Evolution of Air Interface Towards 5G
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Lecture – 11
Fundamental Framework for Waveform Analysis

Welcome to the lectures on Evolution of Air Interface Towards 5G. In the previous lecture, we have started discussing about the basic framework or the signal model which is the primary framework based on which we will study the different waveforms.

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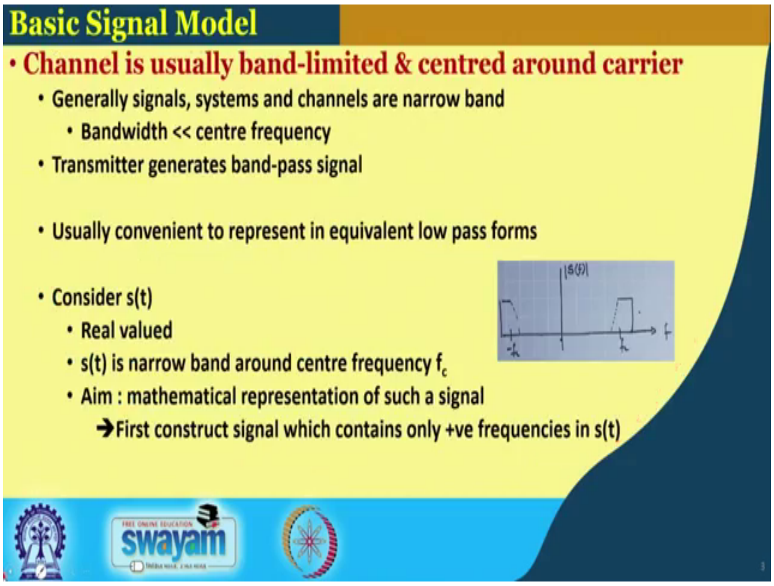

And what we have done in the previous lecture summarily is to discuss about how we set up the system model and we have started off with writing the expression for s of t as is shown in this particular slide, we have discussed this in the previous lecture.

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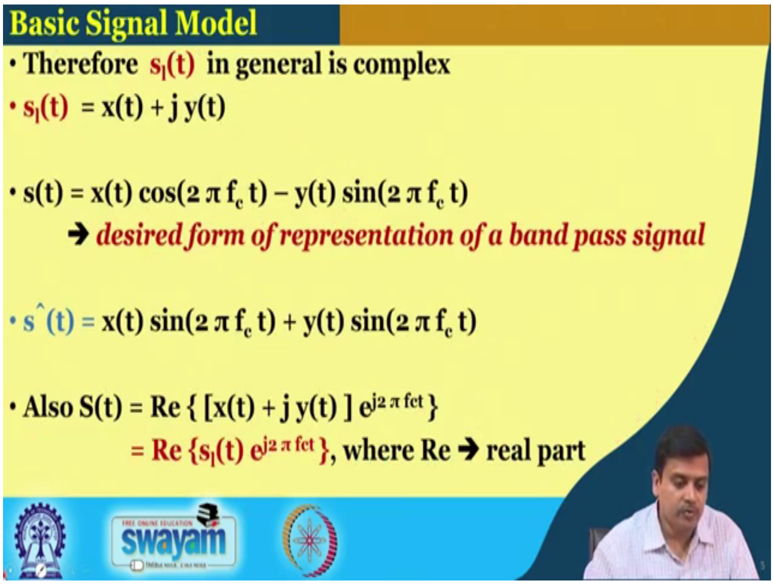

And from which we were able to get the expression of s t which is the band pass signal in terms of the expression which is here where we have the quadrature carriers cosine and sin and we have information bearing signals x t and y t. So, and the h s cap of t which is the Hilbert transform, you can clearly see its the cosine becoming sin and sin; there is a mistake over here, they should be cosine and so on. So, essentially we have set up the basic expression that will be required in all future expressions. So, we will follow this part.

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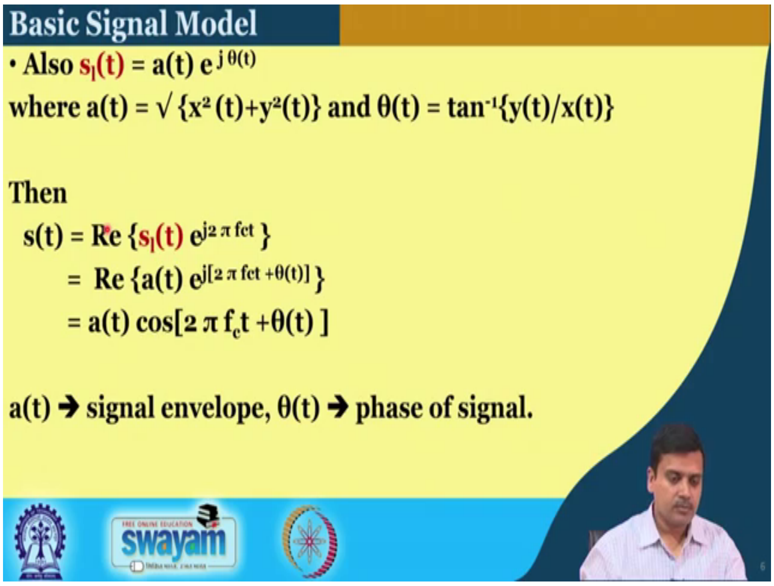

We also said that s l t being complex as was shown in this particular slide.

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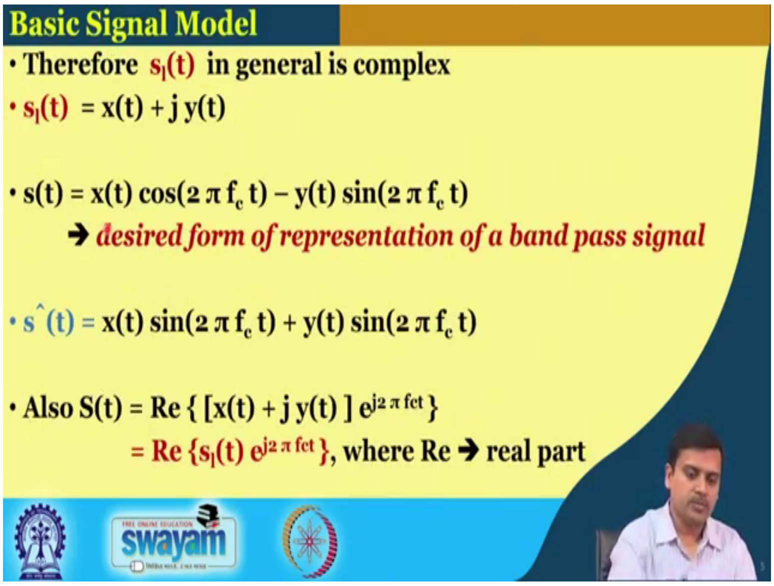

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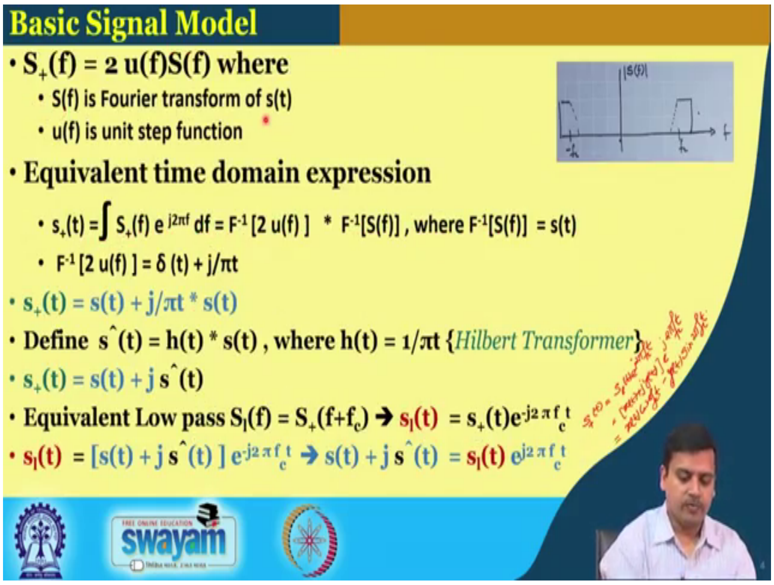

And the one before that s l t is in general complex as it looks over here and therefore, we could write it as in terms of x plus j y.

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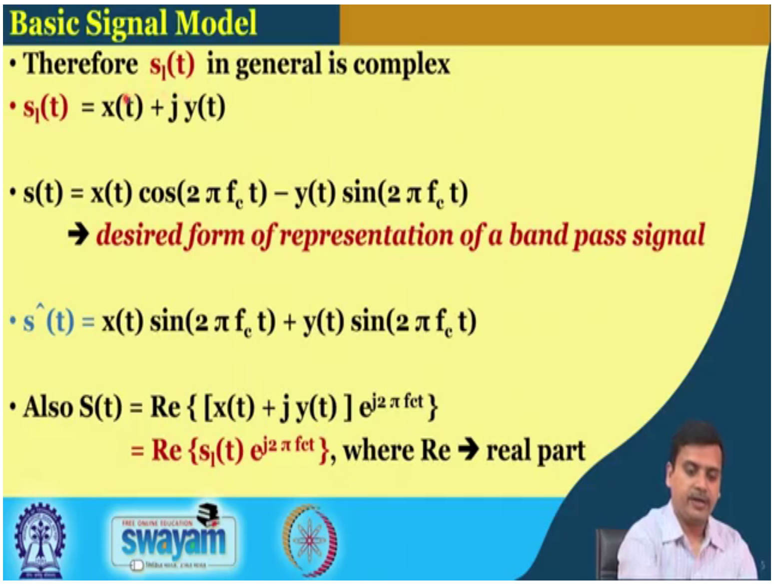

And hence we could also write it as at to the power of j theta t.

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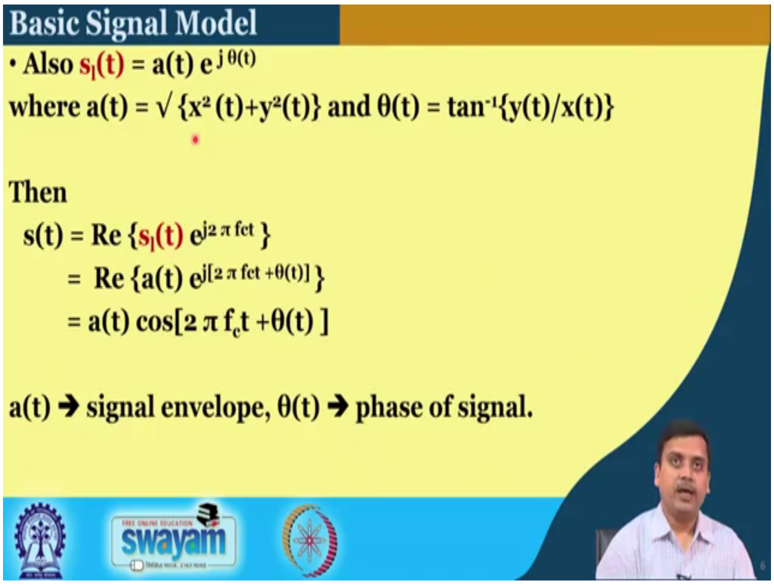

So, a t in that case would be related to x and y as square root of x square t plus y square t and theta t is tan inverse y t upon x t. So, by which we could also write s l t in this form. Now, once you write s l of t in this form then you could write s t as real part of s l t to the power of j 2 pi of c t. s l t you replace by a t to the power of j theta t as given over here and the rest of it comes in this part. So, since you are taking the cos, we discussed this earlier that a t you take the real part; therefore, we get the cos at is real cos 2 pi f c t plus theta t and a t is the signal envelope and theta t is the phase and when you do all kinds of modulation, will be concerned with these two things and the characteristics of the signal are dependent or you can describe them through the expression as given in this particular equation.

So, now, will again briefly look at the baseline simulation sorry baseline modulations because we would ramp up from almost ground 0, but we will do them pretty quickly so that we finally, arrive at our destination and look at the key features what we want to aim at.

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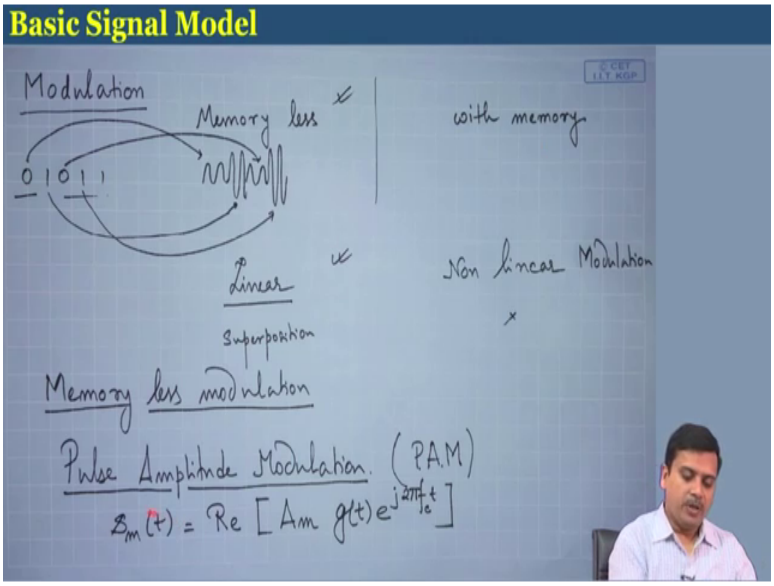

So, a basic one that we all know that there are different kinds of modulation that is with memory, without memory less modulation and with memory modulation and in Memory Less Modulation every symbol or every group of symbols or other bits go into a symbol duration and the next symbol duration which takes the next few bits are independent of any previous output. So, that is a memory less. So, the current output does not depend on what has happened in the past and usually I mean they are linear system. So, you have a Linear Superposition theorem applying on them and things are more or less quite easy to analyze and they have their own issues along with that.

So, this Pulse Amplitude Modulation is one such method; whereas, there are other methods which use memory in the modulation and they are generally the class of non-Linear Modulation and so, they have distinct features, although this is generally followed. So, what you will find is that when we talk about the fourth generation system that is anti advanced, they would be they are using the class of memory less modulation. Whereas, if we look at the second generation, it is with memory modulation because of certain constraint and as we were discussing in the previous lecture that the upcoming that is the next generation beyond what is probably in 5G, we also expect with memory modulation.

So, that is why we would like to go through this basic structure so that we are equipped. So, the basic framework to handle both of them and get insights about how and what is the benefit of different kinds of these systems and how do they influence these anti advanced and the next generation communication system?

So, the pulse amplitude modulation is straightforward where you have the amplitude and this is the gating pulse or the pulse shape and this is the carrier. So, this A m carries the signal and this is the s m t that is the mth signal going in the pass band is represented in this form, which is straightforward extension of what was before. So, in the expression here we had a t. So, a t is essentially A m which is the fixed amplitude and g t is the pulse. So, it is the pulse amplitude modulation, amplitude of the pulse getting modulated pass band signal; therefore, we have the real.

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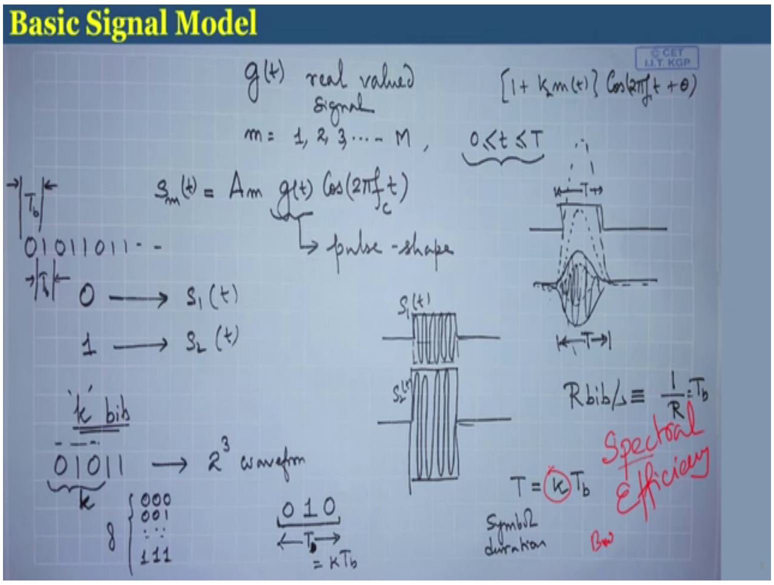

And the g t is real valued and we can also look at the standard amplitude modulation with this and more or less how the signals would be is you have the pulse, there is a certain carrier given by the cost 2 pi f c t which is due to the real part of this and as the amplitude changes, either it could be small amplitude or large amplitude. So, this is S 1 this is S 2. So, for 0 you could have S 1; 1 you could have S 2 and so on and so forth. And if you have more number of bits coming into one symbol; so, if there are 3 bits that go into one symbol, then you have 2 to the power of 3 different waveforms or 8 different combinations or 8 different levels, 8 different amplitude values and we look at pass band signal.

There will be different amplitudes, 8 different amplitudes; all having the same carrier frequency. So, that is how the thing is and the symbol duration will be K that is number of bits per symbol times the bit duration. So, that means, if I increase K, then effectively I am increasing the symbol duration. So, if I am increasing the symbol duration, I am effectively reducing the bandwidth right. So, if we have a smaller bandwidth, then in order to send more and more bits; you would have to go for higher and higher bits per symbol duration and have more number of amplitudes. You could use quadrature amplitude so that you could pack more bits into the system.

But overall the structure remains the same and hence to increase the spectral efficiency that is one of the terms which we have seen before that means, if you are interested in increasing the spectral efficiency, we have seen this term before bits per second per hertz. So, in this case our bandwidth if it is constrained; that means, it is a fixed bandwidth then simply to increase more bits you keep increasing K and thereby, you can increase the spectral efficiency. Of course, the energy consumption also goes up. So, when if you are looking at energy efficiency, then these two things are probably at conflict and there is suitable design has to be done out of this ok.

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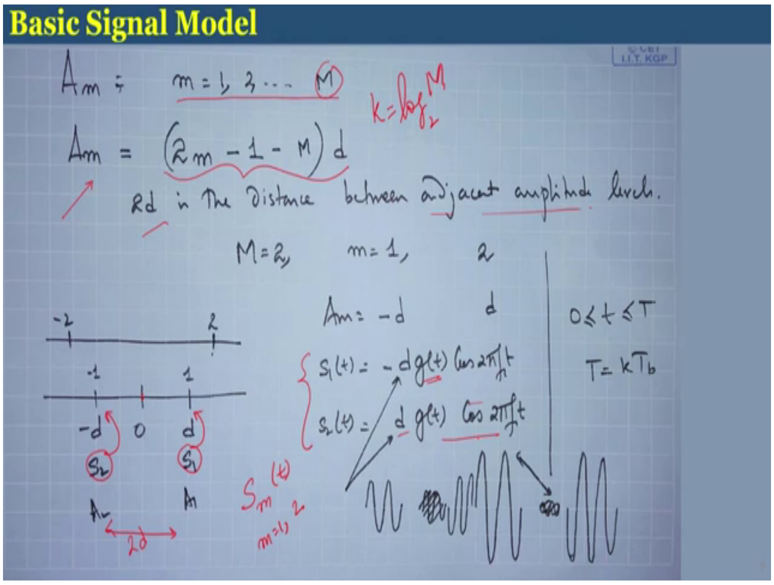

So, now moving down further, again this framework will be useful finally when we get into the more complex waveforms. So, A m that is what we have mentioned earlier will take different values according to the changing values of small m which can go up to capital M and number of bits that go per symbol, it can typically be represented in this format ok. Log base 2 of capital M and you could assign the amplitudes as per the expression which is again pretty standard and well known expression, available in generally textbooks for digital communications.

So, in this we will find that 2 d is the distance between the adjacent amplitudes. For binary case, this is the simple structure that is this is the 0; this is a symbol S 1 which is having an amplitude of d. S 2 having a symbol amplitude of minus d. So, the distance between them in this particular picture is 2 d and this is a very basic implementation and as you can see if I put S 1 as d and S 2 as minus d, our S 1 of t and S 2 of t that means, S m of t; m is equal to 1 comma 2 is what we get minus d. I mean it has got swept over here times g t. g t is the pulse shape we will see the effect cos 2 pi f c t and the other one is d cos 2 pi f c t. So, this is a basic framework which can be simply extended and the spectral efficiency can be improved.

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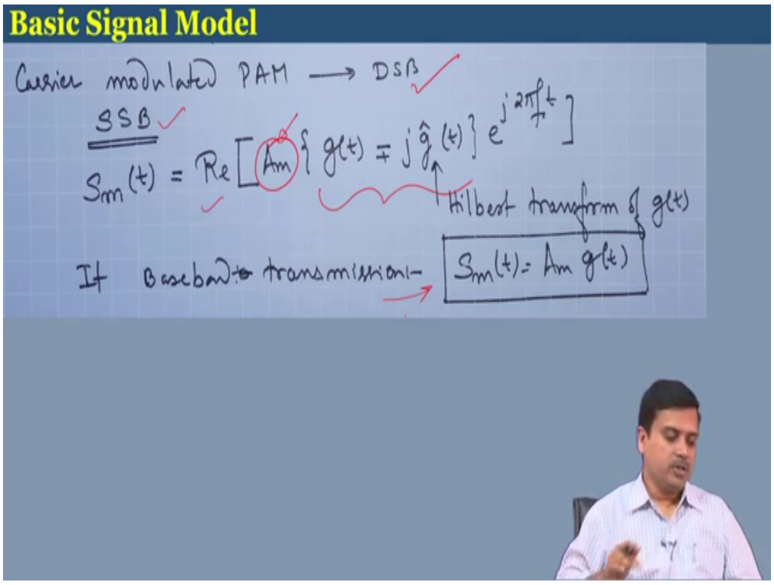

So, when we when you are doing carrier modulation with pulse amplitude modulation, we get DSB that is Double Side Band and in order to reduce the bandwidth occupancy, you can go for a single sideband and in case of single sideband your signal would be like A m and the pulse shape folded and you have a real part of it. So, thereby you have single sided spectrum.

So, you can clearly visualize this particular picture with respect to the signal representation that we had done earlier for s s of t which had s s t plus s l t plus j s cap l t and that is similar to what we are representing over here. Only thing is that on both the real and imaginary it is the same information, then only we are able to do it and in basement transmission, it would appear in this form.

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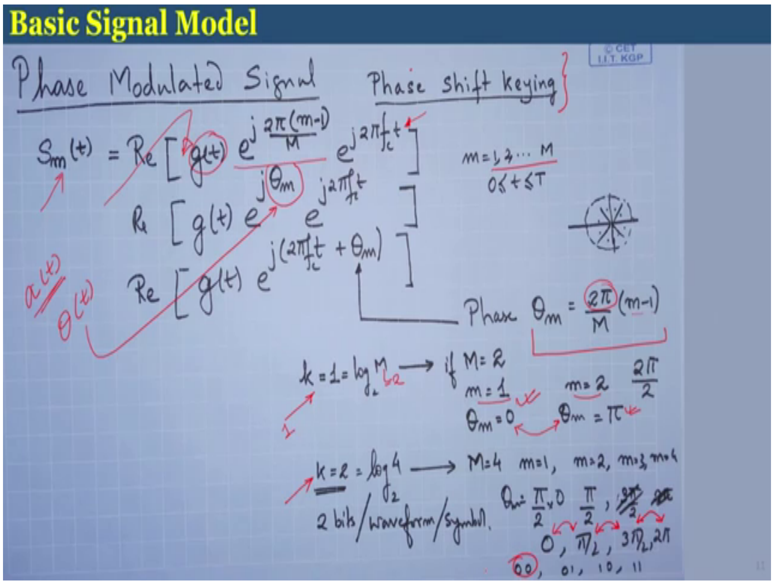

So, these are some of the things which we already know and then, the next important thing that we are going towards and it is very very valid in terms of our discussion for all the things is the phase modulated signal. In phase modulated your g t is the pulse shape and you have a constant amplitude. So, in this representation, it is 1. Whereas, there is a phase that is theta m which is being used over here f c is untouched. So, we said earlier that theta t could be modulated. So, here a t is constant; whereas, theta t it our expression is basically over here.

So, as we take different values of m; m going from 1 to capital M, we get different phases and you get phase modulated signals and in digital domain, it is the phase shift keying; that means, the phase shifts from one phase value to another phase value. So, as you are seeing that theta m can take these phases the 2 pi total phase available, unique phase available is divided by the number of possible signals and then you simply multiply by m minus 1 with varying values of m and you get the different phase values. So, for each phase value, you get a different waveform S m of t and you have as many waveforms depending upon the value of m and you can generate your signals.

So, if k is equal to 1; meaning 1 bit per symbol, then capital M is equal to 2 ok. So, in that case for m equals to 1 and m equals to 2, we get two different signals S 1 and S 2. For m equals to 1 clearly the phase is 0 and for m equals to 2 the phase is pi because that is what you get divided 2 pi divided by 2 multiplied by 1, it is pi.

So, clearly we have binary phase shift keying and again this particular waveform would have similarity with whatever we discussed in binary pulse amplitude modulation as well. So, they are identical in that sense; however, as we increase k ok. So, the 80 remains constant. There is no change over here; only the number of phases increase; so, at the receiver side, if I am able to distinguish between the different phases.

So, clearly as we see here the phase difference between the two signals is pi radians; whereas, here naturally it would be pi by 2 radians ok. So, the error probability here would be more compared to error probability over here because, these constellation are more closely spaced over here than this case. However, in this case every demodulation or every detection results in 2 bits of information thereby it increases the spectral efficiency.

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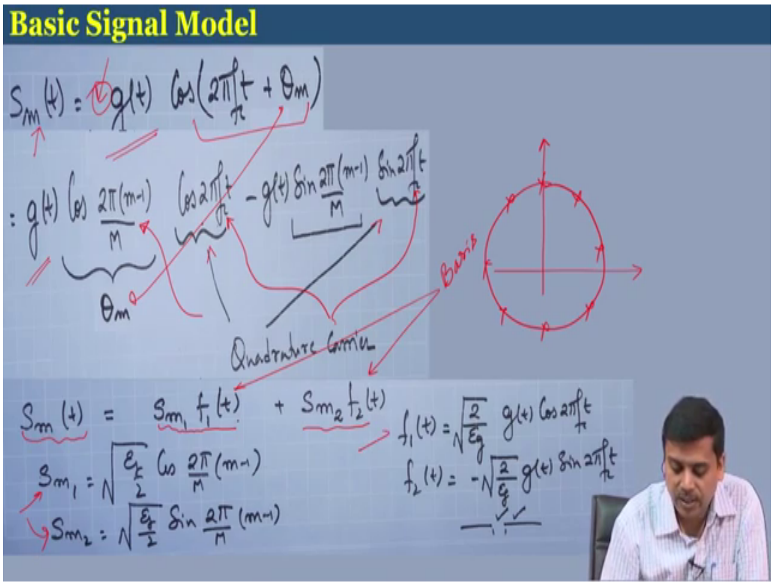

So, what we see over here is the generic expression that is S m t a signal is written as g t times cos two pi f c t plus theta m and you do not have any amplitude term over here. So, indicating it is a constant amplitude you can put one or any other value of your choice and if you expand this term, you are going to get g t which is the pulse cos 2 pi m minus 1 upon m plus cos theta and another term over here.

So, what we see this can also be represented in terms of quadrature carriers because this is the carrier frequency f c ok. So, what we had seen is Quadrature Amplitude Modulation. In this case it is a kind, it can be seen in terms of quadrature amplitude modulation, but the amplitude modulating signal is different than what is used in the other case. So, here this is the amplitude modulating signal and rather it comes effectively from the phase value ok.

So, now, S m t that is the signal that we have can be written as S m 1 f 1 t plus S m 2 f 2 t, again from classical way of writing down digital modulations. So, here what we have is f 1 t and f 2 t are the two basic functions ok. So, basis functions one indicating the cosine carrier; one indicating the sin carrier and then, there are different phase values. So, effectively you have your signal constellations on the unit circle. If you increase the number of modulations to number of bits to 3, then you get 8 such things and you have 8 psk which we are going to see shortly.

So, if it is. So, here what you clearly see is that this is one of the modulating signals; this is the other modulating signal. This is one of the pulse shape sorry this is one of the basis functions; this is the other basis functions and through this you are able to generate the signal in terms of modulating the basis function.

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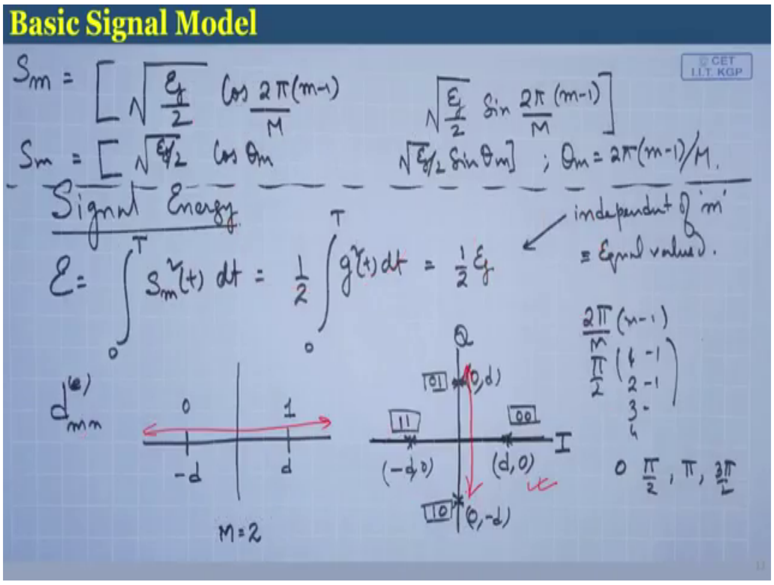

So, as we move ahead what we see in this particular picture is the 4 psk diagram and there are certain basics which I can skip for the discussion in this particular series.

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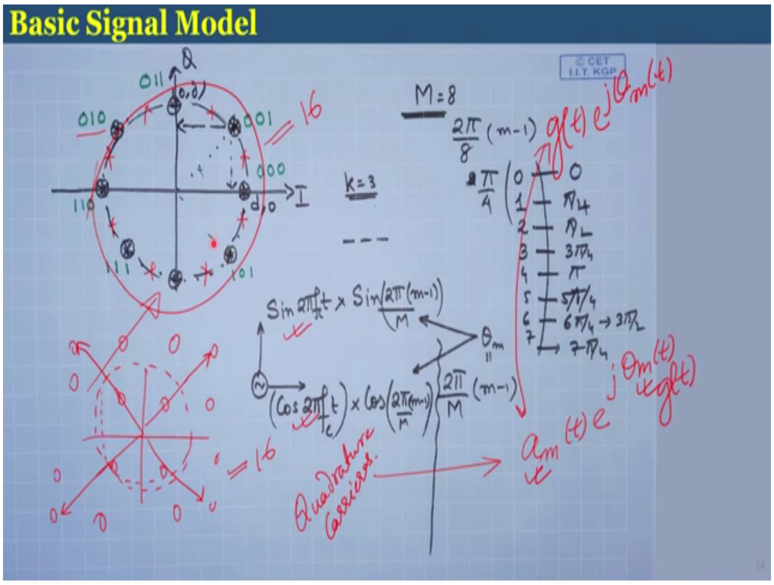

So, what we have over here is the 8 psk model. So, what we see is that at every signal interval there are 3 possible bits that can be used because you have 8 possible levels if you have 8 possible levels, then you need 3 bits to identify the 8 different levels and thereby, you have the 8 psk constellation. Now, this signal constellation is available for use in edge systems which is an enhanced version of 2G in order to use in order to provide better spectral efficiency because the general second generation communication system is not very spectrally efficient although it is bandwidth efficient.

Now, one of the advantage of using an 8 psk is that it is compatible with the bandwidth occupancy of a typical 2G system. So, it does not play around with that. One of the big things is that you can see it is a constant amplitude, the amplitude is not changing. So, the big advantage because of this is the peak to average power ratio is controlled in this kind of a constellation; whereas, if we take a constellation where if we have let us say 4 constellation points over here and some more 4 constellations some more signal points like this.

So, this constellation if I compare this with a 16 psk; that means, if I put in additional constellation points, what we find is that both these systems after agree with the red color, it can take 16 different signals and this can also take 16 different signals both can be represented by a cos 2 pi f c t plus sine 2 pi f c t. That means, both have quadrature carriers ok, but when I compare this and this there is lot of fluctuation in the signal amplitude. So, this mode is to be written as a m t e to the power of j theta m t; where, a m and theta m both vary. Whereas, in this system you would simply of course, there is a g t term which is associated; whereas, if you look at this system it will simply be g of t e to the power of j theta m t. So, here there is no amplitude fluctuation.

Now if you have a constellation which is of lower amplitude fluctuation because here if you see some average level would be somewhere here ok; whereas, there will be fluctuations of peaking amplitudes whenever these constellations are selected right. So, whenever these constellations are selected the amplitude peaks and this would result in non-linear distortions if the power amplifier is operating near saturation. Whereas, here such problems are generally avoided when we are getting into systems where there is constant amplitude such as this particular constellation. So, this particular constellation is more suitable to use along with the second generation system.

So, when second generation systems started providing access to data, they introduced this kind of a modulation so that it is compatible with the earlier modulation format with the bandwidth as well as there is not extra requirement of PAPR. So, the signals can easily be decoded within the same receiver structure. Whereas, if you look at IMT advanced like systems, they use constellations which look like this with this. This particular picture is a 16 QAM picture and PAPR requirements are higher.

So, it is a its a more relaxed system design, there is a more constraint system design and what you will see is that future generation systems are looking towards design of constellation and signal space where there is lower PAPR and lower bandwidth occupancy. So, that means, the foundation or the constraints that were experienced by the second generation system are also being looked at as vital configurations and which could serve as a basis of course, with lot of enhancement and extension towards the next generation systems which have broadband and much larger bandwidth to operate, but overall constant properties remaining the same.

So, from this at least we get a basic idea of what are the factors which trigger higher PAPR or which triggers the need for more bandwidth and how you can conserve the bandwidth and things like that ok.

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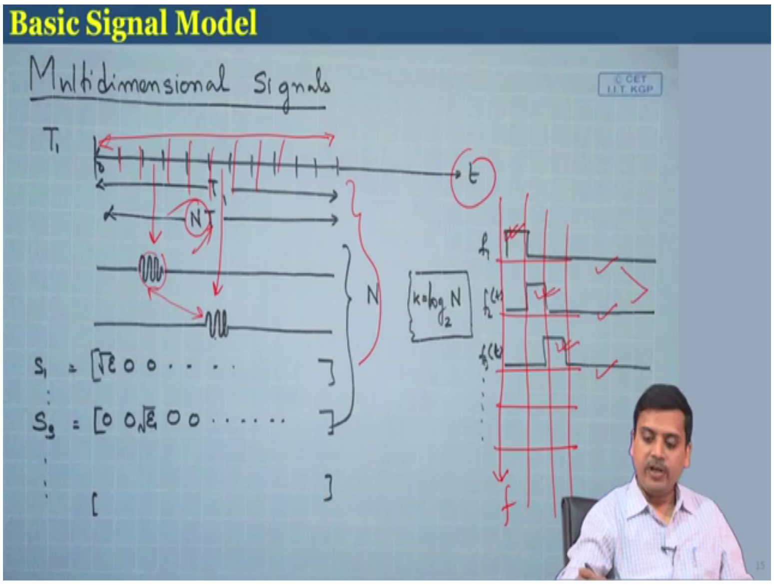

So, at this point we move now beyond whatever we have discussed to something known as multi dimension signaling. So, in the previous expressions what we have seen is that there are 2 basic dimensions right. So, there are 2 basic dimensions. So, in case of PAM, there is only a single dimension one-dimensional. In case of PSK, we can think of two-dimensions and in case of QAM which we have described earlier; we can also have two-dimension.

So, what we have seen in this particular picture there are two-dimensions that is one along this axis; one along this axis; this is also two-dimensional. So, what we are going to discuss is something just beyond two-dimensional. Yes, you can have multi dimensional signaling. So, let us look at the framework because that is again the basis for the next generation systems.

So, in multi dimension systems the concept is not very complicated, but we look at a time duration let us say a T 1 which is represented over here and we divided it into smaller chunks of duration T. So, it is effectively there are N number of such chunks available and you have N such signals that you can choose from and which are orthogonal to each other. They may not be orthogonal to each other, but you can choose them to be orthogonal to each other as well. So, here if I am sending a signal in one of the intervals and in this case I am sending a signal in another of the intervals, then we are able to detect the signal by virtue of being present at a particular time slot. It can also be looked at as a pulse position modulation if you want to put it in that framework, but it is a generic framework of representing things.

Now, instead of writing it in this form; instead of time you could also replace this with frequency. That means, that in this axis which is the frequency axis. So, there will be multiple such frequency options available and one could choose to use any one of the frequencies in every signaling interval. So, what we see in this particular picture as is over here is that in this time interval only frequency f 1 is chosen. In the second time interval only frequency f 2 is chosen and just for the sake of diagrammatic representation in the next interval f 3 is chosen. .

So, in a similar manner you could extend to in other dimensions. So, here you are you are having more than one basis function to describe your entire set of signals. One could also choose to use a linear combination of these different basis functions at the same time as well. It depends upon the type of application, but with this framework, we are now geared towards looking at systems where multiple carriers may be present or different frequencies may be used to separate or identify the information bearing signals.

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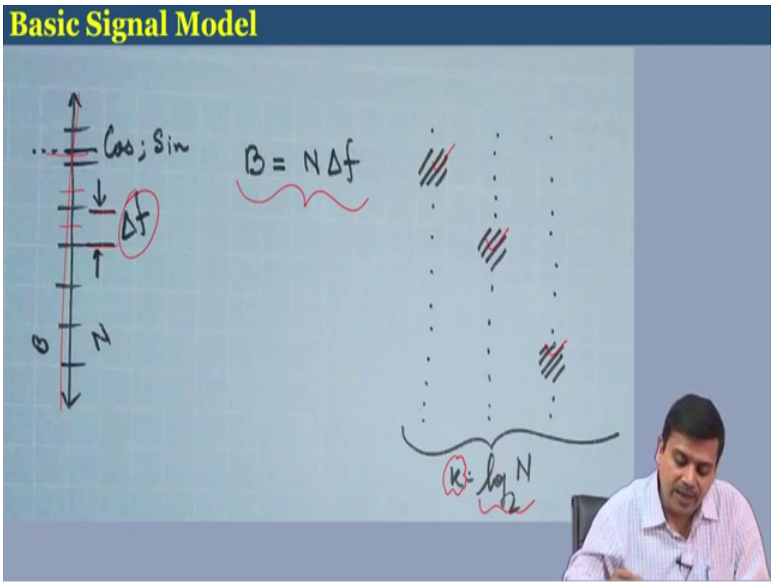

So, the this is this is the basic architecture that we are talking about that there is a frequency axis and sent of frequencies and the frequency axis is divided into sections where the bandwidth of each section is delta f and the total bandwidth is N delta f and overall you would have to select the different frequencies in different time intervals and the number of bits that may be required to select the particular signal is log base 2 of N. Because I have N possible signals and I choose any one number of bits required to represent is simply log base 2 of N ok.

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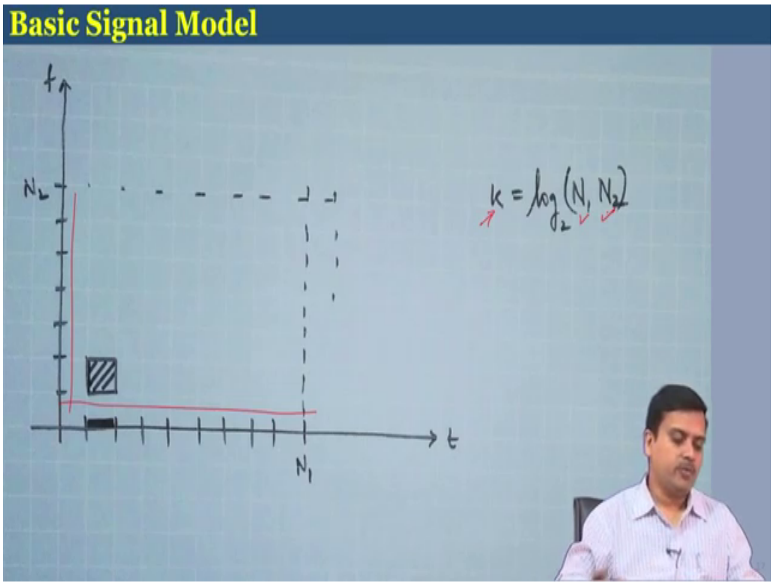

So, you can combine the time frequency together and you can have the frequency domain and time domain together; over all it is number of bits that you can signal over here is log base 2 of N 1 N 2. So, this is an extension of whatever we have discussed in the previous thing and you could use these modulation methods to signal to transmit information from one point to another.

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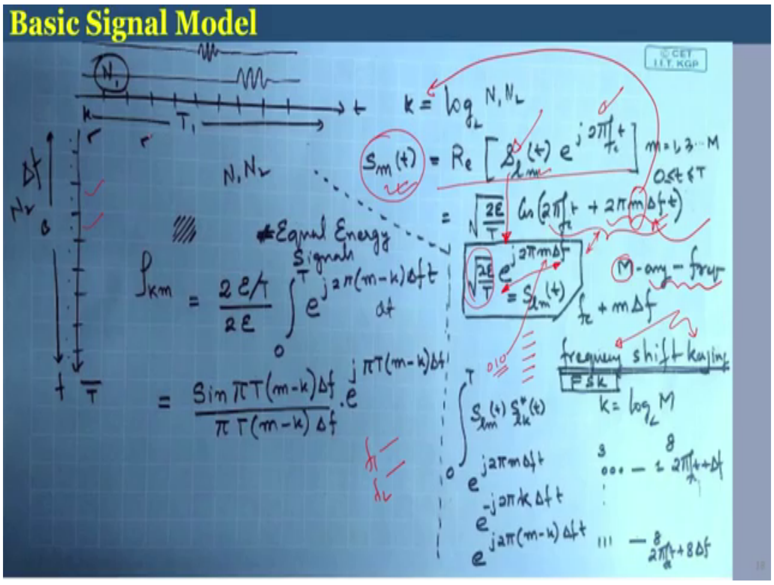

So, what we see over here is again the same thing, but here what we want to point out is that the transmitted signal is represented in a form which is very familiar to us that is real part of s l that is the low pass equivalent of the mth signal e to the power of j 2 pi f c t; where, we can see that we have 2 pi m delta f indicating the message. In other words, by choosing an appropriate value of m, we are in turn choosing the frequency of operation or in other words which particular band to be chosen and thereby, we are deciding our signal right. And every choice is composed of k bits and k bits depending upon the type of system, it could be log base 2 of N 1 or log base 2 of N 1 comma N 1 times N depending upon whether its multi dimensional both in time and frequency or only in frequency.

Now, if we look at the structure as is represented here where the and signal can be having a constant amplitude that is we are describing s 1 of m over here and its only the frequency component which is changing because of values of m, where the values of m is selected based on the bit sequence right. So, if there are 3 bits in the system, then we have 8 different frequencies to choose from and such a system if there are capital M number of such frequencies to choose from, we have M-ary-frequency shift keying.

Now this is a basis for the next important thing which we are going to see. So, in this M-ary-frequency shift keying what we would like to do is to look at a very specific form which has certain special properties. So, typical frequency shift keying, there is some relationship how to choose the different frequencies and frequency separation; but then, there is an interesting form where you could choose the frequencies of your choice; that means, of in the frequency shift keying in such a way that the frequencies are orthogonal to each other. If you are choosing the frequencies as orthogonal to each other, in that case you will be finding that you can operate with the minimum separation between the 2 different frequencies.

So, we would take up the conditions under which the 2 different frequencies can be made orthogonal which will lead us to the basic premise of the next generation of the second generation communication system which is also a fundamental. Or, for this particular discussion framework that we are looking at is also the fundamental framework based on which the fourth generation system or of dm is also designed.

Thank you.