Evolution of Air Interface towards 5G
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Lecture - 20
Waveform for 4G & 5G OFDM (A), SC – FDMA, DFT Spread OFDM (A)

Welcome to the lectures on Evolution of Air Interface towards 5G. And as we have said that we are at a very crucial juncture trying to understand the multi carrier basically the OFDM system and it is very important as we have said also to understand the parameters and how they are related. Although we did not have a detailed discussion on the propagation characteristics, but we have been giving guidelines and hints at every point how do these things influence the design of OFDM. So, when we take a careful look at the propagation one should be able to connect these two different things.

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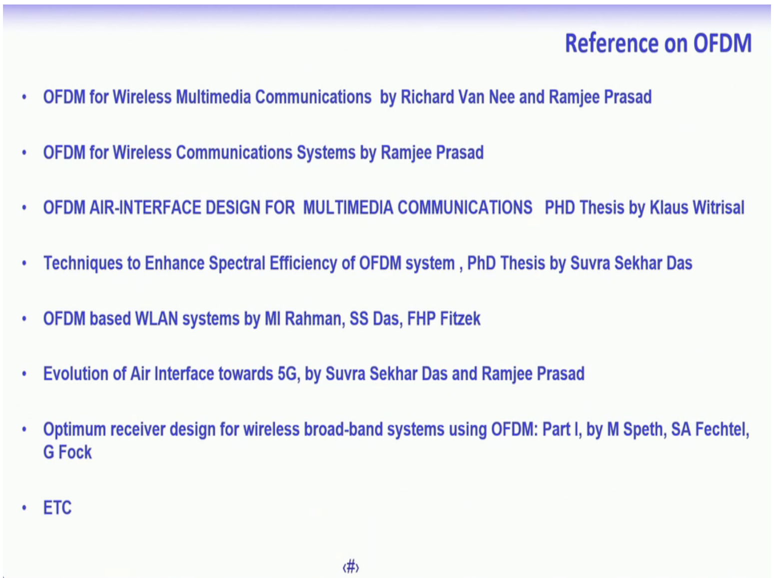

So, before we proceed further I would like to reiterate this is I have said this thing earlier, but like to say again that these references are very very important. Especially, if you are working with 4G and 5G because these leads the foundation for the multi carrier systems, it is absolutely essential that you go beyond the typical notes or the material that we supply and look into these references. And, especially I would say because these are books which are available and this is also a book which is available and interestingly I just tell you that this particular one and E-book is also available at a much lower price and this one is especially relevant for our course. So, this has been made especially for participants of the course, the publisher has made the E-book. So, you can find this in all possible places, it is much cheaper and its soft copies of which is very easy to handle.

And however, these are the references which are especially important for only OFDM part. This will be useful for all other things and these there are actually a pair of references over here, which is also important for the basic expressions. So, I would very strongly recommend you to get these references and use them, this is very easy to read, these are all freely available in the internet. So, it is very important that you go through them ok.

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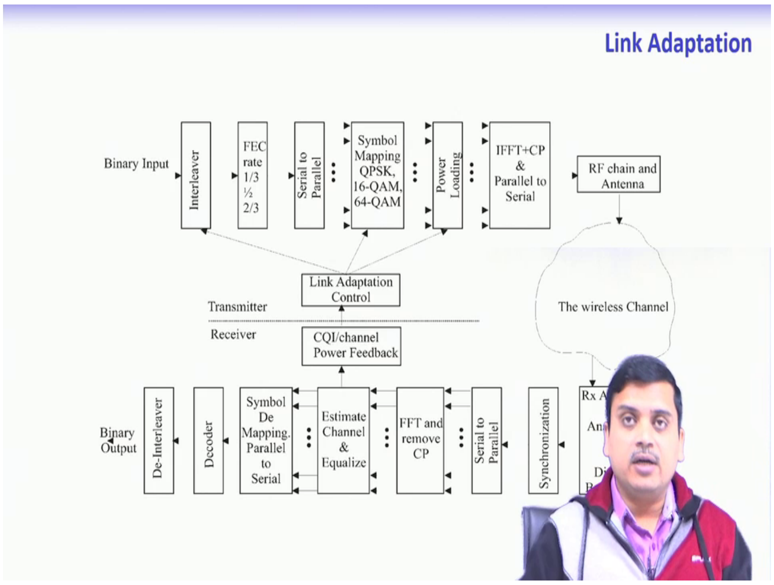

We have also discussed the structure of the transmitter and receiver in the previous lectures. So, please get time to go through them and understand each and every process and try to implement them also. Implementing in MATLAB is not difficult or your own suitable platform that would give you a better understanding of things.

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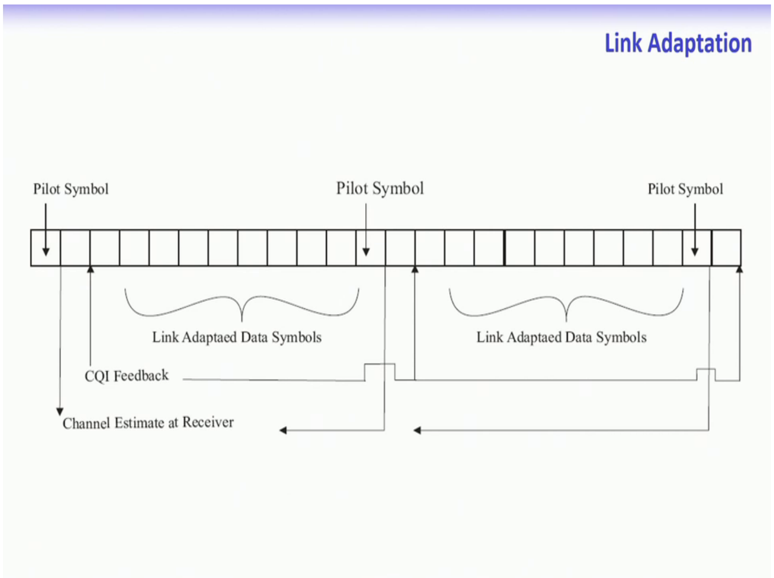

And the link adaptation you may not implement, but it is for you to know and understand the criticalities.

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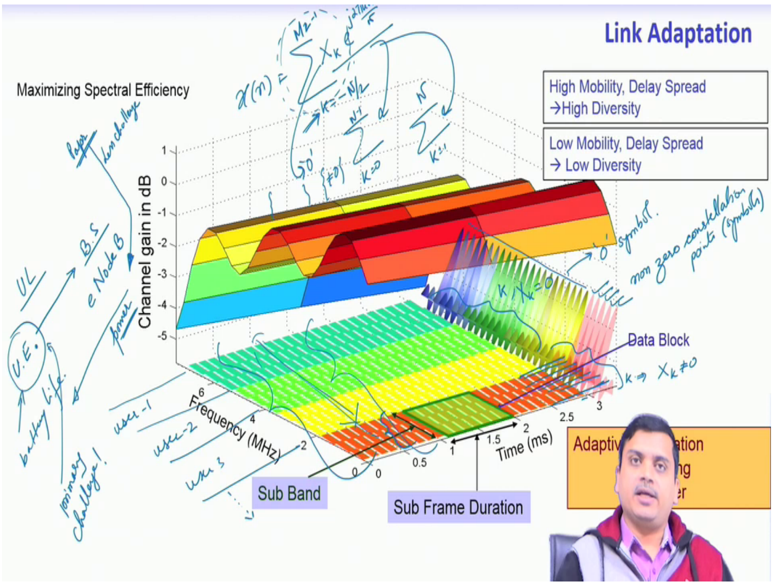

This particular picture is also important in terms of time frequency diagram, because whenever we talk about the query will be especially talking about the frame structure, the frame design or any the other thing; this picture should be available in mind. There is a time, there is a frequency, there is a group of symbols and we have as always said this is the time duration OFDM symbol duration, this particular part this is the sub carrier bandwidth. So, the entire picture should be available in mind when we are discussing such things.

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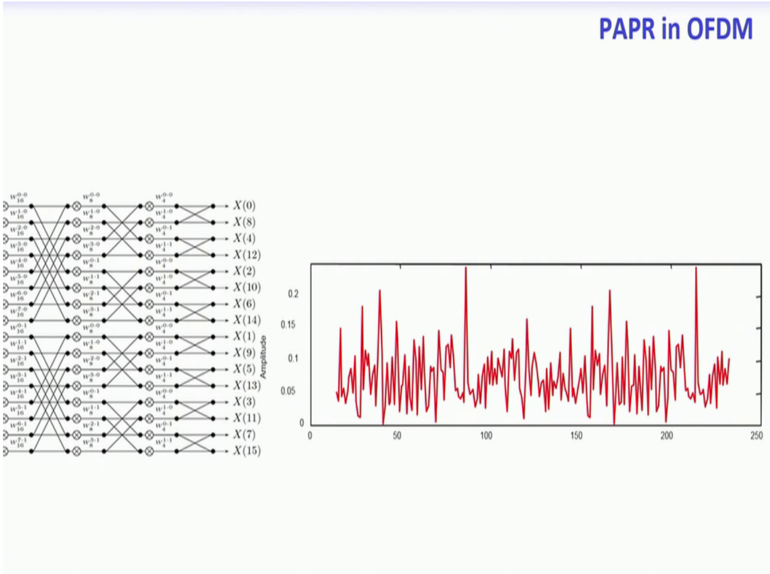

And in the previous lecture we have discussed how the OFDM affects the peak, peak to average power ratio.

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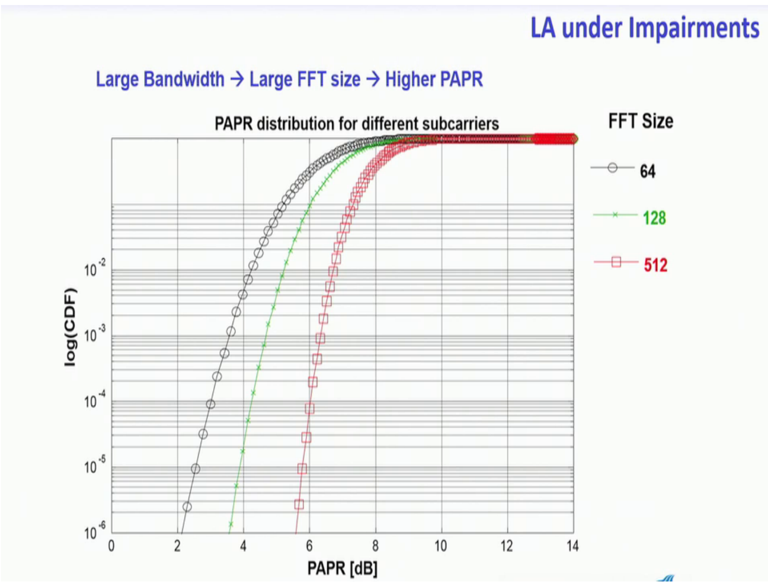

And how the different, I mean the probabilities of getting higher and higher peak to average power ratio increases with the sub carrier width, we have also described how it happened.

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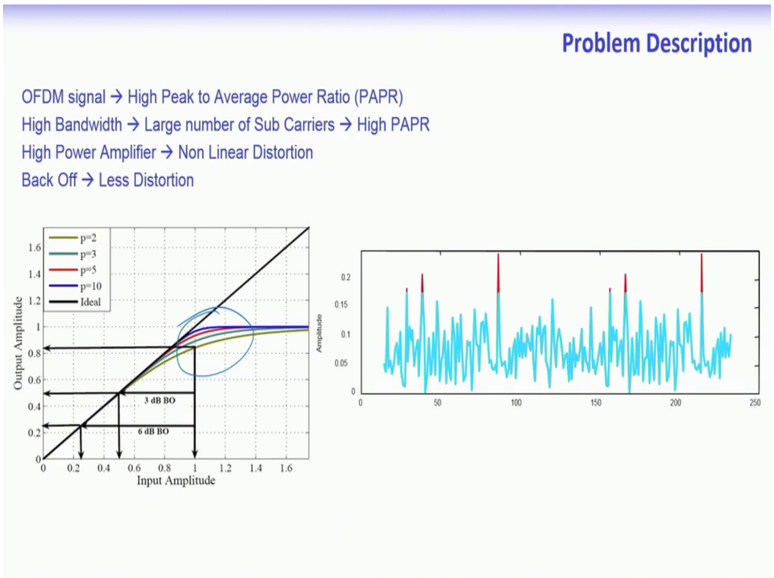

So, these are some things one should be noting carefully, because these are the factors which ultimately affect the design of the system. So, we have also explained how the clipping procedure because of these non-linearity effects of the power amplifier effects in band modulation and there is all kinds of distortion. Again lot of results are available in some of these references, and the references there in. So, it is absolutely essential to understand details you go into those references.

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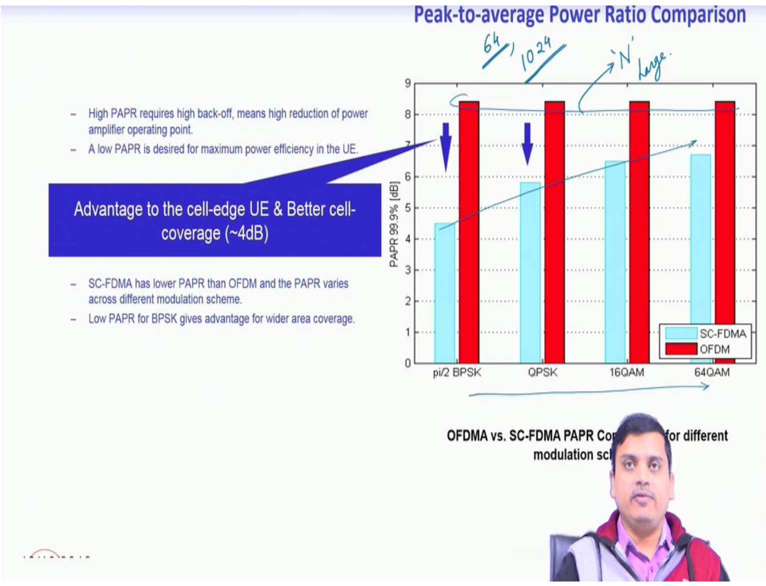

We have also discussed the method to reduce people average power ratio.

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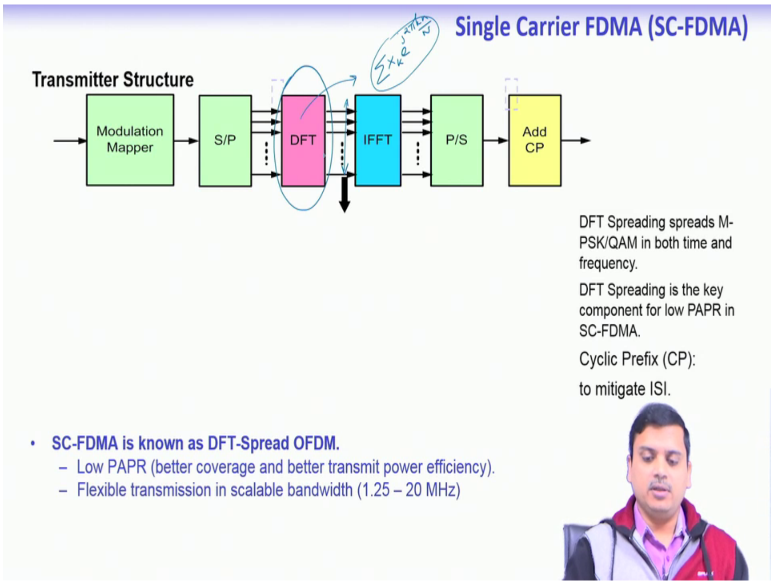

And we have said that one method is to do a DFT spreading; that means, you spread the signal that is going into this IFFT block. So, that the coherent combining that may happen is kind of reduced. So, in case this there is coherence combining this kind of will remove the effect.

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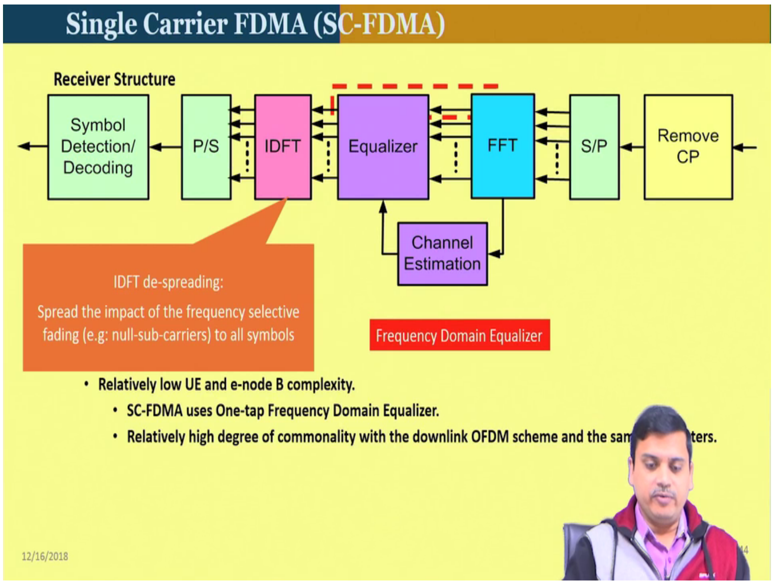

So, with that there is significant reduction PAPR we have also discussed this.

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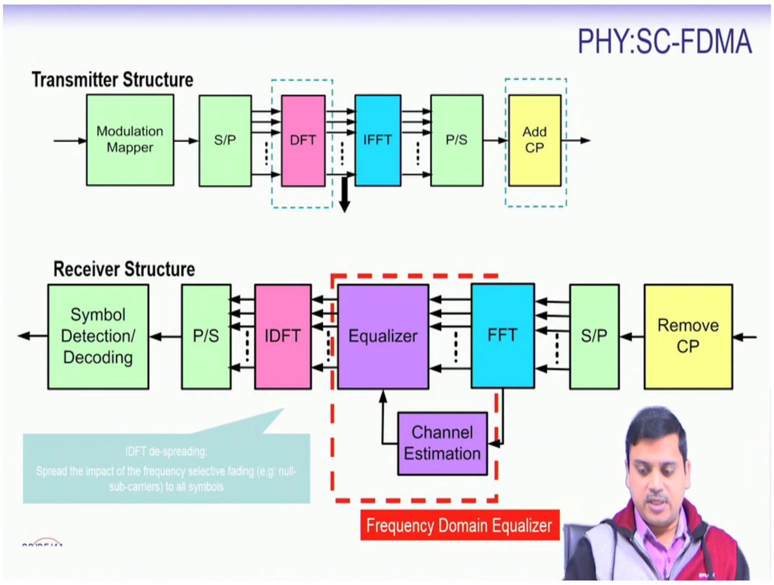

We have discussed the transmitter receiver structure. So, the DFT operation at the transmitter is correspondingly undone by the help of an IDFT of the operation at the receiver.

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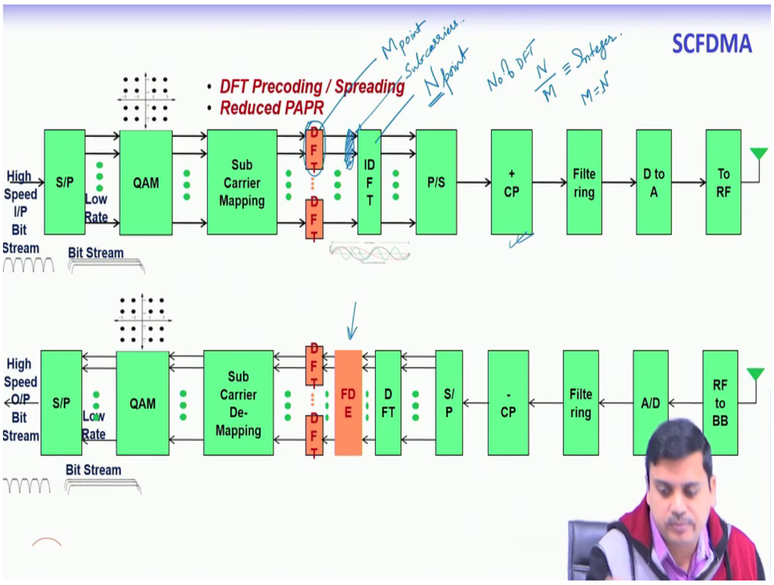

So, this is also very important what we will do today is, we will go beyond this and we will look at some of the important other aspects. So, we have discussed this time fre this generation process.

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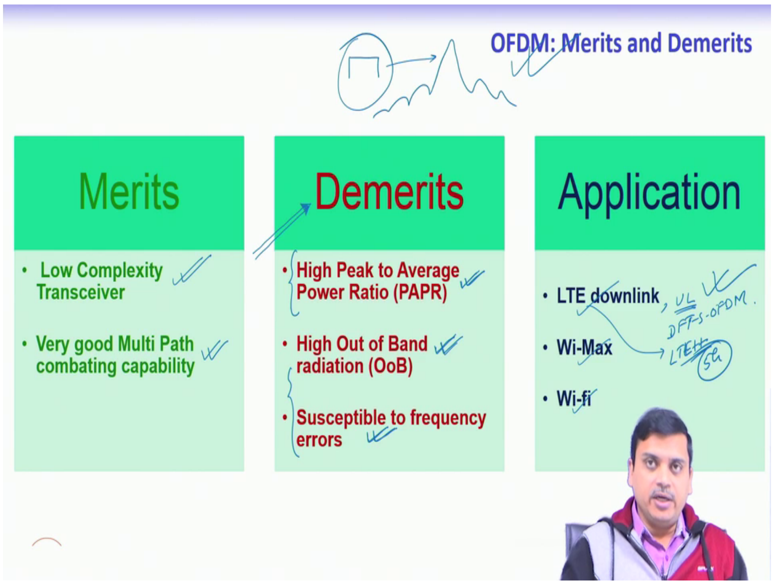

We briefly looked at the metrics and demerits of OFDM. So, we have always started off with that it has very low complexity transceiver simply because of because of FFT architecture, good multipath combating capability this we have discussed in the previous lectures. Demerits peak to average power ratio we have discussed. High out of band radiation we have briefly touched upon; primarily what we have we have explained not only in the previous slide.

But, also in the previous other discussions that a rectangular sync rectangular pulse results in a sync spectrum and a sync spectrum does not die out very very quickly. Susceptibility to frequency errors also we have explained and we will again look at it in details, and these are some important factors which have led to the development of newer methods. So, always we as a researchers or engineers and look at demerits and try to find mechanisms to overcome these problems.

So, they we have already said that there are several methods reduce PAPR and one method we have already discussed. There are methods to reduce out of band and primarily it is about the pulse shape, we will get an opportunity again later to discuss in more details. And startup susceptibility to frequency offsets there are again various methods to do it ok. And applications are of course, LTE downlink Wi Max Wi-fi and in uplink what is used? LTE uplink it is the DFT spread OFDM this is what we discussed in the previous lecture. We also said beyond LTE; that means, LTE plus plus or in other words even in 5G both these techniques; that means, this OFDM as well as DFT spread is used.

So, whatever you are discussing whatever you are studying what are you doing now, is absolutely relevant for the fifth generation system as well. So, we have explained thoroughly in the previous lecture that the typical web team structure as you can see in this particular slide, can be used for further modification with slight changes it can result in very significant things. So, what we said is that, this DFT spreading is done over a set of sub carriers and this causes these individual sub carriers to appear as if they are correlated they come together and it gives the notion of a single carrierness.

At the receiver side because we are doing cyclic prefix, we can avoid ISI you get this frequency domain equalization benefit there is also we have discussed. Now, moving beyond this is a very interesting thing that one can think of is, if you increase the size of DFT. Now what we have said is there are N points in the DFT N point DFT right that is what we have said over here. And we said that let this be of M point right. So, then the number of DFTs that you require would be N divided by M and it is done in a manner such that this is integer this is to be maintained.

Now, if we take the options one extreme option could be M is equal to N this is one extreme option that is highly possible.

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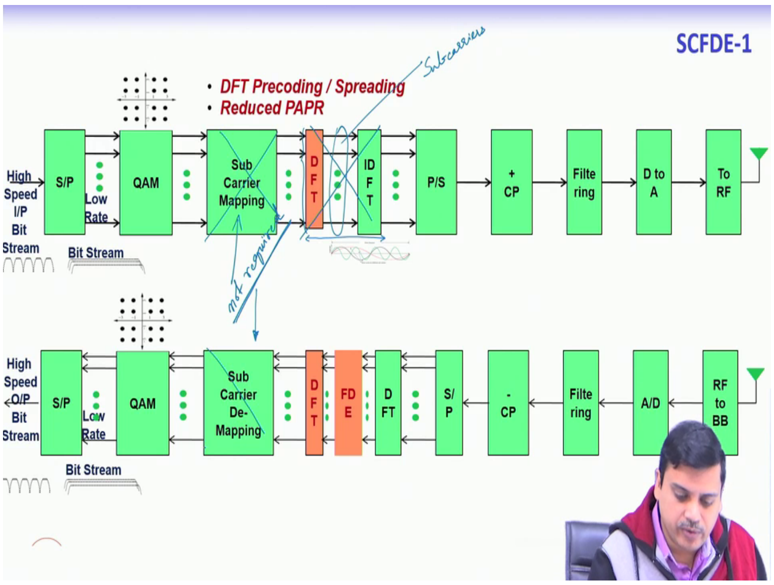

So, if you do that then what happens is that, the DFT spans the entire length of it right. And now you can easily see that the DFT followed by IDFT essentially cancels out each other there is no need to do this operation. So, the DFT followed by IDFT since its cancels out the notion of sub carrier goes away because sub carriers are present over here we have sub carriers ok. And if we go back here, the sub carriers are still present over here ok. So, now, if we stretch it the notion of sub carriers would go away and hence the sub carrier mapping would also not required any further right. So, this is also very very important to note.

Now if we do away with the sub carrier mapping. So, correspondingly the receiver operation of sub carrier D mapping would also not be required. So, now, we are doing away with this part we are doing away with this part and we are doing away with this part ok. So, what we see is that these things are gone from a transmitter receiver architecture and even things become simpler.

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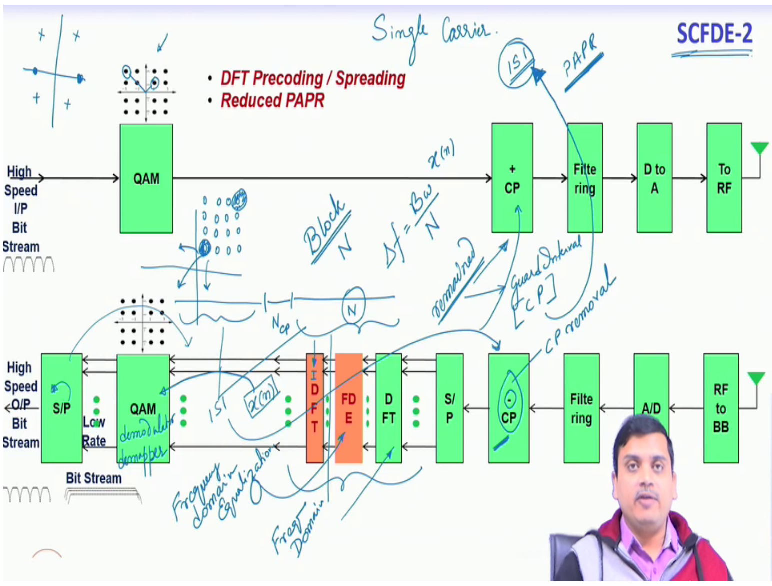

So, here the serial to parallel should also go away that is also not necessary and you have a system which is a single carrier system. So, now we have a single carrier system ok; however, we can maintain the same bandwidth. Now typically this would cause all kinds of problems of a single carrier system. We know the typical problems have a single carrier system that is inter symbol interference right, but what is the biggest advantage of single carrier system is the PAPR; that means, peak to average power ratio is the minimum or is the lowest possible thing compared to multi carrier system ok. We can think of a sinus wide and it has a peak to average power of ratio of a by 2 or 3 dB and if you would assign some kind of modulation QAM modulation, the PAPR would be primarily due to the kind of modulation that comes in. Why it is so? Because if we are thinking of BPSK there is no change in amplitude, if you are thinking of QPSK, there is again no change in amplitude right. But, if we go for the next higher order modulation as given in this particular picture, what you see is that, amplitude of this constellation is different from the amplitude of this constellation. So, the constellation itself brings in a peak to average power ratio.

Now if we go for higher order con constellations so; that means, if we go for 64 QAM. So, this is 16 on any one quadrant you would repeat the same over here and on all the quadrants. So, then if we compare the power with respect to this constellation compared the power with respect to this constellation point it is; obviously, higher. Now this one can easily see in one of the results that we had depicted over here is that, here it shows that how as the constellation size increases the peak to average power ratio increases that, is what you are seeing ok. Because, now this is going towards more of a single carrier system whereas, when we look at OFDM system, the increase is not notable it is not much notable because the PAPR is primarily driven by the factor N and this N is quite large.

Because, if you look at Wi-fi; Wi-fi which is a very small number it is 64 which is also not small. If you look at LTE, the number is around 1024, if you go for the fifth generation the number is even larger ok, but there are different other mechanisms by which one can think of effectively or practically having a lower PAPR. Now one another way of seeing it let us let us carefully take a look at that. If one of the users is being allocated only one such band of frequencies right so; that means, only these frequencies; that means, these few frequencies are going to get non 0 constellation points or symbols. So, for that user all these sub carriers would be getting 0 in the symbol value ok.

So, effectively the active number of sub carriers is restricted to the bands of sub carriers that is allocated to that user. So, when we look at the IFFT operation at the transmitter the x n which is summing over K is equal to minus N by 2 to plus N by 2 minus 1 or let us say it is summing over K is equal to 0 to N minus 1 or you can also sum over K plus be 1 to N. In all these cases X k e to be power of j 2 pi k n upon n that is valid for all the cases. So, what do you see is that, for a large number of k the X k value is 0 for one subset this is 0. For another subset this is not equal to 0; that means, for these subset values of K for this K X k is not equal to 0; for these K X k is equal to 0 correct. So, what does that mean? That when we are adding these up over a smaller set when were adding it up over a smaller set then the peak to average power ratios automatically reduced.

So, now, if the system allows for the user to use only a small subset of the entire bandwidth, in that case the peak to power peak average power ratio is automatically reduced for that particular user right; so because that user is not accessing the entire band. But now if we look the base station; the base station is allocating let us say this chunk to user 1 this chunk to user 2, this chunk to user 3 and so on and so forth. Then from the transmitting end at the x at the base station, what one will find is that the base station has all the sub carriers active in the worst case scenario. When there are lesser users this will obviously, be not the case.

So, the base station suffers a PAPR problem. But look at this we have discussed in the previous class, that in the uplink direction the PAPR problem is addressed in LTE where is it is in the downlink it is not addressed. The main reason we have said is that uplink is user device to the base station user equipment to base station or which is also known as the e Node B the name changes when you go to the fifth generation system ok. So, then the users battery is a primary issue battery life right. So, saving or reducing PAPR make sense whereas, in the reverse direction power is not much of a constraint and one can implement better power amplifiers whereas, the user end you have constraints on implementing the power amplifier.

So, as a result the PAPR problem at the e Node B or the base station is not much of a challenge whereas, it is a primary challenge at the user equipment. This is something what we should remember. So, hence all the solutions and things get designed. Accordingly in the fourth generation the uplink has a solution at the user and in the downlink it does not address it at all and since we have also said now that in the uplink the user equipment need not be sending across the entire band of frequencies.

So, that also helps in the fifth generation, although it allows for DFT spread in the uplink in order to save power, but it can also allow OFDM transmission in the uplink direction.

This is something one has to note very carefully. So, going ahead further from what we have discussed. So, now, what we are discussing is this single carrier FT. So, what we see over here is that, we have the single carrier the next part is what we will look at. So, since we have addressed this problem PAPR is heavily reduced there is the lowest possible PAPR one can think of, but the ISI problem still remains. So, how is this handled and how is the entire framework giving us a facility is that, what we are seeing is as we translated from a standard OFDM system; that means, this was our standard OFDM system as we see one by one blocks are getting removed ok.

But what we are seeing is that all right. So, this part is also removed the CP has remained this has remained. So, this remaining means that you have some guard interval which is revealed as a cyclic prefix right. So, what does this do? This helps prevent the ISI being manifested at the receiver right. Because the receiver does a CP removal this particular part is CP the negative sign over here indicates a CP removal. So, once it removes the CP, the entire block of OFDM symbols. So, we have a block based transmission right and the block length is remaining N as an OFDM nothing has changed. So, basically that same N block length will remain and they will be a CP N CP will also be added to it right. So, that gets removed and then you have the entire block which is free from the ISI of the previous block ok.

So, the ISI between this and this is addressed by the CP that is added and one that is removed. Now, one would argue that one has to apply ISI cancellation, but look at this. Since we have got this CP right our earlier discussion that convolution linear convolution at the in the time domain gets translated to circular convolution in time domain. That means, if we do DFT operation it would appear to be DFT of the channel coefficient matrix multiplied by that of the DFT of the its receive signal strength all with n point DFT; here is something we have to remember right. So, what does that help us in that, every sub carrier now we are seeing a sub carrier all the sub carrier was not present, but we are seeing in the frequency domain with a certain resolution and the resolution that we see is equal to the bandwidth of the system by N that remains.

So, if we can have N very large. So, now, this look at this N one can choose independently one need not be constant because the transmitter does not have any value of N. So, this can be chosen independently with any finite resolution that one thinks of and one can apply this frequency domain equalization. So, this is a very handy technique for uplink. So, wherever power is a major constraint one can easily think of using this particular method single carrier fd for uplink and when one sends it for uplink, these minimum PPR at the receiver and this processing is done at the base station. So, where power and processing capabilities never constraint and one can handle all the ISI in the frequency domain by very easy signal processing.

Now, once you have got this in the frequency domain. So, here you are in the frequency domain one has to do the DFT operation DFT it one has to do the IDFT operation; so, in order to get from the frequency domain to the time domain. So, what we have over here is these pictures, these have to be IDFT at the receiver side these pictures have to be IDFT at the receiver side and these have to be IDFT at the receiver side all these have to be IDFT at the receiver side. So, once we do the IDFT, we get back our signal x n over here what was the signal x n over here?

Free from channel only thing that remains is the noise that one cannot remove and these can be now sent to the QAM demodulator or a better word is demapper we would not use the term d modulator and then one can think of serial to parallel to serial conversion this is parallel to serial conversion or one can think of bringing this module earlier and then doing with one single QAM demapper. So, this is an extreme case of single carrier FDMA and one can do reduce the PAPR like anything.

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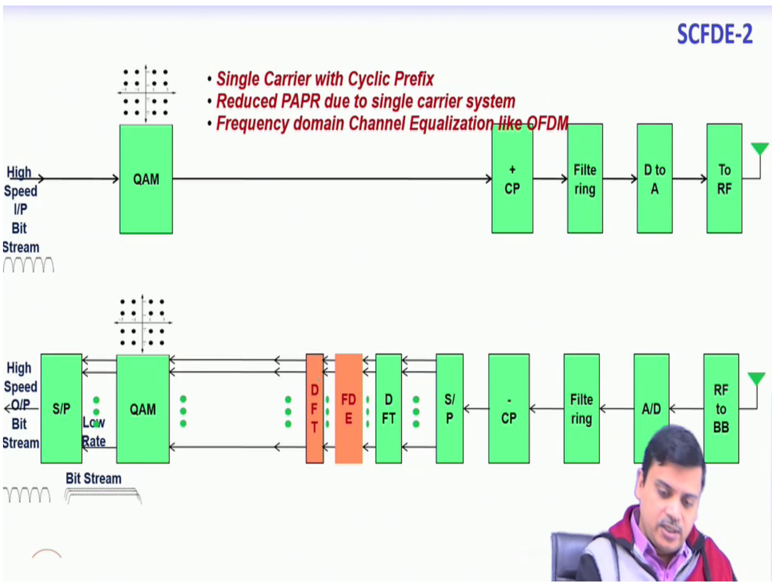

So, after this we proceed further this will also be I.

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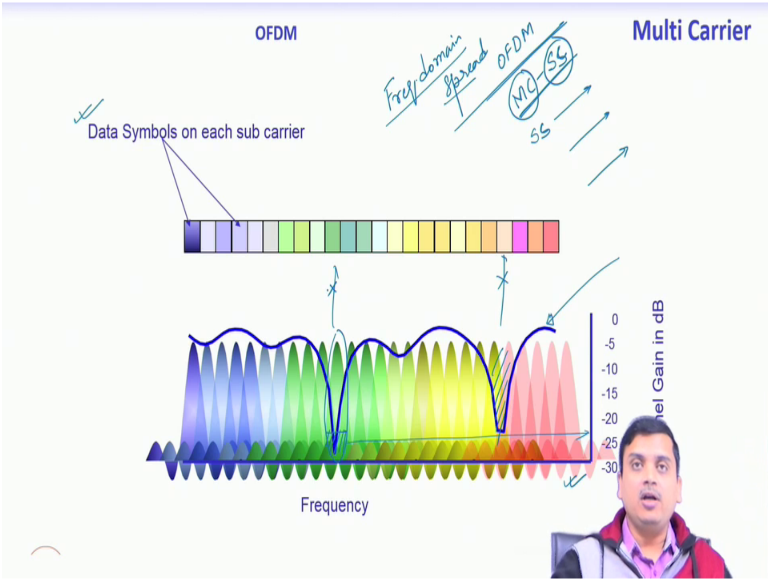

And we look one interesting capability of this DFT spreading. So, what we look at DFT spreading. This is the picture that is important for us. So, we call it DFT spreading now, we look at little bit deeper picture of it. And instead of DFT spreading we would rather call it a spreading system. So, we would simply call frequency domain spread it right. So, that is what we will look at.

Sometimes these kind of things are also called multi carrier spread spectrum. Now there are different realizations of multi carrier spread spectrum one realization is you have spread spectrum communication and they happen on multiple parallel carriers. The other way is that, you do frequency domain spreading; that means, you have a multi carrier system, but along with it you have some kind of spreading. The spreading codes can be obtained as we said earlier from different combinations whatever we have studied in the third generation system.

So, let us look at why should we do it and what are the benefits and what is it related because we can use it in again all future communication systems. So, in a typical OFDM system these are the sub carriers, we are discussing we have been discussing this picture its not new. This represents the frequency domain channel again and let these be the data symbols as has been written over here. So, now, what you can see is that, this particular sub carrier which experiences a deep fade deep fade means the signal attenuation is very large as you can clearly read over here. This set of sub carriers were signal attenuation is very large what would happen is the would go under deep fading and they will not be demodulatable at the receiver right. So, that is what happens.

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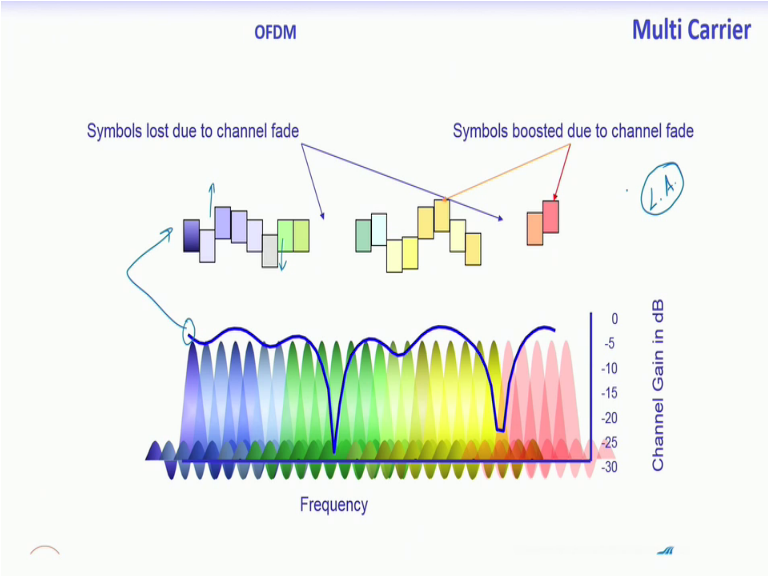

So, these symbols get lost and you cannot demodulate and the other symbols are either increasing in signal power or decreasing in signal power because of the fluctuation of the channel, which is in correspondence to this curve right. So, it means different signals experience different signal to noise ratio. We have said earlier that this is what is utilized for link adaptation right. But now while we have seen the positive side of it the negative side of it is like, there is a lot of loss also and these are not recoverable loss. One can argue that yes, I can go for error correction codes and I can recover, but deep fading losses or something which is always difficult to recover.

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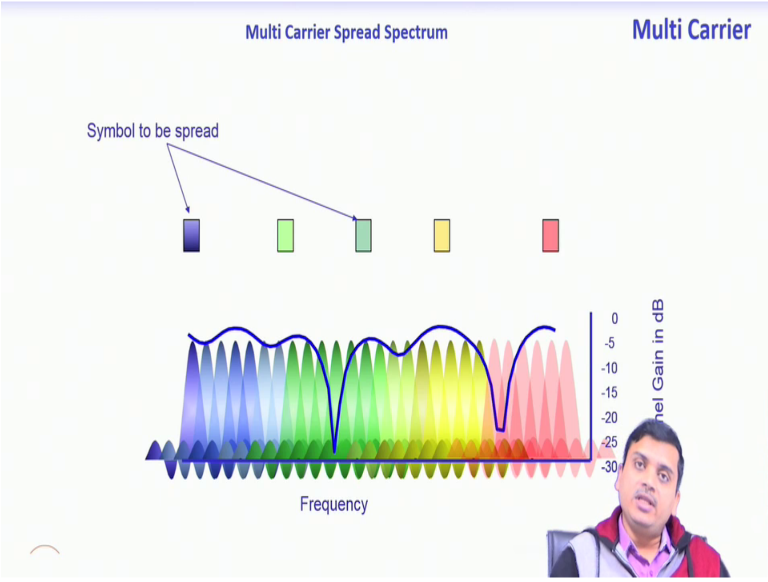

So, we look at another system which is kind of multi carrier spread spectrum. So, now, let us look at this picture because this sometimes helps us in creating better techniques, there have been a lot of investigation in these methods earlier, but these are yet to be practically used. So, we would take this opportunity to discuss these methods. So, that one can potentially take this up.

So, what we are discussing is not something new in context of knowledge, but something which can be exploited even within the same framework that exists. So, let us say we have these colored symbols which are required to be spread, and they get spread as depicted in the next picture. So, we have color coding to help us understand the picture right.

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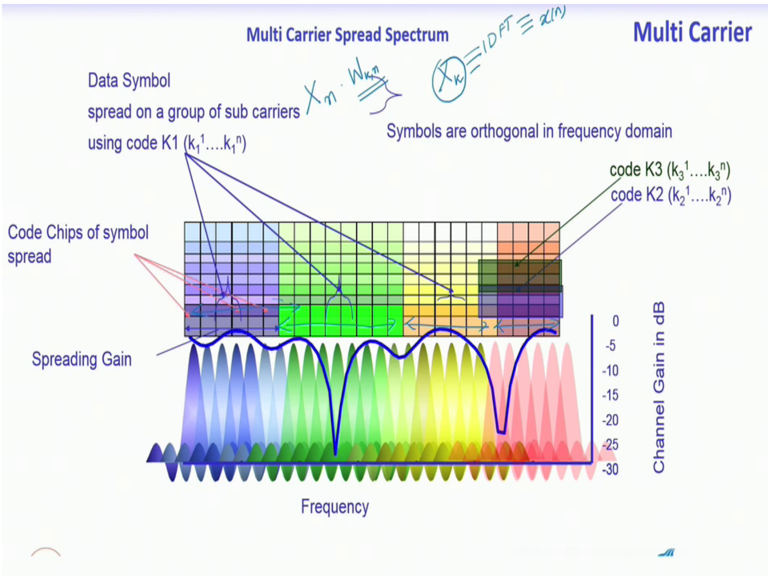

So, now we have expanded these signals. Now, how did we do it? We had X of k let us say, but we will be these X of k was going into IDFT at the transmitter and coming out as x of n ok. So, now, let us take one of these and let us mark it as capital X of n and then with this we multiply with the weight k n which is drawn from a column of the DFT matrix. If you look at the DFT matrix of size n it is an n cross m DFT matrix. So, if we take one particular column of it we are getting one code. One can also think of taking them from the Hadoman matrix. The good thing about Hadoman and DFT matrix is that both are orthogonal matrices.

One can also think of going beyond this orthogonal sequences and going for pseudo random sequences as we have discussed in the third generation system. So, again when we discuss third generation system we said that yes there are certain advantages which you can bring from the third generation system into the multi carrier system which is the next generation system. So, this is one view of such a thing. So, what we see is that, these are the data symbols which have been spread on a group of sub carriers and they are orthogonal frequency. And these are the chips of the spreads. So, as we have said let us say there is one symbol and this is spread across the entire set of sub bands.

So, and this is the spreading gain we have discussed a spreading gain, because same information is contained in this entire set same information is content it is simply spread because the setup frequencies. If one wants to improve the spectral efficiency in that case, one can assign another symbol on the same set of frequencies. So, once when assign one if one assigns another symbol on the same frequency, if these codes that are used to spread them have good properties then what can recover them very easily right. We have discussed that if they are orthogonal there will be no projection on each other and if they are pseudo random the amount of cross correlation will be very less.

So, instead of seeing them in time domain what was the in the third generation, here we are showing the frequency domain picture. So, one can stack up different codes as we are showing in this particular picture and hence one would get a huge benefit in terms of spectral efficiency.

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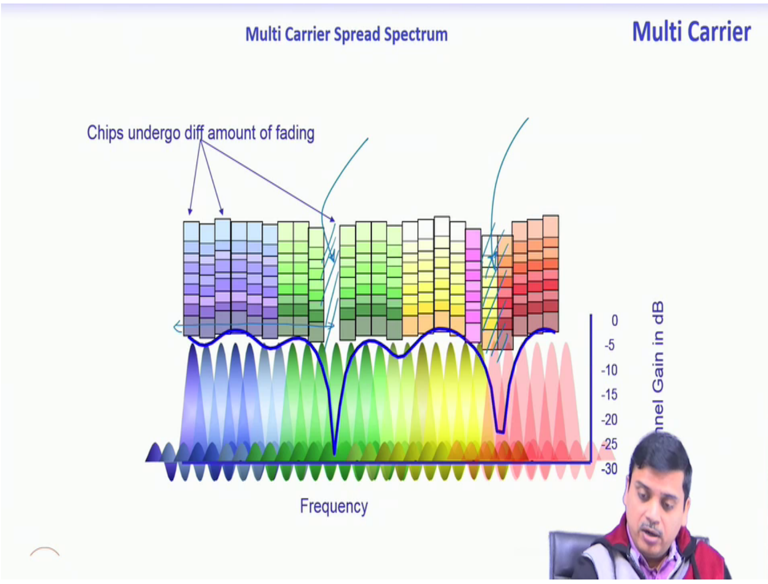

Now, how do we process them? So, when it goes through a fading channel, we will find that these signals are lost as we have discussed. We have maintained the same channel gain in the conjugative pictures, but we will find that the entire signal had been spread across several sub carriers. If the signals have been spread across several sub carriers then even a loss of one or two symbols part of the symbols fraction of the symbols does not cause a major problem.

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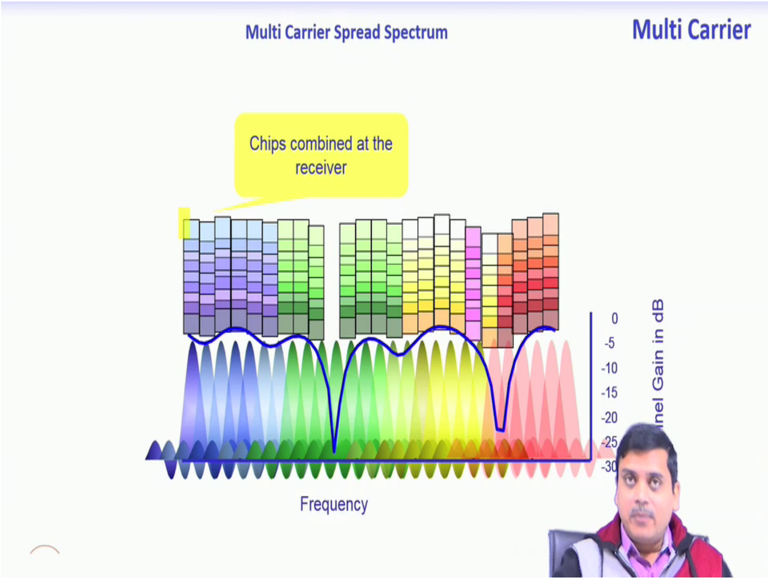

Because one can combine the chips of the code and effectively one can increase the signal power to a sufficient level so, that it crosses the decision threshold.

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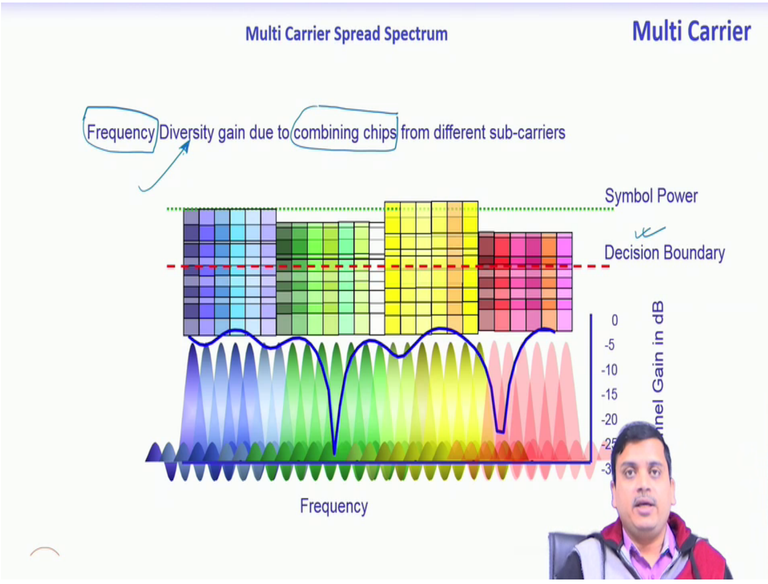

So, again what we see is that, there is combining of chips and the difference that we bring in is that there is a frequency domain combining of chips. So, effectively you are getting a frequency diversity by this method within the same time interval. So, in other systems you had to have a time delay, here within the same time interval you are getting this benefit.

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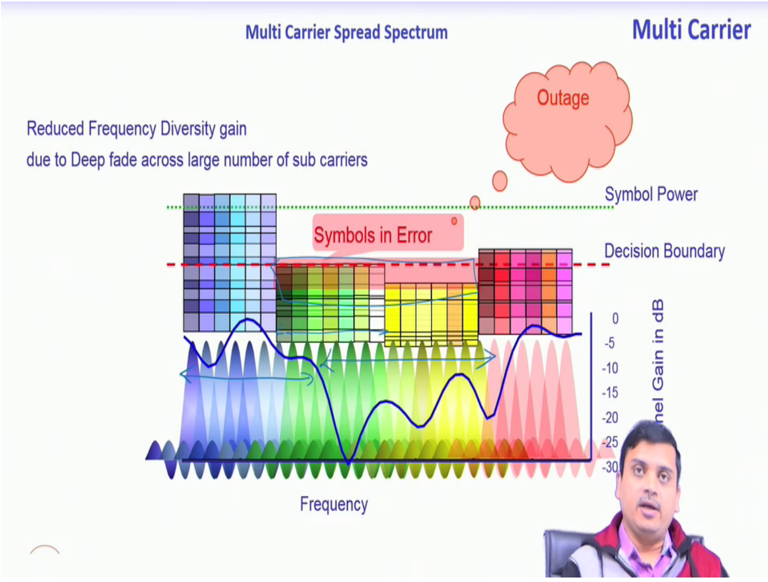

Now, these chips as we said can be drawn from different mechanisms. So, there could be a lot of other problems also like a lot of deep fades and the symbols the entire symbols can go into error, because when we see this here what we have drawn is that there is a narrow section of bandwidth which goes into a deep fade right in these pictures. Whereas, it could be the case that this entire large set of bandwidth goes into deep fade because of certain properties of the propagation channel. So, if the channel properties such that the coherence bandwidth is large, then a large set of frequencies are above the threshold while again a large set of frequencies can be below a threshold.

So, in order to take care of this problem one can think of coming up with mechanisms which would overcome the outage, because a large set of symbols going into deep fade one cannot do anything. Because what we see is that the consequence of symbols they have all gone into feed. The previous picture was only a fraction of the symbols had gone into fade and one could recover them, but here an entire block goes into fade. So, what do you do now is the natural question.

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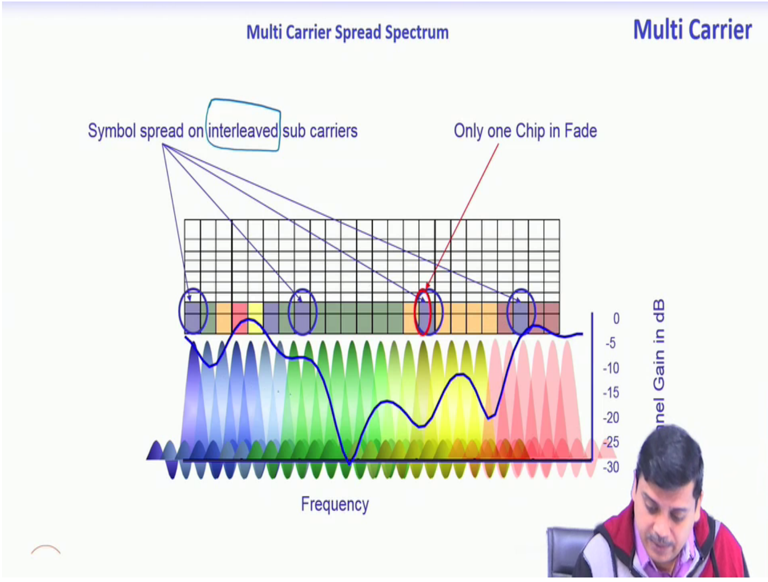

So, what we find is that instead of doing them on consecutive sub carriers, one can spread them on interleaved sub carriers. So, this facility is also very important it is available in Wi max like systems, where you can spread them on different sub carriers rather you can distribute the signal on different sub carriers spreading is not supported over there, but we are discussing something which is beyond the existing systems. So, one can spread them under such conditions what you will find is that, if a signal is spread across in the same situation only one of the chip is not going in fade whereas, others are not going in fade.

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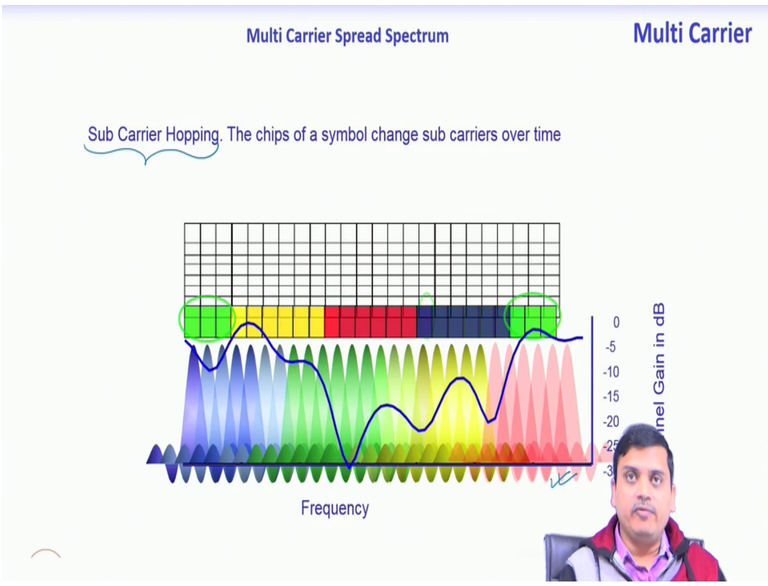

And hence when we have there is also another mechanism by which one can do is that, one can think of doing a combining in terms of frequency hopping mechanism. So, if one talks about sub carrier hopping. Now, let me tell you although it appears that we are talking of spreading and sub carrier hopping right in order to overcome such problems, the hopping mechanism is again a method which has been there in the second generation system right.

So, we are simply taking advantage of the best features which were existing before and combining them with the new features, that are given especially through OFDM. So, we are maintaining OFDM applying those methods on top of OFDM so, as to get benefit.

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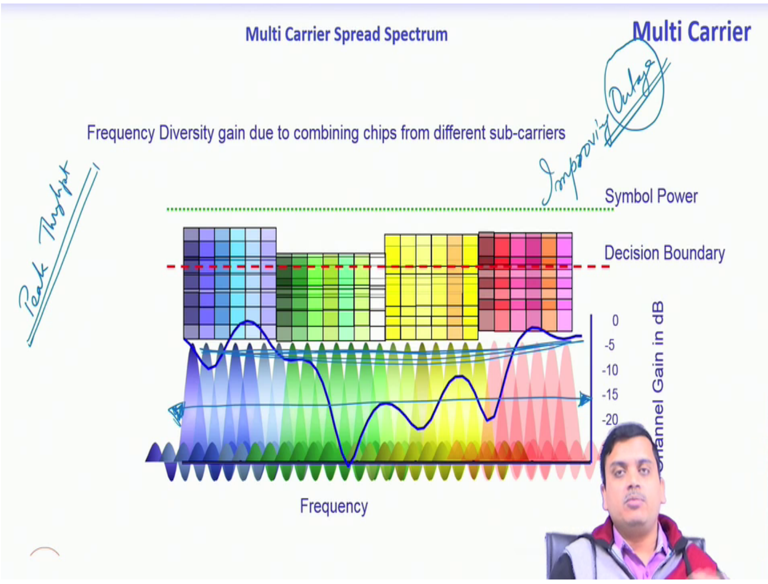

So, if you have the hopping mechanism by which the signals are hopped over different carriers in that case the combining after averaging over the effect. So, what happens is that each of the signal gets averaged over these different sub carriers right. So, this gives some additional benefit that your frequency diversity now increases beyond the subset of frequencies that we consider and it spreads across the entire set of frequency band. That means, your entire band is available for diversity combined what simply happens is that you are improving the outage.

Let me highlight although peak throughput is very important. Peak throughput is something which is very important this is something which is one of the key advertising factors I would say or key parameters when people are moving from one generation to another generation, the other very important factor is the reliability. So, if we have mechanisms like this reliability can be improved significantly and outage is a very very critical factor. Outage determines what is the worst case performance.

So, while we want to increase the peak performance, it is very critical that one improves the outage performance also. Because simply increasing the peak performance does not give us as much a benefit if on the contrary we lose out in terms of outage performance right.

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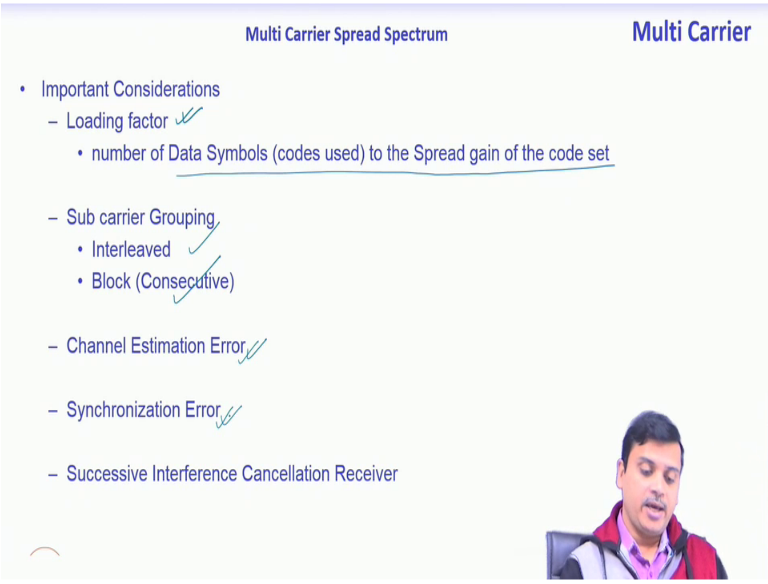

So, some of the important considerations over here is the loading factor, which means the number of data symbols to be used to the spreading gain of the code. So, we have we have discussed the variable spreading factor when were discussing the third generation system. So, similar things can be adjusted over here; that means you can use a variable spreading factor or one can think of instead of putting so, many symbols, one can reduce the number of symbols. If one reduces the number of symbols that are put on to a set of sub carriers, then the amount of benefit that one gets is better because the multi user interference gets reduced in such a case.

So, if one is really constrained with the signal to interference plus noise ratio or signal to noise ratio, then one can think of reducing this loading factor they are by getting even further benefit in terms of spreading gain. One can do in terms of interleaved grouping of sub carriers, block grouping of sub carriers, these are all very critical detailed methods inside this multi carrier system which are essential in order to get the best possible benefit. Channel estimation error is also important because if one is doing kind of additional spreading then this would affect all the symbols not just one symbol.

Synchronization is important we have discussed the effect of synchronization in OFDM. And, to overcome this sometimes successive interference cancellation receivers are also recommended.

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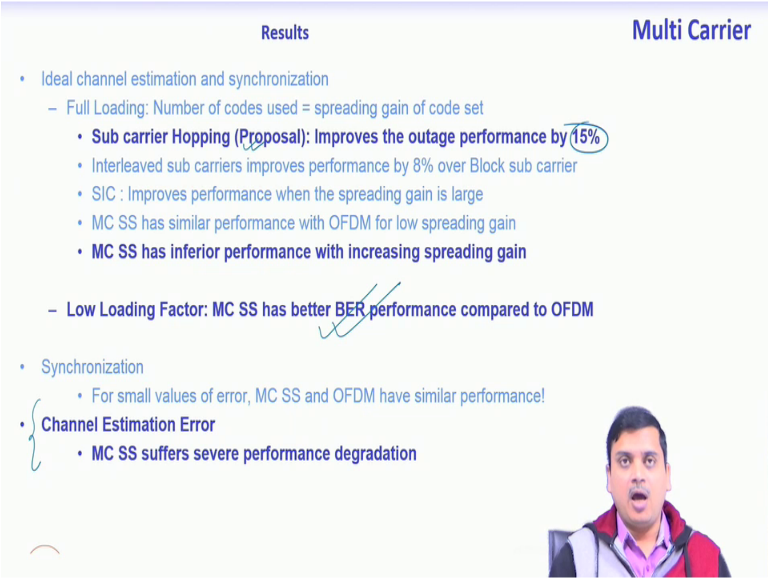

So, there are different results that we had obtained earlier and what one can see is that through hopping one can get a significant benefit in performance and one can reduce the outage better error probability can be used, but when we talk of such spreading, channel estimation error which is affecting one of the symbols if you do OFDM effects several symbols when we do such a spreading.

So, we must take care multitude of these parameters together when you are finally, designing or implementing a communication system. We conclude this lecture over here and we will carry on with further discussion on how these techniques are adopted to the to the fifth generation system in the upcoming lectures.

Thank you.