Evolution of Air Interface Towards 5G

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Lecture - 32
Comparison of Waveforms

Welcome to the course on Evolution of Air Interface Towards 5G. So, till now we have seen the different waveforms and it is high time that we compared their performance against each other. So, that we get a picture of how things would work out and what is the right solution to be picked up. So, till now we have seen various different wave forms like OFDM of course, we have seen its variant then SCFDMA SEFDE then FBMC, UFMC, GFDM and all these different forms that we have seen. We have also seen pre-coded GFDM where there was some modification before sending the waveform which give us performance in terms of lower out of band as well as low PAPR as well as improve BER performance.

What remains was low complexity performance; we did not show you the low complexity results, but they are very details and they are available in different papers. So, it is recommended that you can follow those papers to look at the different architectures, we can reduce the complexities especially of GFDM transceiver systems; for other systems there are other papers which one can easily find out. So now, we get into the discussion on comparison of the different waveforms that we have been talking about.

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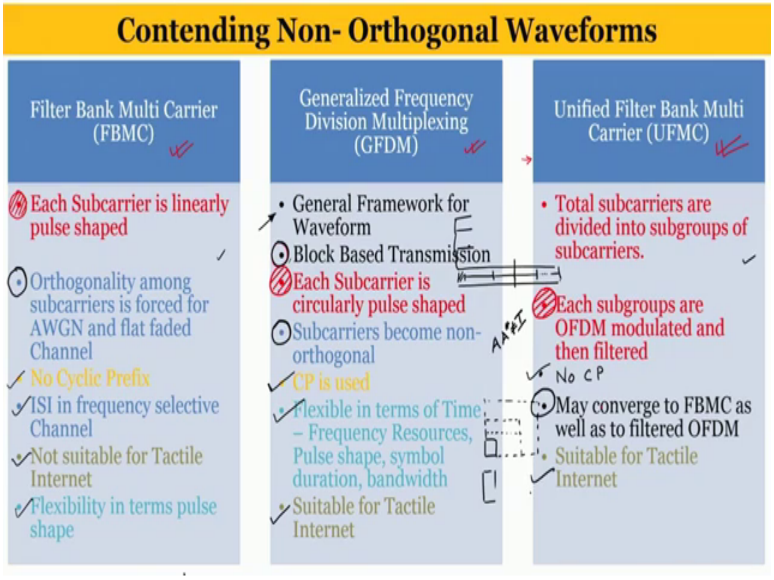

So, we have the three different waveforms which are kind of important. So, the first one is Filter Bank Multi Carrier on the left, then we have Generalized Frequency Division Multiplexing and we have unified filtered multi carrier Unified Filter Bank Multi Carrier system. So, FBMC as we have said it has very good pulse shaping where each subcarrier is linearly pulse shaped. So, you can see the first point of difference or its characteristics right and in case of GFDM each subcarrier is circularly pulse shaped. So, that is where one would compare against each other right.

So, that is the difference and we had also shown the diagram how things would transit from one to another and here what we find is that each sub groups are OFDM modulated and then filtered ok. So, what we see in the first two it is per subcarrier based whereas, in the last one its group based and in OFDM it is for the entire set there is one filtering. So, this is kind of tradeoff between the extremities which are shown in the left and OFDM. And, what we find for GFDM is that it is a block based transmission scheme, this is also that what we have identified that it is a block based mechanism. A block based mechanism in the sense that not just one symbol, but multiple symbols are grouped together and a block is formed and a CP is added in front of the block.

So, its entire block which is processed whereas, this is symbol by symbol processing and this is also symbol by symbol processing on the other hand. It is a generalized framework for wave form, this can be used for translating to other things and then

GFDM can be converted to other forms. The problem here is that the sub carriers become non-orthogonal owing to the different pulse shapes; in a manner that if we take the modulating matrix A Hermitian that is not equal to identity right that is what happens. So, there is the matched filtered receiver that when implemented will not give I mean interference free signals. So, there is lot of interference amongst the modulating signals, but it has several other advantages which we have discussed.

When we look at FBMC the orthogonality among sub carriers is forced for AWGN and flat fading channel that is the advantage. And, in this case what we find is that it may converge to FBMC as well as filtered OFDM depending upon how you configure the entire system right. So, this is again slightly different compared to the other two. In FBMC there is no cyclic prefix, in GFDM there is a cyclic prefix for the entire block, here again there is no CP ok. So, there is no CP for this, in case of FBMC ISI is present in frequency selective channel and it is not suitable for tactile internet, it is flexible in terms of pulse shape. So, one can choose different pulse shapes and get different characteristics. This is flexible in terms of the time frequency resource grid because we said it is a block based.

So, one can reduce the number of blocks, one can increase the number of sub bands in the frequency domain. So, basically a tile can be made in frequency and time as one desires in depending upon the application scenario right one can also think of structures like this. So, it is very flexible waveform. If you look at today's 5 GNR it is also flexible, but does not use GFDM it uses a variant of OFDM. So, potentially the framework is now laid whereby, in the next generation GFDM can easily fit into the framework. This is suitable for tactile internet because, you can make it small duration signal as well and short response time is also feasible, you can make wider subcarrier bandwidth short symbol duration. So, things are feasible in this, this is also suitable for tactile internet. So, these are overall characteristics and then we will get into the relative performance of each other.

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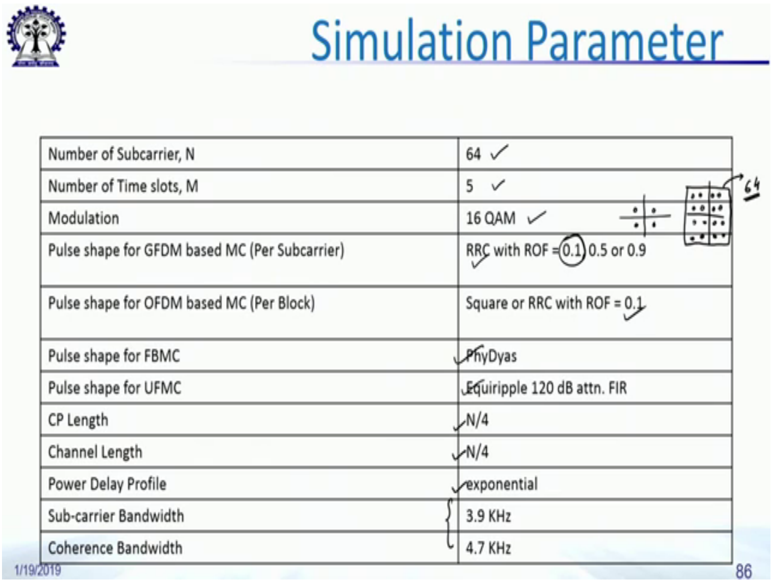

So, to look at the relative performance we take a set of sub a set of simulation parameters. So, where we have taken a 64 subcarrier for simulations its it is just for a primary evaluation and number of time slots is 5, that is a block based system 16 core modulation is used; we did not go for QPSK because QPSK detection can be done by means of only phase differentiation. So, amplitude distortion is not going to affect the system much whereas, if you take a 16 QAM system. So, in a 16 QAM system your amplitude distortion is going to influence significantly. So, we need not go to higher order systems we could have gone to 64 QAM, but it is not necessary because all the different effects are already captured in the 16 QAM's we found a mid path.

In the pulse shipping that is used for GFDM system it is RRC with different role of factors, but we will be looking at this role of factors primarily. And, for OFDM also the role of factor is kept the same with RRC, for FBMC it is PhyDyas filter and there are different filters equilibrium filter for UFMC and so on and so forth. CP length channel length is made same as that exponential partly profile just for the sake of simulations and evaluation performance. And, these are the other two important parameters of subcarrier bandwidth and coherence bandwidth of the system that is used for evaluation.

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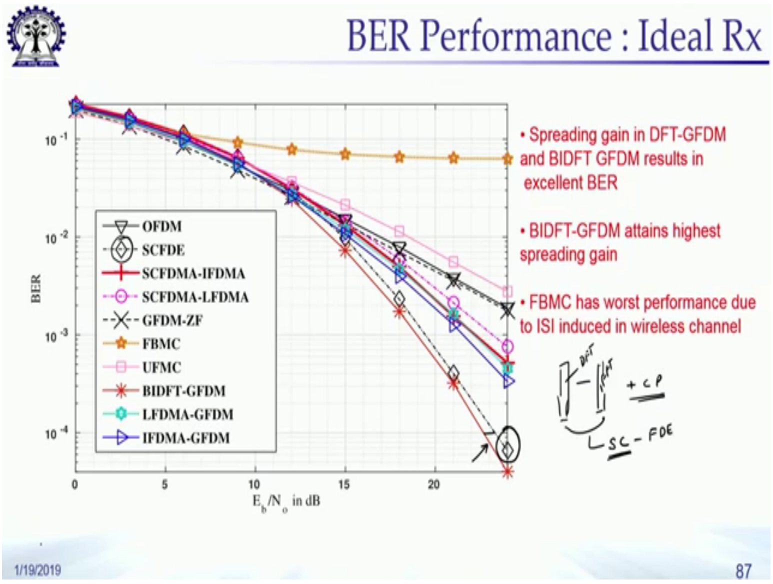

So, this is the first result that we see that is the BER performance with ideal receiver. So, this is something; that means, when you take the BER performance with the ideal receiver; that means, you assume perfect synchronization and all alright. So, with ideal channel information available everything available how do they perform? So, what we find is that in these systems the SCFDMA sorry the SCFDMA system which is sorry the BIDFTM BIDFT GFDM is here; basically this is the set of curves which identify that performance. So, it is basically this set of curves ok.

So, we see that it is the best performance in BER terms because, there is spreading an advantage and we have discussed this earlier.

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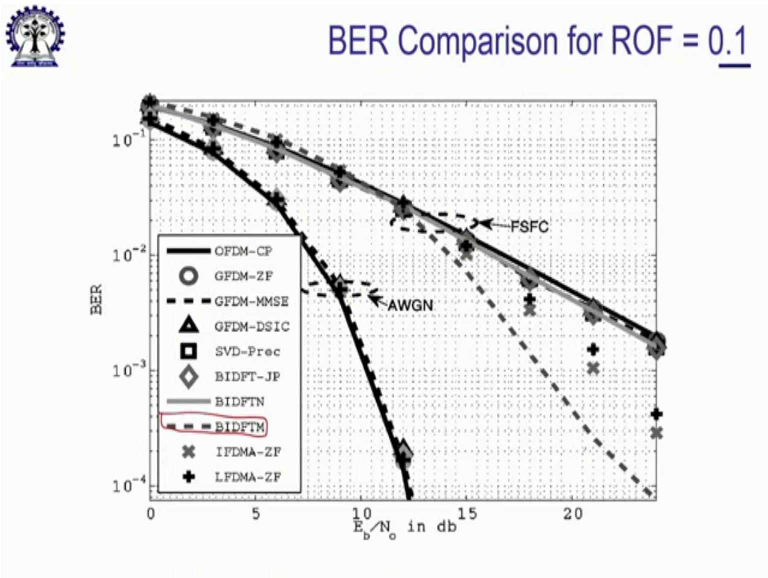

A quick step back you will find that BIDFTM provides this one which we had described earlier provides significant diversity gain.

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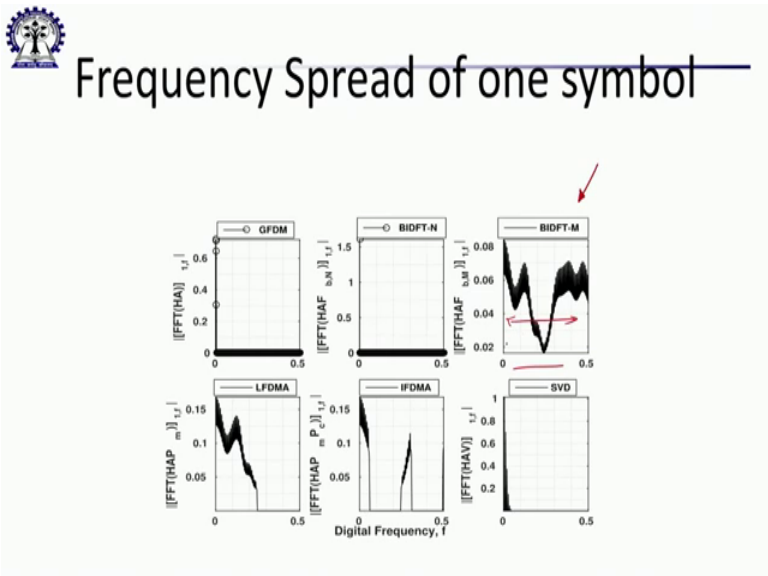

And here is the frequency domain spreading of the signal that helps us understand that across frequency the signal is spreaded. So, when it combined at the receiver it takes advantage of the compare of the combining. And, hence it provides the significant advantage relative to all other waveforms ok. So, then we look at the next waveform which is SCFDE. So, SCFDE is this waveform as you can see which is so single carrier frequency domain equalization. Again this also is pretty good in terms of the fact that you can have the DFT spreading, if you would remember there is a DFT spreading followed by OFDM which is IFFT.

So, if it is of the same size then they cancel out each other and you result in single carrier. If you add a cyclic prefix you can do frequency domain equalization and it retains the characteristics of single carrier. The extra advantage of SNR is because there is cyclic prefix per symbol whereas, here there is per cyclic prefix per block. So, there is some reduction of loss in SNR otherwise they would have the similar characteristics of performance ok. So, moving further we see the next one which is IFDMA there is Interleaved Frequency Division Multiple Access GFDM.

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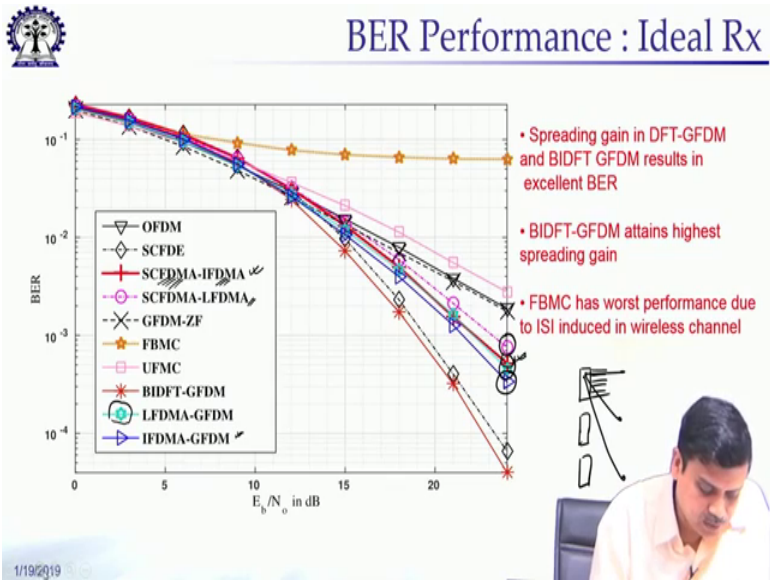

This is this one which we have also described earlier and then we have this one which is localized allocation for GFDM. And, followed by this we have SCFDMA with IFDMA that is a DFT spread OFDM with interleaving and then we have DFT spread OFDM with localized. So that means, you have this DFT spreading blocks, if you allocate them on the same sub on the corresponding sub carriers it is localized. Whereas, if you if you would allocate one of them there, one of them there, one of them there that is kind of interleaved division. So, there we see the performance that interleaving improves the performance right. So, again this is the interleaved which is the performance here, is the localized which is the performance.

And then we move further we see the GFDM system which is the cross, if we follow this that is here with 0 forcing receiver which is matching with OFDM right. So, there is no loss of performance in that sense and then what we have is UFMC over here which is relatively worse compared to these performances. And finally, we have FBMC up there which loses its orthogonality that is what we had pointed out; FBMC has the worst performance due to ISI induced in the wireless channel. Whereas, others can take care of it and in fact, BIDFDM can provide you the highest amount of diversity as well as SNR advantage compared to the other systems.

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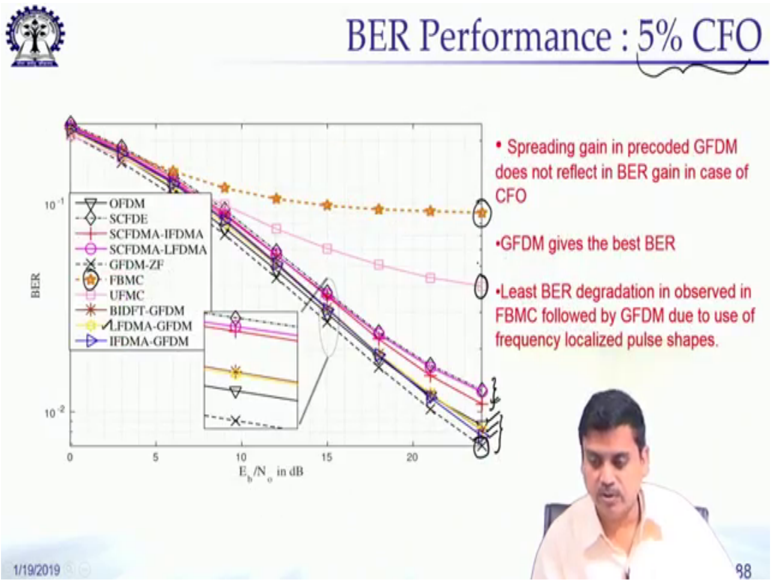

Moving ahead we take a look at the result where we have 5 percent carrier frequency offset. So, that is kind of small carrier frequency offset that is present in the system. So, again what we see is that in this case also because, it has already degraded here things are only worse in case of FBMC. I mean this is not better anymore, but if you just take CFO things would be different, but we have frequency selective fading channel. So, performance is; obviously, different and then what we see is that GFDM with a 0 forcing is most resilient compared to others.

So, this filtering and pulse shaping is helping it to counter some of the carrier frequency offsets and as we go higher up what we see is that interleaved frequency division that is also GFDM. This is also GFDM which is here that is localized allocation and then we find OFDM over here. So, these are close to OFDM, but only slightly better and then we see SCFDMA which is affected by carrier frequency offset and both of the versions NACFDB. So, all of these are worse in performance relative to OFDM which is worse relative to the various forms of GFDM and then we see that EFMC is again up higher up which is already there. So, kind of worse performance is already carried forward so, it is already degraded by the channel conditions.

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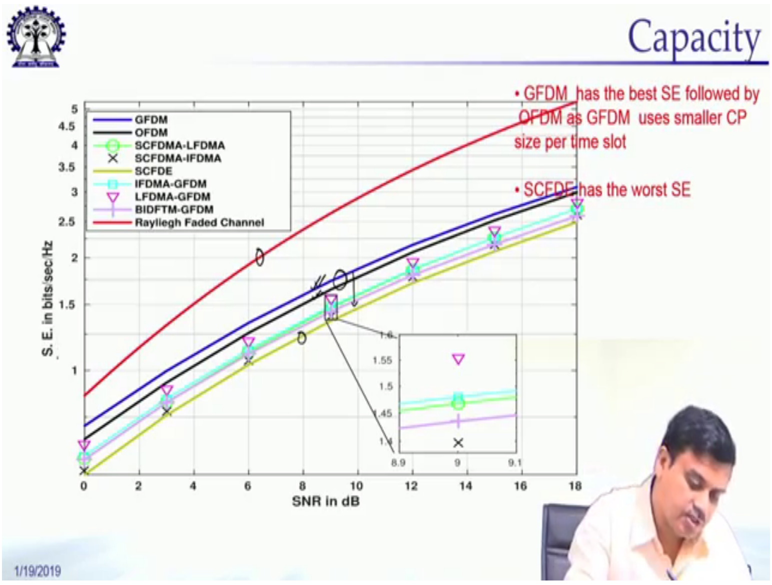

In terms of capacity evaluation again what we what we compare against is the Rayleigh fading channel capacity and then what we find is GFDM is again providing the highest capacity followed by OFDM. And, this gap can be due to the CP loss, then we have SCFDMA I mean these all are pointed out over here and finally, at the bottom we have SCFDE. So, what we see that GFDM is performing better in the frequency selective fading channel as well as under CFO as well as it has the highest capacity capability that spectral efficiency in bits per second per hertz compared to the all other schemes.

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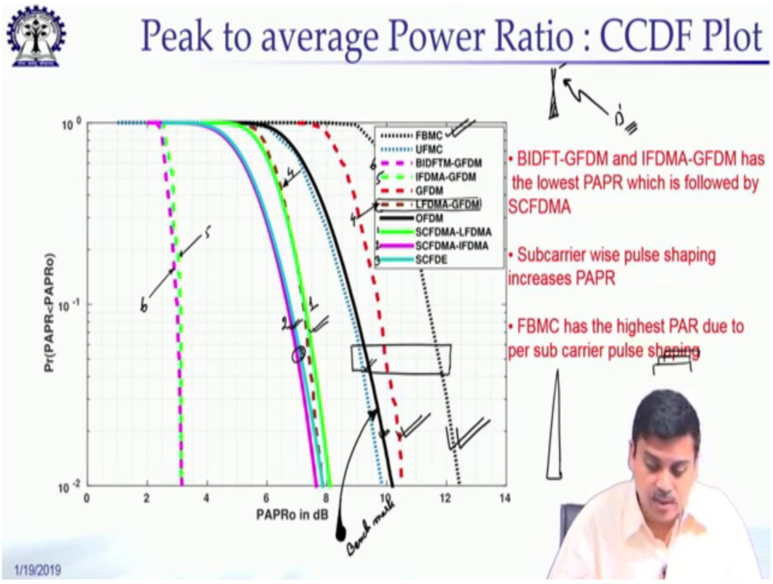

Then we move forward to the other important performance metrics which is the PAPR and we have described the PAPR earlier. And, we have stated that PAPR is important issue because, when we are especially talking about the uplink; that means, when we are talking about sending signals from user equipment to the base station let us say right. So, you would you have a small power amplifier here relative to the one at the base station and you would like your slick signal to be as much compact in the amplitude form as possible. So, that you can operate near the saturation region and you would be able to maximize the utilization of the power available at the user end.

So, that is why we would like to have waveforms which have low PAPR, high PAPR is not desired because you will have to have a back off; back off means lower transmit power, lower transmit power means poor coverage and more wastage of battery especially of the handle devices. So now, if we compare all the schemes what we find is that again FBMC is the one with the highest peak to average power ratio compared to all other waveforms. So, one may find some relevant papers which talks about pulse shaping only worsens the PAPR. So, if you take a rectangular pulse shape and do pulse shaping on top of that especially for multi carrier systems things only become worse and that is what is reflected in FBMC system.

We also see that GFDM by itself has worse performance because it also has pulse shaping on sub carriers. So, one is actually not doing much in case of which is followed by OFDM. So, one can think of OFDM as the reference point because, this is kind of acceptable is used and remember this fact that in 5G they are allowing OFDM to be used in the uplink direction also while, the SCFDMA is still allowed. Although it is still allowed they are going for OFDMA an uplink and there used to be a very popular standard known as WiMAX which was competing with LTE at some point and WiMAX had OFDMA in uplink as well as in downlink. So, OFDM in uplink and downlink whereas, in LTE there was SCFDMA at lower PAPR that was the primary reason.

So, anyway OFDM can act as the benchmark in this in this system right. So, we can take this as the benchmark point and compare others. What we find is UFMC is only slightly better you know, one reason that when you are grouping subcarriers together then effective number of subcarriers could become less or you are kind of playing around with the phase factors with them. However, these three or these few set of results only show us that things are only as good as OFDM or worse right. Things max can be as good as OFDM, if you use the schemes by itself and then we look at some of the variants, that we have analyzed in our work and we will present it here. One of the first things that you will see is that the single carrier or the SCFDMA right.

SCFDMA with localized allocation is significantly lower than OFDM around 2 dB benefit, you can get in terms of PAPR and then with interleaved allocation you get it even better that is here so, this is the first, this is the second. So, this is the first, this is the second that we have just discussed and SCFDE is similar to the second scheme so, this is the third scheme that we have discussed. So, more or less SCFDE gives you a better performance than OFDM systems that is quite expected because, you are having single carrier like performance, but it is derived from OFDM. So, some of the reminiscent things would be providing you a higher peak to average power ratio ok. So, then we take a look at the next thing that is some variant of GFDM that is localized FDMA GFDM; that means, you are doing some kind of an allocation which we have described earlier. So, that performance is coming over here which is again similar to number 1.

So, this is 4 right this is 4 which is similar to number 1 and then we take a look at some of the other GFDM based schemes which is IFDMA. So, IFDMA is interleaved allocation. So, this one which is you can put it as number 5 and then you have the sixth-one sorry this is this is number 5 and then you have the BIDFTM which is number 6. So, once again we find that BIDFTM provides a huge reduction in peak to average power ratio and in fact, it is the best performance. So, it is a pre coded version of OFDM which can reduce the PAPR by a significant margin which can only provide better uplink capabilities. So, with this we can compare the different waveforms with important performance metrics.

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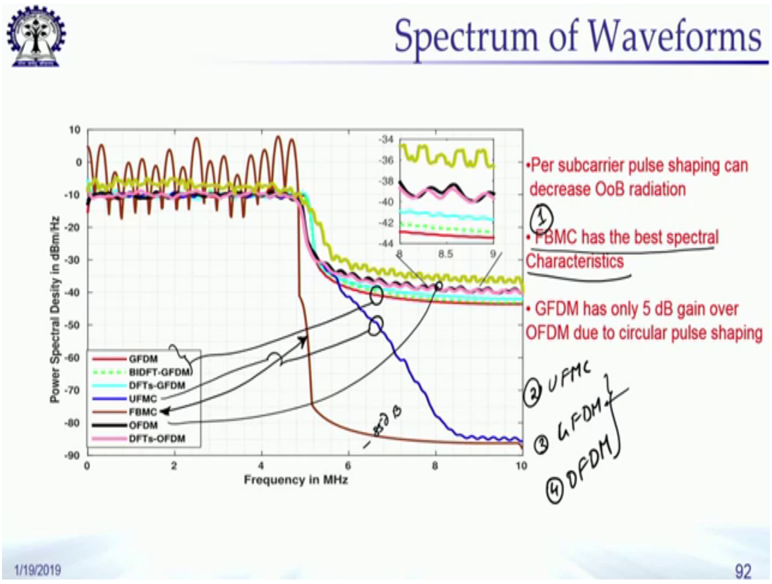

But then we move on to another very important characteristics which is the outer band spectrum leakage right and that is one reason why the filtering has been done on these different waveforms. So, what we see is while FBMC has been relatively weak compared to all other waveforms and the different metrics that we have been comparing, we find that it is the best scheme as far as out of band spectrum leakage is considered. So, you can clearly see from the picture that FBMC is basically this one with the brown color. So, that is the FBMC spectrum and FBMC spectrum is having the very narrow transition region and beyond that the out of band is at the level of nearly minus 85 dB with respect to the peak performance. So, which is very good. So, it is the best in fact, and no other scheme can achieve an out of band performance which is as good as FBMC.

So, if out of band leakage is the most important criteria then of course, FBMC is the one of choice, but of course, one has to remember the other losses that one has to bear with under different conditions. So, if conditions are favorable in terms of flat fading I mean ISI is not affecting the performance then FBMC can be chosen to work in within very narrow bands and signal has to be fitted into such available gaps. In this context what we see is that these two groups of GFDM are relatively worse compared to FBMC ok. So, they are not really as good as FBMC in that sense whereas, again FBMC is coming somewhere in between and this was expected while, OFDM is somewhere up there ok. And, then we also have DFT spread OFDM also along with it.

So, what we find is that in this case FBMC has the best spectral characteristics and we can rank FBMC as number 1 and we can rank f UFMC as number 2. And, then you can rank GFDM as number 3 and then we have OFDM. So, in that order I would put it like that right and of course, if you are able to do some filtering on these then the performance would be somewhat better than what we are seeing in this particular picture. So, overall what we see is that FBMC is very strong spectral characteristics, but worse in other terms whereas GFDM is better than OFDM in terms of spectral characteristics, but much worse than FBMC. But, on the other counts it has a much better performance than the different waveforms.

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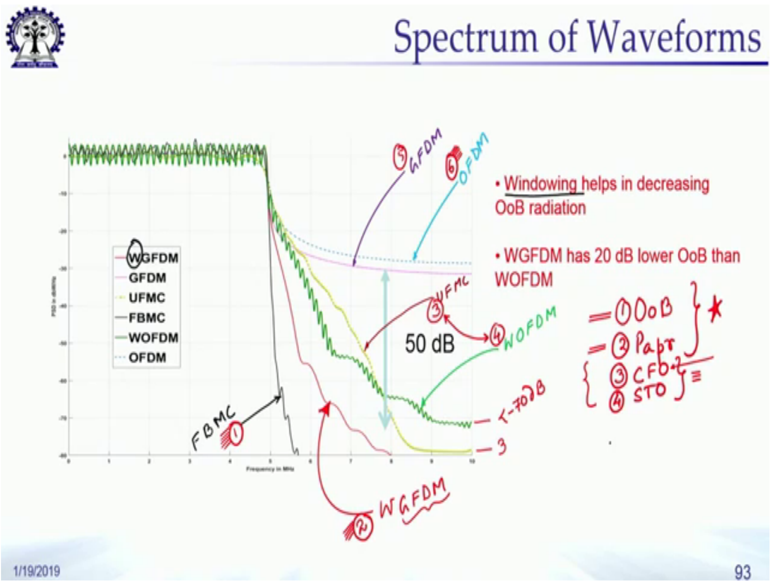

So, now when we look at this particular result we have windowing is what we were just mentioning in the previous one. So, W stands for Windowed GFDM. So now, what we see that the outlook that was presented earlier has changed significantly. So, this result is the one for Windowed GFDM and what we have here the next one is this one is for windowed OFDM and then we would also identify this one as UFMC ok. So, that it is easier to read and then we have here this one as GFDM in its original form and finally, we write this one as OFDM right.

So, we have of course, not mentioned the best scheme which is FBMC which stands its ground so, FBMC has not lost its position. So, again in order of ranking what we see now, is that FBMC would be ranked number 1 in terms of out of band spectral performance ok. And then of course, we have windowed GFDM as number 2 and then there is a question on UFMC and windowed OFDM because, depending upon what we are looking at. So, while transition is faster for windowed OFDM, but finally, it settles down at a higher level its, but still it is less than minus 70 dB ok. So, if 60 dB is acceptable then this is not a problem. So, otherwise we would put them at UFMC has a better performance over here, but transition band is a little bit wider.

So, we can still put UFMC as number 3, OFDM as number 4 or these can be swapped and then GFDM and finally, ranks exposed to OFDM. So, this is one reason why all these waveforms people started investigating. So, what we see is OFDM clearly had very poor out of band leakage performance while, FBMC has the best. And, OF and windowed GFDM is the second best and pretty close to FBMC and if we compare the other performance some variant of GFDM is always having a better performance than all other schemes. So, what we can summarily conclude is that the different waveforms that were investigated, they have improved upon the out of band, they have improved upon the PAPR.

These two are very critical reasons why the different waveforms were analyzed, most fundamental reasons. Along with them there were two more reasons: one was the carrier frequency offset resilience and then there was symbol timing offset resilience. And, these performance are partially reflected only in CFO, we are we have not represented the STO performance, but these are available in different papers and one can look at them. These performances are important because, that would characterize the capabilities of these different waveforms in terms of high Doppler tolerance as well as a synchronous operation tolerance. So, we can compare we can take up the different scenarios and see how they perform against each other and choose the appropriate solution.

So, if a flexible structure is available or if a flexible structure is feasible then one can switch between the different waveforms or they might be able to intermingle or they may be going to stay with each other with a certain amount of performance capabilities.

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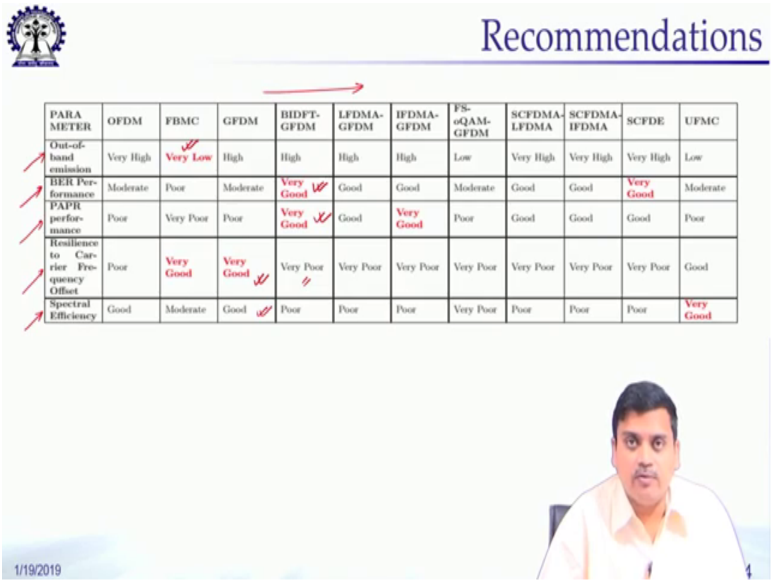

PARA METER	OFDM	FBMC	GFDM	BIDFT-GFDM	LFDMA-GFDM	IFDMA-GFDM	FS-oQAM-GFDM	SCFDMA-LFDMA	SCFDMA-IFDMA	SCFDE	UFMC
Out-of-band emission	Very High	Very Low	High	High	High	High	Low	Very High	Very High	Very High	Low
BER Performance	Moderate	Poor	Moderate	Very Good	Good	Good	Moderate	Good	Good	Very Good	Moderate
PAPR performance	Poor	Very Poor	Poor	Very Good	Good	Very Good	Poor	Good	Good	Good	Poor
Resilience to Carrier Frequency Offset	Poor	Very Good	Very Good	Very Poor	Very Poor	Very Poor	Very Poor	Very Poor	Very Poor	Very Poor	Good
Spectral Efficiency	Good	Moderate	Good	Poor	Poor	Poor	Very Poor	Poor	Poor	Poor	Very Good

We see chart of different requirements kind of here we have out of band emission, we have BER performance, we have PAPR, we have resilience to carrier frequency offset. And, then we have spectral efficiency as the different KPI's and we have the whole different set of waveforms in this axis right, the names are there. What we find is that FBMC has very low out of band which is desired and BER performance is very good for BIDFT GFDM, PAPR wise also this is very good right.

Resilience to carrier frequency offset it is not that strong, but GFDM is stronger and spectral efficiency wise what we find is that GFDM is kind of very good in that sense. So, what we conclude is that there are various conditions under which different wave forms are performing better and there is no one single wave form which outperforms all others in all quarters. So, this is something to be remembered and hence there is still some miles to be covered before there is a clear winner which can be identified.

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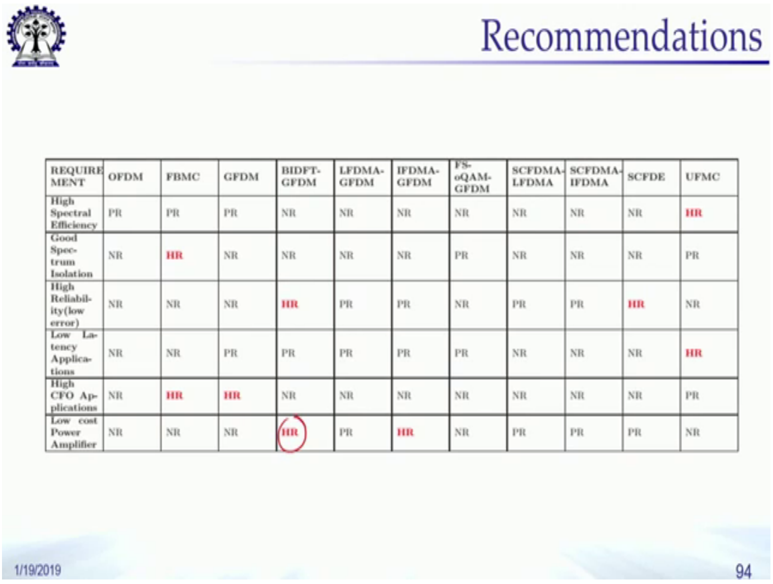

REQUIREMENT	OFDM	FBMC	GFDM	BIDFT-GFDM	LFDMA-GFDM	IFDMA-GFDM	FS-oQAM-GFDM	SCFDMA-LFDMA	SCFDMA-IFDMA	SCFDE	UFMC
High Spectral Efficiency	PR	PR	PR	NR	NR	NR	NR	NR	NR	NR	HR
Good Spectrum Isolation	NR	HR	NR	NR	NR	NR	PR	NR	NR	NR	PR
High Reliability(low error)	NR	NR	NR	HR	PR	PR	NR	PR	PR	HR	NR
Low Latency Applications	NR	NR	PR	PR	PR	PR	PR	NR	NR	NR	HR
High CFO Applications	NR	HR	HR	NR	NR	NR	NR	NR	NR	NR	PR
Low cost Power Amplifier	NR	NR	NR	HR	PR	HR	NR	PR	PR	PR	NR

So, in this particular thing we have identified with the with the marks like HR indicating Highly Recommended and NR is Not Recommended indicating the different waveforms and the different performance different evaluation or different performance metrics which would be working out. So, what we conclude is stated just now that different waveforms has different capabilities and with some more additional work we think that we might be able to come up with waveforms which would satisfy the different conditions in very good manner.

So, that you have a newer version which provides much better benefit than OFDM had been providing. And, we would expect such waveforms to be part of the sixth generation communication system over here. And, in the next lecture we will start discussing about the propagation conditions which will create us which will provide us with sufficient platform to discuss the different MIMOS schemes and understand their performance before talking about a few more issues related to the fifth generation communication system.

Thank you.