Wireless Communications
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Lecture No. # 25
Modulation Techniques for Mobile Communications (Continued)

Welcome to the next lecture on modulation techniques. Today we will look at some of the important linear modulation techniques. First the outline of today's lecture.We will summarize briefly what we have learnt so far then we will look at an important class of modulation techniques called the linear digital modulation techniques.

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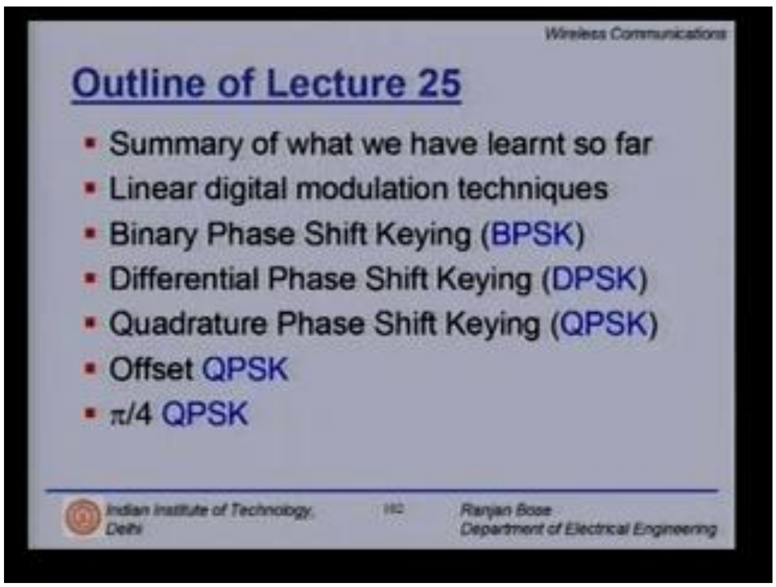

In particular we look at the binary phase shift keying or BPSK then we will talk about the differential phase shift keying or DPSK followed by quadrature phase shift keying or QPSK, offset QPSK an interesting variation of QPKS and the pi by 4 QPSK. So this is the brief outline for today's lecture.

A brief recap; in the previous classes we talked about the power and the bandwidth efficiencies of modulation techniques. We also discussed line coding, we talked about the problem of inter symbol interference which is caused when your bandwidth is limited which leads to the spreading of the pulse and different pulses interfere and the important method of pulse shaping wherein we reduce and mitigate the problem of inter symbol interference.

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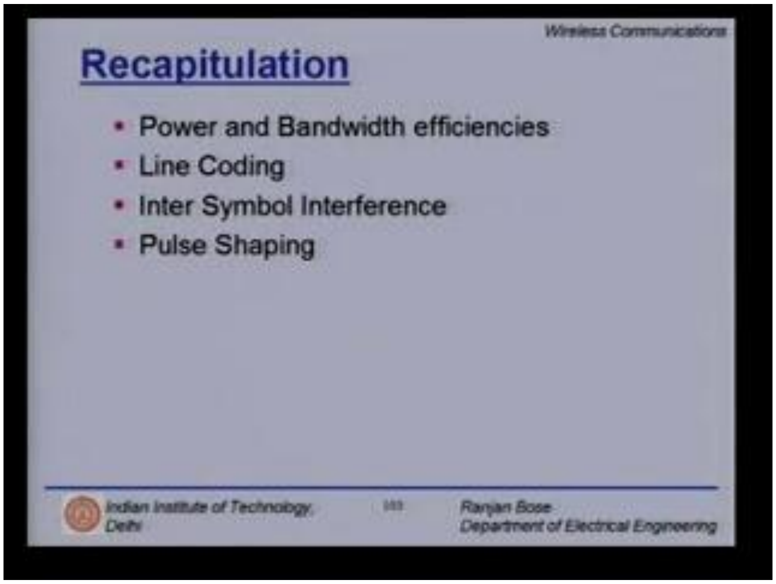

Now let us switch gears and move over to digital modulation and we remember from last class that there are some important advantages over analog modulation techniques. First of all there is greater noise immunity in the case of digital modulation techniques and robustness towards channel impairments.It is found that most of the digital modulation techniques perform better in fading environments which is the normal scenario in most of the wireless communication scenarios. Then again we have easier multiplexing of various forms of information like voice data video, multimedia kind of services where digital modulation technique immediately comes to the rescue as oppose to analog schemes.

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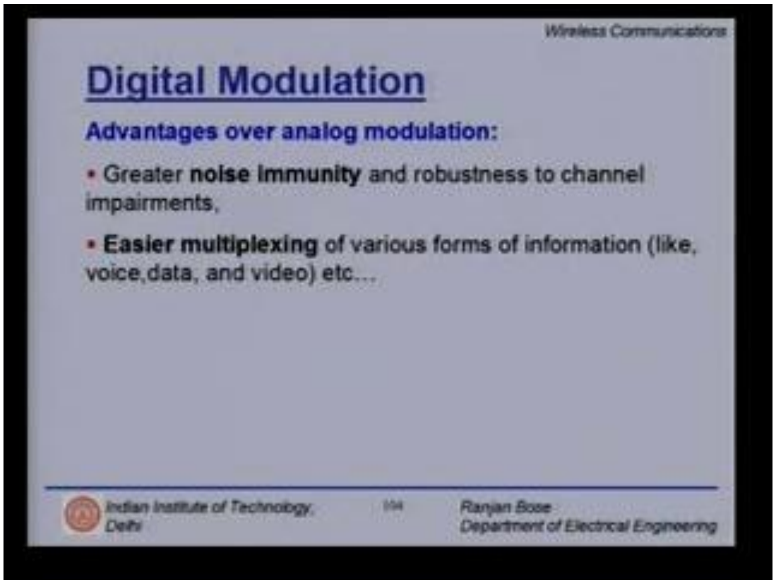

The world has shifted to the digital modulation techniques and today very few mobile communication services even think of adopting analog modulation. In this slide we will look at briefly the different types of digital modulations.

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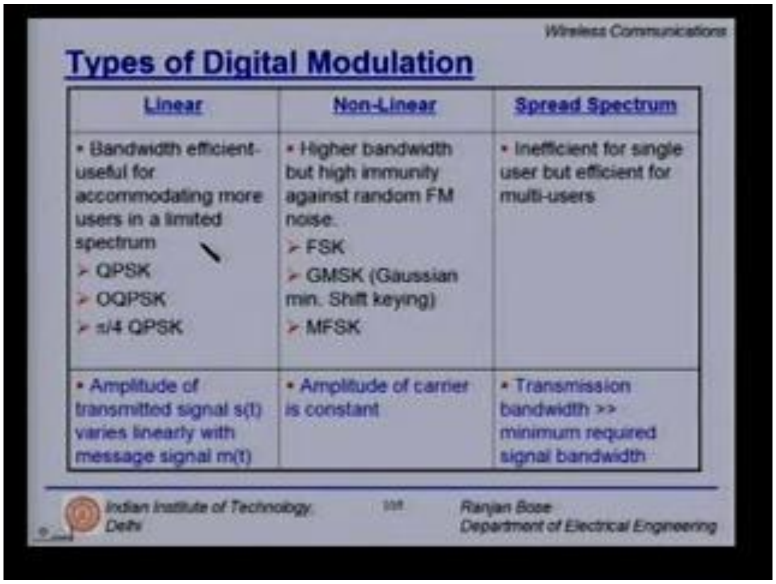

You can classify them into linear, nonlinear and spread spectrum techniques.In linear modulation techniques which we will discuss today in detailare bandwidth efficient- useful for accommodating more users in a limited spectrum. How do we choose one modulation scheme over others? We will discuss that in one of the subsequent slides. In the nonlinear techniques we have likes of FSK, GMSK, MFSK; GMSK is used in the GSM mobile phone standard, we will talk about it in one of the later lectures and of course the spread spectrum techniques which are omnipresent in the 3G standards. Today we will focus on only the linear techniques namely BPSK, offset QPSK and pi by 4 QPSK.

The three basic signaling schemes that we know are the amplitude shift keying, the frequency shift keying and the phase shift keying;our emphasis today will be on phase shift keying. Note that how do you chose a modulation scheme? You have so many choices, how do you evaluate one with respect to another, what are the basic criteria based on which you decide for one modulation scheme versus the other?

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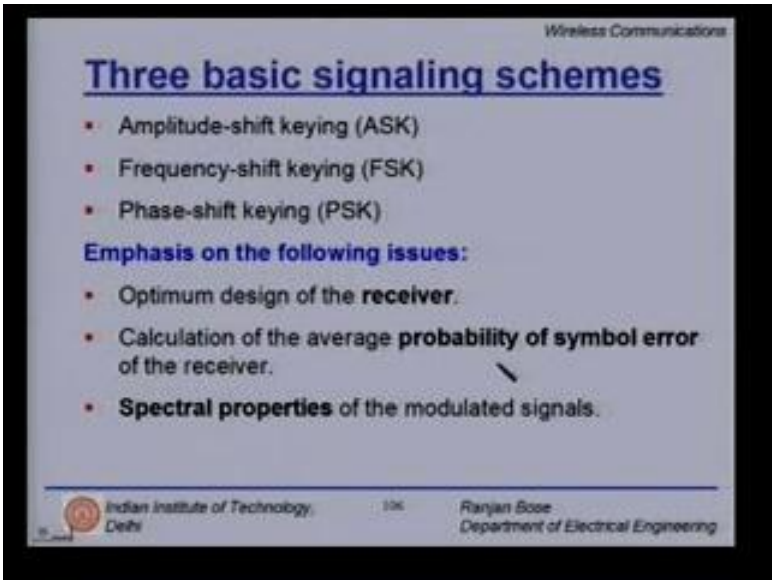

One is the optimal design of the receiver and how easy or difficult it is to implement the receiver. Then the performance which is the bottom line, what is the probability of symbol error of the receiver, given the same signal to noise ratio? It is found that some of the modulation techniques perform better with respect to the other ones and of course the spectral properties of the modulated signals. So you have the complexity of the receiver, the probability of symbol error and spectral properties of the modulated signals has the three balls that you have to juggle in order to choose and pick one particular modulation technique.

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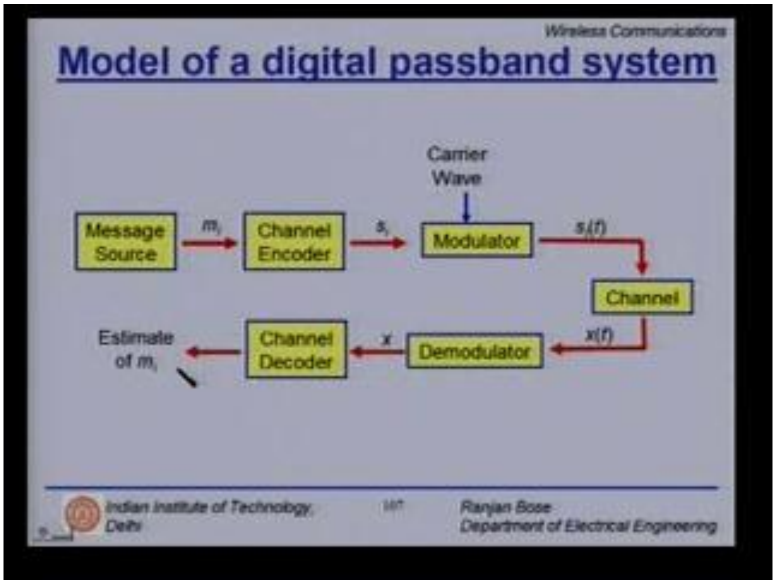

Now let's briefly revisit a model of a digital pass band system. We always start with a message source, it could be a voice digitized or it could be an image or video or fax and we denote it by m_i. Then it passes through a channel encoder, by design we have skipped the source coding part assuming that this is incorporated in here. So channel encoder puts redundancies in a known manner so as to overcome the effects of noise and other channel impairments and we get s_i. Then it is passed through a modulator which must make use of a carrier and then sends out a waveform in the time domain. This waveform is passed through the channel wherein the various channel impairments and noise come into play and what we receive is x (t) which is very different from the s (t).

It passes through a demodulator, the first job of the demodulator is not only to get the possible estimate of the message but it also creates some kind of a limitation on the effects of noise. So it is a technique to overcome the effects of noise introduced in the channel. What we get back is x then you undo the channel coding part which was to overcome the effects of noise here, you do a channel decoder and then finally get an estimate of m_i.

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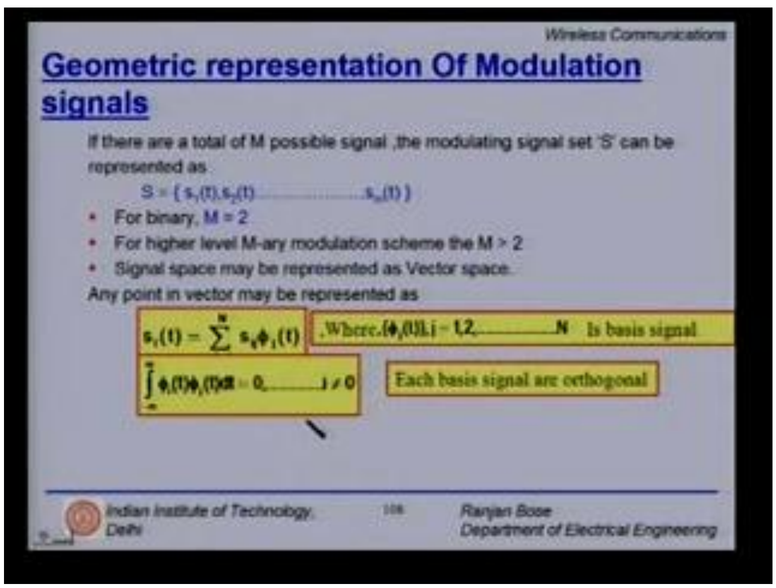

A quick revisit on the geometric representation of modulated signal.If there are m possible signals and the modulating signal set s can be represented as S is equal to s_1 (t), s_2 (t) up to s_m(t).For binary scenario M is equal to 2,so you have only two symbols.For higher level M-ary modulation schemes M is greater than 2and the signal space may be represented as a vector space. What does it mean? Any point in vector space may be represented as S_i as a summation i is equal to 1 through N, N is the dimensionality of the space, S_{ij} phi_i where phi_i(t) is the basis signal which has the property that some integration phi_i(T) phi_j (T) dt from minus infinity to infinity is zero for inot equal to j. Each basis signal are orthogonal and each basis signal is normalized to have unit energy. So what it basically means is that your signal set may be represented as points on the signal space. The dimensionality is N and M represents the number of symbols.

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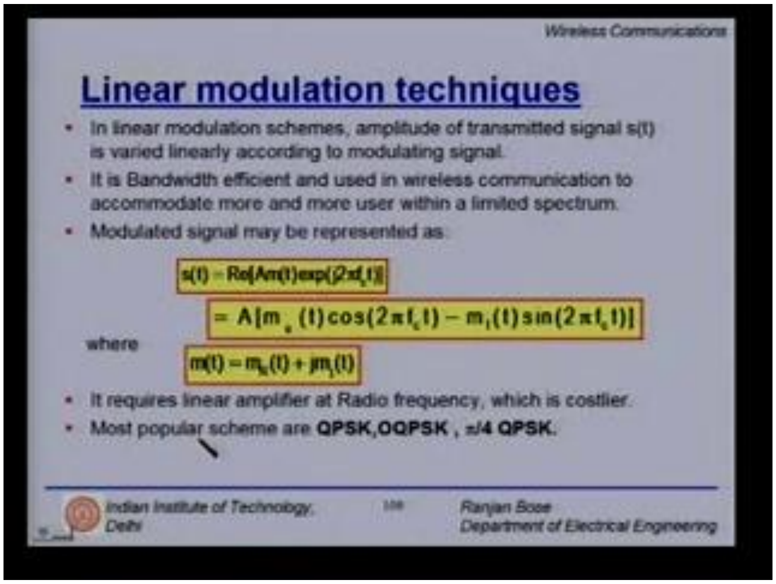

Let us now begin our study of linear modulation techniques. What is linear modulation technique? In linear modulation schemes the amplitude of the transmitted signal S of t is varied linearly according to modulating signal. It is bandwidth efficient and used in wireless communication to accommodate more and more users within a limited spectrum. The modulated signal may be represented as S (t) real part of A which is the amplitude m (t)e raise to the power j 2 pi f_ct, here f_c is the carrier frequency. If expand it out, it can be written as m (t) cos 2 pi f_ct minus m_i sin 2 pi f_ct, m_r is the real part and m_i is the imaginary part, m(t) can be written as follows. It requires linear amplifier at Radio frequency, which is costlier and some of the popular schemes within the linear modulation techniques are QPSK, offset QPSK and pi by 4 QPSK. We will talk about each of them as well as the BPSK in detail today.

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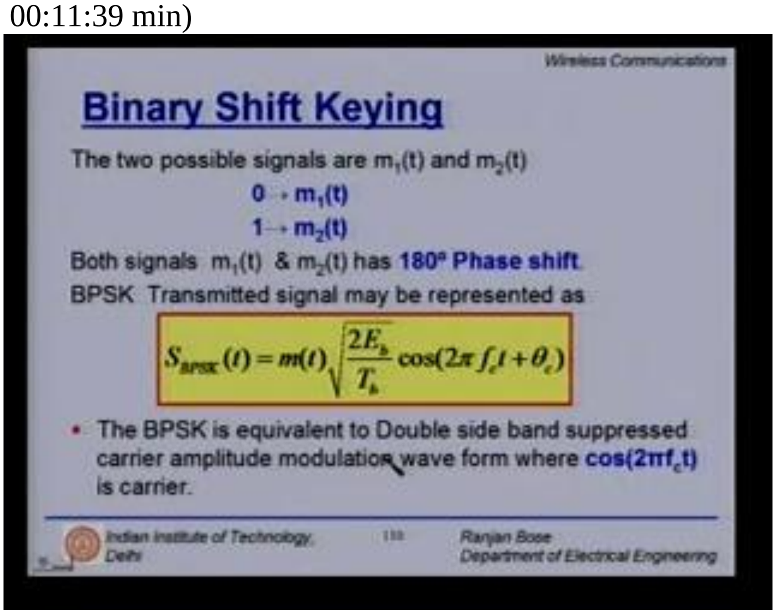

What is binary shift keying? Let us consider two possible signals $m_1(t)$ and $m_2(t)$. Now 0 represents $m_1(t)$ and 1 represents $m_2(t)$. So if I have a strings of one'sand zero's I send $m_1(t)$ whenever a zero is encountered and $m_2(t)$ when a one is encounteredbut in our case binary phase shift keying both signals $m_1(t)$ and $m_2(t)$ has a 180 degree phase shift. So BPSK transmitted signal may be represented as m (t) under root 2 E_b over T_b cosine 2 pi f_ct plus theta$_c$. So in effect the BPSK is equivalent to double side band suppressed carrier and amplitude modulated waveform where cos 2 pi f_ct is the carrier, fairly simple, robust but you have only one bit per symbol. How does the bandwidth of the BPSK look like?

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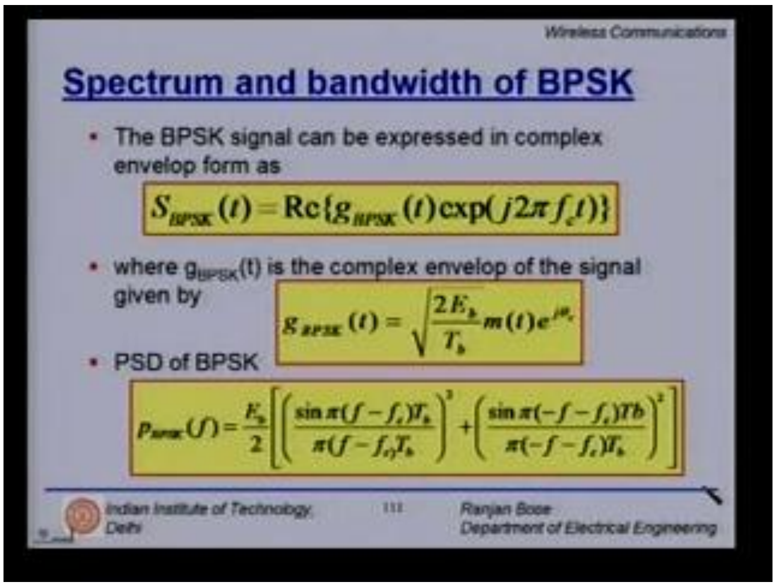

The BPSK signal can be expressed in complex envelop form as follows; real part g_{BPSK} t exp(j 2 pi f_c t) where $g_{BPSK}(t)$ is the complex envelop of the signal given by under root 2 E_b over T_b m (t) e raise to power j theta$_c$. The power spectral density of BPSK can be calculated to be of this form. It is more interesting to plot this out and see how it looks because part of the job of a good modulation technique is to have good spectral properties of the modulated waveform because that has a direct implication on the design of the transmitter and receiver.

So here graphically we have the power spectral density of a BPSK signal. Note that there is a main lobe and there are side lobes. The main lobe is centered at f_c and the nulls are at f_c plus R_b, f_c plus 2 R_b and so and so forth. Suppose you intercept an unknown signal and plot its power spectral density and it looks something like this, possibly this is a BPSK. We will soon see QPSK power spectral density also looks similar except that this nulls instead of being at f_c plus $2R_b$ it's more like f_c plus R_b by 2.

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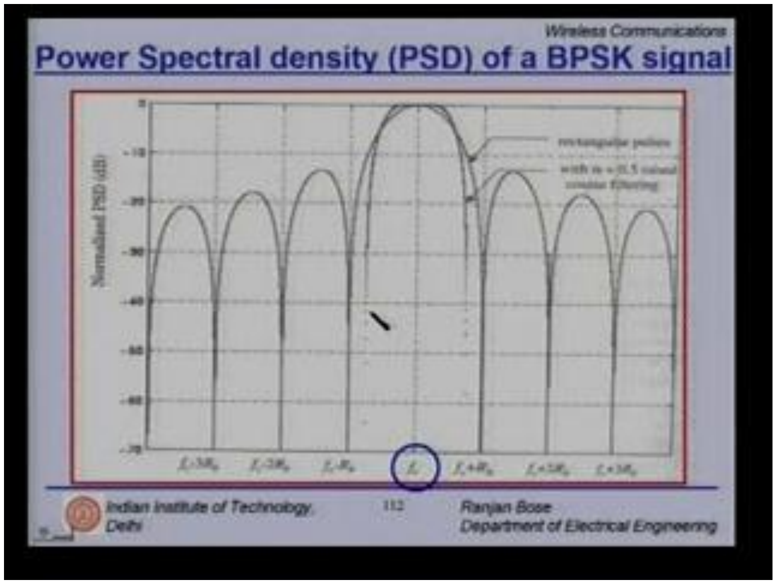

Now if you have alpha is equal to 0.5 raised cosine filtering imposed on it then you have a much narrower main lobe. So the purpose of this raised cosine filtering is to band limit the modulated signal. We will soon see the problems with QPSK when you put this raised cosine filtering, basically band limiting leads to certain problems.

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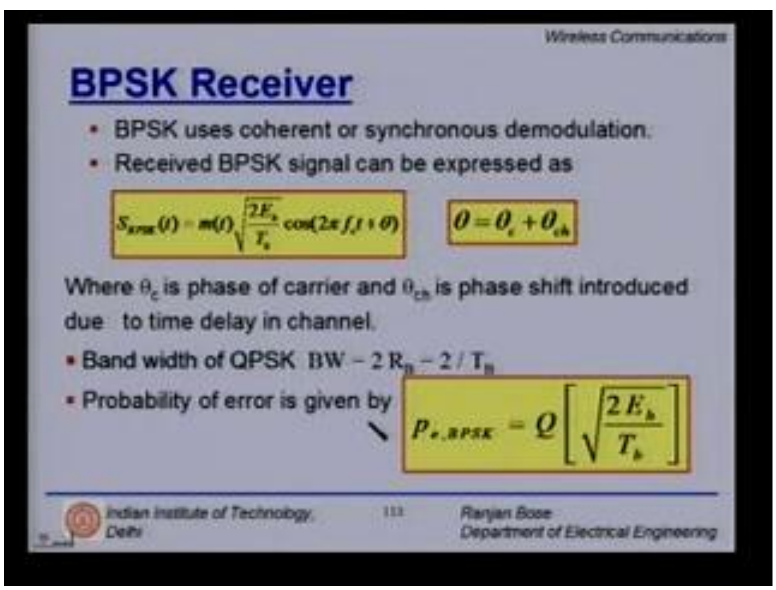

Let's talk about the receiver; BPSK uses coherent or synchronous demodulation. What does that mean? I must have the knowledge of the carrier and the phase also. The received BPSK signal can be expressed as S_{BPSK} in time domain equal to m (t) under root $2E_b$ T_b cos 2 pi f_ct plus theta. Theta$_c$ is the phase of the carrier and theta$_{ch}$ is the phase shift introduced due to time delay in the channel. So what you receive is theta equal to $theta_c$ plus theta channel. The bandwidth of QPSK is 2 R_B is equal to 2 over T_B. Now the probability of error is given by Q function under root 2 E_b over T_b, this is the standard expression so we coat here without the derivation.

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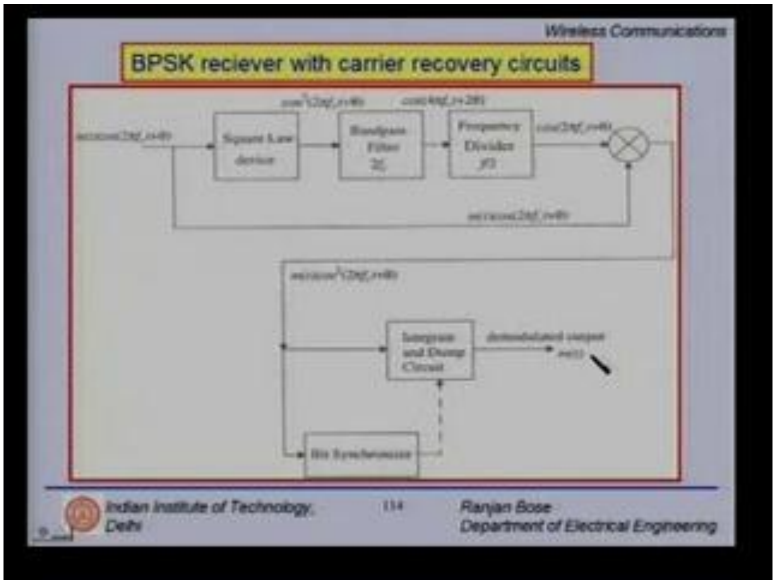

Let us now briefly talk about the BPSK receiver with carrier recovery circuit. So here is your m (t) cos 2 pi f_ct plus theta which we saw in the previous slide as your BPSK modulated signal that is first pass through a square law device. It generates cos squared2 pi f_ct plus theta. Now the moment you band pass filter it at 2 f_c you get cos 4 pi f_ct plus 2theta. Pass it through a frequency divider to recover cos 2 pi f_ct plus theta. You have already m(t) cos 2 pi f_ct plus theta, take it here, multiply and get back this, integrate and dump you get m (t), it was a Dc value so this is the simple BPSK receiver.

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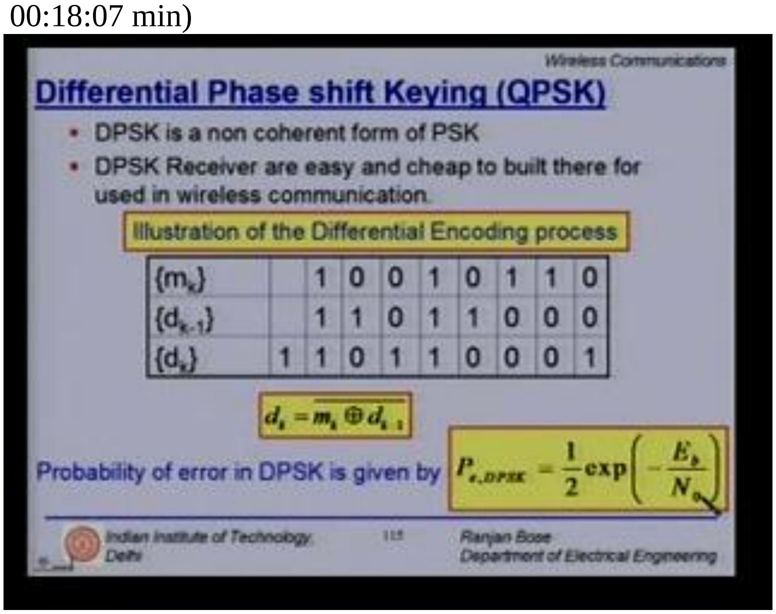

Now the BPSK receiver requires the knowledge of the phase, you have a slight variation called the differential phase shift keying or DPSK. DPSK is a non-coherent form of phase shift keying. DPSK receivers are easy and cheap to built and therefore used in wireless communications.Let us have an illustration with an example. So you have your message m_k, these are bits clearly and that the differential output is represented by d_k and here we have written down d_{k-1} and the k^{th} instant d_k. So if you look if there is a 1 here, there will be 1 here,1 here,1 here 0, 0. So they are just shifted version of each other so d_{k-1} row is shifted to the right with respect to the row of d_k.

Now the rule for differential encoding is very simple, d_k is m_k exsolved d_{k-1} not function.What does it mean? In factif you have a 1 come in then you don't change the output, if you have a 0 coming in then change d_k,0 comes in change from 0 to 1, 1 comes in don't touch 1 let it be 1,0 comes in change the 1 to 0,1 comes in don't change the 0 let it remains and so and so forth.So the probability of error in the differential phase shift keying is given by half exp minus E_b overN_0.

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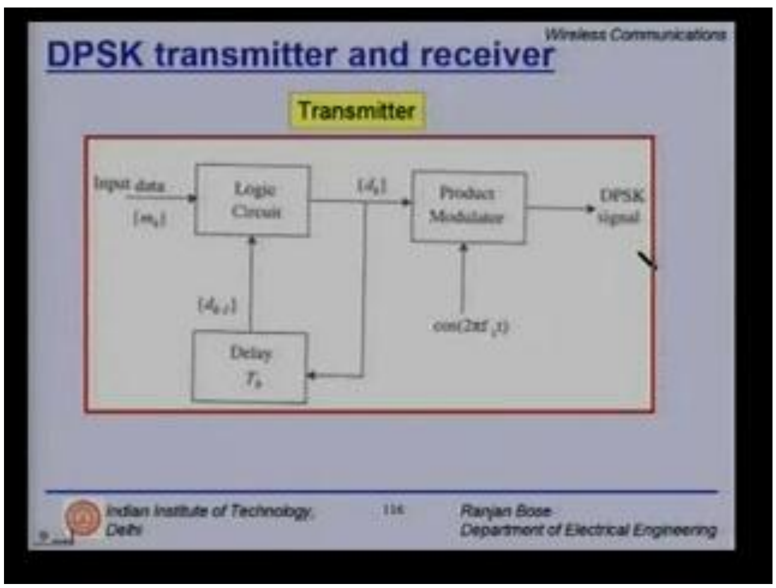

Let us talk about the DPSK transmitter and receiver.So the transmitter is fairly simple exactly doing the encoding process we discussed a while back.Input data comes in, it's a sequence of one's and zeros, it's a binary these are logic circuit and you get a d_k, if you pass it through a delay you get d_{k-1}. All you have to do is if a 0 comes in flip the d_k, if a 1 comes in leave it untouched and you get d_k. Now you have a product modulator so make it plus a cos 2 pi f_ct for 1 or minus cos 2 pi f_ct for 0 and you have your DPSK.

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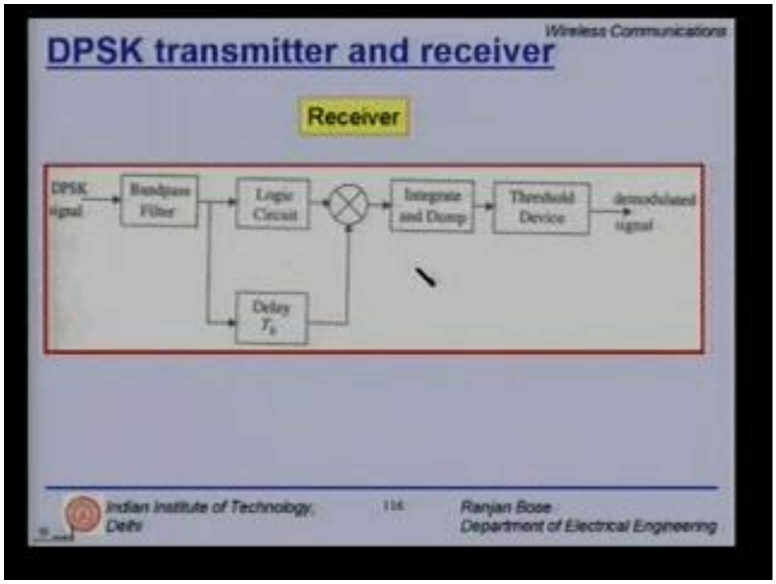

Let us talk about the receiver. You have the DPSK signal, first you band pass filter it. You have a logic circuit and then youhad a delayed version by T_b multiply, integrate and dump to get thedc part out threshold and get the demodulator signal. Fairly simple,this is the added advantage, why DPSK is popular. Very simple design and you do not have to recover the phase because it is simply differentially encoded. Of course it comes with a price, is about a 3 db loss in performance.

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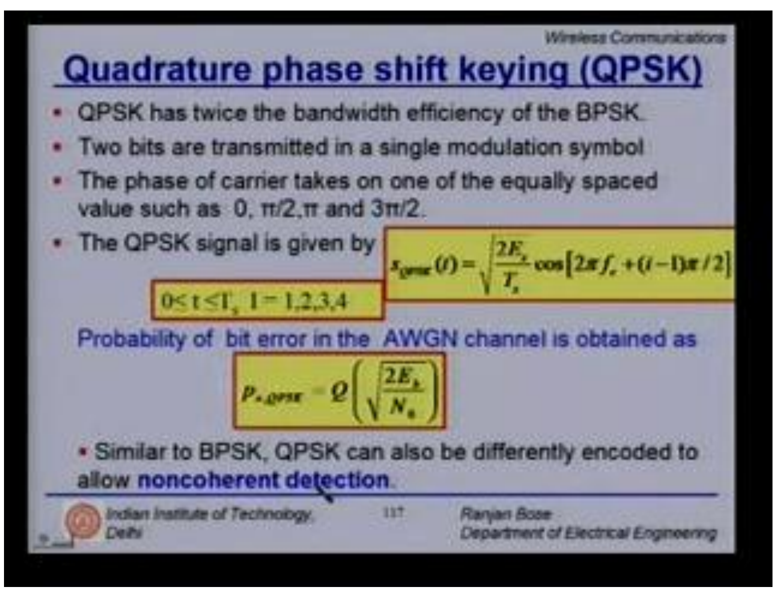

Now let's look at the big brother of BPSK which is the QPSK or quadrature phase shift keying. QPSK has twice the bandwidth efficiency of BPSK so we are actually going to send two bits per symbol as oppose to one bit per symbol in BPSK.The phase of the carrier takes one of the equally spaced values 0, pi by 2, pi and 3 pi by 2. The QPSK signal is given by $S_{QPSK}(t)$ under root 2 E_s over T_s, E_s is the energy per symbol, T_s is the symbol time, cos 2 pi f_c plus one of the 4 phases. The probability of bit error in additive white Gaussian noise channel or AWGN is given by the Q function under root 2 E_b over N_0. Similar to BPSK, QPSK can also be differentially encoded to allow non-coherent detection.

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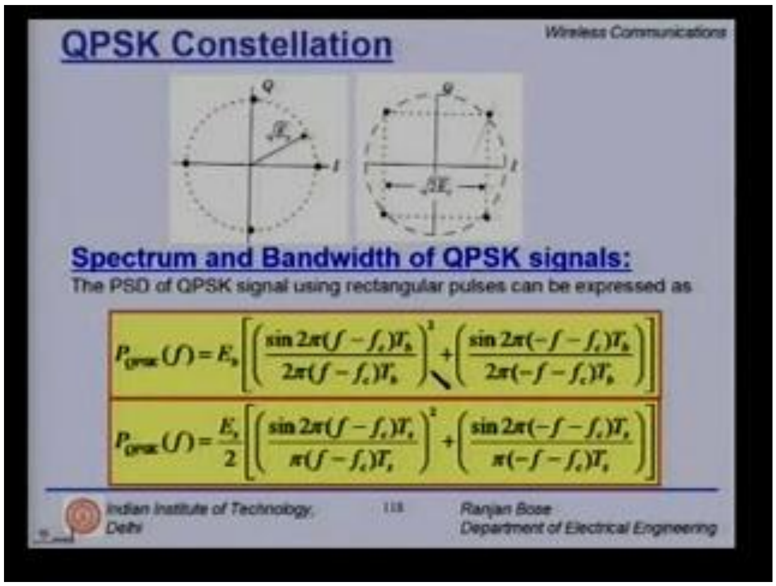

Let us now talk about the constellation diagram of QPSK. So clearly you have the in phase I and the quadrature Q components.This could be your cos omega$_c$t, this could be your sin omega$_c$t or any 2 orthogonal functions. We can map00, 01, 10, 11, or 00, 10, 11, 01 in one of the 4 symbols. The other possibility is pi by 4 rotated version of this. The1 on the right hand side is a more popular implementation. Let us talk about the spectrum of QPSK signal, the power spectral density of QPSK signal using rectangular pulses can be expressed as follows. It looks very similar to that of the BPSK except the nulls have shifted.This is in terms of E_b here it is in terms of E_s by 2.

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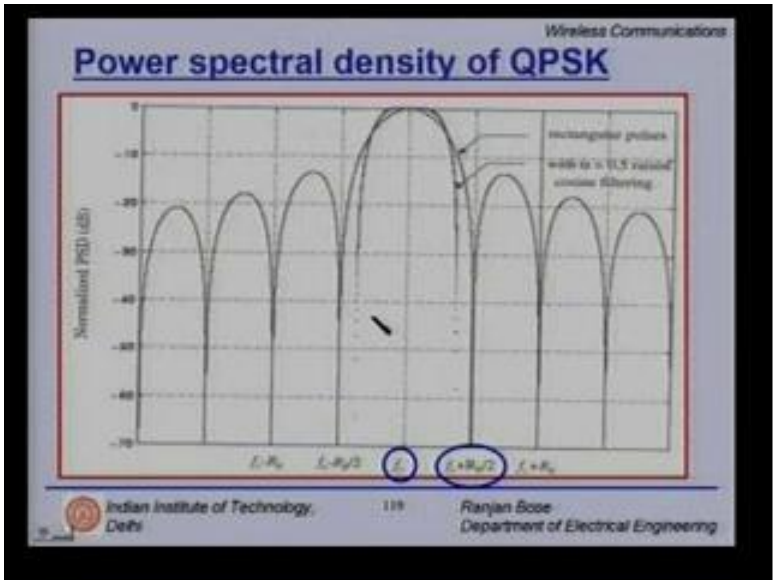

If you plot the normalized power spectral density on the y axis and frequency on the x axis you see that it is again centered at f_c but the first null appears at f_c plus R_b by 2.Had this been a BPSK signal, you would get $f_c + R_b$ here and so and so forth. If you use a raised cosine filter with alpha is equal to 0.5, you kind of shrink the main lobe. Clearly there will be problems when you do so. The problem comes because in QPSK you have occasionally 180 degree phase shift and in those cases when you are passing through the zero then band limiting the process kills the signal.

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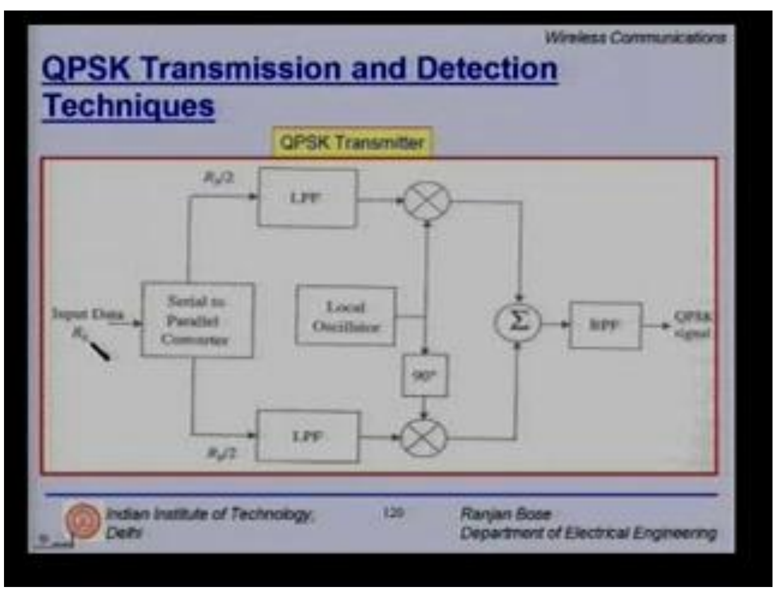

Let us talk about QPSK transmission and detection techniques. First the QPSK transmitter; you have an input data R_b, this is a string of bits one's and zero's. You have to take two at a time because the job of QPSK should take two bits at a time and encode it. However what you do is you have a serial two parallel converter and you split the bits and then you have a local oscillator, in phase quadrature add band pass filter it and send out the QPSK signal. If you have to do the receiver part, you have the received signal, band pass filter it you must have a carrier recovery circuit as discussed before. In phase quadrature multiply low pass filter it, also have a symbol timing recovery decision circuit multiplex because you get from arm one signal for one of the bits, the second bit multiply and for every symbol you get in you get two bits out on this side. So very simple, logical QPSK transmission and detection circuits.

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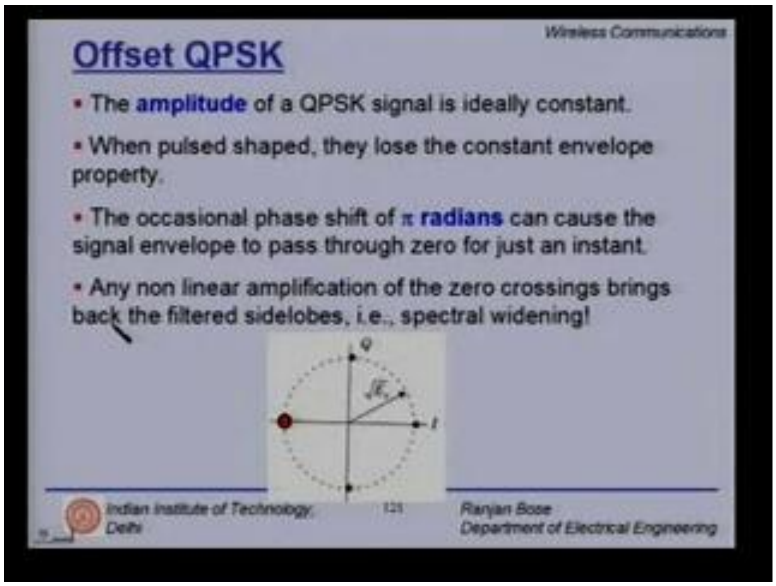

Now let us look at one variant of QPSK, it is called the offset QPSK.Why do we need it? The amplitude of a QPSK signal is ideally constant because if you look at the constellation diagram all the 4 points are located on a circle.So they are equidistant from the origin and the distant from the circle gives you an idea about the amplitude.When pulsed are shaped they lose the constant envelop property clearly you are doing pulse shaped so it's not rectangular pulse anymore, it is pulse shift.Now in QPSK you have no control over what symbols will be transmitted. So sometimes you have transition from S_0 to S_1 which is 90 degree phase shift or sometimes from S_0 to S_2 which is 180 degree phase shift basically pi radiansand then a phase shift of pi radians can cause the signal envelop to pass through the zero for just an instant.

Now any nonlinear amplification of the zero crossings brings back the filtered side lobes, if you remember in the previous slides once you do a raise cosine filtering you eliminate the side lobes.You shrink the main lobe but what is happening is because of the pulse shaping you are just forcing the zero crossings to go to smaller values and when you have do a nonlinear amplification of the zero crossings you have again the side lobes appearing. In effect you are causing spectral widening, you are defeating the purpose of cosine filtering or any of the pulse shaping techniques.

So let us look at the constellation diagram.Suppose you have the standard QPSK constellation diagram, x axis is the in phase, y axis is the quadrature, all the four symbols are located on this circle. Now suppose the first symbol that is transmitted is s_1 so here we label s_0, s_1, s_2 and s_3 but depending upon what bit stream is coming, it is possible that you send the next symbol as this one. So from here to here, so in effect what happen is we had a pi radian phase shift it's a chance, it was possible that the next two bits that come in makes this appear here. So here in this case it is only a 90 degree phase shift.

However if I am here, I can go to another 180 degree pi radiant phase shift.Again I am jumping so in QPSK I can either have a 90 degree phase transition or a 180 degree phase transition.The moment I have a 180 degree phase transition, I am in problem.I have to do something to limit this pi radiant transition and the answer comes in terms of offset QPSK because the moment I have a nonlinear amplification of the zero crossings, I bring back the filter side lobes that is the basic problem with QPSK.

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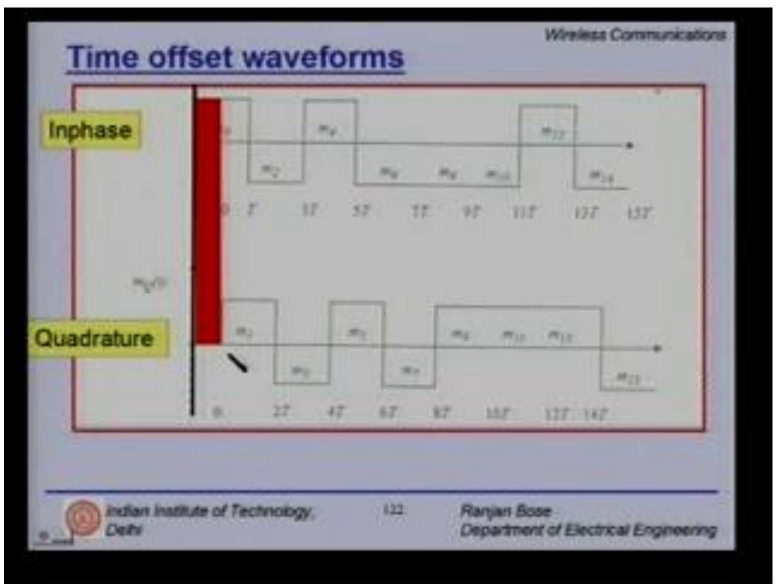

The solution is fairly simple, you generate two time offset waveforms, one for the in phase and one for the quadrature. So let's say for the in phase I have the following waveforms 1 0 1 00 0 1 0 and for the quadrature again I have 1 01 01 1 1 0. I have taken two arbitrary shrinks. What is important is in QPSK I would have sent this one to in phase arm and this one to quadrature. I do the same thing except this time for offset QPSK; I shift my quadrature bit stream by a small amount of given offset. So this offset will ensure its in between a bit that phase shift can never be 180 degrees they can be atmost 90 degree phase shifts because at even though QPSK is dealing with two bits at a time, at any time instant 2 bits cannot change at the same time because I am only feeding one new bit per bit in term.

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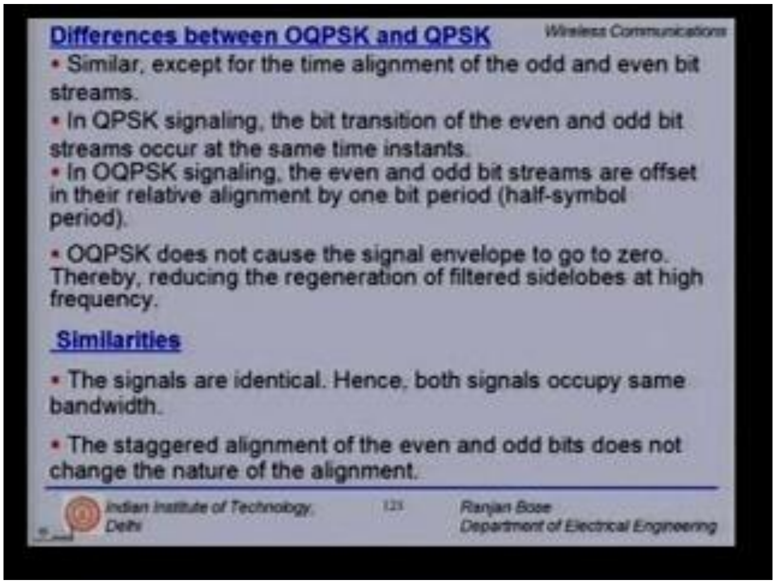

What are the differences between offset QPSK and your regular QPSK? They are almost similar except for the time alignment of the odd and even bits streams. In QPSK signaling the bit transition of the even and odd bits streams occur at the same time instant. However in offset QPSK the even and odd bit streams are offset in the relative assignment by one bit period which is half symbol period.The offset QPSK does not cause the signal envelop to go to zero simple, there is no more fear of a nonlinear amplification of the zero crossing.Thereby reducing the regeneration of the filtered side lobes at high frequency. What are the similarities? The signals are identical hence both signals occupy the same bandwidth. The staggered alignment of even and odd bits does not change the nature of the alignment.

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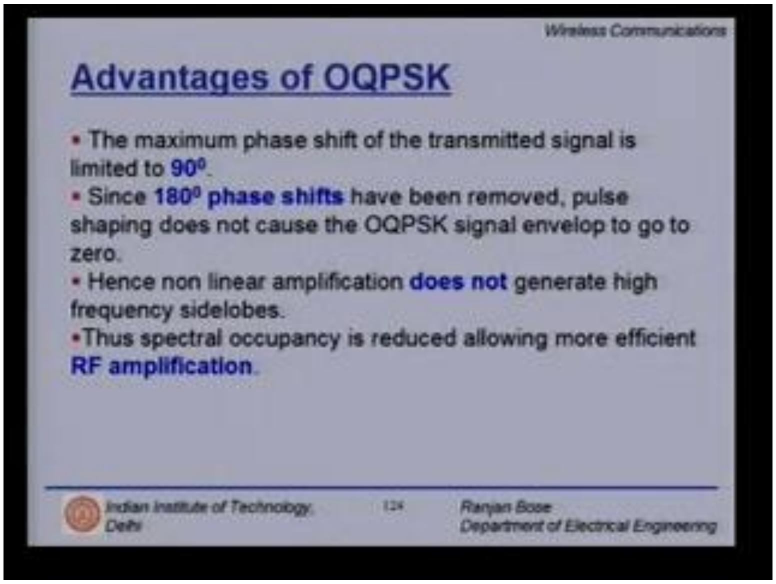

Advantages of offset QPSK, the first and the foremost is the maximum phase shift of the transmitted signal is limited to 90 degrees. That was my biggest fear in QPSK possibly there were several 180 degree phase shifts but since 180 degree phase shift have been removed in this case pulse shaping does not cause the offset QPSK signal envelop to go to zero. Hence nonlinear amplification does not generate high frequency side lobes, that's a spectral occupancy is reduced allowing more efficient RF amplification so your receiver design also improves.

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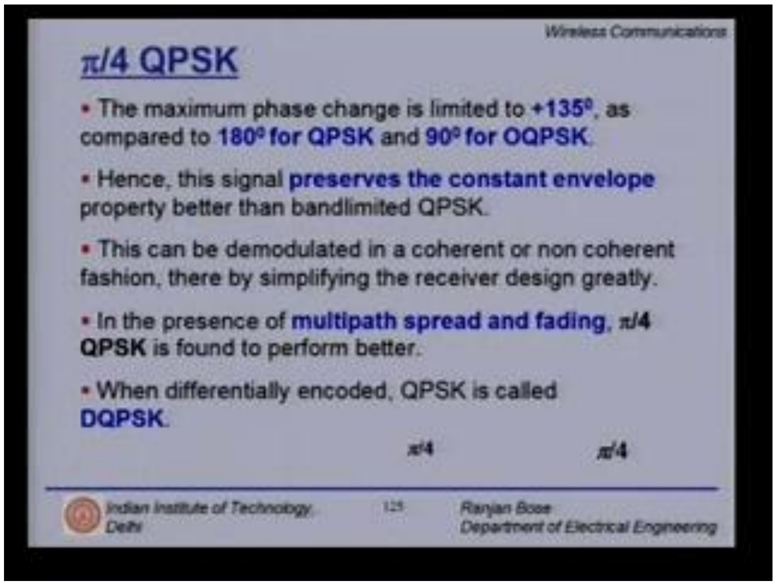

Now let's talk about pi by 4 QPSK, this is a compromise between QPSK and offset QPSK. In QPSK there is a possibility of having 180 degree phase shifts and occasionally 90 degree phase shifts. In offset QPSK you have at most 90 degree.How about reaching a compromise, how about 135 degrees phase shifts? The maximum phase change is limited to 135 degrees though it can be less as compared to 180 degree for QPSK and 90 degree for offset QPSK. Hence the signal preserves the constant envelop property better than the band limited QPSK. This can be demodulated in a coherent or non-coherent fashion thereby, simplifying the receiver design greatly.

Please remember apart from the probability of symbol error and the spectral characteristics of the modulated signal, any modulation scheme must also have a very simple transmitter modulator and demodulator design. Here the receiver design is greatly simplified. Now the added advantage thrown in is in the presence of multipath spread and fading, this pi by 4 QPSK is found to perform better, it just happens. When differentially encoded QPSK is called differential QPSK and pi by 4 QPSK is called D pi by 4 QPSK.

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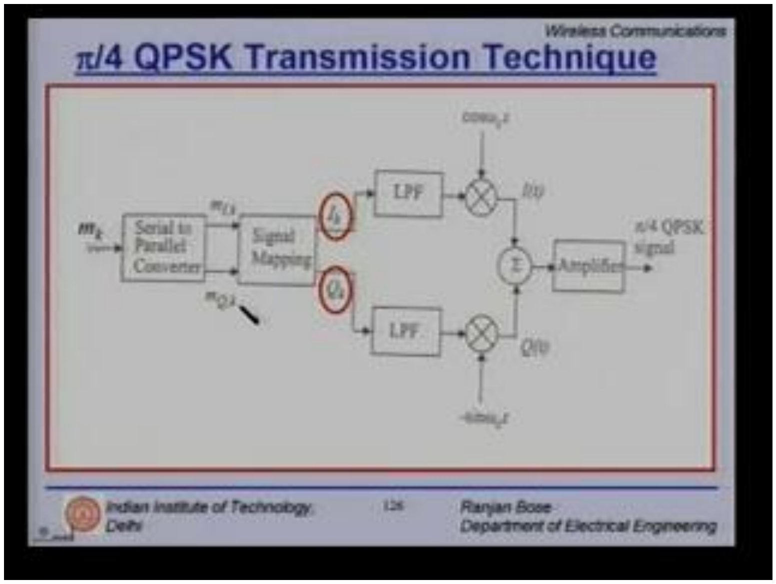

Now let us briefly discuss some of the pi by 4 QPSK transmission techniques. In this slide we have the block diagram of the pi by 4 QPSK transmitter. Clearly we have the bit stream coming in m_k where you have again a serial to parallel converter. I split it up, I get m in phase k, k is a time index and m_Q quadrature, k is the time index. Then I must do some kind of a signal mapping. What are this I_k and Q_k? We will talk about these two in the next slide. So in the next slide we'll talk about what exactly is this signal mapping doing but once you have this I_k and Q_k you low pass filter it and then you have the in phase cos omega$_c$t or cos 2 pi f_ct and sin omega$_c$t with a negative sign. You get the in phase component and the quadrature, add them up, amplify and shoot it off, you get the pi by 4 QPSK signal.

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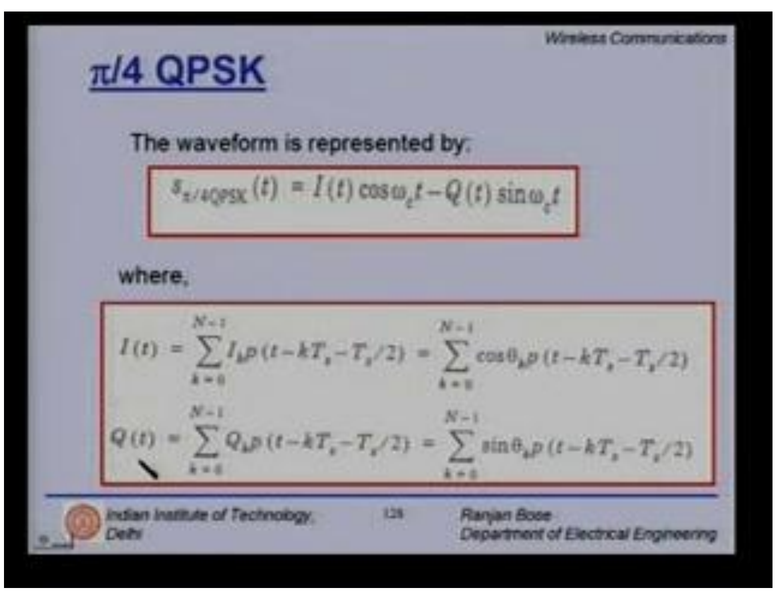

What is important in this slide is to understand how you take this bit stream and having divided into the in phase of quadrature bits, do the signal mapping so that you get I_k from m_k in phase and Q_k from m_k quadrature. So the I_k is I_{k-1}cos phi_k minus Q_{k-1} sin phi_k plus how you do the signal mapping and Q_k is sin phi_k given by I_{k-1} sin phi_k plus Q_{k-1} cos phi_k where $theta_{k-1}$ is equal to $theta_{k-1}$ plus phi_k. What are these $theta_k$'s and $theta_{k-1}$'s? $Theta_k$ and $theta_{k-1}$ are the phases of the kth and k-1 symbols. The phase shift phi_k is related to the input symbols m in phase k and m quadrature k.This m's are the bits we saw in the previous slide coming here which goes through the signal mapping block to give you I_k and Q_k. What is the waveform? The waveform in the time domain for pi by 4 QPSK is I (t) cosine $omega_c$t minus Q (t) sin $omega_c$t, it comes from passing it through the LPF, multiplying with cos and then adding it up. So we are here I (t) and Q (t). I (t) is given by summation from k =0 to N-1(I_kp t - kT_s - T_s by 2) and similarly Q (t).

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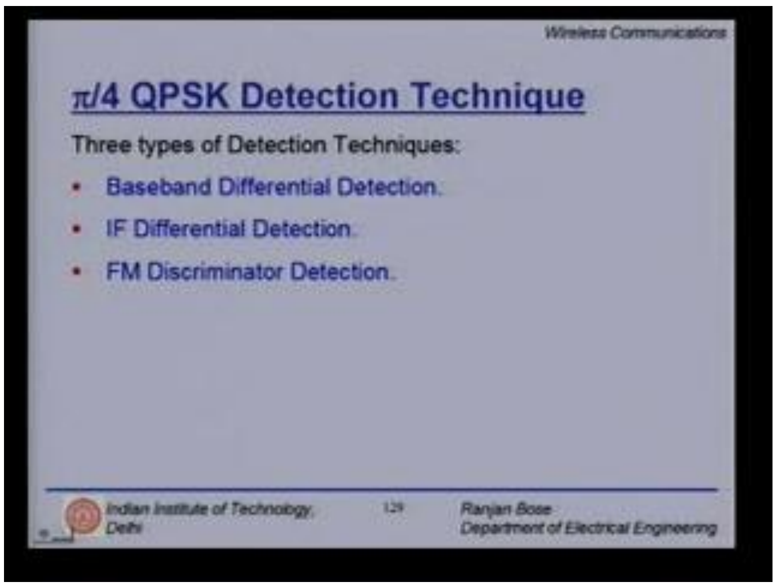

Now let us come to the different kinds of pi by 4 QPSK detection techniques. There are 3 detection techniques and we will briefly go over all of them from the block diagram perspective.
The first technique is the base band differential detection, please note the pi by 4 QPSK essentially works on two constellation diagrams. That is a good way to understand these things. So for every bit that comes in, it alternates between the two constellation diagrams and in that case its only possible to have a maximum phase shift of 135 degrees provided the two constellation diagrams themselves are offset by pi by 4 only.

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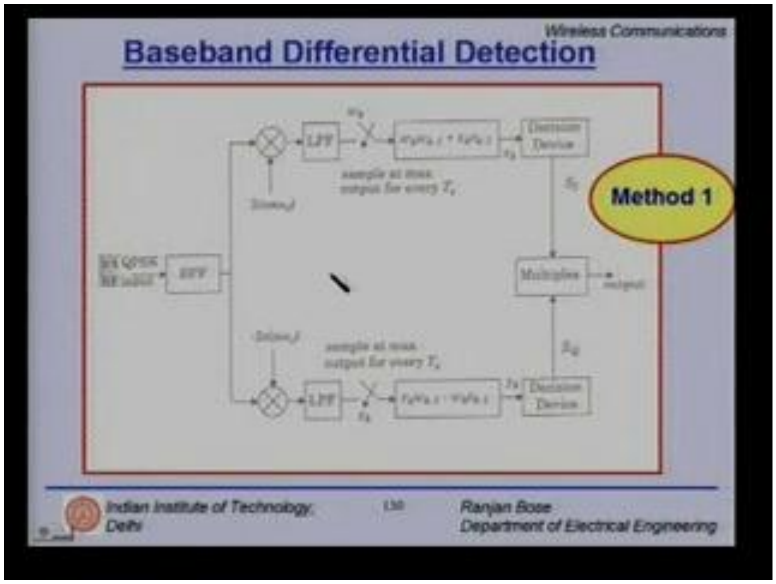

Let us look at how pi by 4 QPSK looks like. Suppose we have 2 constellation diagram, so you have this as in phase and quadrature and here you have 4 points and then you take another one. Again this is your in phase and quadrature and this time you have pi by 4 shifted versions. Suppose you merge them together. What you get? You get points from one and points from the other. Please note that if you have the possibility of switching between case 1 and case 2 then regardless of where you are, you can go from here to either this one, this one or this one or this one (Refer Slide Time: 43:21) because once you have send this one using constellation one. In the next symbol interval you can only use constellation number 2 but constellation number 2 if you see gives you possibility here, constellation one gives you here (Refer5 Slide Time: 43:45).
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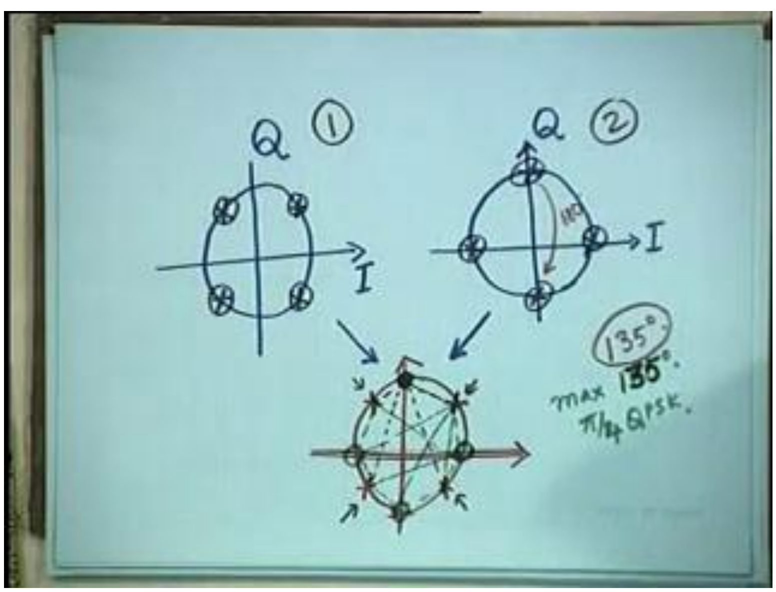

So regardless of where you are, suppose you are sitting here, the next instance you can only work at pi by 4 or here or here or here, so the maximum jump is 135. So you can go from here to here, here to here, here to here or here to here whereas suppose you are sitting in this location, next time you can either go here or here or here or here. Similarly if you are sitting here you can either jump here, jump here (Refer Slide Time: 44:36). So the point that is being made is regardless of whichever symbol point you are, the next transition cannot be 180, it can be maximum 135 degree transition is possible for pi by 4 QPSK. So if you write it, in regular QPSK is possible to have 180 degree phase shifts, in your offset QPSK it's only possible to have 90 degree maximum and here you have a compromise between QPSK and OQPSK giving you 135 degrees. So it's a very interesting way, the added advantage of course we have seen is it performs really well in the case of fading channels.

Now let us go back and look at the pi by 4 QPSK detection techniques. There are 3 types of detection techniques which will essentially use the philosophy of using 2 constellation diagrams offset by pi by 4. These are the base band differential detection, the IF differential detection and FM discriminator detection. Let us talk about the base band differential detection, you have this pi by 4 QPSK RF input coming, of course you must band pass filter it. First because I want only focus on the signal of interest then pass it simultaneously to 2 multipliers, one multipliers it with 2 cos omega$_c$t and the other one with minus 2 sin omega$_c$t, low pass filter it and sample at maximum output for every T_s. You do this for this branch as well as for this branch. If you do the maths you will see, you are getting w_k w_{k-1} + z_k z_{k-1}. These pertain effectively to the 2 constellation diagrams, pass it through a decision device, take a input on which bit was being send of the 2 bits on the in phase and the quadrature, multiplex it and you get back the base band differential detection. So this is method one.

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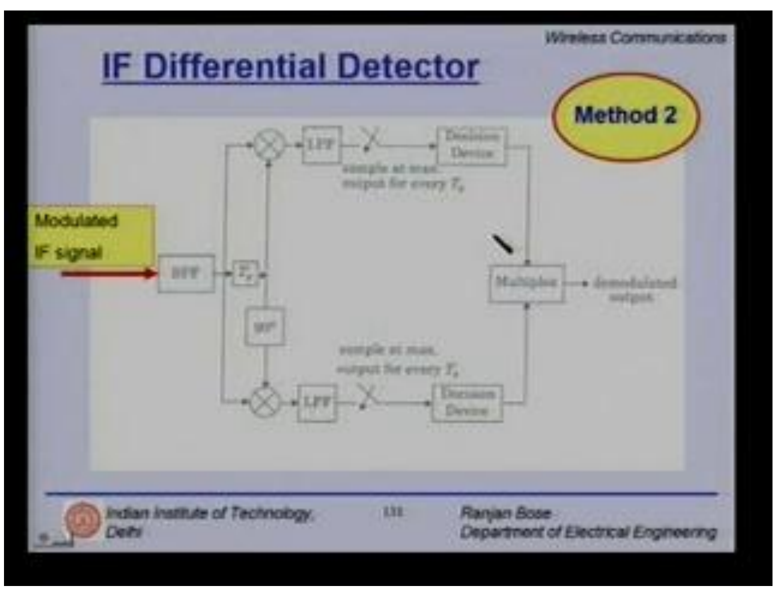

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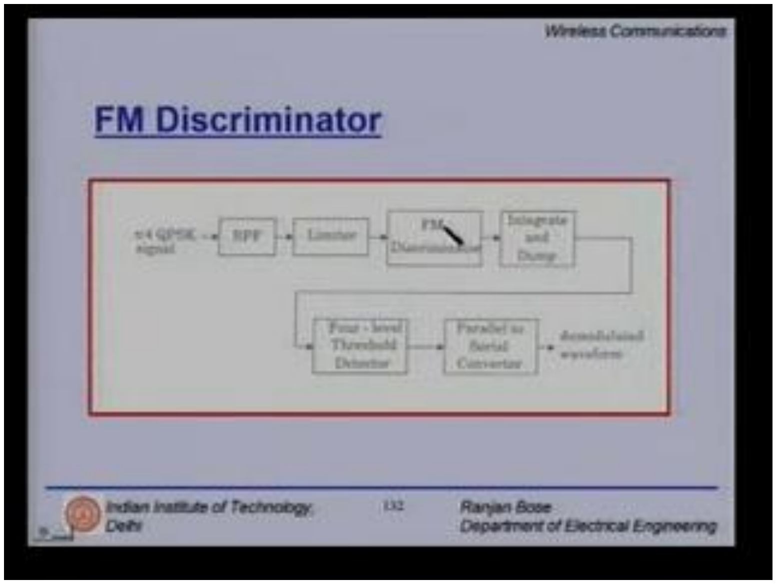

The other technique is the IF differential detector, here the gain is a little simpler. You pass the input through a band pass filter and then you have a 90 degree phase shift cos 2 pi f_ct sin 2 pi f_ct low pass filter it, again sample at max output for every symbol duration decision device, multiplex and demodulate. Where is the complexity shifted? Into the decision devices. So the decision device is to work harder this is your method two. Please note here the modulated IF signal is fading therefore it is called the IF differential detector as oppose to the earlier one which worked at the baseband.

The third method is the FM discriminator method. Here you have the pi by 4 QPSK signal coming in, again begin with have a band pass filtering, limiter and then you have a FM discriminator, integrate and dump. Here you have a four level threshold detector which takes the decision, parallel to serial converter and you get the demodulated waveform output. So these are the three popular methods for the detection of pi by 4 QPSK signals.

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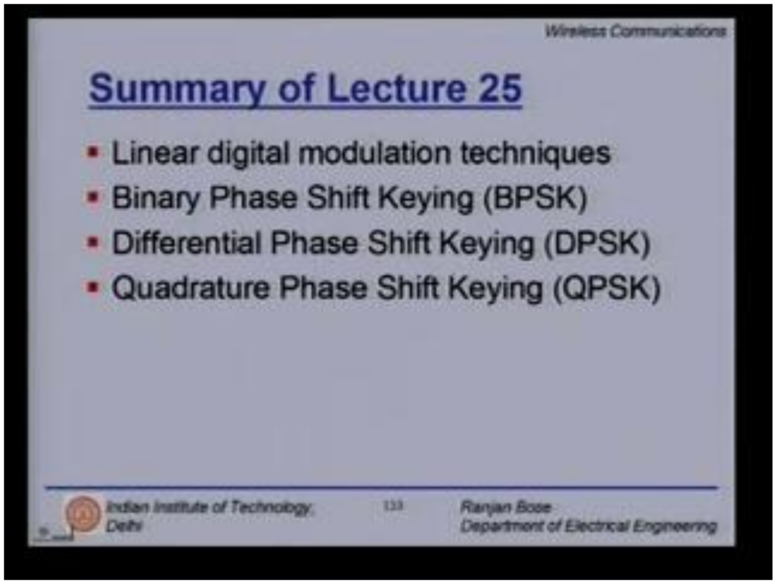

Let us now summarize today's lecture. Today we focused on linear digital modulation techniques. We looked at both the modulating part and the demodulating part. We started off with binary phase shift keying; we looked at the spectrum of the binary phase shift keying, the good generators for BPSK and also demodulators. Then we focused on the differential PSK and looked at an example as to how to carry out DPSK followed by quadrature phase shift keying one of the very popular techniques.