Evolution of Air Interface Towards 5G

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Lecture - 16
Waveform for 4G & 5G (OFDM)

Welcome to the lectures on Evolution of Air Interface Towards 5G. So, till now we have had Overview of the different waveforms that, are there in the second generation and third generation and today has you can clearly see that we are going to discuss the topic which is sorry this is wrong title that we have it is for the fourth generation system.

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And we will be taking about the Waveform in 4G and primarily it will be about OFDM; now, brief few words before we get into the details of the discussion. OFDM as today we will discuss is primary wave form. We have laid the foundation when we discussed the multi carrier fsk. So, when we discuss the multi carrier or M-ary fsk we have pointed out that the system model would remain the same which served as the basis for discussion of 2G and the same wave form or the same structure will be useful when we discuss the fourth generation and beyond systems.

So, we had also discussed how the M-ary fsk could be designed in the manner that the frequencies that are being chosen for operations are orthogonal in nature and we had also said that since they are orthogonal, it is possible that you not only use them for switching between the carriers and letting information flow by virtue of choice of a carrier, you can actually use all the carriers simultaneously and that would have appear as FDM. And since, these carriers are to be chosen in an orthogonal manner, it can serve as a basis for orthogonal frequency division multiplexing and today, we take this opportunity to get into the details of it.

Now, other reasons why this is critical and important because this is a foundation on which most of the modern generation communication techniques are built; so, it is kind of a platform one can say. It is a multi carrier technique and although it is we have discussing 4G, but when we get into the fifth generation we will see that fifth generation essentially stands on the same structure as in 4G, although there are certain variations in the frame format and the way things are used compared to the fourth generation.

But the fundamental element is still fourth generation of or the OFDM system and we will again see today that it is not only the base line for 4G and 5G, it is also the base line for a broad band wireless local area network. It is also the foundation for a broadband metropolitan area networks. It is also a standard for digital audio broadcasting or digital video broadcasting as well as for the satellite the high speed satellite communications.

So, it is a very very important waveform as on date. So, we do not know what is going to happen after 10 years from now, but it is very important to study it and build our basics so that we can understand most of the communication systems which are usually available for commercial purposes.

It has several advantages and there are certain disadvantages. So, our aim would be to understand as much details as possible and that would also give us a key inside into developing newer waveforms a based on whatever you have discussed earlier as well as whatever we are going to discuss in this particular lecture.

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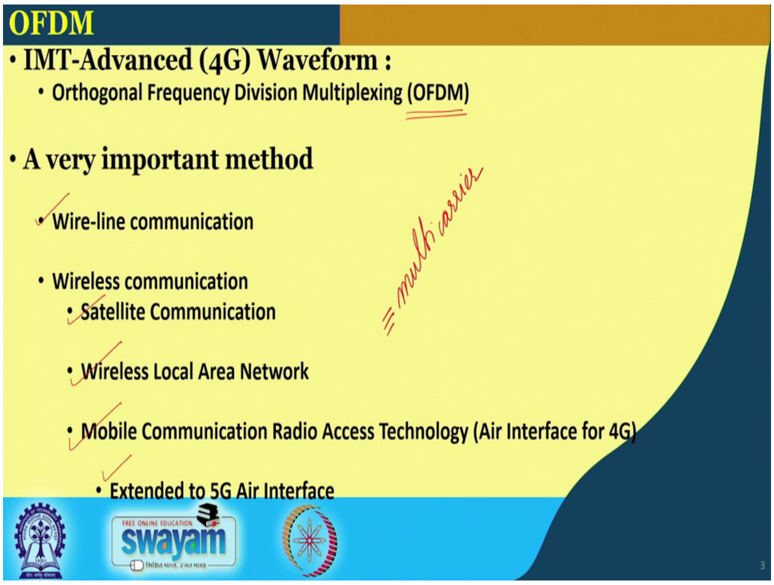

So, moving ahead when we talk about 4G, it is essentially IMT advanced we have already said that and this used OFDM as it is written over here. So, when we talk about 4G the main word that comes to our mind is the OFDM, a technology in terms of air interface. So, it is a very important method as we have already said because it is used for Wire-line communication. It is not used for Wireless communication namely Satellite. We will see that. It is used for local area networks, we have already said that. It is used for 4G as well as its extended version in 5G.

So, not only that it is one of the primary multi carrier techniques. So, it is multi carrier because we will see how these multi carrier concepts come in. We already discussed it once. So, the class of multi carrier techniques have a basis or it can be studied in the perspective of OFDM. There are other views also where OFDM can be seen as a subset of the overall class of multi carrier, but this being very very popular it is also good enough to study OFDM. And, because it is easier compared to other methods and one can digress and move into other techniques and understand them.

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So, brief into the history about the OFDM what we can see that it was initially used in the military systems and that was around the 1960's. In this period it was used in different military systems and this is the different names of the technologies that where using them. So, it is not a new method that is the primary thing. Although it is very popular these days, it is being used on every wireless broadband communication system, but it has been existed for almost 60 years now.

And traditionally when it started to happen what we see is that there was a bank of conventional transmitters and receivers. So, this is pretty normal because we had discussed M-ary fsk as a foundation as we just said and these separations were delta f and here found the relationship for these. So, we said that you going to use all of them simultaneously and in each of them, we said they had a model like e to the power of j 2 pi f k t. This is the carrier where this f k, k equals to 1, 2 so on up to N or you could also index k as minus N by 2 up to N by 2 minus 1.

So, then there again you will be having N carriers and each of this carriers would be getting an x k which is the signal from the constellation and will be sent out. So, what we will get from the first one is X 1 e to the power of j 2 pi f k t. The second one is going to produce X 2. So, this is f 1. Second one is going to produce X 2 e to the power of j 2 pi f 2 t and so on and the last one is going to take X N e to the power of j 2 pi fn of t and each of this X 1 X 2 up to X n. These are element of sum constellation of order N.

What it means is that each will be drawn from a constellation let us say we are drawing the constellation diagram for 16 form. So, each symbol will be drawn from them depending upon the bit sequence. Now it can also be noted that each of these symbols that are coming in, they did not necessarily be drawn from the same constellation. It could also happen that sum of this cons tell some of this carriers take from let us say 16 QAM, while the rest of them can take from 64 QAM or any other combination it can happen.

So, this is generic model it is the generic system layout. It is a generic equation generic frame work and we have said that the same foundation or the same expression have been used will be useful in studying all the future things. So, here what we see is that each one of them as a multiplication operation over here right; each one has a multiplication operation, each one has a multiplication operation.

So, that means, there would be an oscillator in each of the lines. So, that means, there is a signal constellation x k which is multiplied by local oscillators which has a frequency of f sub k and then, it goes out right that is what each of them. And finally, they go out together. So, in the air medium you have a summation of X k e to power of j 2 pi f k t sum over on k and this is your time domain signal that goes into the air. So, this is what we are going to see at each point there will be a multiplication of the oscillators.

At the receiver what we see is that here we have again discussed the orthogonality criteria where we said that at the receiver side whatever signal is received. So, if let us say this whole signal is received and we demodulated by multiplying e to the power of minus j 2 pi f k prime t and we are going to integrate because it is continuous time from 0 to capital T which is the symbol duration d t you can do it in a summation format also.

So, what you will find is that when this frequency index is not equal to this frequency index. So, that means, when k is not equal to k prime, then this entire thing would end up in 0 and when k is equal to k prime, you will find that the entire thing will end up in x sub k that means, the product would be 1. The sum of the entire multiply accumulate and integrate operation would be 1; otherwise it is 0 by virtue of orthogonality.

A digression from this particular discussion, but which is absolutely in context what you can also visualize is when we talked about these spread spectrum system. Essentially what we are saying is that this particular signal that is what we are multiplying is kind of acting as a spreading signal; one can think of it in that manner also.

So, here what we have is that the weights are drawn from exponential function, where as what we discussed there is a more general one where the codes could be drawn from any a function Hadamard is one particular way of generating orthogonal codes. Here if we connect to this we can think of DFT matrix which we will see could act as act also as generation of codes. So, this one can see it as a generalized picture through which one can study either spread spectrum or even multi carrier systems where it is kind of N dimension signaling as such and we have discussed the N dimensional signaling in the past.

So, if one is a comfortable with the notations or description as basics functions; so, what we have these as let us say we can write them as S m other way we will we not write this on S m or let say f prime of k, this entire thing of t. So, this is a basis function. So, we have N basis functions. The codes if they are orthogonal, they are again N basis functions and at the receiver one can think of either a match filter operation, I mean here what you sees the correlations.

So, when you implement matched filter as a impulse response you convolve. So, essentially it turns out to be an correlator receiver because finally, you will be sampling at this time instance T. So, one can also visualize this in terms of N dimensional signal with N basis functions and a match filter operation at the receivers with the particular basis function. So, we project the incoming signal on the different basis functions, read the outputs and then process it further.

So, if you see it in this way then it is a generic representation you can study all the schemes in one particular flat form. So, now, going back again to the way it was developed in 1971 it was it was shown that DFT could be used instead of the bank of conventional transmitters and receivers. So, this entire set of N number if oscillators. So, we would have had N oscillators at the transmitter and N oscillators at the receivers we have at the transmitter and the receiver both sides. So, those could be reduced and one can use a DFT operation. Now DFT operations the advantages it is it can be implemented in digital circuit. It will be much low powered compared to this entire set of oscillators that are to be used.

So, this was a turning point when it was not restricted to defense applications because cost is an important factor. So, things could become easier to implement and with the advent FFT, which co which could realize a DFT operation even at lower complexity. So, order of N log N is the complexity. So, one could finally, realize OFDM in more easier fashion and OFDM techniques was started getting used a specially in devices where power was a critical factor.

So, today when we look at things we have handled devices and most of them are power critical because we would like the battery to last longer. So, we would have had this kind of methods which use oscillators we would have been able to get only limited game, but because we could implement in digital circuits and we could use FFTs the gains of OFDM became much more useful much more translatable and there was a proliferation of different techniques which could use OFDM. So, it is started with this HDSL as we are seeing HDSL that is what is written here.

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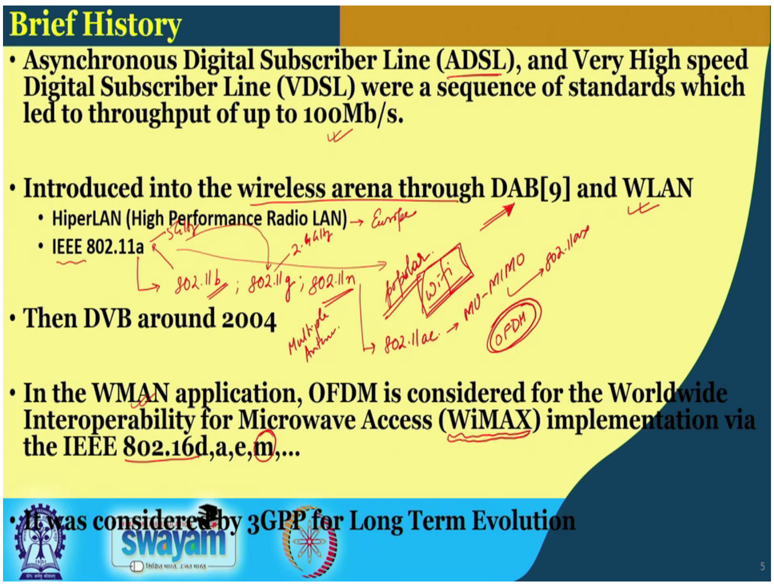

So, that is high bit rate digital subscriber line, where it was used. Then there was ADSL where OFDM also used very high speed digital subscriber line and at that time it could produce 100 mega bits per second which was very large titrate at that instant of time and I said earlier, it was also introduced into the wireless domain through digital audio broadcasting. You can find these specifications in a particular reference which will point out and it was also proposed for using WLAN that is wireless local area network.

In wireless local area networks, there were two proposals. This particular proposal was from European region which is HiperLAN and this is as can be seen its an high triple E proposal and what we have today this is somehow more popular and you usually associate the term Wi-Fi with such a technology that is wireless vitality and there are different forums which address it. But primarily it is the 802.11a which got OFDM into the systems..

In this series, there was 802.11b which did not use OFDM, but then there was 802.11g which again use OFDM and it kind of super posed 11a and b in a manner that it could interoperate with a earlier standards and it was designed for the 2.4 GIGA hertz ISM band width. ISM band this was primarily for the 5 GIGA hertz band. So, in the 2 this basically translated the 11 a into the 2.4 GIGA hertz band.

Then, there was 802.11 n standard which is basically extension of OFDM with multiple antennas and after n, it was 802.11 ac which is started supporting MU-MIMO Multi User MIMO, you will get an opportunity to see them and finally, it is getting evolved in to 802.11 ax which is supposed to get finalize sometime next year. So, all of these are still having OFDM as their primary base line physical layer. So, there is the huge number of devices which are going to operate with OFDM. There is a huge number of device which is already operating with OFDM. So, it is very important that we look into it understanding it in such a details that we can take care of the problems which it is still facing.

The wireless metropolitan area network also used OFDM. So, you can say that almost every broadband axis system is using OFDM and it is popularly known as WiMAX. This particular name is more popular just like Wi-Fi was more popular instead of 802.11 a. WiMAX is kind of more popular in this domain and it is the 802.16 series of standards primarily e802.11 m which was the contending technology for 4G and this also branded as the 4G technology. So, what we see is that there is a huge number of different standards which are using OFDM because of several advantages right. So, we will get into the details and see how it is helpful.

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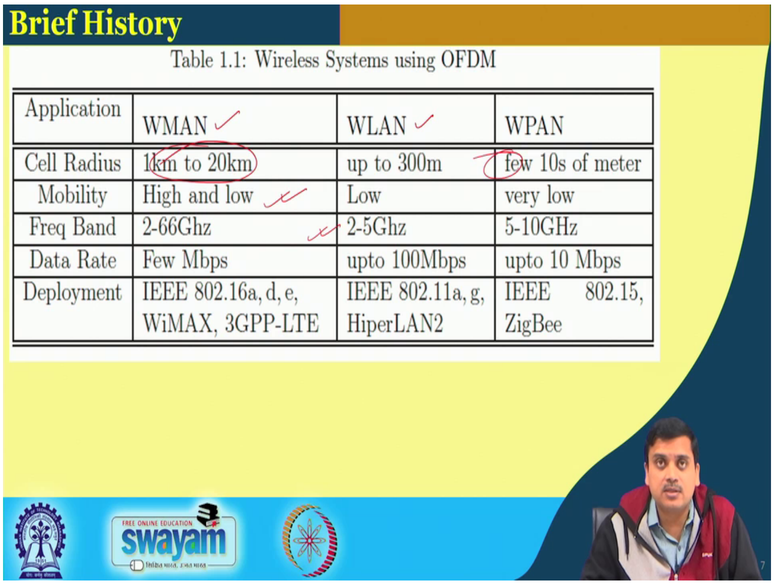

So, just a brief comparison of the application scenarios, what we see is that it is used since it is used in WLAN, WMAN and WPAN. So, right from cell radius of a few kilometers up to few 10s of meters of distance, it is useful and it could support high and low mobility right and it could also operate in different frequency bands.

So, these are so, it has a huge dynamics city associated around with it, as a huge flexibility and all although it is. So, easily said and done. It is important that we get into the details of how it operates and what benefit it brings.

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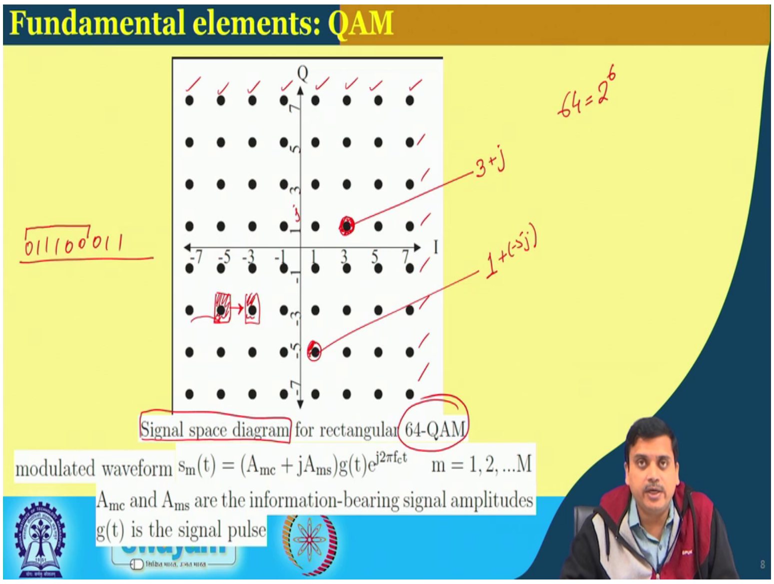

So, since we are talking about the IMT advanced or fourth generation communication systems and we have said that this particular air interface brings in a larger amount of spectral efficiency, higher amount of spectral efficiency amongst the different things which brings in spectral efficiency we had showed QAM. So, quadrilateral amplitude modulation what we see over here is the picture of a 64 QAM signal space diagram.

So, that is also written over here it is a signal space diagram for the 64 QAM and you can you count there are like 64 such dots 8 across column wise and 8 across row wise. So, they are 64 in all and each position in this particular constellation diagram indicates information carrying symbol. So, this particular signal for instance would be having the notation 3 plus j because this is the jth j axis the i axis this is the j axis and this particular signal constellation is going to be noted has 1 plus rather minus 5 j right.

So, like this you going to have all this constellations mart and depending upon the bit sequence that comes in 0 1 1 0 0 whatever it is one has to take 6 bits; at least 6 bits at a time because you have 64 which is equal to 2 to the power of 6. So, 6 bits are required to select one of this points and the way this points can be arranged like gray coding can be used where the difference between the neighboring symbols is at most 1 bit.

This is also very important because it could reduce the error probability when there is a symbol going into error. So, if you are decoding let us say this particular constellation point and instead of this one make some mistake of decoding this constellation point at most one bit would go into error if you are using gray coding methodology. So, this is something which we have studied in digital communication which you know. So, it applies directly in such systems.

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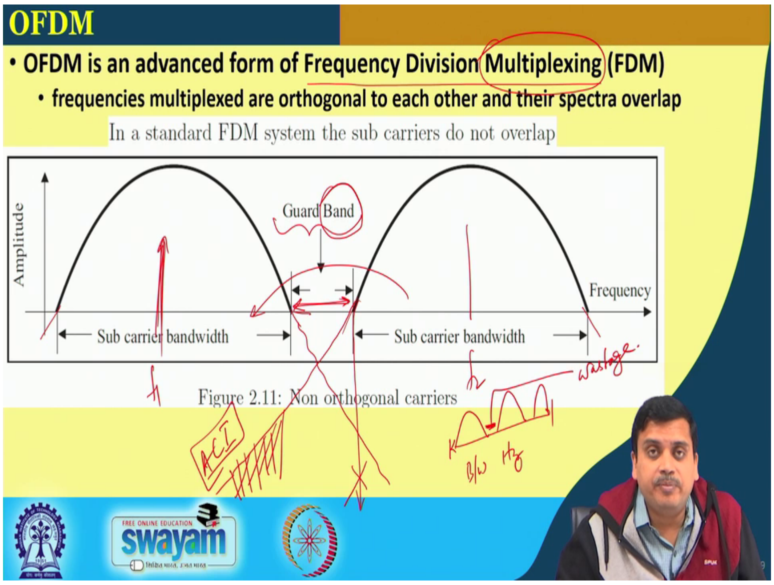

So, now, when we start discussing OFDM in details as the name reads out the most prominent part is to be remembered is a frequency division multiplexing. This is very very important. So, what it means is that there are different carriers and these carriers are multiplexed. So, since we are talking about carriers it is a frequency carriers there frequency division multiplexing.

So, when we look at classical frequency division multiplexing system, we have one carrier here let us say f 1; another carrier here f 2 and this is the spectrum occupancy or the spectrum characteristics of each of the carriers. So, to avoid signals from leaking one into another; one would specify a certain amount of guard band. The reason one has guard band because let us say the signal dies out like this right.

So, when one is demodulating this particular desired signal, one can get a significant amount of adjacent channel interference. So, one can get adjacent channel interference. To avoid adjacent channel interference if I increase this separation to a good amount, then the amount adjacent channel interference can be reduced. Because under all circumstances it is never possible to have a ideal nitro filter; that means, one which falls down vertically this kind of a thing is not possible.

So, one would always get a stretch in the frequency domain. So, one way to reduce the stretch one way to reduce the overlap is to increase the separation through guard bands. So, if one does this one can clearly see that this is something which one has to used only to improve the signal quality and why are we looking at this because it is band. It is a band of frequencies spectrum is very very costly, we all know this thing very well.

So, better ways to improve or improved ways to utilize the spectrum is like very much important and we have said that spectral efficiency is one of the terms. So, we will talk about spectral efficiency what we effectively mean is that given a certain band width. So, this is a certain amount of band width it given in hertz. So, if I am using spectrum like this. This is simply wastage, we can call this as wastage because you are not using it to send information or rather you are using it to increase the signal quality which you have to in order to maintain the QAS.

So, when we look at OFDM, things are better its one reason for using OFDM because it is the best possible modulation or multiplexing method which will give the highest possible spectral efficiency.

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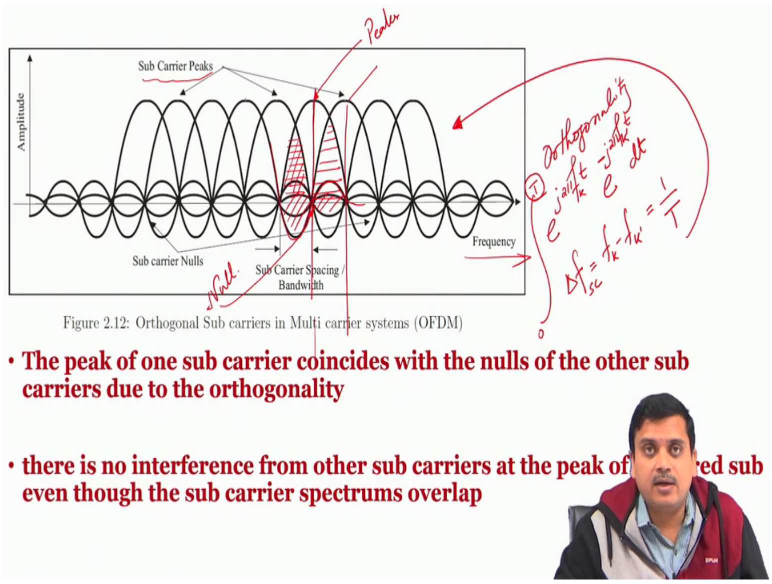

So, if you look at OFDM what we find is that this is again the frequency axis as the same as in the previous picture and the spectrum overlap what you see is that this spectrum, there is an overlap clear overlap. So, if this is my desired frequency of operation what you see is that this portion there is an overlap of the adjacent channel frequency and there is an overlap of the adjacent channel frequency on the left and right hand side both.

Also the other components that means, if we take this particular carrier; this carrier is also going to produce interference. So, there will be a lot of overlap. But now, although we are doing this so, compared to the previous picture, the advantage here is that if this is the desired peak as has been pointed out the sub carrier peaks; what we see is that the null occurs at this point, there is a null.

So, null means all the different sub carriers they have a 0 crossing at this point. So, if they have a 0 crossing when we are using this particular carrier to demodulate the signal, we are not going to any impact of the adjacent channel interference. So and why can this happen because we have already discussed the orthogonality criteria. We discussed in a previous class and we also mentioned in todays beginning part that each of this carriers which you are calling as sub carriers, they are e to the power of j 2 pi f k t and the neighboring carrier is e to the power of j 2 pi f k prime t right.

So, if we try to see the projection of one on another and take the integration over the interval 0 to t and this is exactly what we have done to check the orthogonal, we have to find the condition for orthogonality. So, the condition for orthogonality met gave us that if f k minus f k prime should be equal to 1 upon T. This is the same symbol duration T that we are talking about this is basically the sub carrier spacing.

Then, one can get orthogonality. So, we have used these criteria to get our signal. So, since we have used this criteria to get our signal this would obviously, mean that they are overlapping with each other because the sub carrier band width is kind of spreading on both the sides; whereas, we are placing the sub carrier at half that interval.

So, although they are overlapping by virtue of orthogonality one is not getting any influence of any neighboring sub carriers. So, this way one can save a huge fraction of bandwidth and this is the smallest spacing that one can think of when we discussed MSK we did say that minimum term comes because of this smallest separation that is possible and that is by virtue of orthogonality.

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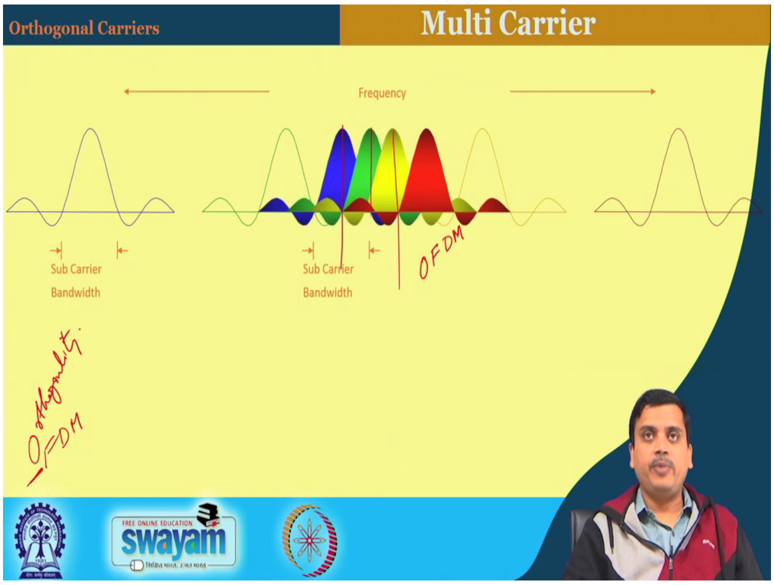

So, this is animated picture which helps us understand what is actually happening. So, this particular version is kind of general FDM you can say and if you will let change the what you will find is that now these are orthogonal to each other. That means, the peak is coinciding with the nulls of all other sub carriers and then what we result is in OFDM. So, basically in this blank this orthogonality has come in to give us this particular result and as you can clearly see that there is a huge saving in bandwidth by virtue of using orthogonal carriers and although they are overlapping, they are not interfering with each other and one can decode the signals.

So, this is one of the main reasons why OFDM is. So, popular and its being used as a major technique in all possible broadband wireless communication systems, where spectrum is very very costly and one would like to make the best use of such a spectrum. So, we close this particular discussion over here and we will take on further discussions in the future lectures.

Thank you.