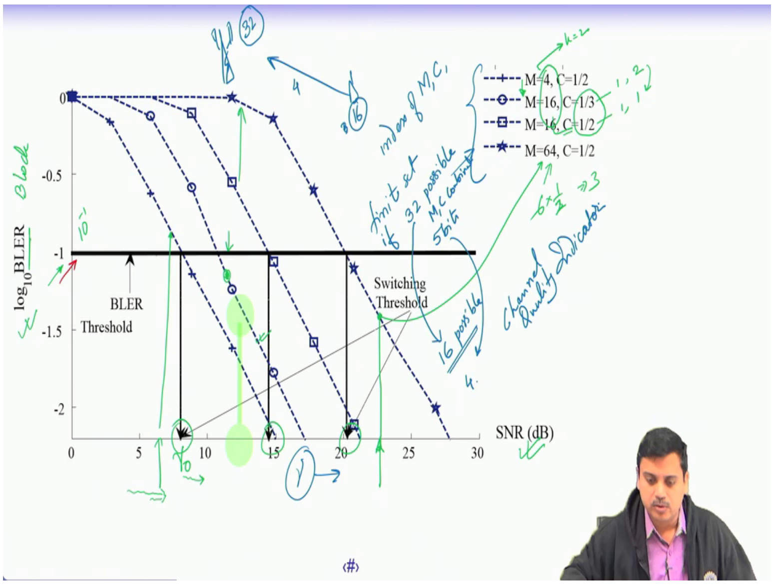

So, moving ahead we discussed how different modulations are to be chosen and there are different SNRs which in thresholds there is a requirement of error probability.

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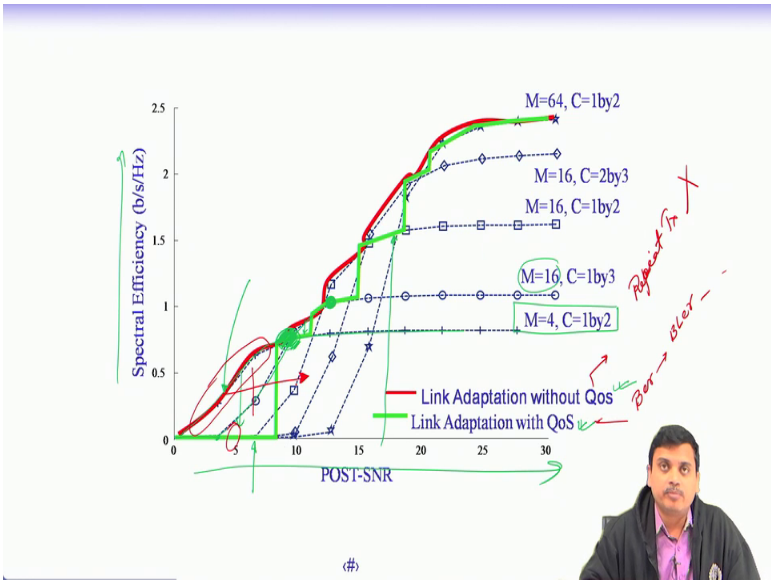

We have also discussed in the previous lecture about how the spectral efficiency curves change one when one has QoS requirement; that means, there is a threshold on Ber which can be translated to block error rate and so on and this on without QoS that means, there is no constraint. So, one keeps on transmitting the best possible signal that gives the highest spectral efficiency; however, the problem is no criteria on error probability is maintained ok.

So, these curves are without having without having any throughput computation considering repeat transmission repeat Tx is not taken into account. So, if you take repeated transmission into account these lines which appear to be higher than these green lines they are going to be even worse. So, they will shift to the right because when you repeat transmission the spectral efficiency loss is huge. So, to avoid that some prior link threshold is prepared and that is through this BLER threshold. So, over a over the last mile over the last that is the link between the base station and the access sorry the access point and the user device 10 to the power of minus 1 or 0.1 block at the rate of threshold or packet at the rate is well accepted we have also discussed this flow of things we have also said that how things flow in this particular sequence of events.

So, just briefly initially there is transmission from the transmitter be at the base station or the user equipment; that means, in the downlink or uplink direction. So, we are taking any one particular direction the fluctuations of the channel are measured in the channel estimation module. So; that means, when we discussed about channel fluctuations here when we discussed the channel fluctuations it is assumed that during channel estimation process this particular signal strength or whatever is the signal strength here gets measured. That signal strength is converted to a particular modulation and code rate whatever is supported because one can measure the SNR on this axis once the SNR is measured then one can choose which of the supported MCs is MCs can be used and the index.

So, the index of M modulation and code rate combination can be set back to the transmitter. So, because otherwise if look at it we can have various different modulation in code rates, but there is only a finite set. So, if we have let us say 32 possible combinations if; that means, if there are 32 possible MC combinations then one will require 5 bits to identify them. And this is some time reduced by choosing 16 possible combinations and hence you reduce to 4 bits; that means, every signalling will be having 1 bit less, if we take the large number of resource blocks. And, large number of users accumulated number of overhead bits would be significantly meaningful and why 1 bit is been considered under this conditions is that we are talking about the control channel.

So, one would usually prefer to have a lower control channel than the data channel because data channel is the one which contains the actual pay load the data, but control channel is necessary without which there is no meaning can be assigned to the data channel it cannot be utilised in a better manner. So, in order to have an efficient implementation there is limitation on the control channel.

So, would like to use lesser number of bits, but we still want to have control channel. So, there our mechanisms which are used to reduce the control channel signalling overhead. And so, what we find is that suppose we are using 16 levels to be fed back; that means, every alternate level are used to fed back the other side; that means, if let us say the user equipment feeds back information to the base station right, so it uses 4 bit feedback let us say. So, base station knows that.

So; that means, from 16 levels it gives a feedback, but the base station knows that there are 32 possible levels. So, using a prior information about the block error rate which the user has been sustaining the base station has flexibility or the decision making capability that whether to allow the particular MCs of choice or may be reduce it by one half step or increase it by one half step. If the conditions have been good for the past few occasions, past few occasions means past few transmissions then the base station can take things in a little bit optimistic manner and it can rather choose one of the intermediary stage.

So, these are various mechanisms which are also deployed and considered to improve the throughput performance or spectral efficiency performance which is directly not visible, but when one goes to implement these things then these control channel and feedback becomes of primary importance. And this index that is the feedback is sometimes called the channel quality indicator. So the channel quality indicator is what we mention over here. So, the channel estimation feeds back this channel quality indicator this is we have briefly mentioned in the previous lecture, but today we had discussed little bit in more details. The channel quality indicator is fed back to link adaptation unit as we have just described and it takes the final decision of what is the value of modulation in code rate to be used along with power control and then it sends back the data.

So, there is one entire loop of feedback and then that feedback is used for communication of the actual information in the later cycle. So, what happens in the first cycle when some prior data is coming to the user during that time whatever channel estimation feedback is given to the base station is used for the next iteration. So, this particular diagram below on the time axis indicates the sequence of events that is there is a pilot symbol which is used for channel estimation channel is estimated followed by feedback and then it is used for data transmission. Now it is to be ensured that this interval of time is less than coherence time that is what we have said the loop time should be less than coherence time, now loop time uses several frames because when the transmission happen it happens in frames.

So, at least one transmission followed by another transmission at least two frames come into picture and each frame consists of several sub frames, each sub frame consists of several symbols right. So, what we effectively see is that multiple symbols a large number of symbols should lie within the coherence time this is very very critical. So, effectively it means that our earlier condition that T Tu is less than Tc is not sufficient it should be much much less than Tc is the condition that we have to use. And we have also said that simply not Tu we should take Tu plus Tgi which is the guard interval into the account and make much much less than the coherence time ok.

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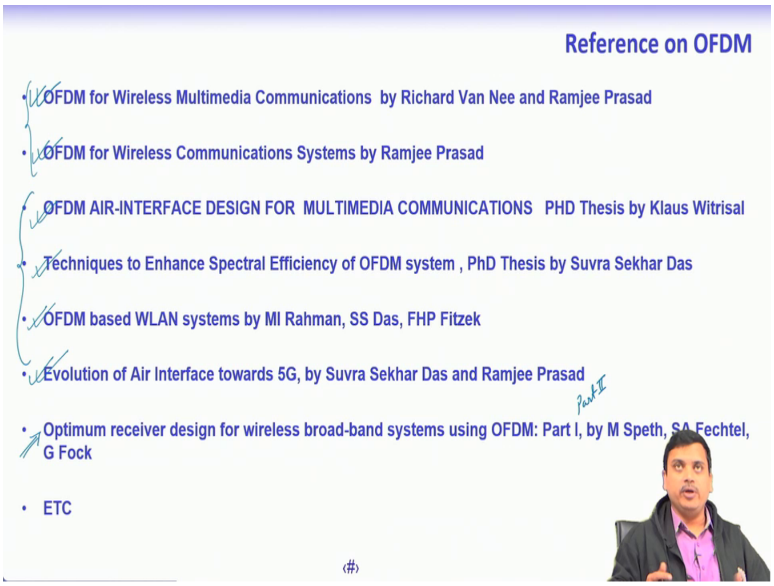

So, at this point I would take short digression and would like to point out several references on OFDM which are very very useful. So, because we have only limited opportunity to discuss the things, but it is always recommended that you look for references beyond this and which contain where you can give more time take your own time read them through. So, that you can understand the details in much clearer manner much easier fashion; so, this is one of the early reference books that are available it is it has been followed widely there has been second reference which is also pretty popular.

So, one can use this particular book as well and thereafter if one is not having access to these books there is this PhD thesis by Klaus Witrisal which also contains good details of the OFDM system model which we have been following over here. And this particular thesis also contains summary a very quick summary of things, there was another report which is also publicly available the these things are freely available one need not use any payment for them they are absolutely freely available which also contains a break down or analysis of OFDM in much much easier fashion in very very simple words.

This particular book I have already referred to which we are mainly is the guidelines for this particular course is also useful. And finally, I would also recommend the paper which is given over here there is part I and there is also part II of the paper which also provides an excellent framework for writing down the expressions of OFDM and doing all kinds of analysis alright.

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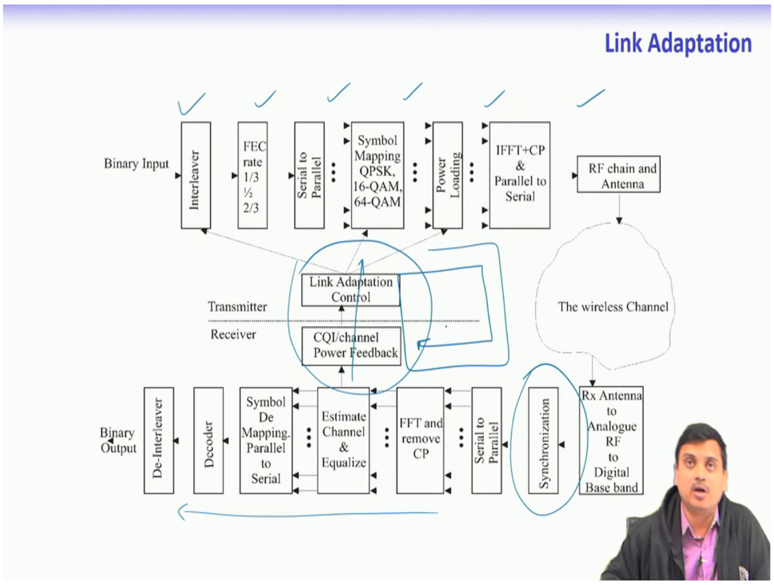

So, this is the typical flow and we have simply added these two parts, we have already discussed the transmitter structure earlier where we have actually discussed all more or less the signal flow through all these blocks. So, we will not discuss it again. So, in the receiver side exactly opposite operation happens.

So, only this synchronization is something which is an extra part we have also discussed about them and then the receiver processing is in the reverse order of the transmitter and there is this feedback loop. And so, effectively cycle of events goes on in such a process which is also a very important part of OFDM communication.

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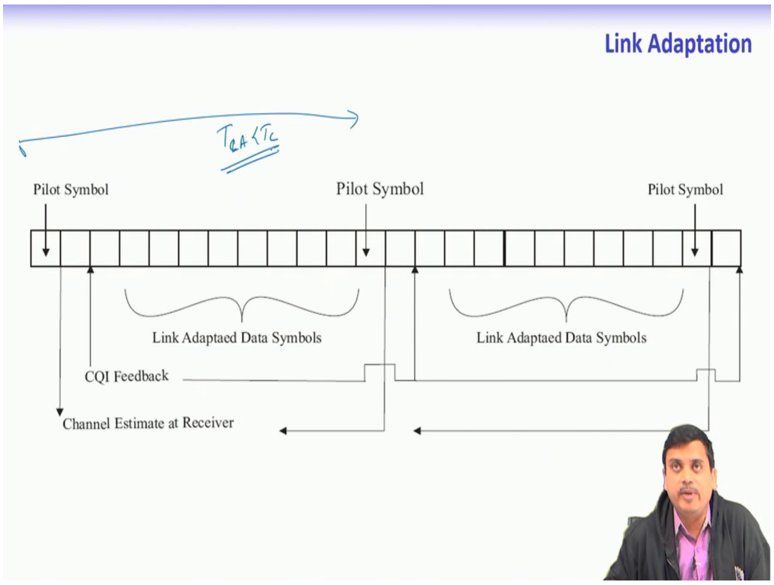

So, we have discussed about this particular picture where there is pilot, channel, estimation feedback and link adapted. So, what is effectively meant is that this period should be less than. So, if I call it TLA this should be less than T c. So, this condition has to be maintained and it keeps on repeating.

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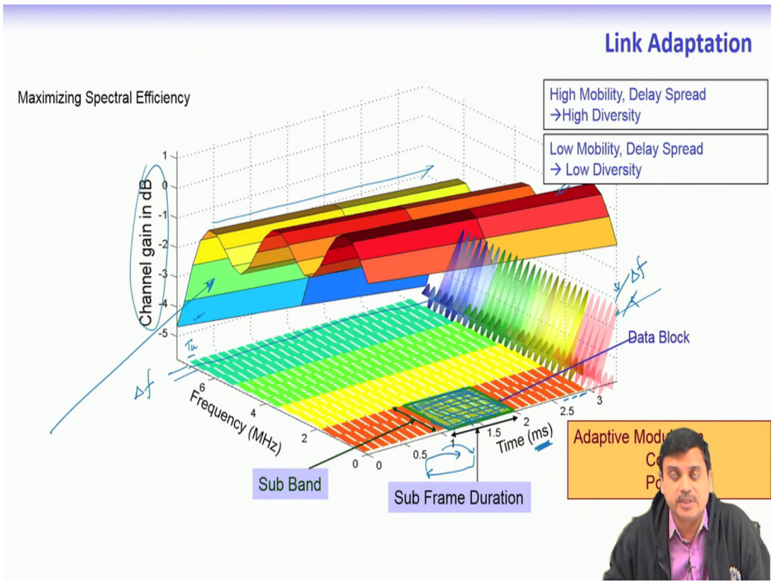

So, this is the overall picture of things. So, if we look at the details of it what we see is that we have described a channel fluctuation figure earlier. So, I will just quickly get back to the channel fluctuation figure. So, that it helps us. So, this particular picture what you see is that the unit of time is seconds and I have said this in earlier discussion and this is off course given in mega hertz. So, if we go down further now and look at the picture based on whatever we have discussed. So, what we find it is this particular section which is containing the channel gain in dB is effectively assumed in version of it where now our time scale is in milliseconds.

So, that is a big difference and since its in milliseconds what you see is that in time axis the fluctuation is pretty slow change in colour indicates the change in the values and a redder colour the colour which is more red indicates a higher value a bluer colour indicates a lower value ok. So, that is how the colour pattern or colour coding goes. So, what we see is that in the frequency domain the fluctuation has more or less remained, but again if you go back we will go back to the earlier picture what we will find is that we have captured up to 15 megahertz in this particular image and here this resolution is 0.05 milliseconds 0.05 seconds ok.

So, now we are showing a picture which is only up to this much that is a much smaller duration and the resolution in time is also in milliseconds. So, the picture looks different over here and the fluctuations appear to be lesser and these smaller units are basically delta f subcarrier spacing and this unit is Tu. So, this is for representation purpose that we have drawn this particular picture. So, these are reflecting the subcarriers. So, that you can clearly see that if you proceed along this line its one of the subcarriers and any one of the subcarriers has a spacing of delta f and each of them are Tu durations.

And as we have said earlier that several such OFDM symbols in time are grouped together and several such sub carriers are grouped together to form a resource block as has been marked by this colour and I am putting a shade on this which is the resource unit on which all kinds of link adaptation procedure is done. So, this unit in its multiples have to flow from transmitter to receiver for estimation receiver to transmitter again for feedback information and then it has to go. So, this needs to be understood, we will get back to more detail on performance analysis again later on.

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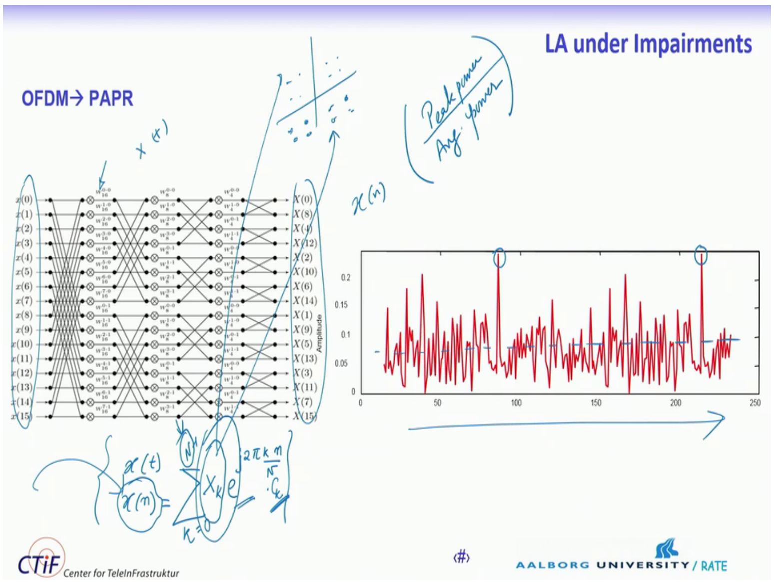

So, now, let us look at some other important parts of OFDM. So, if we look at typical OFDM generation process we have said that an IFFT operation happens at the transmitter. So, in the IFFT operation; so; this is the butterfly architecture of the implementation. So, there is several multiply and addition operation which happens right, so if you look at the time domain equation x of t or x of n rather if you do it in the discrete domain x of n we had said it is sum over k Xk e to the power of j 2 pi k n upon N N for any one OFDM symbol.

So, now these are the. So, this is the you can this particular picture has small x on this side and capital X on this side you can also reverse them and simply put appropriate values of weight and things would be either FFT or IFFT. So, if you have taken only one particular picture. So, what we have done over here is that we have actually considered this in this particular representation if we see that several such X ks gets simultaneously added ok.

So, when several such X ks gets simultaneously added there is of course, a weight factor. So, what we see over here is summation of several such constellation points these are constellation points chosen from the symbol mapper. So, once these are chosen from the symbol mapper then what we have is that each of these numbers are random realizations. So, if each of them are random realizations then what we see is there is an addition of random numbers. So, this itself is a random number. So, every sample in time is a random number and the variance would depend upon let us say I put k is equal to 0 to N minus 1 or 1 to N upon the length or the numbers that we add, as the value of n increases the variance becomes larger and larger.

So, what it effectively means is that the fluctuation of the signal in time increases as the number N increases now what is the impact. So, let us look at this. So, this particular picture of what we have is the time domain signal for is the time domain signal for typical OFDM what we see is that there are several peaks which occur and there is a certain average level of the signal. So, what the problem we see over here is that the peak power to peak average power there is a peak to average power which is very high in case of OFDM which is again a typical problem.

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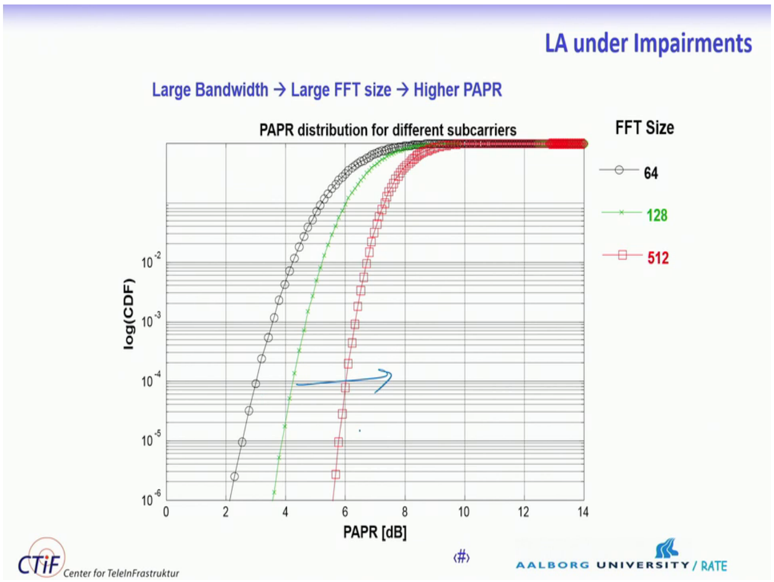

Now, why it is a typical problem we will see. So, in this picture it is shown as the size increases the probability of getting higher and higher values is more and more and more ok.

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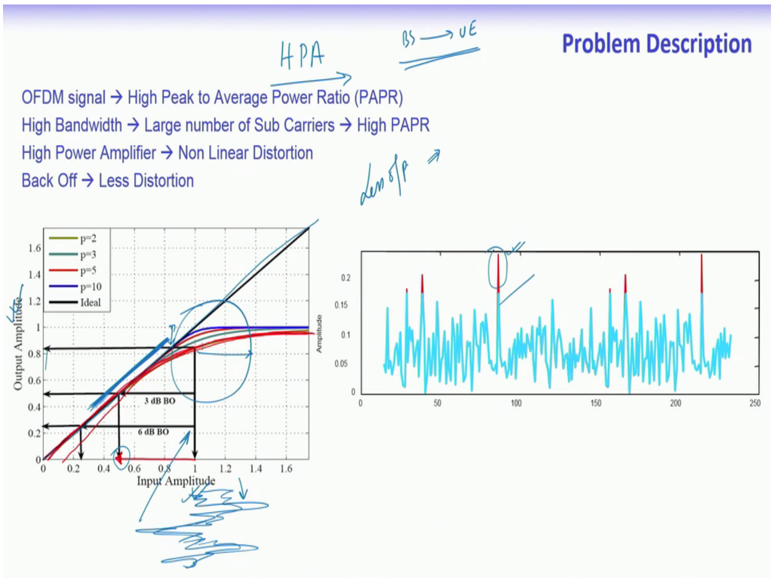

So, in this particular picture what we can show the signals finally, go through the High Power Amplifier right, they go through the HPA before being transmitted outside. So, when they go through the HPA we need to look at the characteristics of the high power amplifier, the high power amplifier ideally speaking should have a linear curve this is the input amplitude this is the output amplitude. So, it should ideally have a linear in that case whatever signal goes in goes out with the same shape characteristics there is no variation of the shape characteristics. But, in all practical systems the performance or the characteristics of the power amplifier is not linear rather it is non-linear right the way we have drawn other curves or the way I am tracing one of the curves is non-linear ok.

So, this curve is more or less non-linear and then what would happen is that one would desire that the signal is operated as high input power as possible because the amplifier at higher input power is operating with higher efficiency. And if it operates at a back off then efficiency of the power amplifier is less, now why we talk of back off because, if we are moving away towards from the saturation point then we are more or less in the linear region of the operation. So, if you are in linear region of operation then the signal goes out in an undistorted manner ok, but the problem is we are going to get less output power, less output power would mean that the signal or the operation has to be sustained for a longer duration of time in order to send the same number of bits right plus there is a power efficiency loss.

So, this effectively leads to greater loss of battery power especially at the handled devices. So, for OFDM a PAPR causes lot of restrictions in the having large coverage area. So, we need to have several mechanisms in order to take care of this, but for the downlink direction; that means, for the base station to the user equipment the problem is not much because, base station is having power supply from the electric grid whereas, the user equipment side it is the battery. So, this is very very critical factor.

So, if one has to use a back off there is a significance reduction of the range one would like to have a situation where on would be using as much power as possible in other words one who is interested to have signals which is low PAPR. So, now, if one if one does send the signal over here then what happens the input signal goes on something like this and as a result if we see the output signal they will be when the signal rises the gain at the output is much less. So, the output signal we will find does not follow the input signal so much especially in the saturation region.

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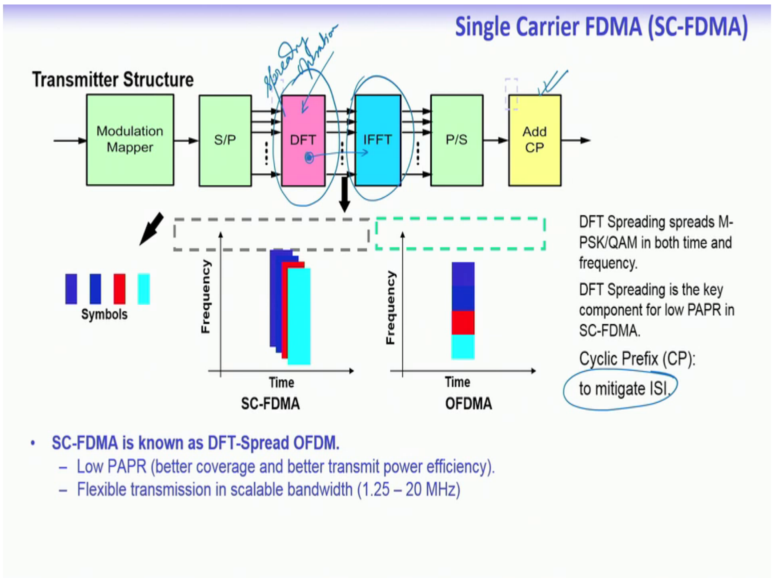

Now, this clearly changes the time domain shape of the signal. So, if it changes the time domain shape what it would result is there is obvious impact in the corresponding frequency domain shape. So, once it impacts the frequency domain shape it causes a lot of in band distortions, lot of in band distortions results in ultimately causing a poor signal to interference plus noise ratio at the receiver side. So, graphically what we find is now this overlaid blue coloured picture shows whatever signal that comes out now; obviously, the spectrum characteristics of this signal is worse than this is different rather than what is originally present in the red coloured signal.

So, if the spectrum characteristics signal content has changed then it would; obviously, effect the signal that it carries and hence the quality of signal at the receiver would be distorted which would lead to higher bit error rates. So, to overcome that single carrier FDMA is proposed the single carrier FDMA is simpler in the sense that it introduces a DFT in front of the IFFT operation. So, a DFT in front of the IFFT operation it simply does it cancels out the effect of IFFT, now there is a genesis for this kind of studies is that what it simply says is that since there is a combination of these weights that causes a large variation.

So, the large variation would happen if they add up in phase if by some mechanism the in phase addition can be destroyed then the fluctuations or variations can be made less. So, in order to do that at every point one can think of multiplying by Ck where Ck is some code sequence ok. So, code sequence can be taken from various different aspects one could be adamant code could be DFT code. So, here what we are discussing is that instead of thinking of the DFT operation it is some kind of a spreading operation peak to average power ratio. But the cyclic prefix addition is still maintained all though it appears like a single carrier system because cyclic prefix helps to mitigate the inter symbol interference and one can operate using the FFT at the receiver along with it one can use the frequency domain channel equalization, because frequency domain channel equalization is much much simpler.

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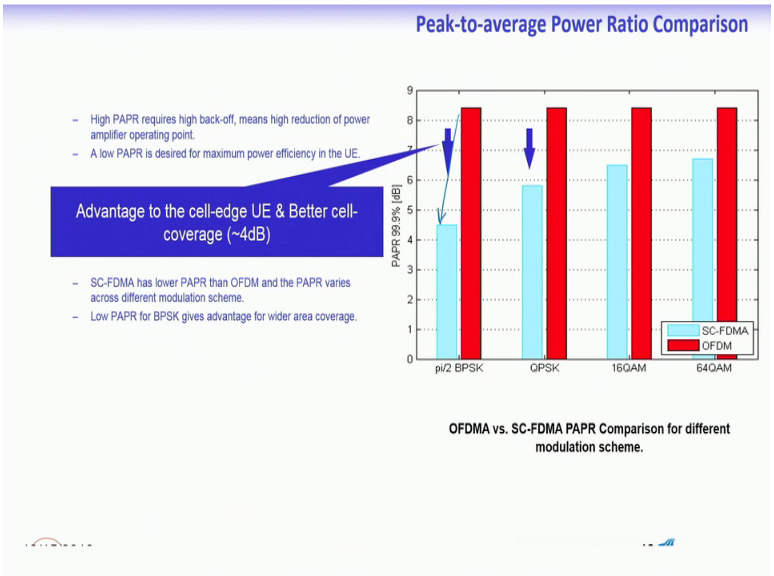

So, people have found through results that there is a significance reduction in the peak to average power ratio if one uses different if one uses this DFT spreading mechanism.

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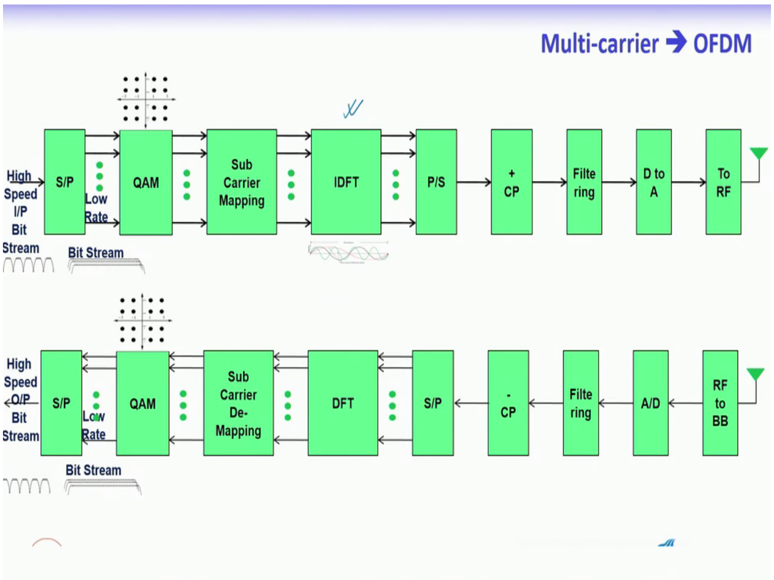

So, will move forward and take a look at the OFDM structure. So, this is the OFDM structure which we have discussed at the transmitter side there is a IDFT operation. Now, to change or to look at what kind of change is one can think of we have already discussed about merits and demerits.

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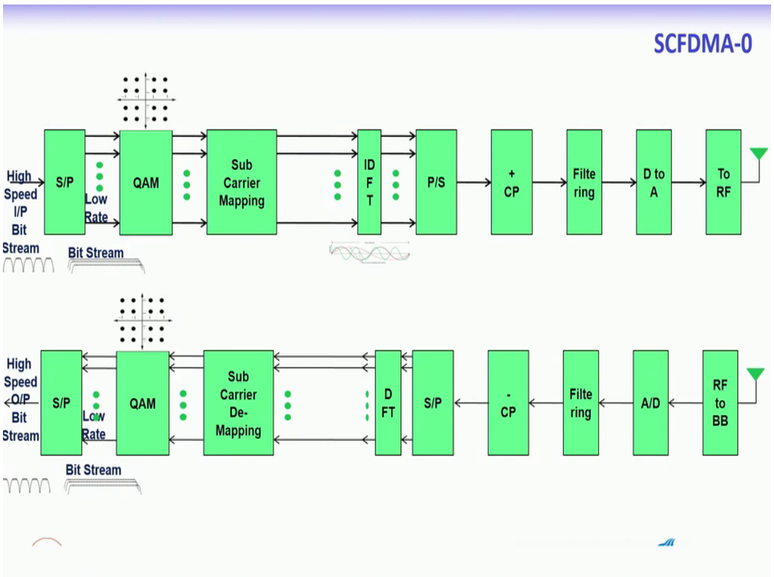

We would like to show you through a minor change in the figure how different things can be realised simultaneously over the same kind of architecture. So, if we focus on this picture this is the IDFT operation at the transmitter and the DFT operation at the receiver.

So, as a first step we are simply showing that nothing has changed it is the same IDFT operation in the transmitter and same DFT operation at the receiver, but pictorially we have just modified it to show a translation that can be thought of.

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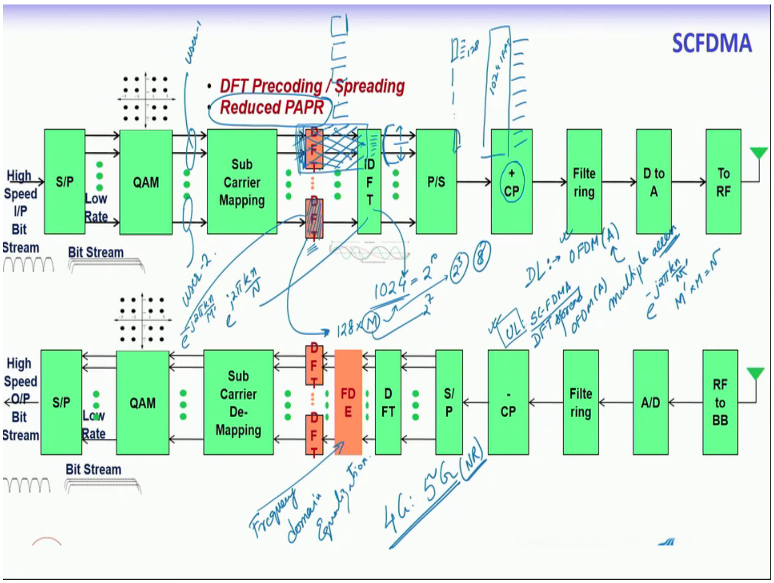

Now, DFT spreading is introduced before it so, DFT spreading kind of over a smaller set of bandwidths. So, if you have say 1024 carriers in the IDFT operation then one would like to add DFT of various sizes to get various benefits. So, one could think of a 128 size DFT. So, if one does 128 size DFT one would have M number of such 128 point DFT that would result in 1024 point IFFT mapping. So, if this is 2 to the power of 10 this is 2 to the power of 7. So, we have 2 to the power of 3 number of that is 8 number of such IDFT such DFT operations happening.

So, as if 1 2 3 up to 8 such DFT operations each one is going to produce 128 point output and all of these will be feeding into a 1024 point IFFT operation afterwards and then whatever we get is what we get. So, now, what we will find is that this particular section, this particular section if we focus on this particular section the DFT along with these carriers they smudge out each other and as a result one can think of getting a larger bandwidth of equivalent to a single carrier system. So, as if there is there are multi carriers have gone away and a single carrier of this much bandwidth has come into play ok.

So, now this can cause confusion that since we were talking about single carrier all the effects of ISI in single carrier would come into play, but now what we are seeing is that the cyclic prefix is still being added. So, this addition of cyclic prefix would maintain the ISI free characteristics in the time domain between the different symbols and this would also allow us to go for a frequency domain equalization ok. So, this frequency domain equalization makes things very very easy one can use a very simple architecture per sub carrier only one tap equalization and hence one can proceed with the things.

So, if we follow through some of the steps shown that from the OFDM system to translate to DFT spread system which has a very low PAPR because it kind of randomizes parts of the signal, we can actually have the same system with a minor path switching. That means, when we are doing the OFDM, we would like to use one particular set of components when we are doing DFT spread we can use another set of components rest of the components remain more or less the same with not much variations. And in fact, this is used in 4 G systems. So, in downlink in 4 G systems they allowed to use OFDM and it is rather A it is a multiple access part.

So, the resource block that we have discussed is to be used for different users in other words it means that some of these carriers of this are grouped and allocated to let us say certain user and other set of subcarriers are grouped and allocated to another user and so on and so forth alright. So now, in downlink OFDM is used and in uplink single carrier FDMA or SC FDMA as it is called is used another name for SC FDMA is DFT spread OFDM A ok. So that means, this particular operation is as if it is doing the spreading operation on top of the DFT or the IIDFT operation.

So, this is called a DFT spread OFDM and spreading codes are derived from the DFT matrix e to the power of j the DFT matrix gives you e to the power of j 2 pi k n upon N because here you are going to get e to the power of j 2 pi k n upon N and here we will be getting e to the power of minus j 2 pi k n upon M ok. So, not M sorry we can put it as M prime indicating a different size because here I have used M so, therefore, I am choosing M prime over here. So, M prime times M would be equal to M so, you can see that M prime multiplied by M should be equal to M. So, that would set everything proper. So, this would make the things appear like single carrier. So, what we have one single carrier wide band another single carrier another single carrier.

So, the still multi carrier, but each one of them are having a wider subcarrier bandwidth only because it helps reduce PAPR. Now, at the receive at the user equipment side so, when you are doing uplink user equipment is sending information to the base station. So, if one does DFT spread PAPR is less if PAPR is less then one can go for the higher transmit power, one can go closer towards saturation powers the efficiency of the power amplifier is higher as well as one can radiate higher amount of power and hence the overall system improves the power budget of the system and coverage can be improved.

So, this way downlink OFDM A is preferred in uplink SCDFMA or DFT spread OFDM is preferred in 4 G as well as the same thing is supported in 5 G communications. So, when we look into the 5 G NR we do not have to revisit this particular aspect again that this OFDM structure is followed in downlink and in uplink this DFT spread OFDM is also supported because, it would give lot of benefit to low power devices to have a larger coverage and a better battery life.

So, with this what we find is that our discussion on multi carrier systems especially with orthogonal carriers lays the foundation for the frame work or wave form structure or the physical layer signalling procedure for the 4th generation as well as the same thing for 5th generation which we have been discussing. And, which we have been saying when we were talking about the foundation of wave form analysis or the frame work based on which we have started discussing the waveforms. We will continue on this and look into other variants of waveforms that exists we will also look at the frame structure for 5th generation and what are the additional benefits of the 5th generation air interface in upcoming lectures.

Thank you.