Evolution of Air Interface towards 5G
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Lecture – 13
Waveform Design Aspects for 2G

Welcome, to the lectures on Evolution of Air Interface towards 5G. In the previous lecture, we have discussed about the framework for wave form design and we have seen the structure through which we are able to address a wide variety of wave forms and we have seen the baseline structure through which we can address multicarrier waveforms. So, we will quickly revisit whatever we have discussed in the previous lecture and we will continue with our discussion.

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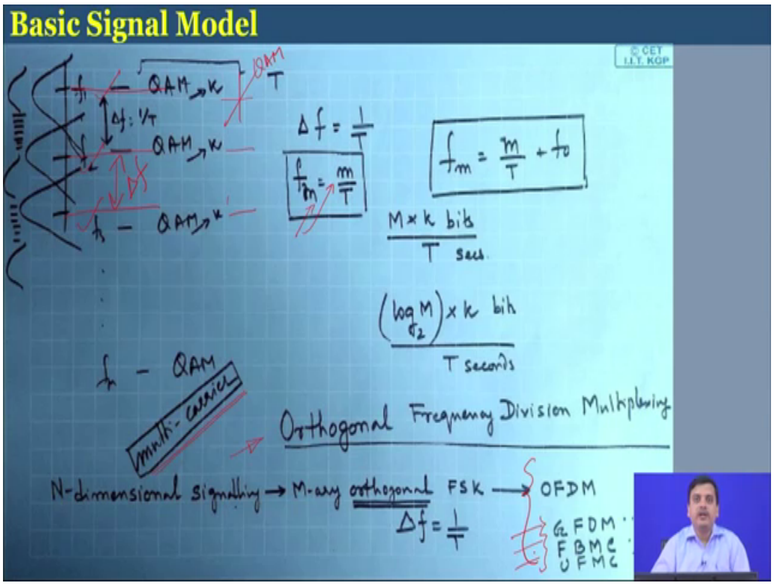

So, what we have discussed in the last lecture is that there would be multiple different carriers and these carriers can be orthogonal to each other in the way that the frequency separation is spaced so that it is 1 upon T and the m-th carrier is m times 1 upon T. And, there are two possibilities one is the selection of one of these carriers and that is FSK and the other option is that you can choose to use all of them while each one of them you can choose to do QA modulation and the second form translates to orthogonal frequency division multiplexing as well as this gives raise to the structure for the multi carrier communication systems.

And, we have also highlighted that this particular structure gives raise to various different waveforms which were contending waveforms for the fifth generation communication system. So, this with this base line structure when we revisit these details we are better equipped to discuss them in a more detailed manner.

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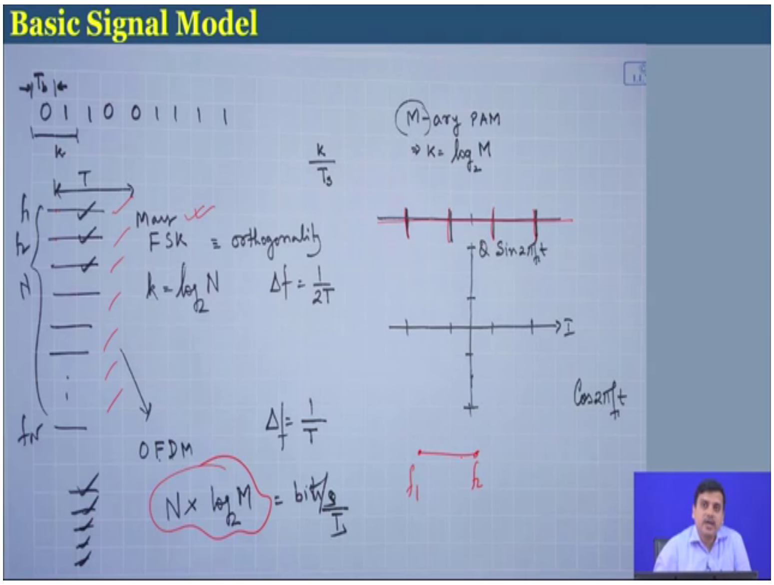

So, in the M-ary PAM case what we have said that each of the signals they occupy different amplitude values. So, instead of here as we all have been saying that each of the values are simply different choices and we have also discussed the bit rate that could be taken forward by this multicarrier waveform and also have compared that it is several times more than the bit rate that can be carried by M-ary FSK.

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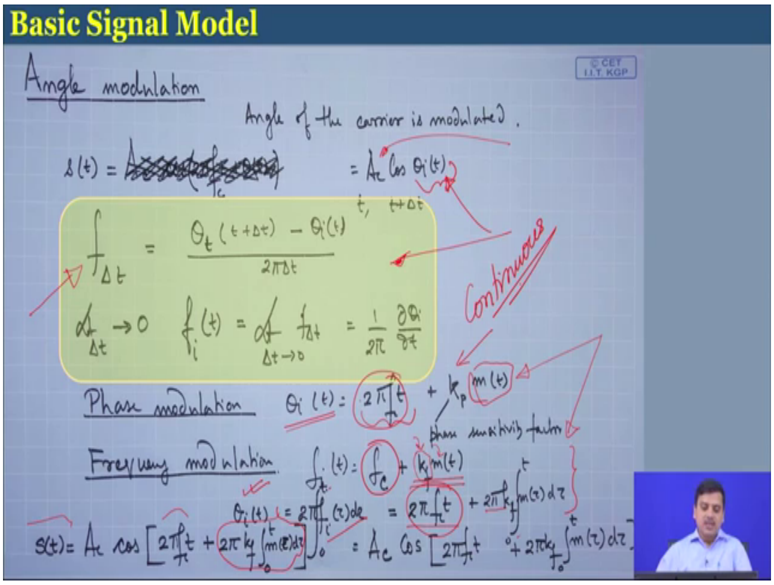

So, this is also what we have discussed in the previous lecture and now we move forward to the next important class that is the one which is based on angle modulation. There are some details which act as a fundamental triggers to the change or the wave form design for the next generation. So, in angle modulation we all typically know that the phase angle of this signal is modulated whereas, the amplitude is kept constant. Now, in the frequency modulation we have seen on FSK the frequency is modulated, but here it is the angle.

And, the rate of change of phase is the indication of the instantaneous frequency. So, in this manner if we do frequency modulation we also have some kind of a phase effect. So, I mean they are very difficult to distinguish and hence we have said that you do either phase or frequency along with that you can also do amplitude modulation. So, in phase modulation simply the total phase of the carrier or the instantaneous phase is consisting of the carrier terms which is 2 pi f c t, along with an additional phase term which is taken care of by the m that is the modulating signal.

And, we have discussed the 8-PSK structure before in the frequency modulation there is this f c and along with this there is the message signal which gets modulated with the particular sorry, the frequency gets modulated with the message signal and there is a certain scaling factor which decides the depth of the modulation.

So, if you look at the phase of the signal which is given by theta i t that is the instantaneous phase, you integrate from 0 to t 2 pi instantaneous frequency d tau and this results in 2 pi f c t which is the carrier term; that means, this term which is common with the phase modulation along with that we have 2 pi k f which is the frequency modulation index along with it an integration of the modulating signal. So, the difference with phase modulation and frequency modulation is in this particular term in one case it directly appears as a signal and the other case that is an integration of the term.

So, when we look at the s of t which is the past band signal as we have been discussing since the since we have been discussing the signal model we have 2 pi f c t that is the carrier term and the modulating signal which contributes to the phase in this particular manner, ok.

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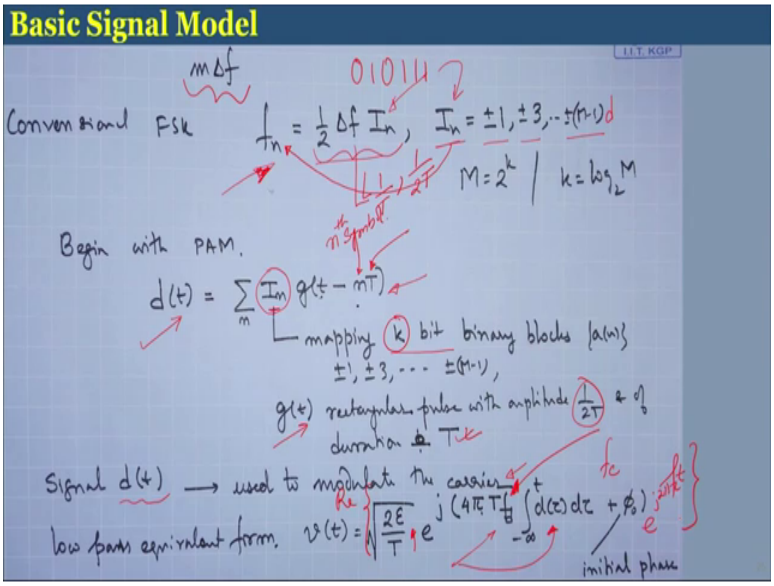

So, when we look at the conventional FSK: in conventional FSK as we have been saying the m delta f a are the different frequency values which are used and hence the f n that is the choice or the chosen particular frequency is decided based on the modulating signal. So, what we can do over here is we can have a pulse amplitude modulation of the initial bits. So, if there is a 0 1 bit stream that keeps coming those bit stream you can send it to a pulse amplitude modulation and whatever signal you get out of it or the discrete signal you can use it to choose the frequency through this particular relationship.

So, these values as in PAM can take plus minus 1 plus minus 3 plus minus M minus 1 and there could be another scaling d that gets multiplied and once you multiply with delta f then accordingly you can switch between the different frequencies what we have been discussing. And, this delta f can be chosen to be 1 upon T or 1 upon 2T depending upon the particular realization.

So now, what as we have just discussed we consider d t indicating the signals I n as described over there along with it let there be some pulse shape which is denoted by g t and T is the duration of the pulse and n indicates the n-th signal or the n-th symbol, and here when we choose this In it has the k bit binary block and this k-bit will depend upon the number of different frequencies that you are going to have in the system. Incase of rectangular pulse shape you can take g t to be 1 by 2T is basically constant in the duration of T and then you can set up your entire signal.

This signal d t can be used to modulate the carrier frequency and then we can have our conventional FSK can be realized in this particular manner. The low pass equivalent form of the signal because whenever we are discussing the signals we are always considering the low pass from which we have said since the beginning. So, what we see over here is the low pass equivalent form when f d indicates the frequency deviation corresponding to the k f notation that we had used in the previous page. And, what we see over here of course, there is no modification of the amplitude and the instantaneous frequency is dictated by the data signal.

What you can also see is that the baseband or the equivalent low pass form does not have any f c term which is quite obvious and pretty natural and expected. So, when you do an up conversion you simply multiply this by e to the power of j 2 pi f c t and then you take the real part of this, right and then you can generate your entire signal, ok.

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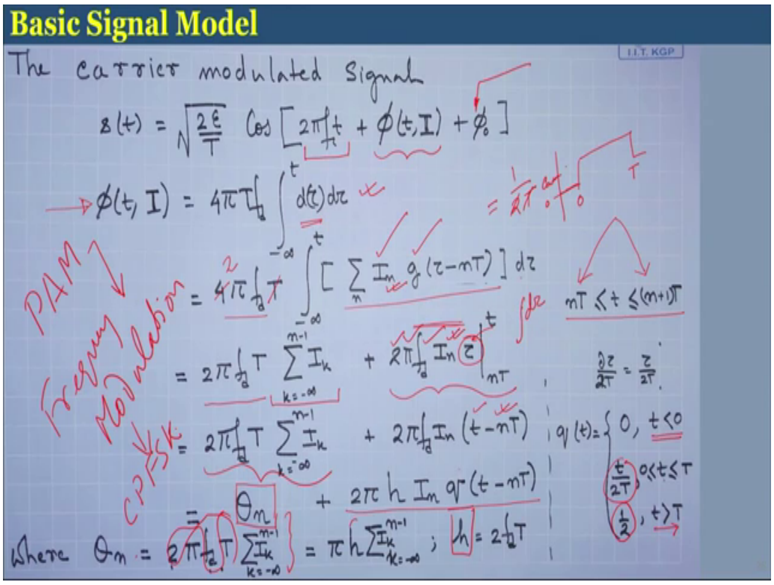

So, the carrier modulated signal you could write as we have just said that after you take the real part you get the cos 2 pi f c t term and there was this initial phase component which was available over here. So, this initial phase component is present over here ok. This initial phase component is available and this is the phase due to the modulating signal which we have captured over here. So, this is the expression which you have seen in the previous slide and then you can expand and see how this thing works out.

So, when you look at this entire signal the constant term is over here, we expand d t by definition as we have described over here we have defined d t in this particular line. And, hence we use the same d t over here we have expanded it over here which includes the pulse shape as well as the index of the modulating signal. So, now, if we are interested in the time interval which is between the n-th and n plus 1-th symbol; that means, the end of n-th symbol and it is moving to the next symbol we can expand or we can solve this expression and we are going to get 2 pi f d T and a summation of all the previous symbols I k from k equals to minus infinity to n minus 1 and the rest of the term is integrated from 2 pi f d I n and nT to t correct.

So, this particular thing we get because g t we have said is equal to 1 by 2 T this 2 and this 4 cancels to give a 2 term which we get over here this T and this T cancels out. So, there is no T term in this particular expression. There is no T over here if you are focusing on this particular part pi comes as it is, f d is present as it is I n because we are taking the n-th signal. So, I n and what you have is integrate d tau because it is 1 by 2 tau. So, you are left with integration of d tau. So, integration of d tau would be tau from nT to t. So, hence you have the particular first part which is as it is.

The second part 2 pi f d I n and you replace T over here you get a t and when you get when you replace tau with n T you get this particular form,. So, this part which is the prior part can be represented as theta n which is kind of the accumulation of the phase due to all previous modulations. Whereas this part what we have over here is the one which influences the current symbol. Now, this q t if you analyze for t less than 0, this has to be 0 because q t is integration of g t and g t is simply 1 upon T for the duration 0 to T, correct. So, there is a constant value below this before the value of 0 it is a value of 0 and here it is some constant value, ok. So, this is 0 less than for t less than 0 and for t lying between 0 to capital T it is t upon 2T and that is what we have utilized in getting this particular value.

Now, beyond t is equal to capital T you get a value of half with a sub replacement of the variables. So, therefore, what we can see is that the accumulated phase component is simply the expression which you have written over there and in this expression you integrate this T 2 and f d together and you represent that by the term h that is small h which you also call the modulation index. So, this is how we will expand the expression.

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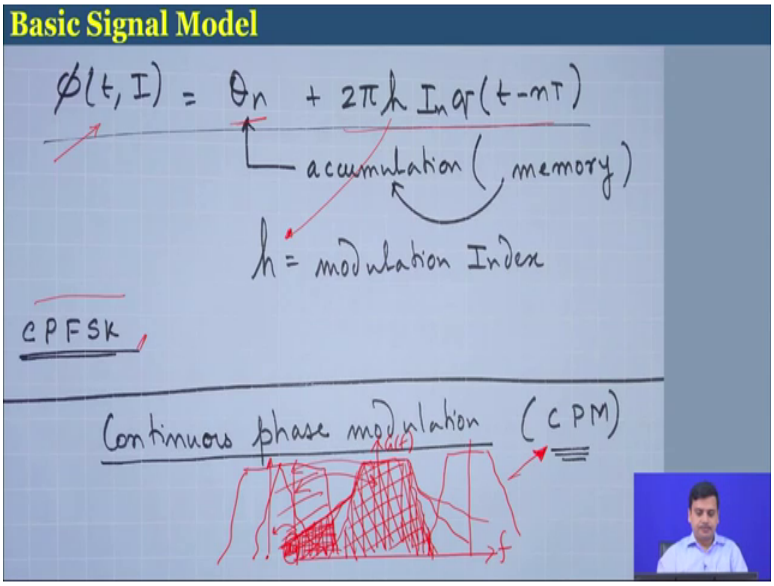

So, what we have is the phase term contains an accumulation of all the previous memory as well as the term on the right what we have over here where the h term what we just saw in the previous slide is the modulation index. So, depending upon different values of h you can get the different terms. So, in this manner what we have actually arrived at is something known as continuous phase FSK signal.

So, if we go back a few steps what we will find is that if you are doing instantaneous frequency modulation; so, if you are doing instantaneous frequency modulation through this; that means, simply you are choosing it in this manner then what would happen or rather if we were switching between the different frequencies so, at any one instant of time one would have to switch from one frequency to another frequency. In a very short duration, that is the duration of time when the pulse is changing from 1 to the next which is almost tending to 0, there is a huge shift in the frequency so, which gives rise to a huge amount of sideband. So, that is what is reflected over here.

So, if we see over here that the instantaneous frequency would go to very large values if we suddenly change the frequency from one point to another. So, if we do a conventional FSK communication then the bandwidth requirement is usually larger. Now, to reduce the bandwidth requirement what is done is the phase is kept tried to be made continuous.

So, to maintain the phase continuity what is done is the steps that we have visited; that means, we do a PAM signaling first, once we do the PAM signaling then we follow it with a frequency modulation. So, there is PAM followed by frequency modulation which would give raise to continuous phase frequency shift key. So, if we do continuous phase frequency shift keying we are avoiding the abrupt changes whenever the signal changes from one signaling interval to the next signaling interval. So, we will see the consequences of such of modulation format and such a modulation style very soon.

So, this CPFSK comes under the general class of continuous phase modulation systems. So, if you have a continuous phase modulation system the overall thing implies that there is no phase discontinuity. Now, the lack of phase discontinuity or rather if you have phase discontinuity then at every instant whenever there is phase discontinuity the bandwidth becomes pretty large and when we have to use the spectrum very efficiently we would like to have the signal part which goes outside the desired band of frequencies to be as small as possible.

So, typically you would have a certain spectrum of a signal which would appear let us say like this, this is your f axis and this axis is your gain or the spectrum of the particular signal. So, if you are doing instantaneous then your out of band emission is larger and if you would do continuous phase then you would have avoid abrupt changes and you could restrict your signal to a spectrum which is pretty well contained.

Now, if your single is pretty well contained then the neighboring channel which one has to send the next neighboring signal that will not have much interference from this particular signal; now you can clearly see from this diagram that if your spectrum would have been like this, then there would have been a huge amount of interference due to adjacent channel interference. So, if you have to reduce the adjacent channel interference then you have to place these two frequencies much further apart. So, now if you would have placed instead of here you would have placed this particular frequency over here then your channel would have appeared like this and then the portion of interference would have been restricted to only this much.

Now, if we could contain our signal to a sharper transition bandwidth right, in that case we could have the carrier frequencies which are in adjacent channels much closer to each other. So, this is one motivation why one goes for such modulation method. So, when we look at this second generation modulation schemes it is a class of CPM signal which was used. When we go to the future generation; that means, the fourth generation it comes under the orthogonal frequency spacing which also results in a very closely packed signal and if you look at some of the contending wave forms which were fighting for his position in 5G maybe they appear in 6G.

They include the orthogonal spacing; that means, the spacing maintained is orthogonal. However, along with that they use certain filtering techniques by virtue of which the signal one of the main objectives is to maintain the signal within a certain defined bandwidth, ok.

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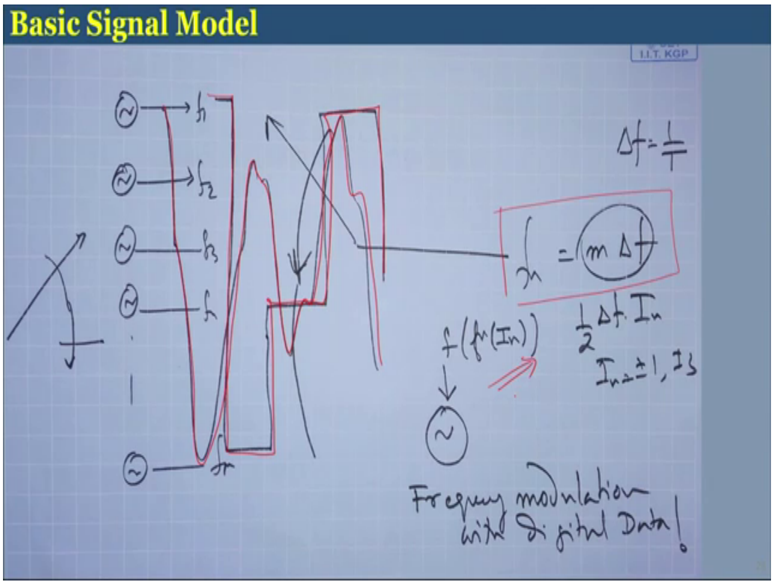

So, what happens here is kind of can be seen over here that instead of having instantaneous jumps from one frequency to another frequency what we have rather is a continuous sweep from one frequency to another frequency. So, if you have this kind of a transition there is more smoothness into the whole transition, obviously, it is expected that your, the bandwidth or the excess band width or out of band emission would be much lower than the system where you would have instantaneous frequency transition as in a conventional system, ok.

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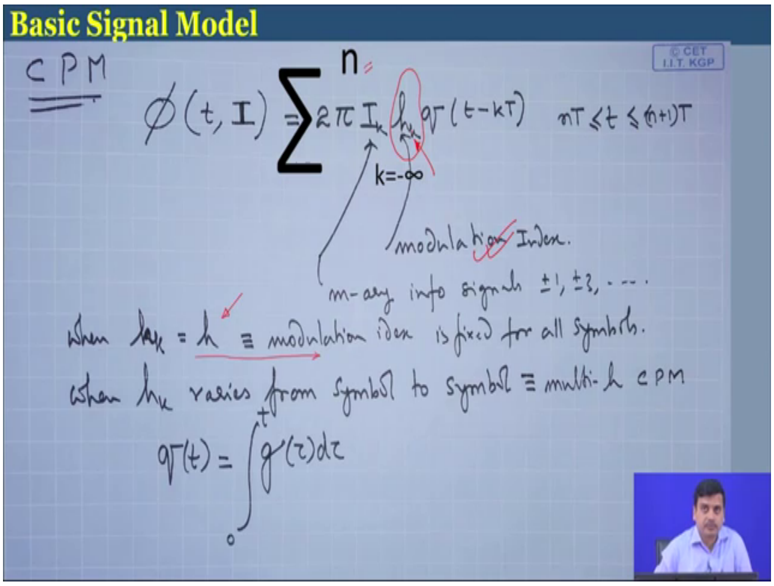

So, if we look at this CPM system now; so, the continuous phase modulation system has a generic form, you can easily see that this generic form captures from k equals to minus infinity up to k equals to n where as there we had separated out to k equals to minus infinity n minus 1 and we had an additional term. So, this is a more generic way of representing the whole thing where this is the modulation index and here as you can see that this particular h is also written with the sub k indicating that each symbol may also have a different modulation index.

So, the scheme that we will be looking at is the one which has the constant modulation index, right. So, that is what is used in the most commercial systems. However, if you have very specific requirement you can have a varying values of h if you want into the system for specific characteristics of the signal, right.

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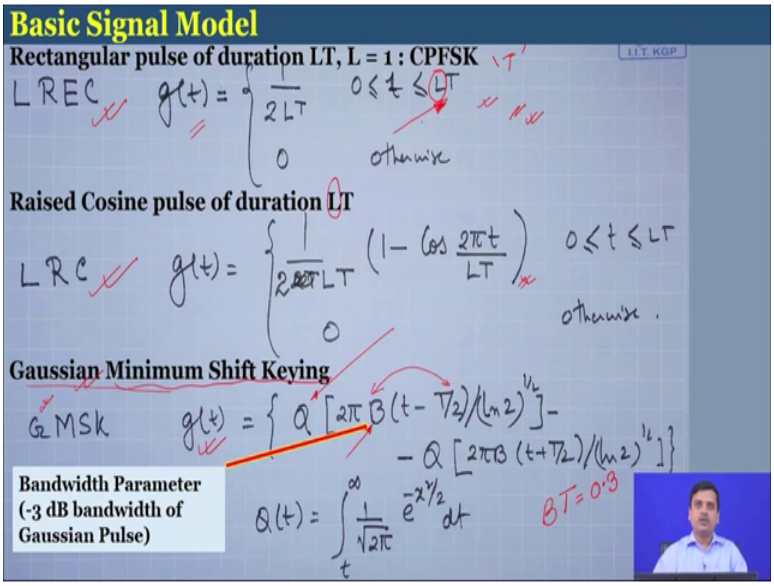

So, now these signals can have different pulse shapes; that means g t. One of the common pulse shapes which is used is the rectangular pulse shape and which is one we have considered in the previous discussion, the pulse shape could also be raised cosine pulse shape, ok. So, this is also a pretty standard and more easily acceptable pulse shape the advantage of this pulse shape is that it is much more compact in frequency where as this is less compact in frequency. But, it has its own other advantage this has its own advantage; this is easier to process and this requires a little bit more complex processing.

However, the overall gain in this particular system is much superior, but again if you look at multicarrier systems, a rectangular window helps you maintain orthogonality. So, each has their own pros and cons and one has to choose the pulse shape based on the application and overall scenario.

Amongst this there is also another very important pulse shape which is Gaussian pulse shape and what we have along with that is the minimum shift keying we will very soon see that. So, the Gaussian pulse shape uses g t which is described by this expression where Q is the Q function it is the variable defined Q function. And in this expression there is this B term which has been introduced which is the bandwidth parameter or the minus 3 dB bandwidth of the Gaussian pulse.

So, here when we talk about the second generation system the parameter BT where you can see that B and a T term over here which is the time bandwidth product is usually restricted to a value around 0.3 which results in one of the best possible spectrum occupancy of the signal.

So, to summarize in all the previous discussions we had a g t in place you would easily remember that all the discussions that we did there was g t in place and this particular set of results is one where we have taken g t to be rectangular. So, instead of that you could also take g t which could be the rectangular as we have said, it could be the raised cosine, it could be the Gaussian pulse shape also. And, another important factor which would like to point out is in these cases the pulse duration need not necessarily be restricted for a duration of T. You can see from here that this pulse shape can go up to L times T ok. So, that is why it is called LREC and you can have more than 1 pulse duration; that means, you are having the longer pulse duration. The advantage you have is that you can have narrower and more sharper transitions.

So, that is why you have an extra multiplication factor and such systems where the signal portion is extending beyond T duration where T is the symbol duration. So, when the signal pulse shape expands more than that you usually call those systems as partial response signaling and whereas those signals which are restricted to within the duration of T you call them as the full response signaling. So, this is classically available in textbook you can refer to them, but we would we are revisiting them because they are our basis for understanding the wave form structure for second generation as well as fourth, fifth and other future generation system.

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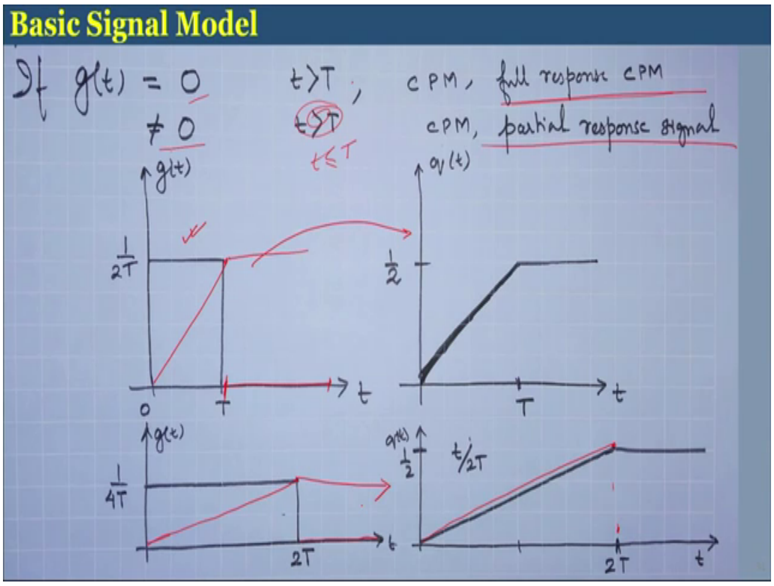

So, in case of g t being for the full response signal we have g t equals to 0 for t greater than 0 and it is not properly written for t less than or equal to sorry g t is equal to 0 for this thing and g t is not, this is well written, sorry. I made a mistake over here. It is rather this is absolutely right whatever is written over here that in case of g t being 0 for t greater than 0, what we have is that it is called full response signaling which is what you just described and g t not equal to 0 for t greater than 0 is what you have partial response signaling which I just described.

So, in this case if it is rectangular pulse shape g t would appear in this form and q t which is the integration of g t would appear in this way alright which you can clearly see that once it reaches the value of half after integration of this thereafter the value remains constant because this portion the signal is 0, ok. Now, if we look at the LREC for 2T; that means, where it spans two symbol duration then the integration of g t is going up to this value half till the duration of 2T. Because if you keep integrating this signal the signal is going to integrate like this and there after it is 0; that means, no more accumulation is happening and hence it is maintaining that same value, ok.

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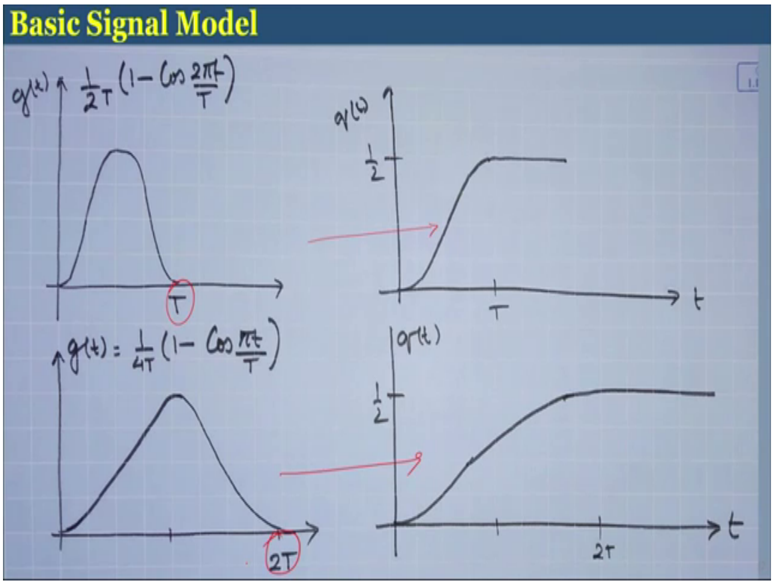

So, if it is raised cosine you can see a smoother transition, you can also see a smoother transition, but; however, in all cases the continuity is maintained, ok. So, in this case the raised cosine is up to a time duration T in this case it is up to a time duration of 2 T.

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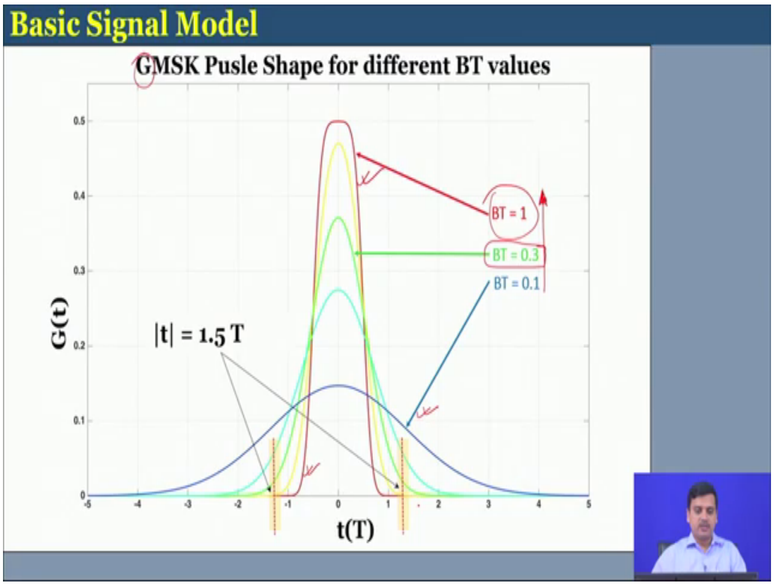

Now, this particular figure is one for the GMSK pulse shape or the Gaussian pulse shape we will talk about the MSK very shortly. So, in this case what we see is that the pulse shape for various values of BT values, ok. So, BT equals to 1 is the one which is shown over here and BT equals to 0.1 is what we see over here.

So, what we see is that as the bandwidth increases factor for the same value of t the pulse becomes more and more closely packed, alright. Whereas so, to find out tradeoff between the bandwidth occupancy and the pulse duration and spectrum efficiency BT equals to 0.3 is the one which is used in modulation and in such systems you can also see that around t equals to 0.5 one could truncate at least this particular 1 in such a manner that you can have minimum errors, right.

So, since these ultimately stretch to infinity there will be a certain truncation point which has to be followed otherwise your signals maybe out of you it will be difficult for one to process and it will be unnecessarily long versions of signal which required to be processed at the receiver.

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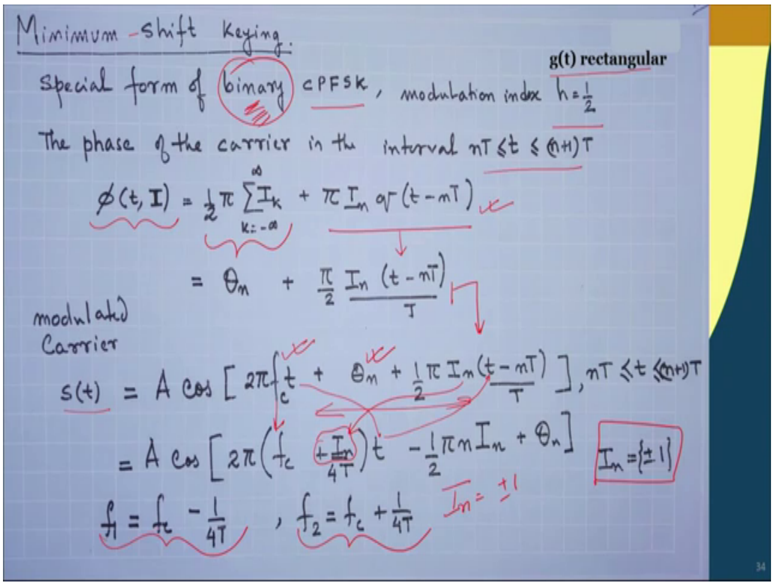

So, now let us look at the MSK part of the representation of GMSK. So, one of the things to be remembered is that it is the MSK signal has g t which is rectangular. So, when we go to GMSK it becomes a Gaussian pulse shape instead of a rectangular pulse shape. So, in a standard MSK it is a CPFSK signal with modulation index of half and the carrier phase in the interval whatever we have written in the previous slides you can easily recall that it is written in this form.

And, it is a special form of binary FSK; that means, only two values of I n are selectable. So, as discussed earlier theta n is given in this expression and the corresponding expression over here translates to this one, which also we have discussed in the previous few pages, if you go back again to them you want to easily get them.

So, now, we remember that this was inside the cosine function, so again we have got back S t which is the modulated carrier there is f c t there is previous accumulated phase as well as the particular term which we have just seen in the previous step. So, if we process if we process this particular set of algebraic expressions what we find is that S t can be written as a cos 2 pi f c plus in by 4T along with this 2 pi term. So, if you look at this if I take out 2 pi over here I am going to get I n by 4T as representation of this, there is a t because of this and there is a t because of this. So, you have this particular term.

Now, I n can take either plus 1 or minus 1, right. These are two values that I n can take. I n can take plus or minus 1 because we are talking about binary FSK, right. So, if you take I n as plus 1 or minus 1 your f 1, one of the frequencies will be f c minus 1 by 4T and the other frequency f 2 would be f c plus 1 by 4T, just if I replace this one this whole value as plus 1 and minus 1. So, we have two different frequencies. So, as if we are switching between the two different frequencies and one frequency is f c minus 1 by 4T and f and f c plus 1 by 4T.

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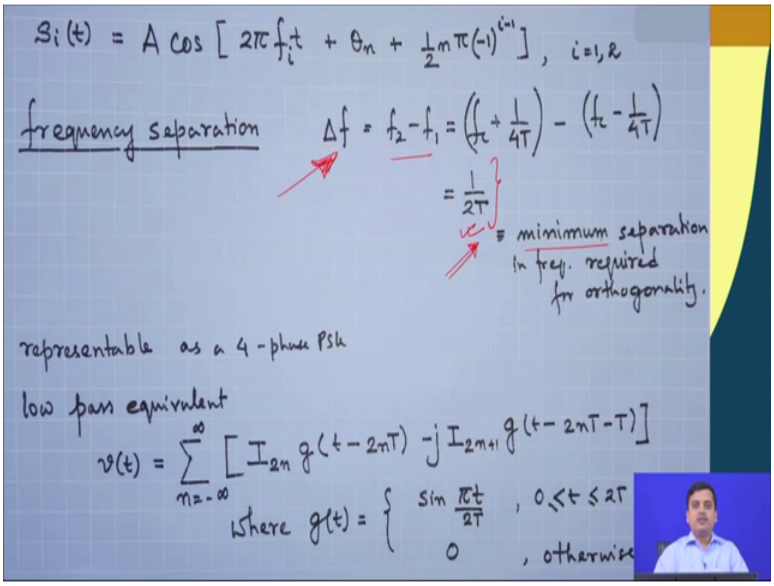

Now, if you look at the frequency separation in this case what you get is that f 2 minus f 1 you would equate it to be 1 by 2T. So, what we can see is that when we choose MSK we are landing up in a situation where the frequency separation is turning out to be 1 by

2T and what we have also seen before is that this is the minimum separation of frequency that is required in order to maintain orthogonality.

So, this is why we usually referred to this as the minimum frequency shift keying and if we add the Gaussian pulse shape along with it then we are going to get the GMSK signaling and hence the primary reason for doing this is that the spectrum occupancy of this is much lower compared to traditional communication systems and we can have a much compact system.

The other advantage is that the peak to average power ratio is also low because you are not changing the amplitude, but you are only changing the frequency or in other form the phase. So, the amplitude is remaining constant and hence we are getting a constant amplitude or a constant envelope signal with only frequency shift that to the minimum separation along with the continuity in the phase which would give raise to lower out of band emission.

So, in the next lecture we will look at the spectrum occupancy of such signaling techniques and appreciate the importance of maintaining continuity in phase or choosing the appropriate pulse shape which is again a motivating factor for the future generation air interface or wave form design.

Thank you.