Advanced 3G and 4G wireless communication
Prof. Aditya K. Jagannatham
Department of Electrical Engineering
Indian Institute of Technology, Kanpur

Lecture - 34
PAPR in OFDM Systems and Introduction to SC-FDMA

Hello, welcome to another lecture in the course on 3G 4G wireless communication systems. In the last lecture, we had looked at the distorting effects of the carrier frequency offset on the OFDM system, that is when the transmitter oscillator and the receiver oscillator are not synchronized that is there is a frequency offset, what is what is the impact of this frequency offset?

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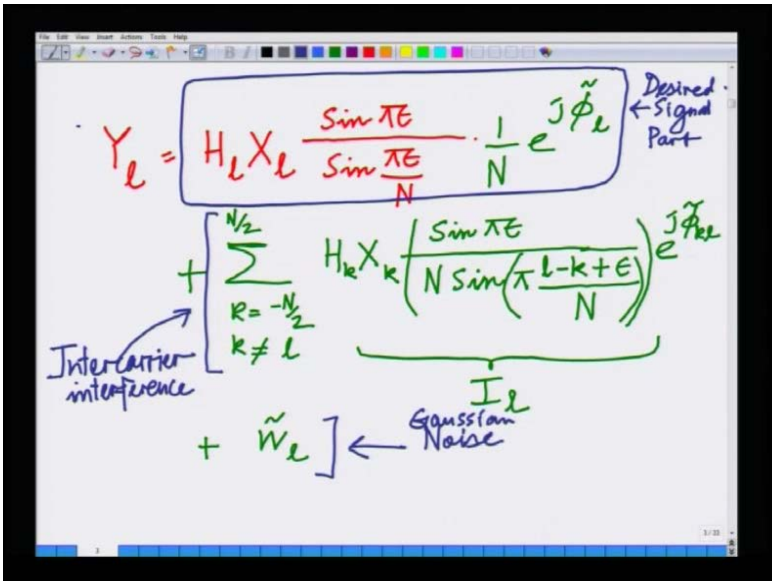

That is what we characterized in the last lecture, we had said that because of the presence of a spurious carrier frequency offset, there is a loss of orthogonality at the receiver in the OFDM system, which results in inter carrier interference that is inter sub carrier interference. Now, we have a signal component in the received signal plus an interference from the adjacent sub carriers plus the usual Gaussian noise as is shown here in this slide.

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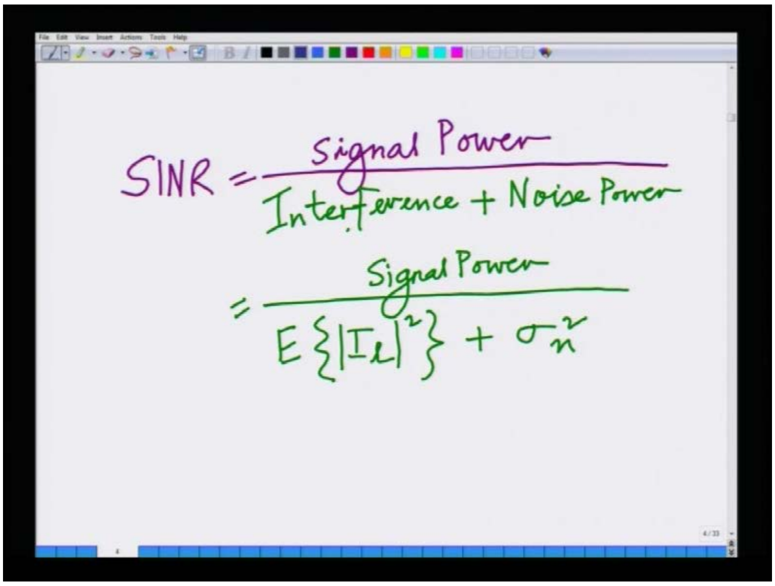

Hence, the signal to noise power ratio now can be characterized using the signal power. To the interference plus noise power since we have an SINR that is signal to interference plus noise power ratio at the receiver and last… In the last lecture we had actually developed a model to characterize this signal to interference plus noise ratio at the receiver.

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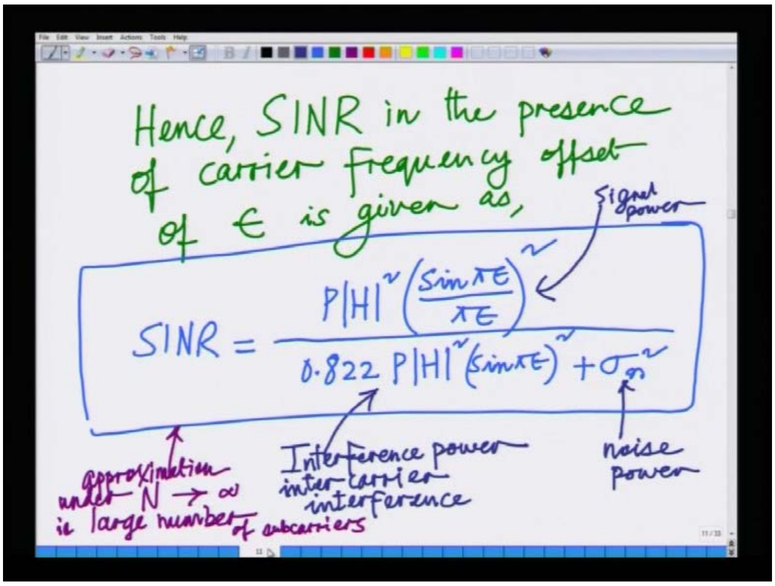

We had seen that the SINR at the receiver can be characterized as follows. That is signal power which is P magnitude H square that is the average channel gain into sine pi epsilon by pi epsilon whole square, where epsilon we said is the normalized carrier frequency offset divided by 0.822 P magnitude H square sine pi epsilon square plus sigma n square. The numerator is the signal power the denominator is the inter carrier interference that is the interference power plus the wide Gaussian noise power, alright? So, as you can see the interference power adds to the noise power, which results in the net degradation in the SNR.

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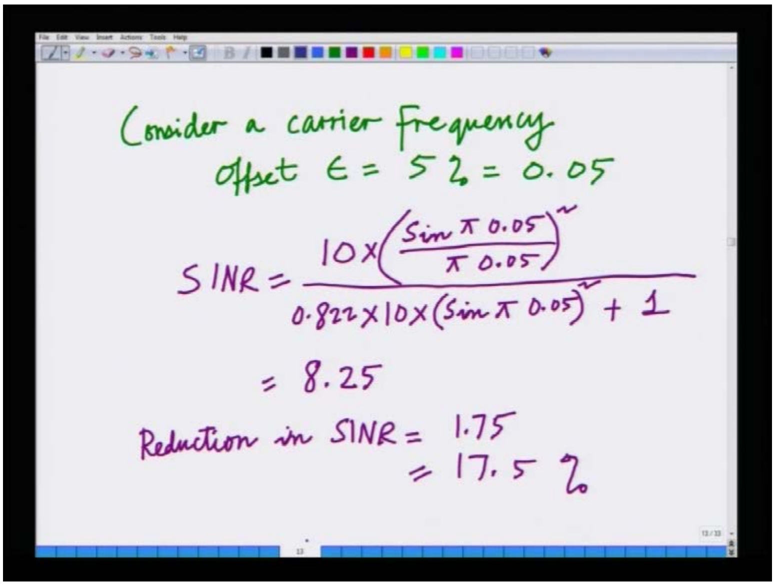

In fact we had looked at an example. And we had said for a simple case with about a 5 percent carrier frequency offset the reduction in SNR is close to about 17.5 percent.

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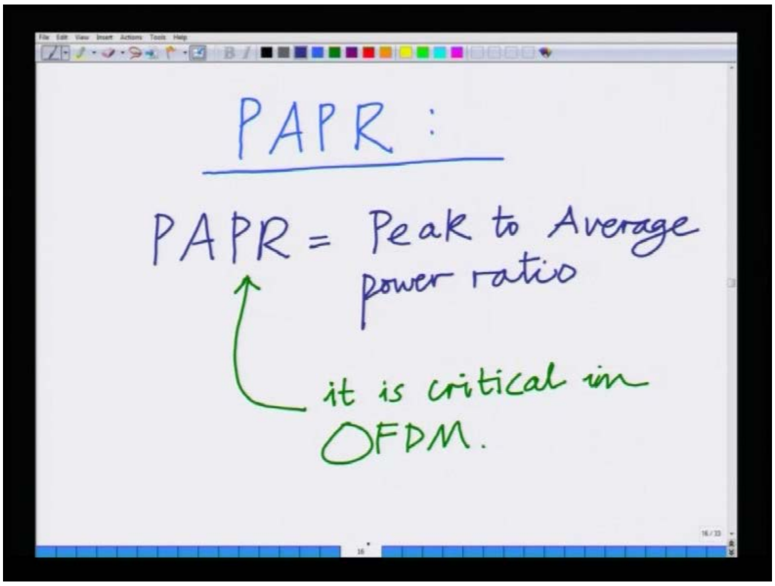

And then we had started looking at the PAPR issue that is the peak to amplitude power ratio in this OFDM system.

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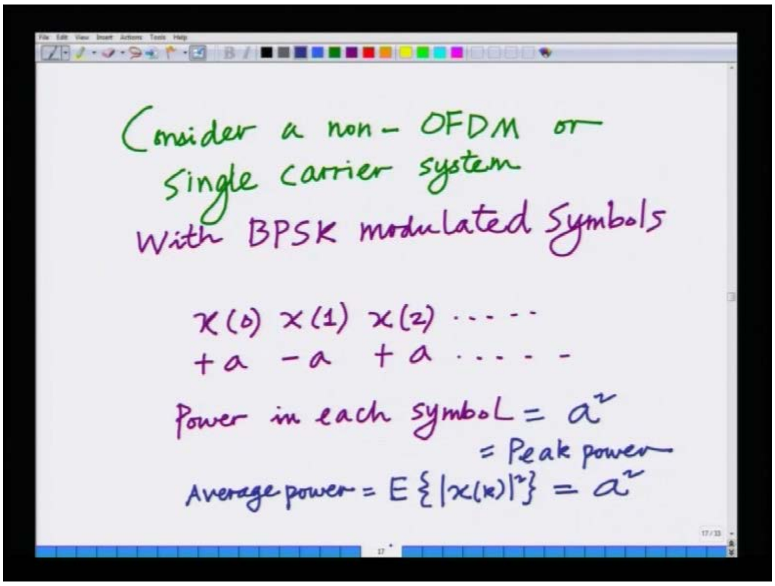

All right, we said PAPR stands for peak to amplitude power ratio and we started looking at a PAPR of a conventional single carrier system where with BPSK and amplitude level a, we said the average power across symbols is a square the peak power is a square because each symbol is plus or minus a.

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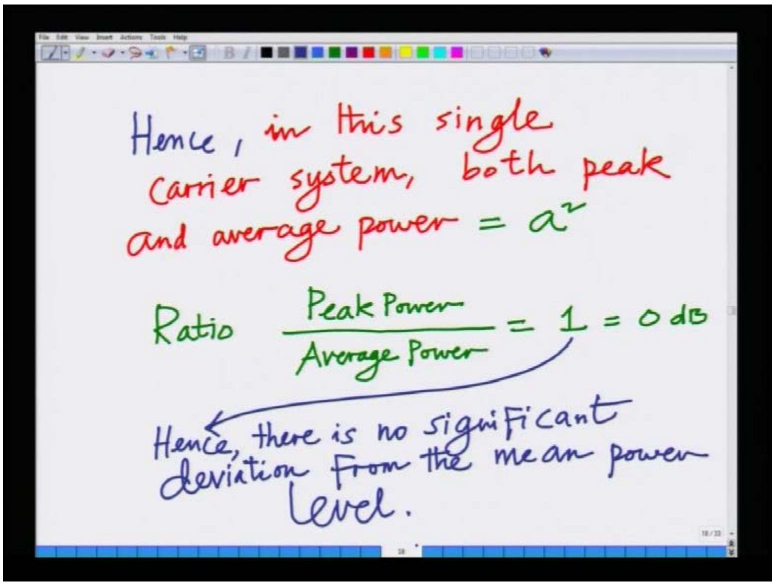

Hence, the peak average power ratio is a square divided by a square which is close to which is one practically in practical systems it is close to 1 and its essentially 0 d B. Hence, there is not a significant deviation of the power of the instantaneous power level over the average power. Hence, we are able to say is the swing is not very large over the mean power level. Now, we want to carry forward this discussion and look at how the peak to average power ratio looks in an OFDM system. Remember this is the PAPR peak to average power ratio in a conventional single carrier system how does it look in an OFDM system? That is what we want to look at next.

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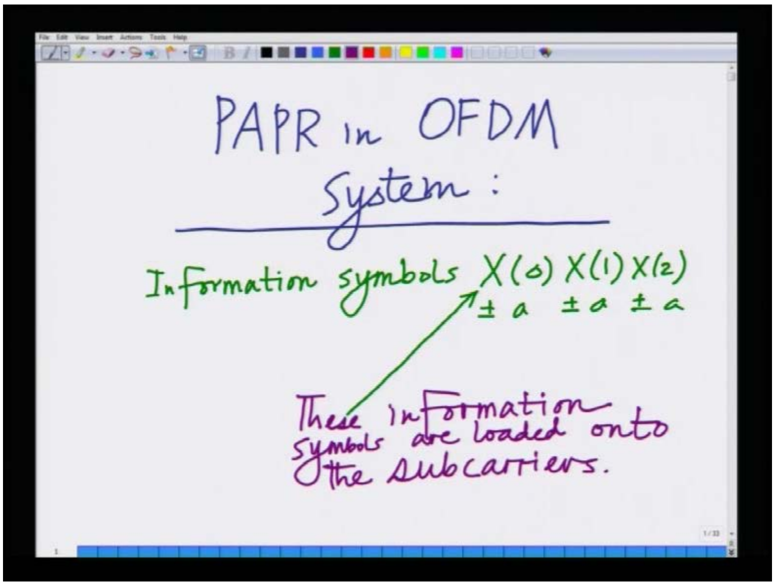

So, right now we want to start by looking at a PAPR of an OFDM system. So, consider so PAPR so PAPR in OFDM system. Now, in OFDM remember we are not transmitting the symbols as it is, but we are loading the symbols onto the subcarriers and then we are taking the IFFT of these symbols before transmitting these symbols. So, we are considering the IFFT with these symbols, all right?

So, in an OFDM system the information symbols X 0, X 0, X 1, X 2, let the information symbols be given as some plus or minus a, plus or minus a, plus or minus a and so on. Now, these information symbols are actually loaded on to the subcarrier symbols sub carriers. So, this information to these information symbols are loaded on to these information symbols they are loaded on to the subcarriers, all right? Hence, the transmitter symbols are X 0, X 1, small x 0, small x 1, up to small x n minus 1, which are actually the IFFT samples of these information symbols.

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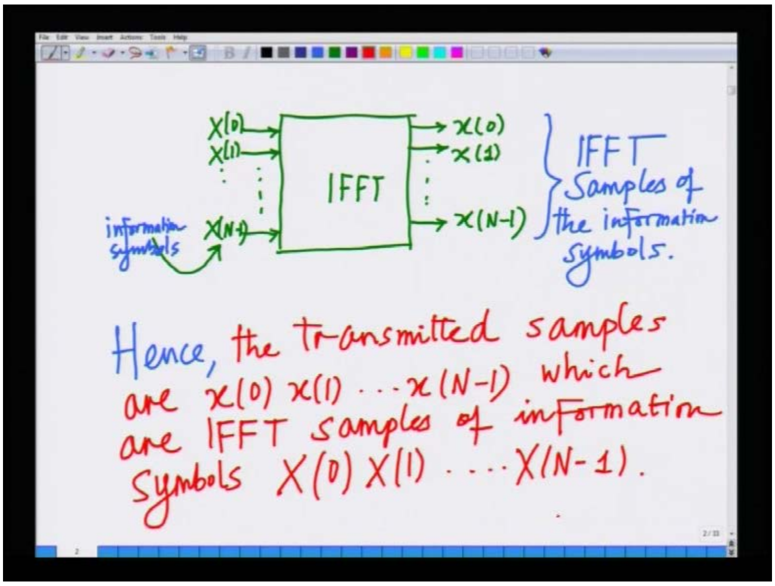

So, what are we doing? We are taking these information symbols, which is we are taking these remember in an OFDM. We are taking these symbols X 0, X 1 up to X N minus 1 and we are performing an IFFT on these symbols to yield the small x 0 small x 1 up to x n minus 1. So, we are taking this capital X which are loaded onto the subcarriers forming these IFFT samples. So, these are the information symbols and these are the IFFT samples of the information and these are the IFFT samples of the information symbols. Hence, the transmitted samples are this x small x 0, x 1, x n minus 1, which are the IFFT of capital X 0 X 1 X N minus 1.

Hence, the transmitted or the transmitter samples are X 0, X 1 up to X N minus 1, which are the IFFT of the information symbols or which are the IFFT samples of information symbols. IFFT samples of information symbols capital X 0 capital X 1. So, in OFDM as we are very well familiar we are not directly transmitting the information symbols, but before transmitting the information symbols we are performing an IFFT operation over these information symbols and we are then transmitting the IFFT samples, all right? So, this is what we already know about an OFDM system that is in the sense that we are not transmitting the symbols themselves, but we are taking in IFFT operation before transmitting the symbols.

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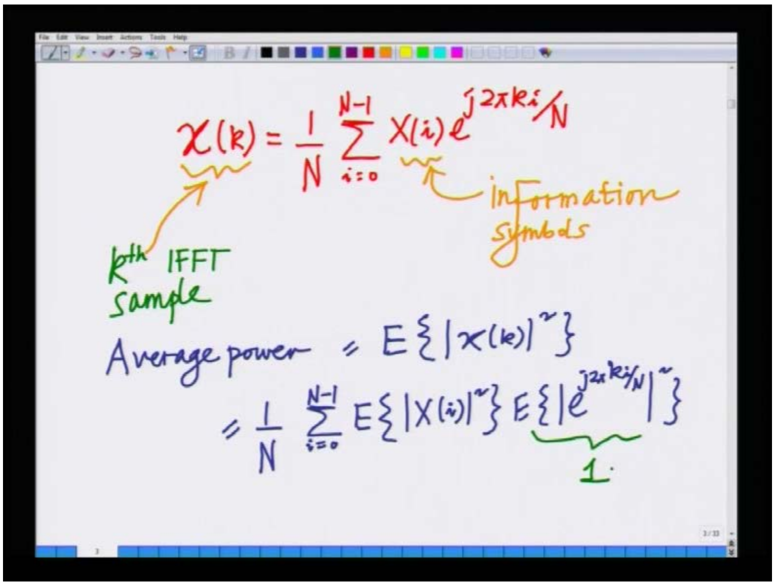

Hence, the symbols are given as the x or the samples are given as the k th sample is given as summation 1 over N, which is essentially the IFFT the n point IFFT I equals 0 to N minus 1 X i e to the power of J 2 pi k i over N. So, this these are the information symbols and this is the k th IFFT sample. These are the information symbols and this is the k th IFFT sample. The average power is given as now. So, now what we want to see we want to characterize what is the mean to average power? That is the peak to average power ratio of these transmitted samples, because we are not directly transmitting the information symbols. So, we want to characterize what is the peak to average power characteristic of whatever is being transmitted on the medium how does that how does that look like that is what we are essentially interested in characterizing.

So, let us look at the average power of this thing, what is the average power? What is the average power the average power is nothing but expected magnitude x k square that is nothing but 1 over N square summation I equal O to N minus 1 expected. Magnitude X i square from the above into expected magnitude e power J 2 pi k i by N whole square. Now, we know that expected magnitude, this is simply a face factor that is expected that is e power J 2 pi k i by N. Simply a face factor expected magnitude e power J 2 pi k by N square is in fact this is 1. Hence, this is nothing but expected magnitude x k square.

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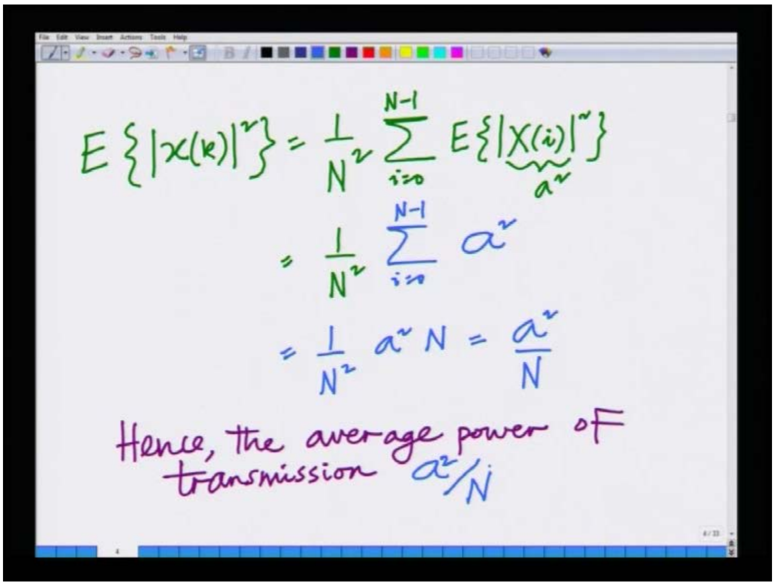

It is nothing but 1 over N square summation i equals 0 to N minus 1 expected magnitude x i square. This is nothing but remember, each x i square in fact each x i is an information symbol that is plus or minus a. Since, x expect x i magnitude x i square is nothing but a square. Hence, this is nothing but 1 over n square sigma i equal 0 to N minus 1 into a square, which is 1 over N square into a square into N equals a square over N.

Hence, the average power hence, the average power of transmission, hence the average transmission power in this system is a square divided by N that is the average power. But how does the peak power look like in this system? How does the peak power look like in this system? In fact what we are going to find is that the peak power can be significantly higher. Let us look at the peak power in this system for instance. Let us look at every sample. Let us look at, let us look at one specific sample.

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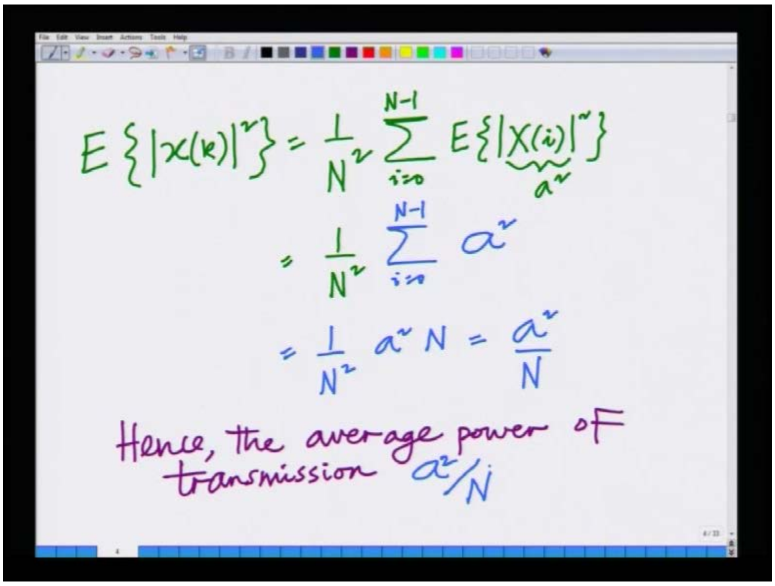

Let us look at the 0 th IFFT sample, which is 1 over N summation i equal 0 to N minus 1 X i e power J 2 pi i times 0 divided by N because we are looking at the 0 th sample, which is nothing but 1 over N summation i equals 0 to N minus i equal to 0 to N minus one summation of X I, all right? This is sort of this is essentially the component at the transmitted sample transmitter corresponding to time 0. Now, let us consider case in which all x i's are actually equal to each x i is plus or minus a probability half.

Let us consider a scenario to characterize the peak where all x i is are actually equal to and the same sign and are equal to plus a. So, X so let us consider a scenario or X 0 equals X 1 equals so on equals X N minus 1 equal plus a and then what do we find we find that x 0 in that case the small x 0 equals 1 by N summation i equals 0 to N minus 1 X i is actually 1 over N summation i equals 0 to N minus 1 of a, which is actually a. Hence, the peak power or the instantaneous power equals a square. Now, let us look at the result below before it says the average power is a square over N.

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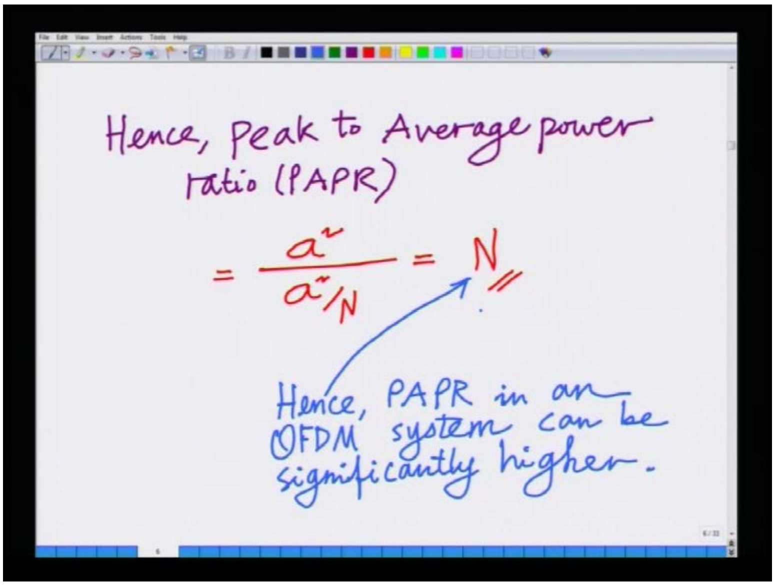

The peak power is a square hence, the peak to average power ratio hence, peak to average power ratio hence, the peak to power average power ratio PAPR is nothing but a square divided by a square divided by N, which is equal to N. Hence, this means, that the peak to average power ratio remember in a single carrier system it is close to 1 in an OFDM system is very high or very high because remember end number of subcarriers can be as high as 1024, which is there is significant deviation of the instantaneous power or the peak power about the mean. Hence, hence PAPR in an OFDM system can be hence the PAPR of an OFDM system can be significantly higher that is there is a significant swing of the instantaneous power or the peak power with respect to the mean power. Hence, there is a significant swing of the instantaneous power with respect to the peak power.

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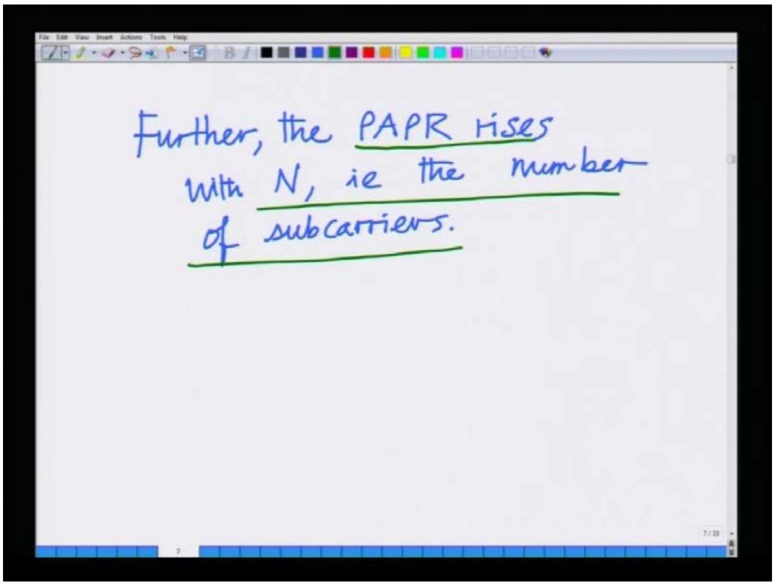

Further what we observe here is interesting; it says that this peak to average power ratio with this rises with N, which is the number of subcarriers hence the peak to average power hence or further the PAPR raises with N that is the number of… Hence, the PAPR raises with the a capital N, which is the number of subcarriers in this is a key observation, which is the PAPR increases as the number of subcarriers increases.

This is a problem, which is a high deviation of the peak. Why is this raising? Why is this high PAPR or why is this high deviation of this peak power with respect to average power rising that is arising? Because, of the IFFT preprocessing, normally in a single carrier system there is no preprocessing however in OFDM because of this IFFT preprocessing we are actually enhancing the instantaneous swing of this transmitted symbols over the average level.

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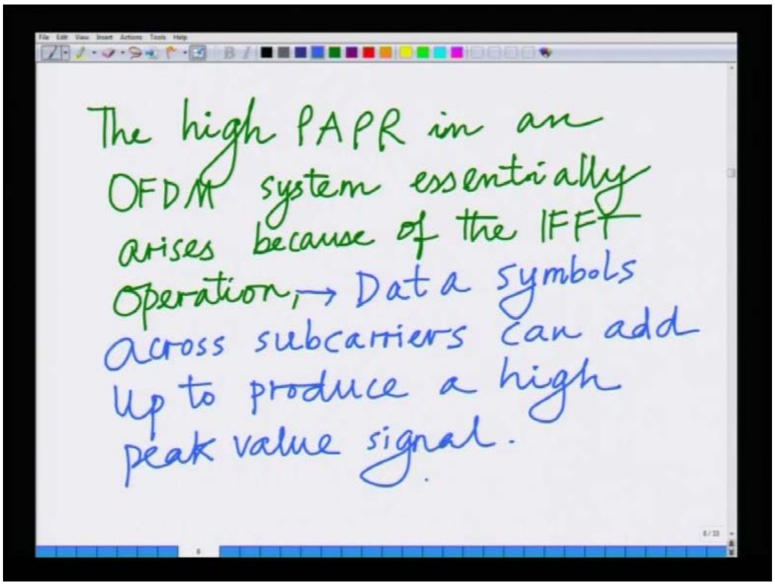

Hence, the high PAPR the high PAPR in an OFDM in an OFDM system essentially arises essentially arises because of the IFFT operation because of the IFFT operation. Where the data symbols across different subcarriers can add up to produce a high peak value signal this arises. Because, data symbols across subcarriers can add up to produce a high peak value signal. So, the PAPR is essentially arising out of the IFFT operation in OFDM and why it is arising because remember these different symbols loaded on to the subcarriers are random. And depending on their nature they can occasionally all add up across the sub carriers to produce a high peak value that give raise to a very high instantaneous swing with respect to that normal mean value.

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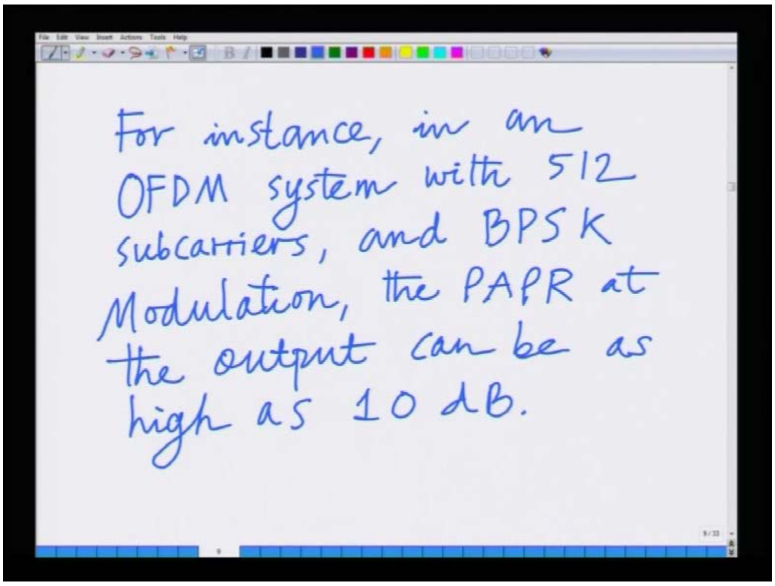

For instance and for instance in an OFDM system with about 512 subcarriers and BPSK modulation, this swing can be as high as 10 dB for instance in an OFDM system. For instance in an OFDM system with 512 subcarriers and BPSK modulation and BPSK modulation. The PAPR of the output can be as high as 10 dB for the instance in an OFDM system with 500 about five 512 subcarriers.

BPSK the PAPR system can be as high as 10 dB that is 10 times peak power compared to the average mean by which means, a significant deviation of the peak with respect to the average value. How do we represent a PAPR? How do we characterize the PAPR comprehensively? We characterize that PAPR of a system using the CCDF function or the cumulate complimentary cumulative distribution function.

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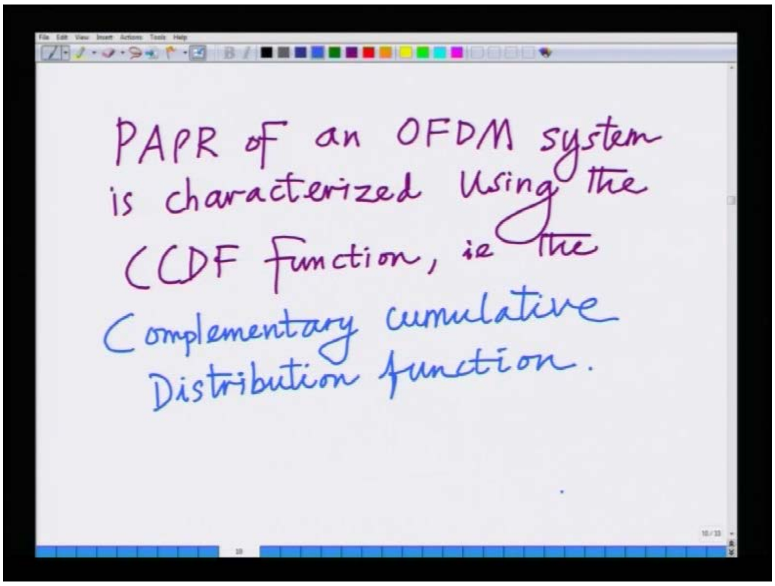

Hence, the PAPR of an OFDM characterized using the CCDF. The CCDF system is function that is the complementary cumulative distribution function that is that is the complimentary complementary cumulative this is characterized using the complementary cumulative distribution function. What is the complementary cumulative distribution function?

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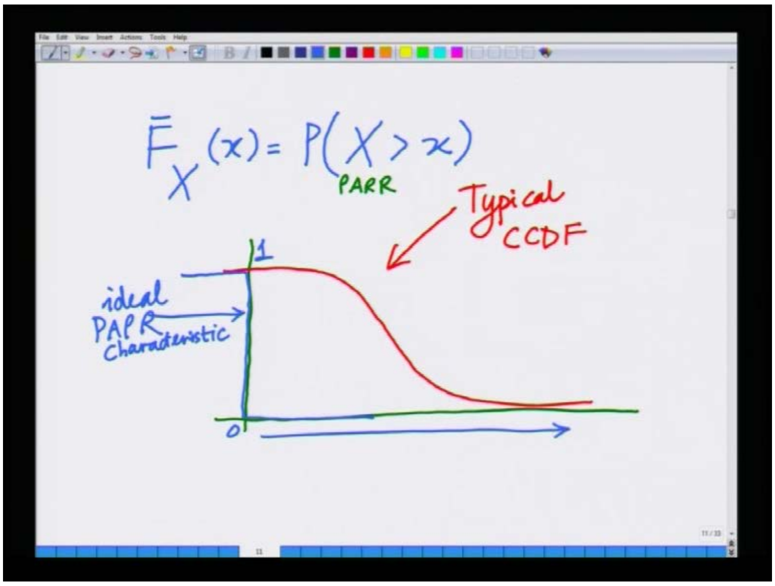

Let us consider a random variable X, the CCDF which is denoted by F bar X of F of x is simply the probability that X, which is the random variable in this case we can consider it PAPR X is greater than this value small x. That is this x can be this random variable which is essentially the PAPR remember because the symbols are random. So, the instantaneous power or the peak power is random for a group of symbols is random depending on the combination of symbols. Hence, it is the random variable it is best characterized by a distribution function. Here we are using the complementary cumulative distribution function, you might be familiar with the cumulative distribution function, which is essentially the probability that x is less than capital X and that starts from a 0 and goes to 1 from the properties of random variable.

The CCDF on the other hand is simply 1 minus the CCDF, which is the probability that x is greater than capital X and that starts from 1 and slowly goes down to 0. That is for higher values of a higher values the probability that random variable is greater than larger values is progressively smaller. So, the CCDF if you plot the CCDF a typical CCDF looks like this. So, this is a this is a typical CCDF it is starts at 1 and progressively of course, it goes down to 0, all right? So, it starts at 1 is progressively goes down to 0 and that is the probability that x is greater than x.

In odd case, what is the probability that PAPR is greater than at certain threshold? So, that characterizes and we want this curve to progressively be towards the that is we want the PAPR to be as close to 0 dB as possible that is ideally we would want this PAPR to look like this, this is the ideal PAPR characteristic of in fact of single carrier system. That is PAPR is exactly 0 dB that is property if the probability 1 it is a less than 0 dB and with probability 0. It is greater than 0 dB that is its always exactly 0 dB, that is what we want the ideal, but in practice especially in OFDM systems, we see that it has a high PAPR value, which significantly deviates from the 0 d b a 0 d b a ideal desired characteristic of PAPR value.

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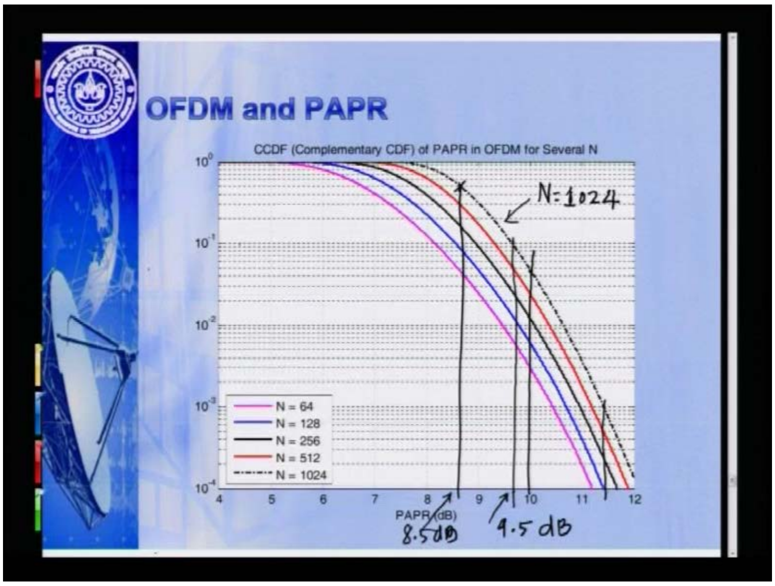

For instance this plot here it shows the PAPR of OFDM systems for several different sub carriers that is the PAPR for N equals 64 for N equals 128 N equals 256 and so on. As we see the number of sub carriers increases the PAPR gradually increases. The way to read this plot is as follows; for instance let us say we want to find the PAPR corresponding to N equals 1024 sub carriers and I want to do it for a level corresponding to 9.5 d b. For instance here I draw this line at 9.5 d b approximately 9.5 db, what we see is the probability that the PAPR with N equals 1024, the probability that the PAPR is greater than 9.5 d b with N equals 1024 sub carriers its 10 power minus 1.

That is 0.1 or 10 percent probability that the PAPR is greater than 9.5 d b. Similarly, the probability that the PAPR is greater than 11.5 d b is 10 to the power of minus 3 or 0.1 percent, so on and so forth. So, given a number of sub carriers what you can find from this is, what is the probability that the p a p r is greater than a certain threshold in fact the further this curve is to the right, the higher the PAPR is all right? In fact, if you want to look at what the average PAPR is all you have to do is you have to look at the 50 percent point that is for you would look at this point here.

For the for the N equals 1024 and you will see that the PAPR is 10 d b that is 50 percent probability with 50 percent probability. This is the median with 50 percent probability the PAPR is actually the PAPR is actually greater. I am sorry, this is not the 50 percent point, the 50 percent point is the 50 percent point. It says with 50 percent probability, the PAPR this is roughly. Let us say 8.5 d b, it says that with 50 percent probability the PAPR is actually greater than 8.5 d b, all right? So, that is the median point for this a PAPR distribution, which can be obtained from the PAPR CCDF function. So, that is the importance of the CCDF of this PAPR function. So, coming back to our PAPR discussion, now let us highlight, let us talk about why this PAPR is such an important quantity in OFDM system?

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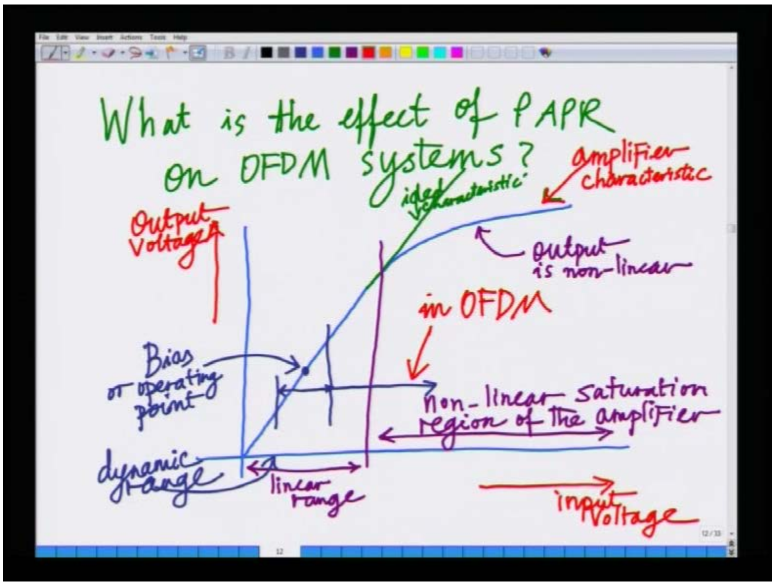

What is the problem with PAPR, what is the problem caused by PAPR? That is what we want to understand, what is the what is the effect effect of PAPR on OFDM? What is the effect of this PAPR or OFDM system? For that we have to understand a little bit about what is the characteristic of these different devices in the transceiver? If you look at specifically, if you want if you want to look at the amplifier every amplifier has what is known as an amplifier characteristic.

So, if you have an amplifier, it looks as like amplifier characteristic, which shows with respect to the input voltage. What is the output voltage? So, with respect to so this in the this is the amplifier characteristic, if you want to look at amplifier every amplifier. This is the amplifier characteristic, this is the input voltage and this is the output and this is the output voltage. Now, remember the amplifier, the ideal amplifier characteristic looks something like this. The ideal amplifier characteristic ideal characteristic looks something like this.

This is the ideal we just no matter what input voltage we provide, the output voltage is a scaled version of the input voltage. That is its amplified and a scaled version of the input voltage, no matter what input voltage you provide, but in practice typically the linear characteristic this is what is known as the linear region. The linear amplifying region, this is the linear range. The linear amplification range of any device exists only over a certain voltage range, if the input is larger than that voltage rate.

What happens is the output is no longer linear, but the output is non-linear. We say the this region that the amplifier is saturated this is known as the non-linear or the saturation region of the amplifier. This is the non-linear this is the non-linear saturation region of the amplifier. Now, typically our amplifiers or typically the amplifiers in systems are biased around a certain operating point. This is the biased or it is biased roughly in the middle of the linear range, which is also known as the dynamic range. This is also known as the dynamic range of this amplifier.

Now, as long as the signal swing is limited to this dynamic range or those things or linear range, the input and output are linearly related. That is around this mean if the deviation is not extremely large, but around this mean if the deviation of the voltage is small, then the signal is still confined to the linear amplification range singular to an SCFDMA system. However, because in an OFDMA system, the peak can swing very, the swing of the instantaneous power can be very high compared to the mean this crosses over into the non-linear range this is in OFDM.

The problem in OFDMA system is because we have non ideal amplifiers in practice, which have a limited linear amplification range and the swing of the peak power can be very high compared to the mean it crosses over in to the non-linear range in which the amplification is non-linear. Once the amplification is non-linear all the properties of OFDM seize to hold that is orthogonality is lost there is going to be severe inter carrier interference and so on and so forth.

So, once the non orthogonality aspect of this amplifier essentially comes in because of the high swing in the high swing in the peak power over the mean power it cross the amplifier crosses over in to the saturation region. Hence, the output is no longer linearly related to the input which means OFDM properties sieze to hold, which means the orthogonality is lost similar to an carrier frequency offset. You essentially have that is similar to the distortion there the orthogonality is lost.

So, we have interference and this interference in fact increases with the effect of nonlinearity increases as the peak distortion because as the peak swing increases it crosses over more and more into the saturation region, which means significant distortion significant inter carrier interference, which means again significant problems at the OFDM, OFDM receiver because there is a loss in the signal to noise power ratio.

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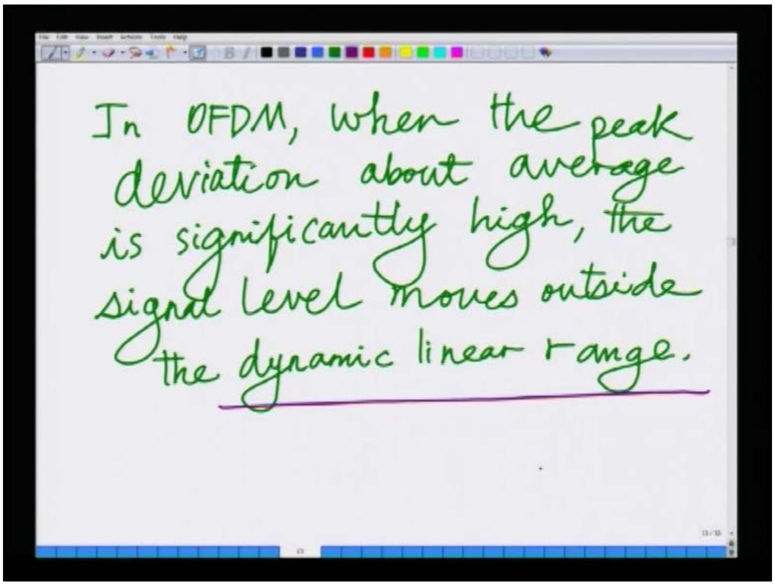

Hence, what we can say is if the peak deviation in OFDM when the peak deviation when the peak deviation about average is significantly high, the signal level moves outside of the dynamic linear range. Hence, when the peak deviation is high the signal level crosses over into the non-linear or the saturation range of the amplifier. Hence, once the signal moves into the non-linear range the amplification a the amplification becomes becomes non-linear resulting distortion and inter carrier interference and high PAPR in OFDM system.

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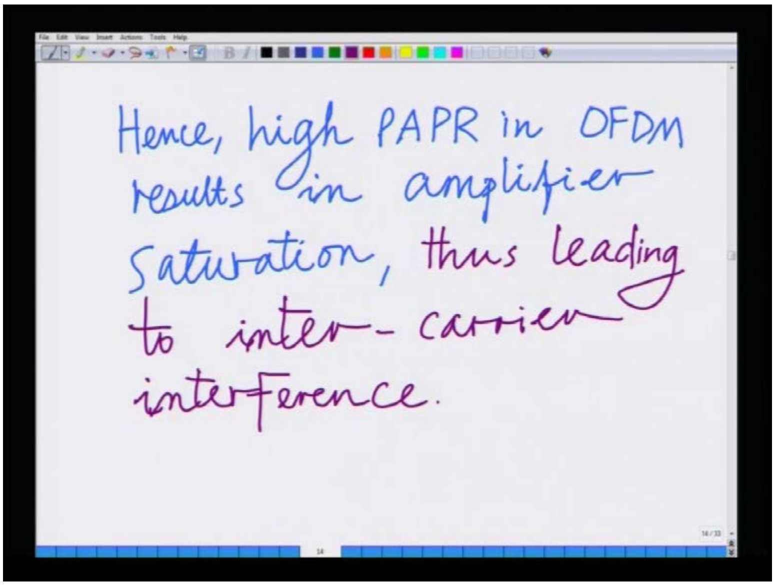

Hence, high PAPR in OFDM results in amplifier saturation, in amplifier saturation results in amplifier saturation leading to non-linearity and essentially distortion and inter carrier interference leading, thus leading to inter carrier interference, thus it leads to inter carrier interference because essentially it results in loss of orthogonality. The non-linearity, let us say loss of orthogonality, which results in which leads to inter carrier interference. Now, we want to see issues or we want to see solutions to tackle this problem of PAPR, so the main issue we want to address next is to tackle that is how to tackle the PAPR problem and for this specifically to tackle PAPR a new technique or is proposed this is termed as SCFDMA.

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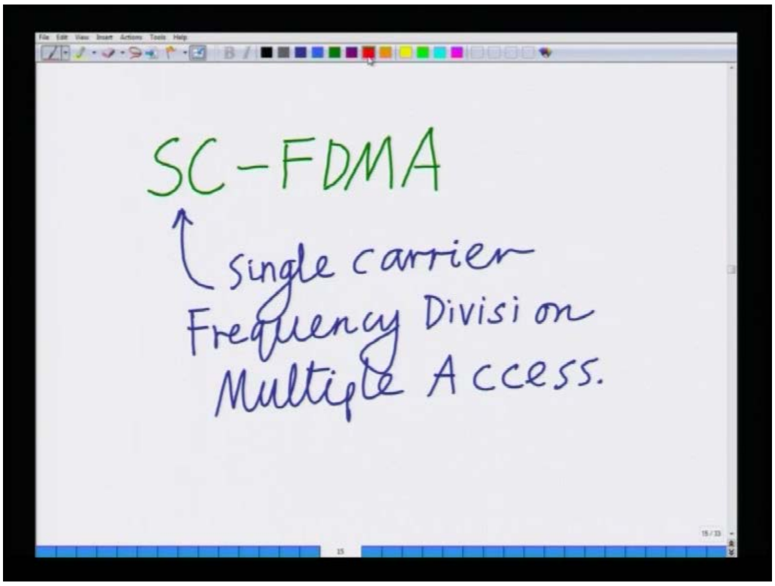

So, SC-FDMA is a variant of OFDM, it stands for single carrier frequency division multiple access.

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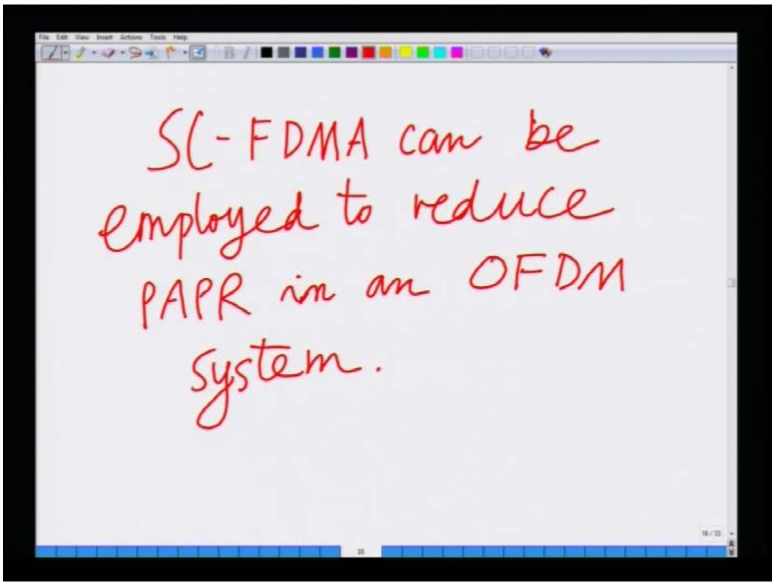

SC stands for single carrier, FDMA stands for frequency division multiple. SCFDMA stands for single carrier frequency division for multiple access and we say that an SCFDMA can be employed to combat PAPR or reduce PAPR. So, SCFDMA can be employed to reduce PAPR in an OFDM. So, SCFDMA employed to reduce PAPR in an OFDM system, all right? So, SCFDMA is that technology, which is a single carrier frequency division for multiple access technology, which is in fact employed in 4G.

It is employed in LTE that is long term evolution, which is a 4G wireless standard. In fact it is employed in LTE to reduce to specifically for this problem of PAPR to address this high peak to amplitude power ratio, to solve this high peak to power aptitude power ratio in OFDM, which otherwise needs to amplifier saturation and non-linearity and distortion in inter carrier interference in OFDM. So, to understand SCFDMA, let us go back and let us again take a look at how a typical OFDM transmitter looks like, all right?

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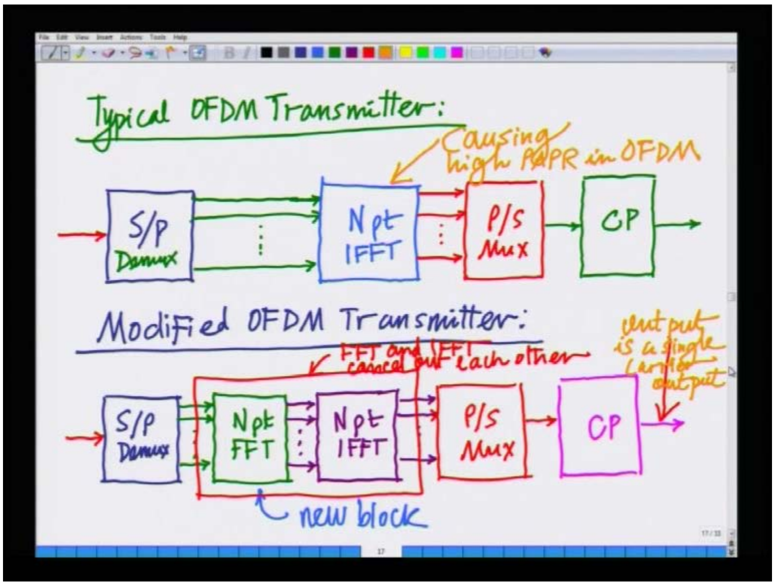

So, typical OFDM transmitter that is, how does the typical OFDM transmitter look the typical OFDM transmitter has a serial to parallel demux and followed by it has a serial to parallel demux operation followed by an N point IFFT. Then what we have is we have a parallel, we have a parallel to serial muxs operation or a multiplexing operation. Then we have the addition of the cyclic prefix as usual. Then we have the addition of the cyclic prefix this is the typical OFDM transmitter.

So, this is the serial to parallel this is a de multiplexing operation that is you make a block of signals you take the N point FFT, you take the parallel to serial you take the cyclic prefix and this we are saying the N point IFFT is creating a problem because this results in the signal here having high PAPR. So, this N point IFFT. This is essentially causing the this is essentially causing the high PAPR in OFDM. This N point IFFT inverse force for a transformer operation essentially causing the high PAPR, this is essentially causing the high PAPR in OFDM. We said this is a problem so to solve this, we slightly modify the OFDM transmitter as follows.

So, the modified OFDM transmitter is follows, the modified OFDM transmitter is as follows that will be the same as above, that is first we take a block of symbols that is we perform the serial to parallel de multiplexing operation. Then we perform then we perform the n point FF, then we perform the N point FFT here that is before performing the IFFT. We perform an N point FFTI, will explain the logic for this shortly. Then now we give this the rest is same as before that is now we perform the N point IFFT, we perform the N point IFFT and then we perform the, then we perform the parallel to serial multiplexing operation.

Then we add the cyclic prefix as usual and then we transmit. So, this block here this is the N point IFFT, which is the new block or which is the change with respect to the previous OFDM transmitter. Now, look at what is happening here? If we look at the N point IIFT and if you look at N point FFT and if we look at the N point IFFT I am taking the N point FFT followed by the N point IFFT, which means the both are inverses of each other, they cancel out. So, this is the cancellation effect the can FFT and IFFT cancel out.

So, the FFT and IFFT they actually they cancel out each other, which means whatever is serial symbols that you input are the same symbols that are coming at the output except for the addition of cyclic prefix. So, this looks like the same single carrier so the output here is essentially a single carrier output. So, output so output is a single carrier output, which means the PAPR is close to 0 d b or PAPR is close to 1 or 0 d b, all right? So, by introducing this n point IFFT block, you are now essentially reducing this OFDM system to the earlier single carrier system, all right?

So, to reduce the PAPR what can be done is an FFT operation can be introduced here. However, single carrier systems of course, as we said again we come back to the same issue, which is how to solve the inter symbol interference problem in this single carrier system. Hence, what we do is as a trade of we don’t perform here an exactly N point FFT, but some M point FFT where M is slightly smaller than N, so as to still not move completely towards a single carrier system, but retains some properties of OFDM as well as reduce PAPR. So, a achieve a trade of what can be done is by using N FFT.

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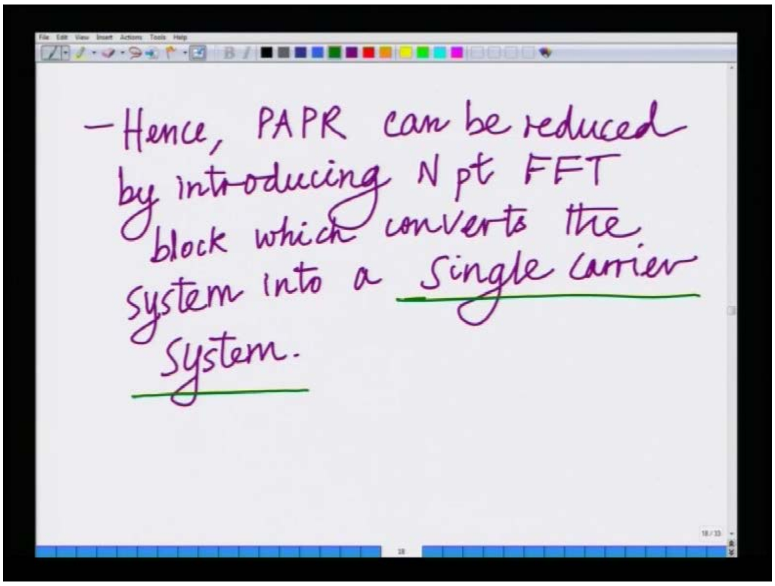

Hence, what we realize is hence PAPR can be reduced can be reduced by introducing can be reduced by introducing the N point FFT block, which converts the system FFT block, which converts the system into a. So, the PAPR can be reduced by introducing a N point FFTblock, which converts the system into a single carrier. It converts the system into a single carrier system. However, we do not want to completely move towards the single carrier system, but we want to retain the properties OFDM also.

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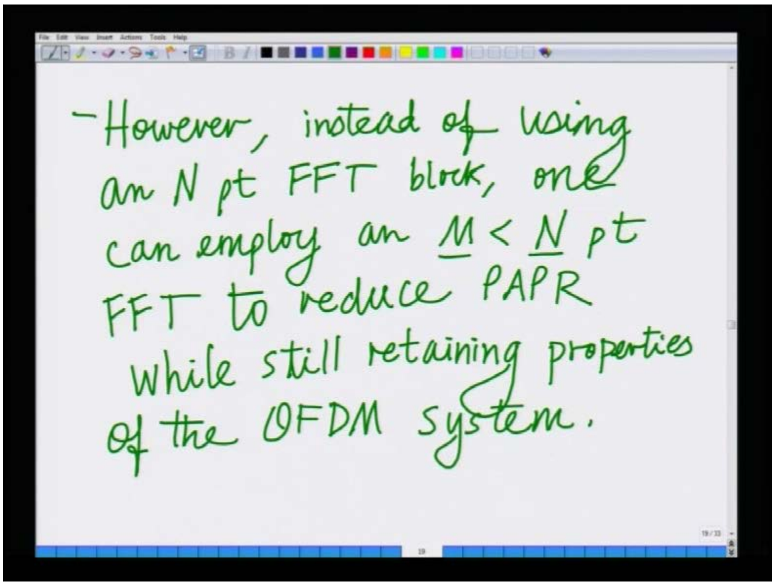

Hence, instead of M we will use an N, slightly which is significantly less than M point FFT. So, as to reduce the PAPR at the same time retain the properties of an OFDM system. However, instead of using an N point FFT block one can employ an M less than N point FFT to reduce PAPR, while not while still retaining properties of the OFDM system. So, M is less than N that is the key M less than N. Point FFT to reduce PAPR, while remember OFDM is very important to tackle inter symbol interference. That is inter symbol interference in these frequencies of the OFDM system.

So, we want to do an FFT to reduce the PAPR, but we still do not want to do a complete N point FFT because that will move again towards single carrier system introducing the inter symbol interference. So, we want to trade off between these two so we are going to do an M point FFt, which is where M is significantly less than N. So, what is the proposed architecture? Now, you want to look at in detail the actual proposed architecture that is what is, so how does the proposed architecture? How does the SCFDSMA transceiver transmitter schematic look like?

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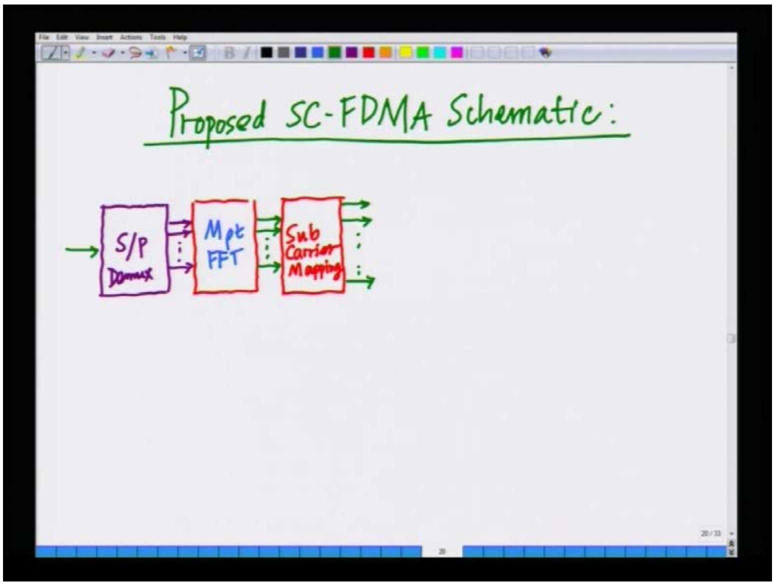

So, we want to look at the proposed SCFDMA? How does the proposed SCFDMA schematic looks as follows? That is I have a serial to parallel, again this is the demux operation that we had earlier when we form a block of symbols. Now, instead of directly doing the 50 here here, we have some M. So, we have a smaller number of symbols, so here we are going to do now an… So, we are going to take only M symbols instead of N, so here we are going to do

N M point now. After we do this M point FFT, we are going to map these M symbols to N subcarriers.

So, we are going to map these M symbols to N. So, we are going to do a subcarrier mapping. So, we are going to do a subcarrier mapping and now out of this sub carrier mapping here at this point, we still have this is M symbols. Now, after we do the sub carrier mapping, now here we have N symbols. So, we do M point, we take M symbols we do an N M point FFT. Then we map to capital N sub carriers, remember we said M is much less than N, all right? So, due to lack of time, I will stop here at this point and we will continue again in the next lecture and complete this SCFDMA transmitter schematic.

Thank you very much.