Evolution of Air Interface towards 5G
Prof. Suvra Sekhar Das
G. S. Sanyal School of Telecommunications
Indian Institute of Technology, Kharagpur

Lecture - 19
Waveform for 4G & 5G (OFDM) (A)

Welcome to the lectures on Evolution of Air Interface towards 5G. So, we are at present at the middle of a very important analysis or wave from discussion, which is OFDM which we had started in the previous lecture. And this is very very important I would always say that its very critical to understand this, because when we go into 5G we will not discuss the details of it will be only using the parameterization. So, it is essential that we understand as much detail as possible for this particular structure.

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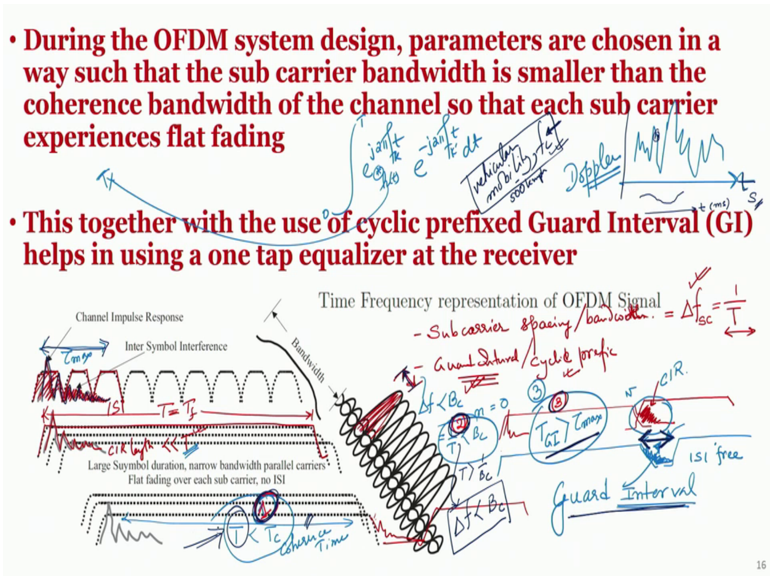

So, what we were discussing in the previous lecture was about the, resilience towards multi path and some of the parameters that are of interest. So, we were talking about the three important parameters as we have pointed out here. So, we have actually identified this number 1 over here, and that is the time interval for the OFDM symbol should be less than the coherence time. We will discuss the coherence time and the 1 upon T or in other words T should be greater than 1 upon B c which is other way of looking at it.

So, it is basically the sub carrier bandwidth 1 upon T is effectively the delta f must be less than the coherence bandwidth. So, this is the point number 2 that is what we were discussing yesterday. So, the sub carrier spacing should be less than coherence bandwidth or this sub carrier bandwidth is less than the coherence; bandwidth means that, each sub carrier experiences is a flat fading. That is what we were discussing here that, this width should be less than the coherence bandwidth ok. We will understand coherence bandwidth later on, but as of now we briefly given an explanation that there is fluctuation in time sorry there is a impulse response, which causes of fluctuation in the frequency resulting in frequencies electric fading.

And the other thing is that the guard interval which we are discussing in the previous lecture, that is the interval that is necessary for separation between two consecutive OFDM symbols, which is the guard interval that is what is written over here. So, this guard interval should be greater than the tau max, which is the maximum access delay of the channel. The maximum excess delay of the channel has been pointed out over here which is the maximum length of the extension of the channel impulse response right. So, these three things we must remember and we said why these are critical, because this coherence time comes from Doppler; we have talked about Doppler over here. So, signal strength fluctuating with time. So, we would like that over the duration of our consideration all that appears very very small in this particular diagram.

But this is an order of seconds and when we are these I mean seeing it with higher resolution. So, we would see that the signal that the channel is fluctuating something like this. In this scale this is the time axis and this may be in milliseconds or microseconds and we will see that with the parameters of interest that this time in duration is in the order of microseconds. So, when that is in the order of microseconds, when these fluctuations appear so, much changing in order of seconds, in order of microseconds, they almost remain constant.

So, but however, when Doppler becomes very high and effective Doppler, a Doppler is basically due to mobility. So, you have vehicular mobility, we will look at the exact expression and the carrier frequency both influence the Doppler of course, the angle at which the signal is arriving at the receiver is also important. So, as the carrier frequency increases right we have discussed in the fifth generation millimeter wave is one of the bands and also higher frequencies towards 6 gigahertz are also being contemplated. So, there even under same mobility condition, a higher frequency causes increasing Doppler.

We have also seen that 5G requires to support 500 kmph kilometers per hour so; that means, the mobility support also increases hence Doppler is a critical factor.

So, under very very high mobility conditions are very high Doppler conditions, these constraints become important ok.

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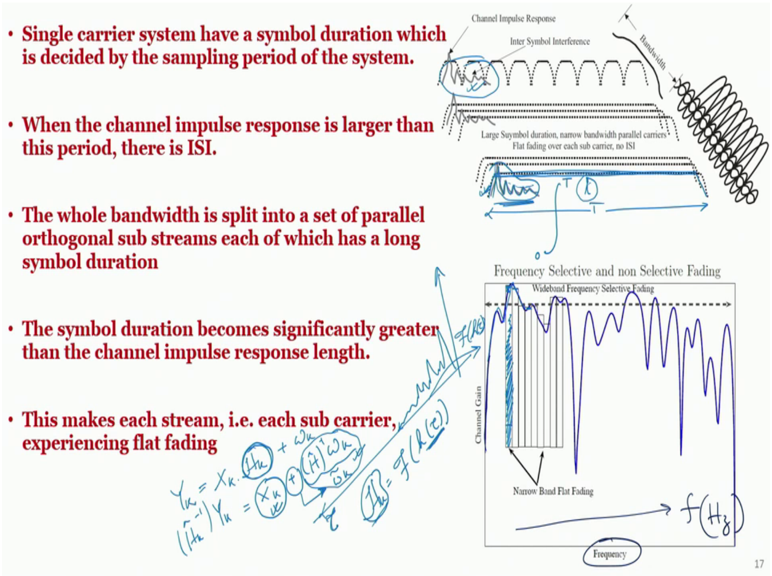

So, this in this particular picture we have carried forward whatever we have been discussing earlier. So, here we have the frequency domain picture. So, we have the frequency axis. So, this is the f axis in hertz or megahertz or whatever is the unit one wants to use. And this bluish line that we have over here indicates the fluctuation of the channel with respect to frequency. So, this fluck this changes and this is because if this is your delay axis or the time axis and this is your signal gain axis.

So, the channel impulse response if it appears in this manner, then if you do a Fourier transform of this of h of tau and you take the magnitude of it mod squared of it, you would get fluctuation in the frequency domain which looks like this. We have discussed this earlier and each of these units which is the sub carrier bandwidth we can say; they should be small enough so, that each encounters nearly flat fading condition. So, this pictorially depicts what is going on and it is kind of flat fading situation.

So, effectively when we look at the time domain has given over here, the signal as if sees a single equivalent path. Because all of these paths get added up together by virtue of match filtering because, we have said that the receiver processing will do an integration from 0 to T. So, T is this duration. So, if this is the duration of T, then all these values get accumulated right they of course, get accumulated by multiplying with the pulse shape. But, here again we have said that in the interval of T that is a for consideration for OFDM, this remains a rectangular pulse hence it is a constant value.

So, effectively all these paths get added up together. So, they add up to form an equivalent impulse or equivalent sample value of a particular phase. So, if it is a single equivalent delay that would result in a flat fading across a sub carrier. So, each sub carrier sees a single equivalent path and hence it resolves it or it sees it into a flat feeding channel for that particular path. So now, if we take one sub carrier at a time in that case at the receiver side we are we will see that that X of k gets multiplied by H of k this expression also will see in due time, that effectively this is the flat fading equivalent of the channel.

So, you are received signal structure would look like this in the frequency domain. And hence, since this is a scalar equalization is very simple, one of the most elementary equalization would be to if I know H let us say H cap, I could take an inverse of it and multiply with Y cap I will be left with X cap the desired signal plus H gap inverse W k; that means, there is some process to noise, this can be considered as process noise and this is the desired single.

So, as if the signal is corrupted only by noise by additive noise and the noise is of a certain variance. Now, H again we will see later on that H cap is basically the Fourier transform of h tau what we are talking about here and this particular channel impulse response is under most of the circumstances that we will consider would be 0 mean giving raise, I mean in non-line of sight conditions validating conditions. So, if this is 0 mean, then the mean of the process noise is also 0 as well as what happens is only the sigma value of noise gets changed. So, this results in only a change in the noise variance right.

So, this way it helps one have less complex receiver. In otherwise if we were processed in time domain, what we are seeing is that there is ISI and one needs to take care of it by implementing ISI canceling receiver, which increases the complexity. Because this has to happen for every symbol and even then you would still have some kind of residual interference because, of which the error will reach an error floor at will simply not decrease to the smallest possible value ok.

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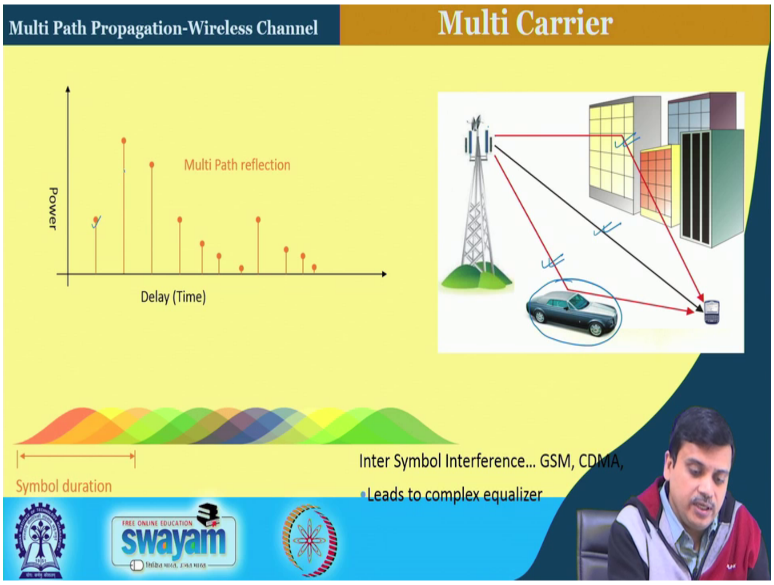

Moving further, this particular picture is essentially talking about what we have been explaining its rather more pictorial and this simply says that if there is a transmitter, the signal propagates through multiple paths one could be direct line of sight. They could be another reflected path from moving vehicle and it could be reflected from different kind of surfaces. And, as a result of which an impulse would appear as echoes or these are the delayed version of the impulse that one receives and in a typical single carrier system there would be inter symbol interference.

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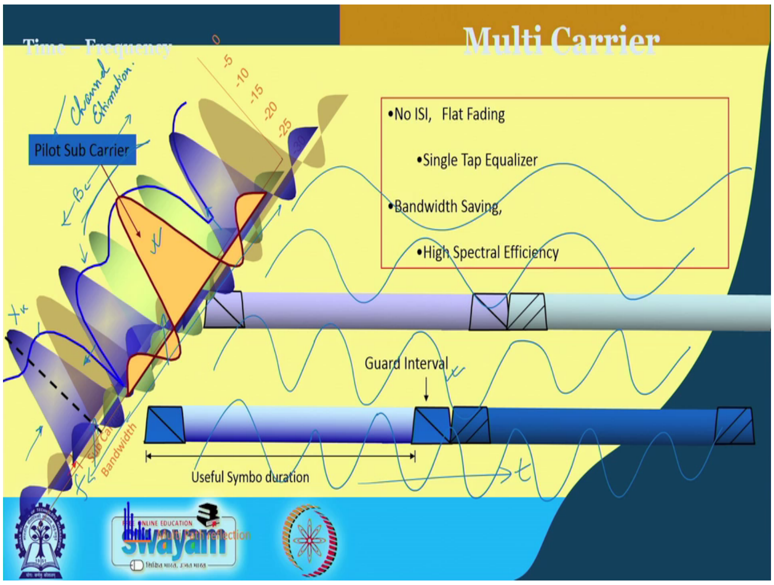

So, if we again graphically look at the multi carrier system, each of the sub carrier which occupies spectrum which is like a sink and there is guard interval. So, this matches with whatever description we have given before and this is a useful symbol duration which has become long ok. So, there is a cyclic prefix which gets added between the guard interval. And, since you have a long symbol duration, the bandwidth is narrow, it is a narrow band and earlier you had a wider band and symbol durations were small right. Symbol durations were small means these, the entire system bandwidth would have been large and that would have experienced, select frequencies selective fading across the entire band of operation; so, will clear up these single carrier systems right.

So now, since you are occupying a smaller band, the question arises that what do we do with the other bands? Again the answer is very simple that you send them in parallel. So, once you send them in parallel, this also matches exactly with a definition of the transmitter architecture. So, each one of them are sub carriers carrying symbol X k. So, this is a sub carrier index k 1 this is another sub carrier index k 2, and they will all of them would be in parallel. And this particular picture gives a complete time frequency realization or one can extend ones imagination that this is the time axis and this is the frequency access.

So, frequency axis can be in this direction ok. So, overall the time frequency signal would look like this and we had said earlier that in one of the carriers this would be the sub carrier frequency. The next carrier could be having the sub carrier frequency which goes there, the next one would be having cycles and the next one would be even having a faster frequency, but all integer multiples of the previous one. And, what we have given over here is that, one needs to estimate the channel coefficients. So, because this is these are fluctuating.

In reality these channel fluctuations are not as fast as typically represented in this diagram and they usually remained constant over a few number of sub carriers ok. So, that is the coherence bandwidth over which remains constant and hence pilot carriers need to be introduced, pilot sub carriers by pilot we mean the sequence which is known as the transmitter and at the receiver. So, that means, it is known both at the transmitter and receiver which is use for channel estimation ok. So, some of the carriers are used for pilot channel estimation, rest of them are used for data communication ok.

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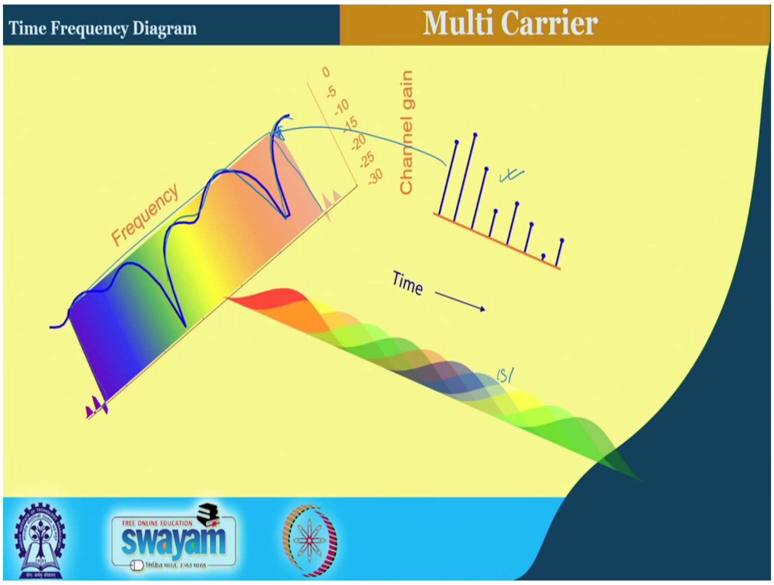

So, this is just the similar picture given in a more illustrative manner that, single carrier system with ISI on this side and frequency selective fading as you can clearly see because the bandwidth would be pretty large. In this case whereas, when we go for this is the translation that happens from a single carrier system to a multi carrier system, this is the representation of the channel impulse response. And from channel impulse response we have the channel transfer function, which is this fluctuation and effectively each of the sub carrier receives fluctuating.

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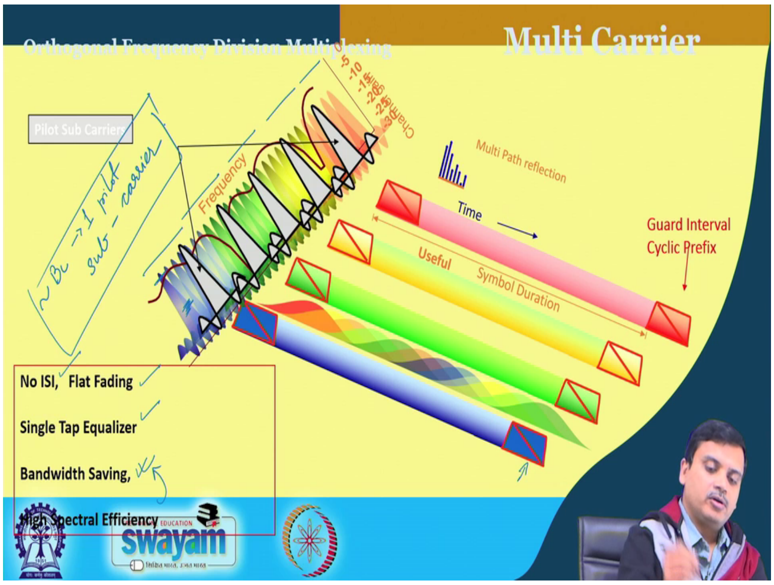

So, is a cumulative picture and one can visualize what is going on, which results in flat feeding per sub carrier. No ISI that due to multiple reasons mainly because of introducing a guard interval and because of flat fading, there is single tap equalizer. This bandwidth saving because of overlappingness of the spectrum and that not only gives bandwidth saving its primarily because, the spectral efficiency has been increased. And, as shown in the previous one, we here depict all I mean the distribution of pilots all over.

So, that in different sections of the coherence bandwidth; one can introduce a pilot. So, roughly speaking for every coherence bandwidth there needs to be one pilot carrier. So, one can say one pilot sub carrier. So, this is important in order to estimator channel ok.

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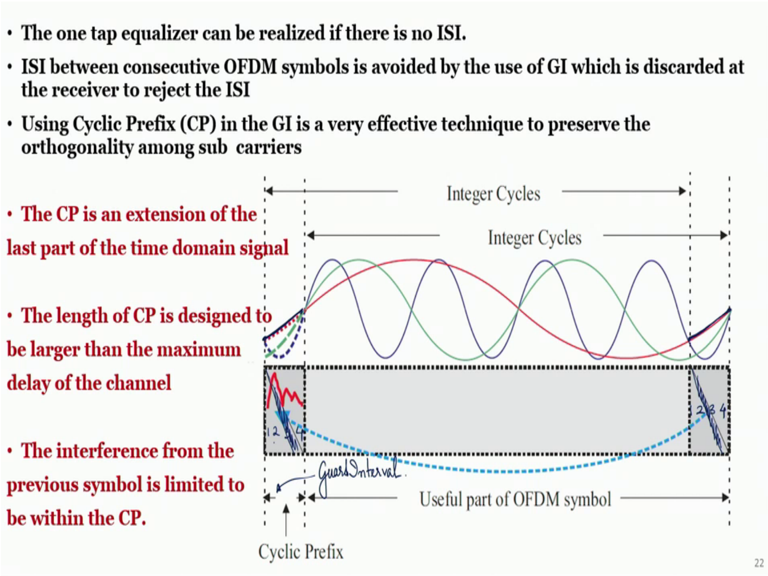

So, we now discuss the cyclic prefix part. So, this particular way form structure is you are well used to by now given all the descriptions, and we have said why the god interval is necessary. But, then instead of simply having a null in the guard interval what is done is, a cyclic extension of the signal is done right. So, we will discuss the cyclic prefix part over here.

So, if this is the entire symbol duration as it is written over here useful part of the OFDM symbol ok. So, this is the useful part OFDM symbol. So, all your figures you must have realized that it covers, this particular part ok. So, that is the part it covers alright. And now what is done is this particular portion as given over here, I would rather write it as guard interval ok. So, this is the guard interval part ok.

So now, instead of leaving it blank, the last part is carried forward to the first part. So, as you can see the picture, this portion this entire portion, we have indicated it by this kind of a line and were indicating it by this kind of line. So, that this continuity or the ease of understanding is maintained over here it is copied in this part. So, if I say this as 1 2 3 4 this be labeled as 1 2 3 4 in that manner ok. So, if we see how it is copied, this particular portion goes over here and this particular portion goes over here. So, this part of the waveform which is copied the red colored one, which I am marking with a blackish color is basically over here as you can clearly see that and the other wave form, which is over here is being copied over here.

So that is how the cyclic prefix extension is done yes. So, with this cyclic prefix there is a lot of advantage we are going to discuss that.

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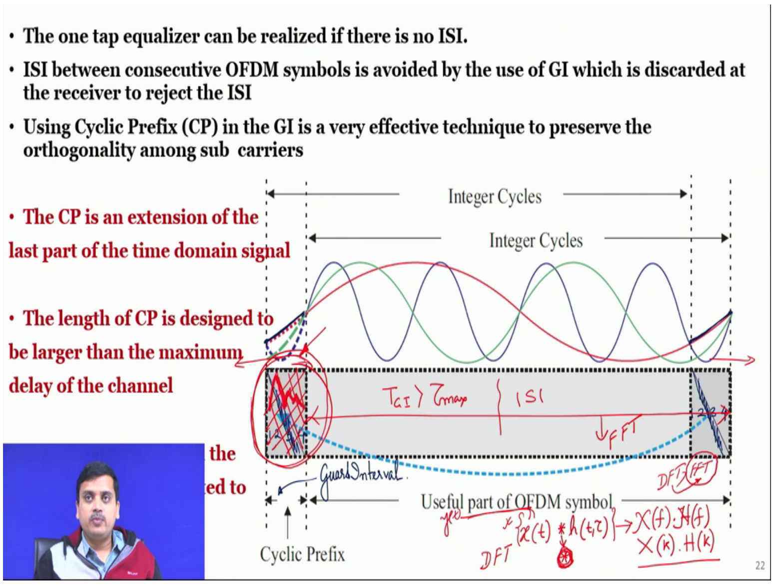

So, let us look at what is happening in the guard interval part this channel impulse response, as we clearly see over here the channel impulse response which is here. It is subsumed within the guard interval that is one primary reason and we have said that the card interval should be greater than tau max. Tau max is the maximum length of the channel. So, this prevents inter symbol interference inter symbol means inter OFDM symbol interference ok.

So, this one thing and because of the cyclic prefix that is what we are getting; yeah in the in the receiver when the signal goes to the channel what we know is that, if x t is the signal it actually gets convolved with h t comma tau; tau is the delay and t is the time axis now when we process it at the receiver, we use a DFT operation ok. So now, the d when we look at the time domain convolution operation, if I take the Fourier transform, it would appear X of f the dual of it. The X of f multiplied by H of f whereas, if I do a cyclic extension; this convolution turns to be a circular convolution ok. So, when it turns to a circular convolution if I do a DFT, then it would result in X of k which is a DFT of x t and H of k which is a DFT of H t correct.

So, at the receiver since we will be implementing an and FFT operation because of the transmitter we have implemented and IFFT operation. So, at the receiver will implement an FFT operation FFT is the realization of DFT and in the time domain, it corresponds to the circular convolution. So, the circular convolution would be effective if we have a repetition of the signal or as if the signal is repeated in time. I mean if it is repeated in time and between the convolution linear convolution it appears a circular convolution. So, what we see is that this enables us to use the DFT operation at the receiver, which can be implemented by FFT rights. At the transmitter we have the IFFT operation and the receiver we have the FFT operation. So, again we recall that we have been discussing this DFT which gets finally, translated to FFT has a very low complexity implementation and one of the main reasons why OFDM became popular is because of its low complexity implementation.

It had all several advantages, but because of the complexity it was not being taken forward. But once this thing came into being this FFT operation, OFDM became very very popular. And since we are having this cyclic prefix; that means, extension of the signal in the front part of it the linear convolution which happens in the channel appears as a circular convolution. So, the circular convolution if you take the DFT of this entire operation which is the receive signal.

So, this entire signal is y of t which is received if take the DFT at the receiver opposite operation of the transmitter, it works out as product of the corresponding frequency components. So, everything fits into plate place and whatever ISI happens at the receiver part, one would be rejecting this component one will be rejecting this particular part and one will be concentrating only on this part which is the desired signal part useful OFDM part and it will pass it through the FFT operation at the receiver. So now, instead of leaving it blank if we bring a cyclic prefix to it, it helps us avoid ISI as well as use FFT operation and the receiver and provide low complexity processing as well as low complexity channel equalization.

Now amongst several other things one we one should remember that, if one is using a guard interval one is actually using less signal energy. But if one is using a cyclic prefix then some extra amount of energy is being wasted in some form and the part of transmission over here. But that wastage is kind of beneficial by overall lower complexity operation at the transmitter or at the receiver side, but; however, there were many works in this regard and there was a lot of work which was done to reduce the effect of cyclic prefix or the having some cyclic prefix and this is still an important issues still an important area, because spectrum is very very costly.

So, if one can find out methods by which we can remove or at least reduce cyclic prefix significantly, while maintaining a low complexity operation at the receiver plus providing low complexity channel equalization then that would be a highly beneficial scheme. Now, one can think of that I reduce guard interval, but complexity goes up that is not accepted because if guard interval is removed then spectral efficiency increases, but then one has to deploy inter symbol interference canceling receiver for every sub carrier and then the exponential growth in complexity.

one also has to remember the FFT operation has to be utilized. So, taking everything into consideration if one comes up with a better mechanism, then that would be highly acceptable and highly desired by this community which works at multi carrier systems.

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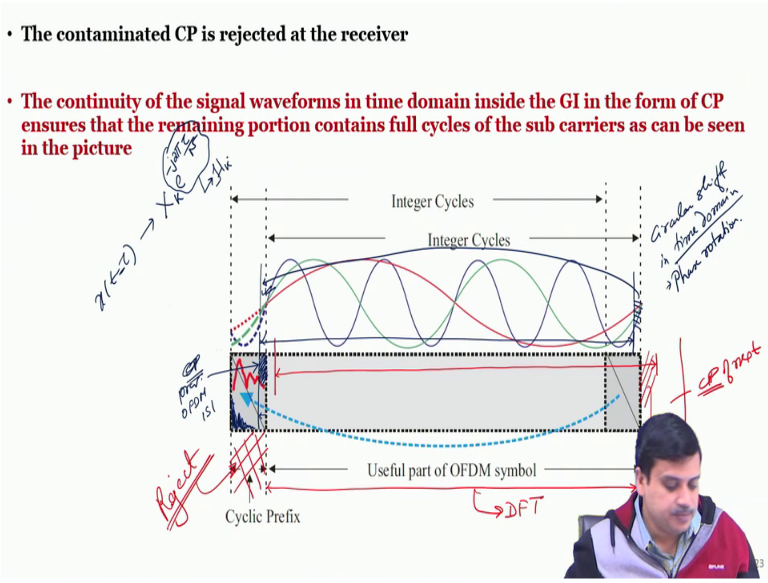

This is almost the same picture that we have, but it is much cleaner picture.

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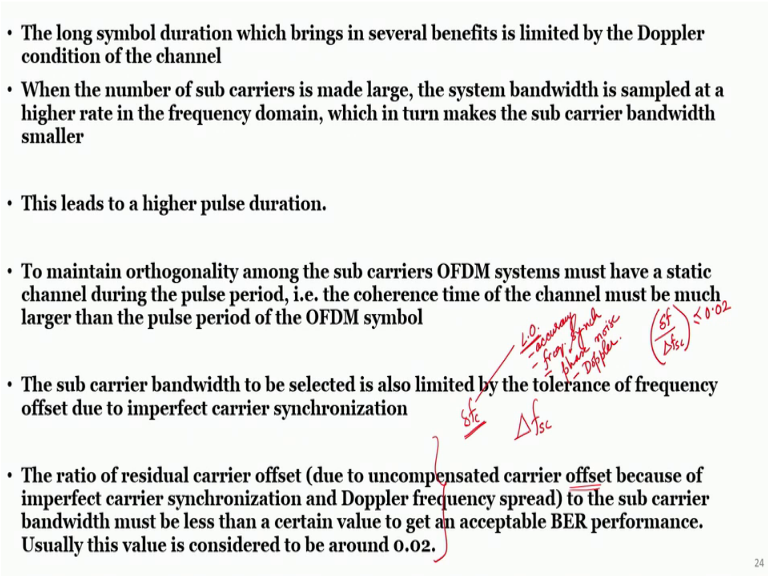

So, you have discussed more or less the important issues and this particular slide more or less summarizes the parameter choice, and one important thing that we have over here is especially in the last part over here which talks about a certain tolerance factor. So, what it says is that, if we know that the there is a certain sub carrier spacing this has to be decided and we know that there is a maximum amount of offset in the carrier frequency, we are talking about offset. Now this offset could be due to various reasons, one is a lo performance the local oscillator performance which is kind of the accuracy of the look local oscillator. Frequency synchronization capability and then they would be accuracy would also include the phase noise of the oscillator and there would also be presence of Doppler which we will discuss in greater details.

So, to take care of this one rule of thumb or easy way one can one can remember or one can understand is if one compares this ratio delta f by delta fsc; if this is a less than 0.02, then one can more or less get around 20 dB of signal to interference plus minus ratio and this interference is self interference. So, if one is maintaining this rule of thumb, then one can get a good inter carry interference and that would be a factor which helps design this sub carrier spacing. So, what has to see there are several factors which are usually chosen in order to design the OFDM system parameters.

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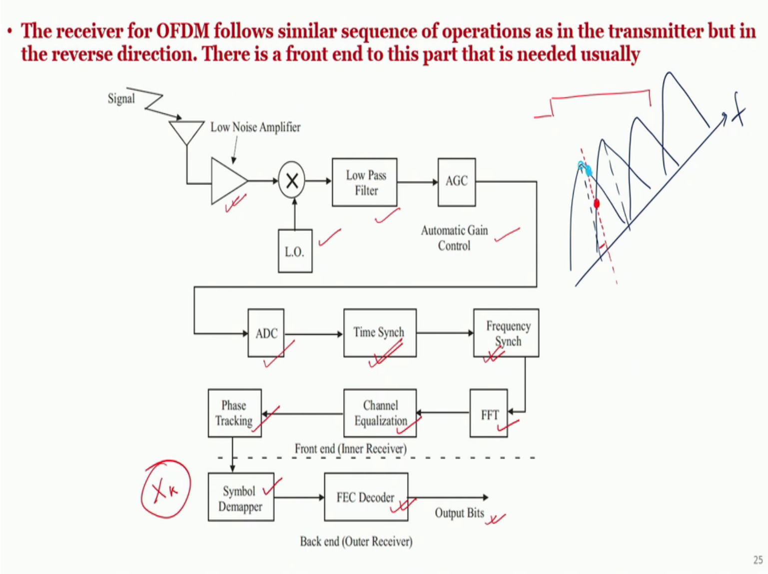

So, this is the overall flow of things. So, we have at the receiver the low noise amplifier where the signal comes in, followed by the local oscillator which is used for done conversion, a low pass filter they would be automated game controller, analog or digital conversion time sink frequency sync. Now these are very very important because we will see that if we have the signal. So, let us go back to this particular figure and we said that we are going to use this useful part of the signal for processing at the receiver by rejecting this cyclic prefix. And the receiver you are going to reject the cyclic prefix and process this part and send this part to the DFT operation ok.

So, now there are some possibilities which come in; one of the possibilities that there is not a perfect timing synchronization and hence instead of starting at this point one starts at this point ok. So, one starts at this point; however, one uses the standard length of the OFDM symbol. So, one stretches beyond the OFDM symbol. So, if one stretches beyond the web team symbol what happens? The cyclic prefix of the next OFDM symbol comes in cyclic prefix of next.

So, if the cyclic prefix of the next level symbol comes in. So, this portion one is going to experience inter symbol interference alright. So, this is very important. So, as a result one can think of instead of going to the left there could be going to the right, they could be also other possibility that one has synchronized to this point and has reached up to here because that is the useful portion.

So, if one has done it in this manner, then what is the problem there is a problem? That this particular section which contains the impulse or the inter symbol interference from the previous OFDM symbol from the previous OFDM symbol, then that results in ISI right. So, there is always a problem of ISI if you are not perfectly synchronized and if there ISI and that is huge reduction in signal to interference plus noise ratio and hence bitter rate would increase.

Now, if the guard interval is kept slightly larger, is usually kept greater than the maximum channel impulse response then and the channel impulse response dies out earlier; see the channel impulse response finishes at this point then there is a certain amount of margin which can be made available. So, even if you are synchronized a little bit to the left, it is not much of a problem why there is not much of a problem because, one would be receiving signal up to this part. So, one would not be getting this, because one has synchronized to the left, but one can recall that this part is already copied over here right. So, this part is already copied. So, one is not losing any information.

But since there is a shift as circular shift is there in time domain. Since there is a circular shift in the time domain so, this would result in a phase rotation in the frequency domain. Because x t minus tau would result in the frequency of e to the power of minus j 2 pi tau by N kind of a phase rotation that can happen in the in the frequency domain. So, this kind this frequency rotation can be corrected because this will become indistinguishable from the phase rotation which is introduced by the channel. So, if discussed that here there is a channel that gets multiplied.

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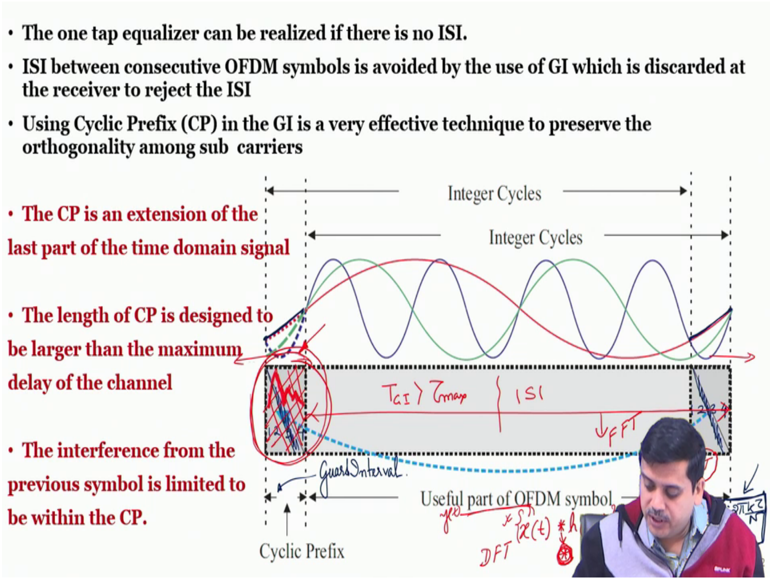

So, if you are wrongly synchronized you are going to get some phase rotation part, which is e to power of let us say minus j 2 pi k tau by N ok. So, this particular phase rotation now this is a complex quantity. So, this complex quantity one will not be able to distinguish any further, they will be integrated together to one channel coefficient all right. So, that means, synchronization is very critical; however, one is little bit to the left, it is not much of a problem. In terms of frequency domain synchronization, there is big issue we have said some things and we will discuss further that, if this is the frequency domain representation of the carriers and we have assumed that they will remain orthogonal. Now if there is frequency offset. So, in that case the receiver would instead of being aligned over here the receiver gets aligned at a slightly different point.

So, if the receiver is aligned at a slightly different point in that case, that desired signal that reduces instead of being sampled over there the desired signal amplitude has reduced as well as the interference signal which is from the neighboring carrier comes over here. So, there is again heavy inter carrier interference. So, which results in loss of orthogonality you can clearly see there is loss of orthogonality, heavy penalties paid. So, therefore, these are very important factors for OFDM system design. After one has successfully synchronize them the FFT operation at the receiver channel equalization, we have already said this there is phase tracking term which are some details of it symbol demapper; that means, you are actually finding out what this constellation means in terms of bits for followed by forward error correction code and output bits this is the overall flow of what happens at the receiver.

So, we stopped our discussion over here in this particular lecture we will move on to the next lecture and whatever we have discussed we will present the analytical model which you can go through in your own time will briefly go through them and look at some other important aspects which need to be remembered when discussing about OFDM.

Thank you.