Wireless Communications
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Lecture No. # 22
Modulation Techniques for Mobile Communications

Welcome to the next lecture on modulation techniques for mobile communications. the outline of today's talk is as follows.

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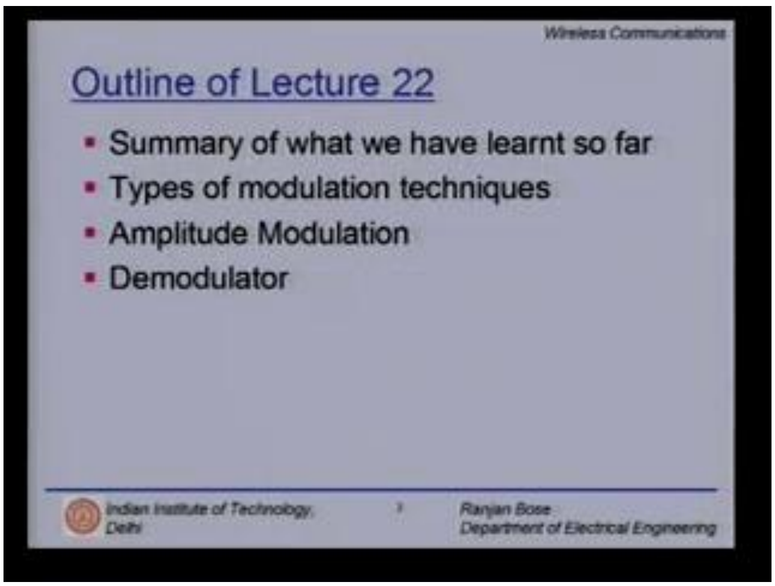

We will briefly summarize what we have learnt so far before we embark upon this new topic. Then we will look at the different kinds of modulation techniques popularly used for mobile communications. Specifically, we will look at amplitude modulation and the demodulator part.

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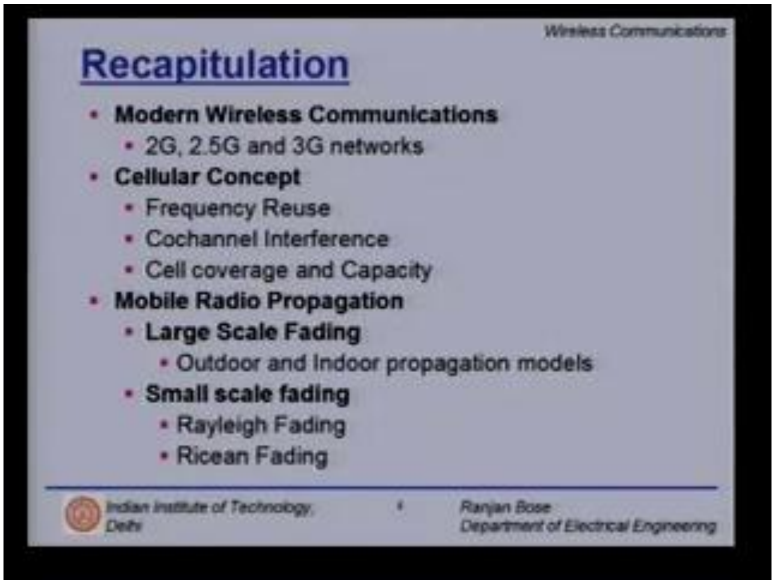

A brief recap of the previous lectures. We looked at the modern wireless communication systems. We looked at the 2 G, 2.5 G and 3G networks. We talked about WCDMA and CDMA. 2000 in the 3G networks. Then we introduced the concept of cellular communications where we looked at frequency reuse leading to co-channel interference. Finally the notions of cell coverage and capacity. In the last few lectures, we have been looking at mobile radio propagation where specifically we looked at large scale fading and small scale fading. Under the domain of large scale fading, we specifically looked at outdoor and indoor propagations models. For a small scale fading, we discovered that Rayleigh fading model fitted well when there is no line of sight whereas Ricean fading model worked when there exist a line of sight. Now having learnt these concepts, we now move on to the next portion of the course which deals with modulation techniques, both analog and digital modulation techniques. Our focus will be on digital modulation. However for the sake of completeness, we will revisit the analog modulation techniques also.

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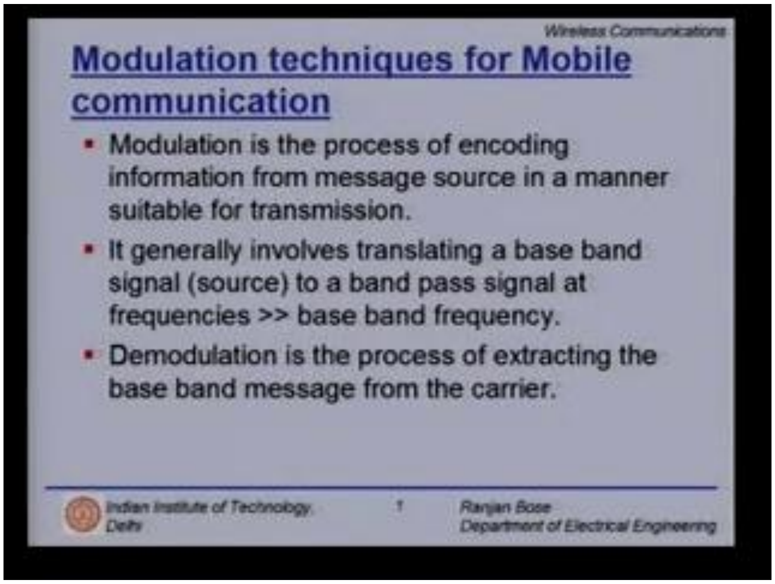

What is modulation? Modulation is the process of encoding information from the message source in a manner suitable for transmission. What is hidden here is there is a way to also ensure that certain quality of service is also there. So modulation by definition not only helps you to transport your message from ‘point a’ to ‘point b’. It also ensures that you do so without making too many errors. So that the quality of service is maintained. It generally involves translating a base band signal from the source to a pass band signal at frequencies which are much greater than the base band frequency. The demodulation is simply the inverse process. It is a process of extracting the base band message from the carrier.

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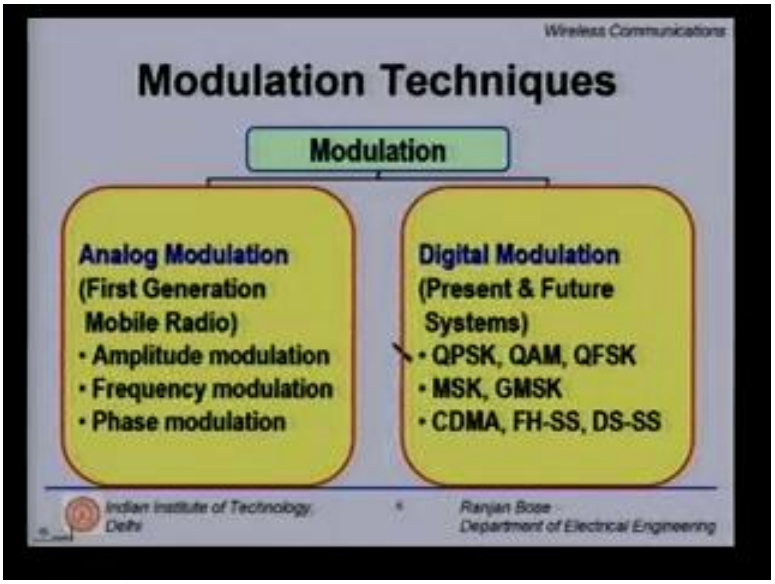

Now let us broadly classify the different modulation techniques. Very broadly modulation techniques can be classified into either analog modulation or digital modulation. Analog modulation was popular with the first generation mobile radio systems and still can be used for radio receivers at home. However digital modulation takes the biggest piece of the cake and this is where more than 85 % of today’s communication systems work. At digital modulation techniques, under the analog modulation we have popular amplitude modulation or AM frequency modulation or FM and phase modulation. For digital modulation which will be used also in the future communication systems, we have the popular QPSK, QAM, QFSK's, MSK’s and GMSK’s. We will look at these in the light of various standards for mobile communications also. Today we will look at amplitude modulation.

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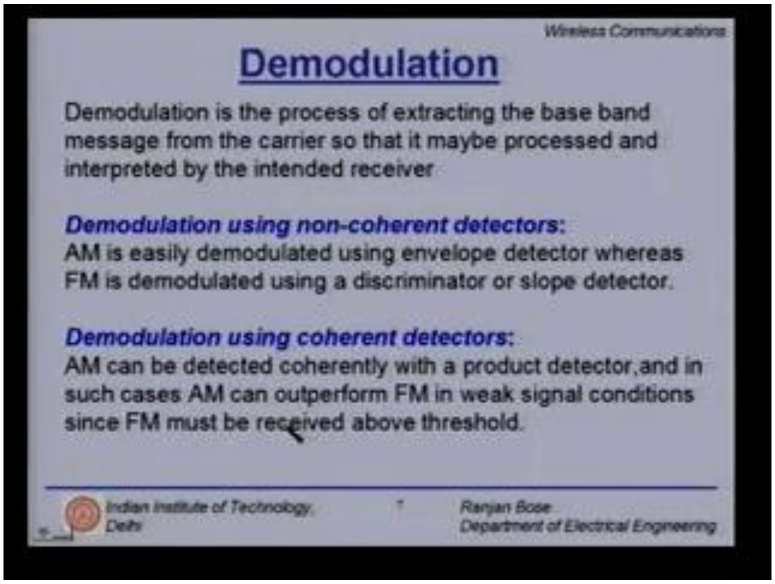

What is demodulation? Demodulation is the process of extracting the base band message from the carrier so that it may be processed and interpreted by the intended user. Now we broadly have two kinds of demodulation. You can demodulate using non coherent detectors. So if you are specifically talking about the analog modulation techniques where the popular ones are AM amplitude modulation and FM frequency modulation, AM is easily demodulated using envelop detector whereas FM is demodulated using a discriminator or a slope detector. Today we will also revisit the relative advantages and disadvantages of AM versus FM. on the other hand, if you have the luxury to have coherent detection; you build a demodulation technique using coherent detectors. AM can be detected coherently with a product detector. We will look at it and in such cases AM can actually outperform FM in weak signal conditions low SNR since FM must be received above a threshold. But we will see that FM has a better noise tolerance than AM and the signal strength is not too weak.

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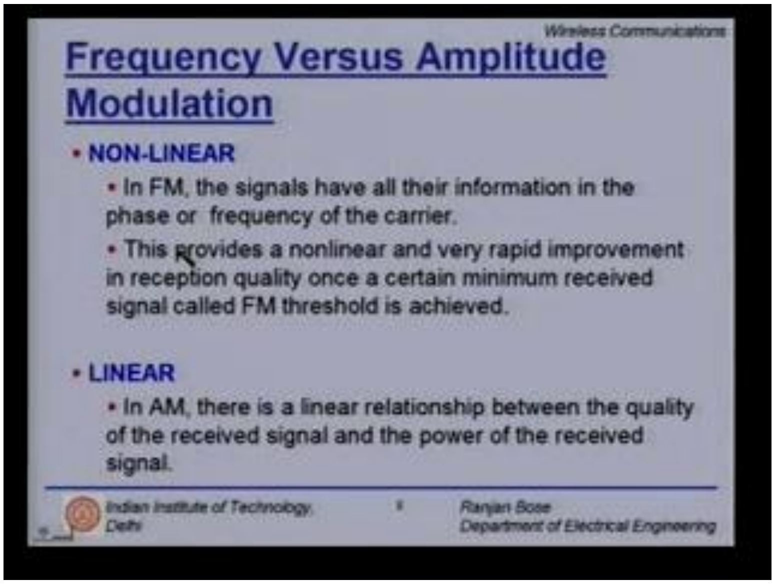

Couple of slides on the relative advantages and disadvantages of FM versus AM. Let us look from the perspective of linearity and non-linearity in FM. the signals have all the information in the phase or the frequency of the carrier. Nothing is in the amplitude. This provides a non-linear and a very rapid improvement in reception quality once a certain minimum received signal called 'the FM threshold' is achieved from the linearity prospective in AM. There is a linear relationship between the quality of the received signal and the power of the received signal. So how fast is the improvement taking place depends on whether you are using AM or FM.

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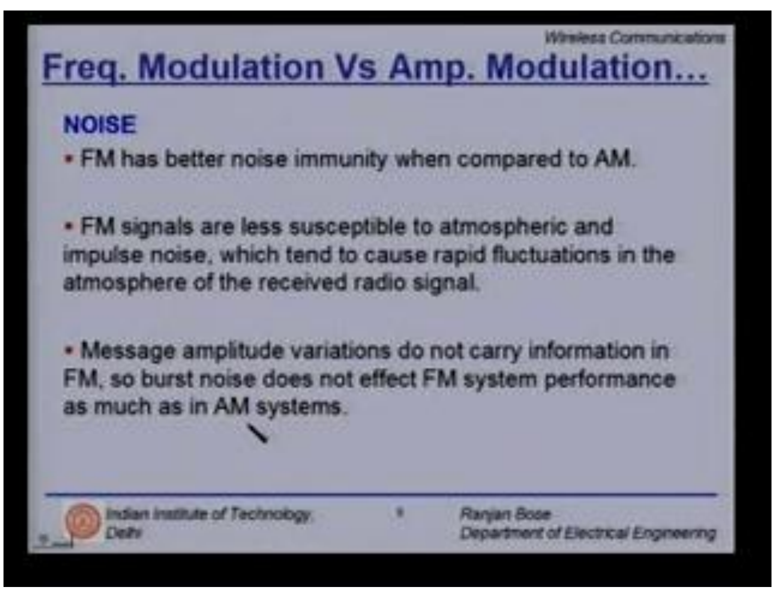

Let us look at from the perspective of noise how does FM behave with respect to AM FM has better noise immunity when compared to AM FM signals are less susceptible to atmospheric and impulse noise which tend to cause rapid fluctuations in the atmosphere of the received radio signal. The message amplitude variations do not carry information in FM. so burst noise does not affect FM systems but AM systems are drastically affected once the amplitude is tampered with. Clearly, if you put AM and FM in fading environment, we will have bad repercussions for AM.

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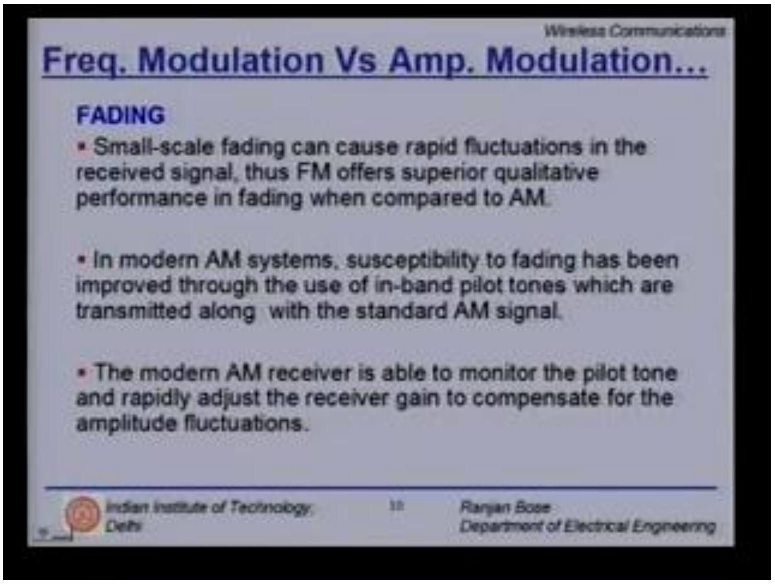

For fading, small scale fading can cause rapid fluctuations in the received signal in the last couple of classes. We have seen exactly how rapid fluctuations happen and what could be the popular models to have a stochastic modeling of the random process. Since amplitude can get adversely affected in fading channels, AM suffers. On the other hand, FM offers superior qualitative performance in fading as compared to AM. So we are not talking about noise. We are talking about fading environments. However modern, AM has a work around in modern AM systems. Susceptibility to fading has been improved through the use of an in band pilot tone. What does it do? These pilot tones are transmitted along with the AM signal and we monitor the received amplitude of the pilot. If the amplitude is lower than a certain level, we pump it up. We increase the gain at the receiver thereby counteracting fading. So the modern AM receiver is able to monitor the pilot tone and thus rapidly adjust the receiver gain in order to compensate for the amplitude fluctuations. You definitely have to pay a little bit in terms of power but then your quality improves drastically. Still AM is not as good as FM in fading scenarios.

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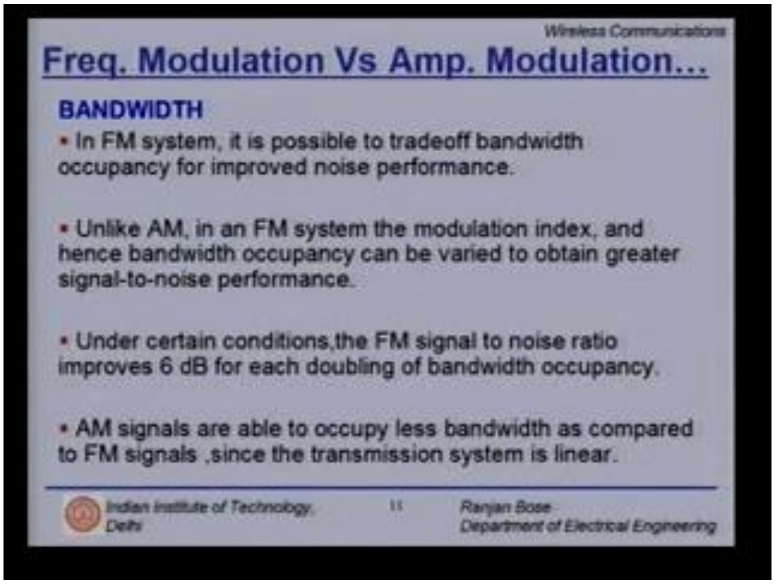

Let us compare FM and AM from the perspective of band width. In FM systems, it is possible to tradeoff bandwidth occupancy for improved noise performance. This is important. You have a freedom. You have to choose how much bandwidth you want to expand and how much quality improvement in terms of your performance you can obtain. Unlike AM, in an FM system the modulation index and hence the bandwidth occupancy can be varied in order to obtain greater signal to noise performance. Under certain conditions the FM signal to noise ratio improves 6 dB for each doubling of the bandwidth occupancy once you're above the FM threshold. AM signals are able to occupy less bandwidth as compared to FM signals since the transmission system is linear and there is no notion of tradeoff between bandwidth and noise performance. FM gives us that design flexibility. Please remember AM, FM, etc. were in the standards of the first generation mobile communication systems and since then have been ruled out.

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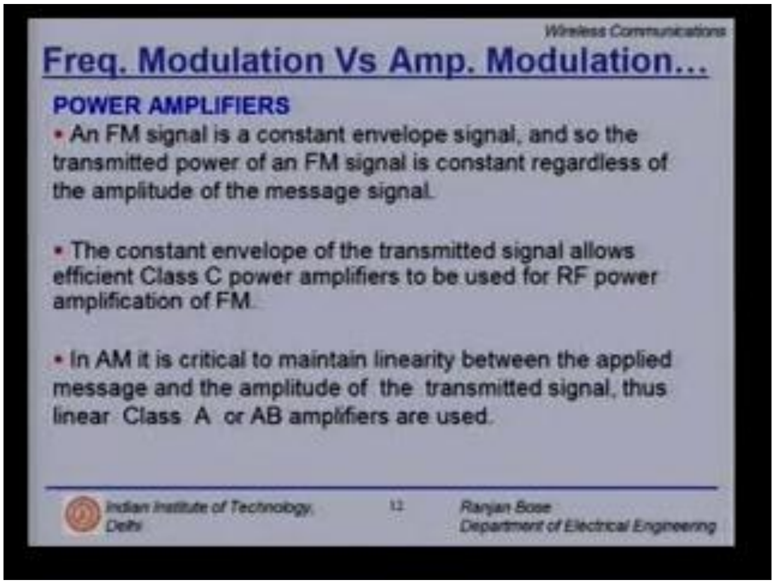

Let us talk about FM versus AM from the perspective of power amplifiers. An FM signal is a constant envelop signal. There is no information in the amplitude of the signal and so the transmitted power of an FM signal is constant regardless of the amplitude of the message signal. This is very important. The constant envelop of the transmitted signal allows efficient class C power amplifiers to be used for RF power amplification of FM. so we are talking from the perspective of the transmitter. The transmitter is easier from the perspective of power amplifiers in FM, whereas you will see that the demodulator for FM is more complex than that of AM. In AM, it is critical to maintain linearity between the applied message and the amplitude of the transmitted signal. Thus a linear class A or class AB amplifier must be used. So the transmitter is slightly more complex in AM from the power amplifier perspective than FM.

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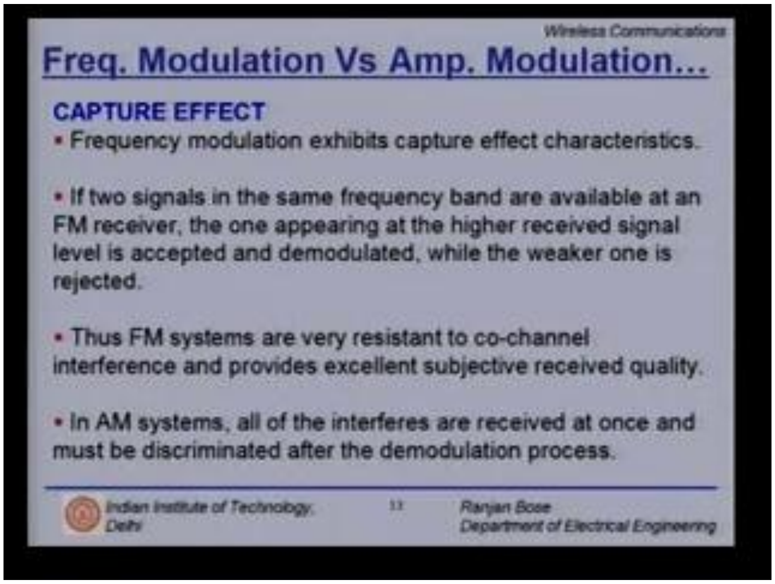

Let’s go to capture effect. Frequency modulation exhibits capture effect characteristics. If two signals in the same frequency band are available at an FM receiver, the one appearing at the higher received signal level is accepted and demodulated while the weaker one is rejected. Think of co-channel interference. FM has an inherent expertise to reject the weaker signal even though it is in the band. It will only pick up and amplify the signal at the slightly higher signal level. These FM systems are very resistant to co-channel interference and provides excellent subjective received quality. No such luck for AM. In AM systems, all the interferences are received at once and must be discriminated after the demodulation process. Many times it is impossible to separate the co-channel interference if I receive it in AM systems. That’s not the problem with FM system. This is called the capture effect.

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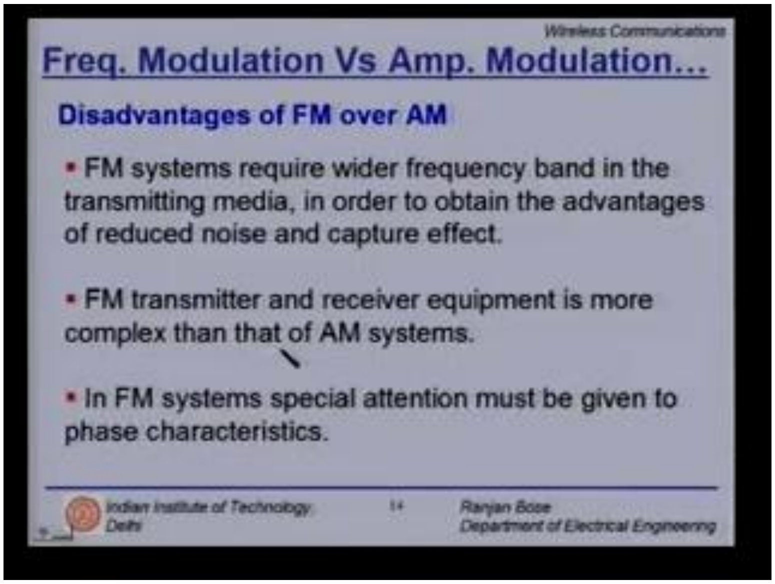

The picture is not all that rosy all the time. So the disadvantages of FM over AM are as follows. First FM systems require a much wider frequency band in the transmitting media in order to obtain the advantages of reduced noise and the capture effect. So the biggest disadvantage or so to say "the price you have to pay for better performance" is an increased bandwidth requirement. Also the FM transmitter and receiver equipment is more complex than that of AM systems. Hence more expensive. In FM systems, special attention must be given to phase characteristics. These are the three disadvantages that FM faces with respect to AM. But still it is the preferred choice. The question being asked is: where does power amplifier fit in here? We have seen in a previous slide that power amplifier per say is easier and less complex to design in FM transmitters. However the rest of the modulation circuit for FM is still complex. So barring the power amplifier part, FM transmitter is more complex and hence more expensive than the FM AM transmitter. Similarly the receiver equipment is also more complex in FM. FM is generally a more complex system.

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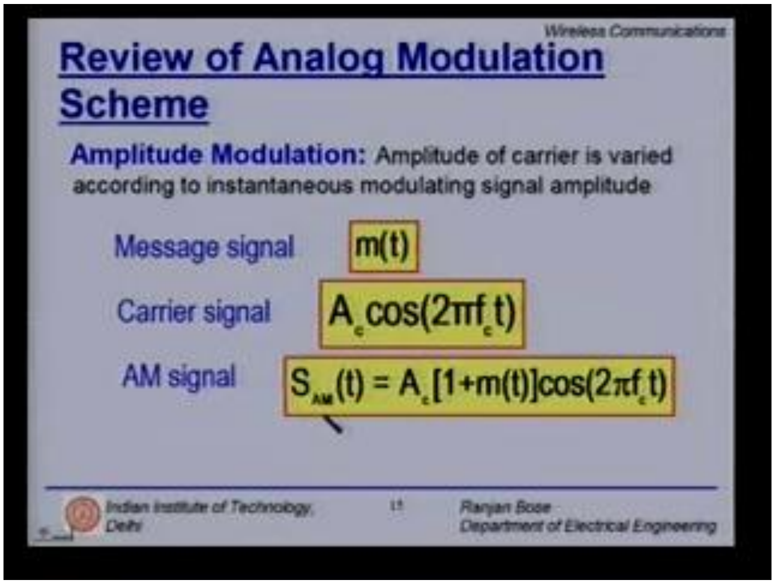

Now let us spend some time reviewing the analog modulation techniques. First let us look at the amplitude modulation. The philosophy is very simple. The amplitude of the carrier is varied according to the instantaneous modulating signal amplitude. So the information is clearly sent by changing the amplitude of the carrier. We need a carrier and then we change the amplitude of the carrier according to the message. It's very simple. Your message signal is m(t) and you have your carrier signal which is A_c cos 2 pi f_ct. Here A_c represents the amplitude of the carrier. So subscript 'c' is for the carrier. f_c is the carrier frequency. AM signal is nothing but A_c[1 + m(t)] cos (2pi f_ct) here. Please note that I could have simply had m(t) times cos 2pi f_ct. But it will have certain problems. So I am adding a carrier. Here also this is the AM signal in its most basic form.

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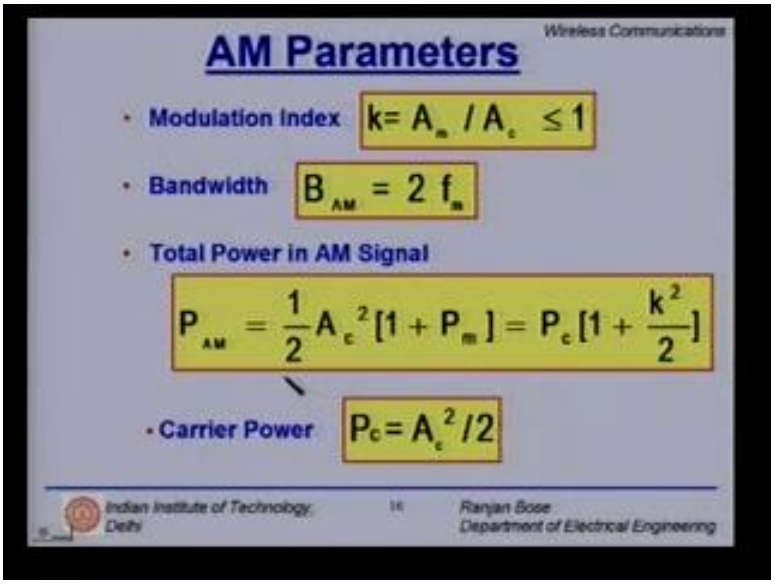

What are some of the parameters? The ratio of the peak amplitude of the message to the peak amplitude of the carrier is called the modulation index. It is less than or equal to one. The bandwidth for AM is twice FM the maximum bandwidth of the message signal. The total power in the AM signal P_{AM} is given by the formula half A_c squared $1 + P_m$ and the carrier power P_c is A_c squared by two. So with this, we know everything. There is a need to know about the AM signal. We can quantify AM signal by these four equations.

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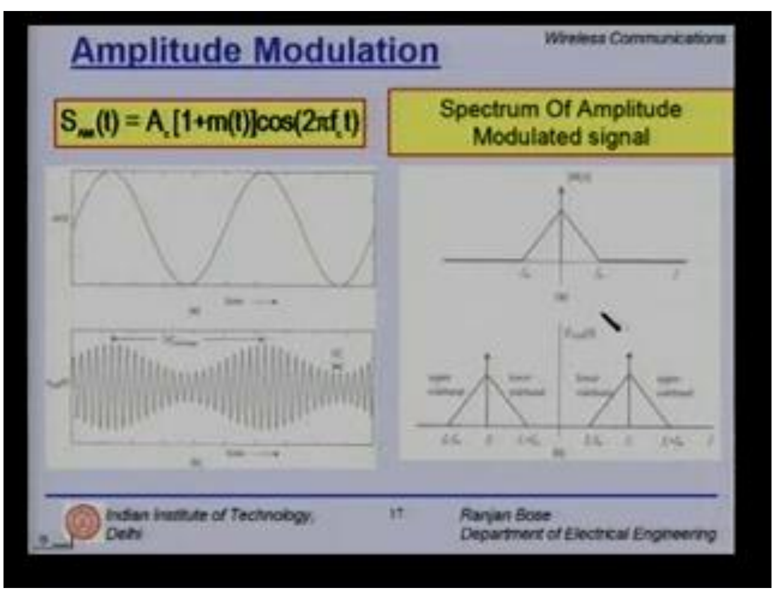

Let us look at a very simple example. Let us first talk on the time domain. Here assume this is a part of your message and the carrier here is modulated with respect to the message even though I have taken a pure sinusoid. Here it could be any speech signal or any other kind of waveform. In the time domain, the modulated signal can be given as follows. it has the meassage as well as the carrier in the frequency domain. you can have the message signal represented like this. So clearly some arbitrary message signal not clearly a sinusoid. A sinusoid will put an impulse here. So it is some message signal and once you have an amplitude modulation, it is shifted at the location of the carrier. Hence this gives you the need for twice the bandwidth required for your message. Multiplication in the time domain is convolution in the frequency domain and hence you just convolve the message spectrum with two delta functions representative of the cosine carrier and you get the message signal at these two locations. Thus the spectrum of the amplitude modulated signal looks something like this.

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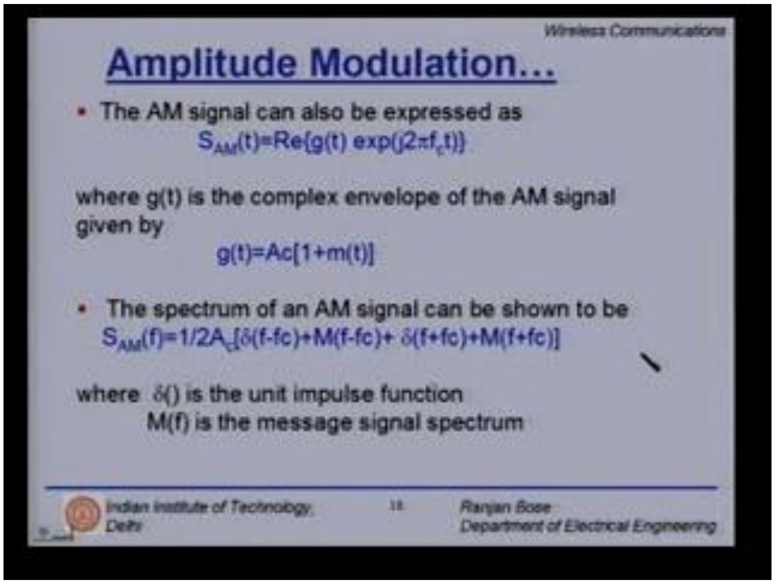

The AM signal can also be expressed as follows in terms of a real part. Then gt power j 2 pi f_ct where gt is the complex envelop of the AM signal given by gt = A_c 1 + m(t). The spectrum of an AM signal can be shown to be as follows. As you can see here, there is a delta function at the carrier frequency plus the Fourier transform of the message signal at the plus and minus f_c levels. delta is the unit impulse function. Mf is the message signal spectrum. It is a very simple depiction of the frequency domain AM signal.

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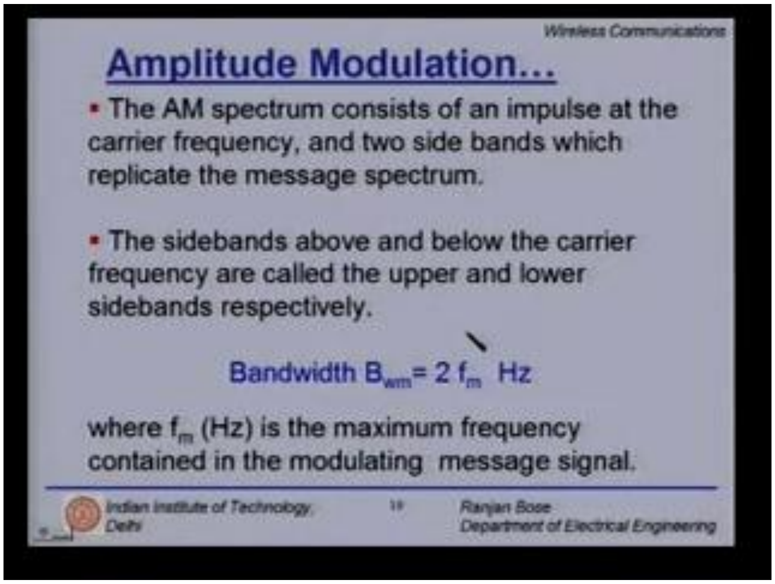

The AM spectrum consists of an impulse at the carrier frequency and two sidebands which replicate the message spectrum. The sidebands above and below the carrier frequency are called the upper and lower sidebands respectively. The bandwidth is twice FM the bandwidth of the message signal where f_m is the maximum frequency contained in the modulating message signal. So in some sense it is. This method is expensive. We are using twice the bandwidth than what is required to actually send it. The simplest way is either to send the upper side band or the lower side band; the replicas of each other.

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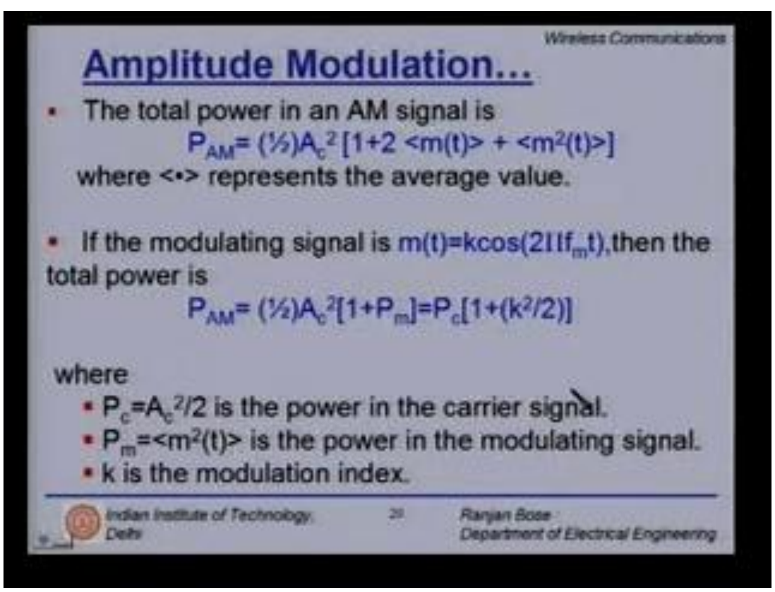

The total power in an AM signal is given by this formula where this triangular bracket represents the average value. If the modulating signal is m(t) k cos 2pi fm(t), then the total power is given by this formula P_{AM} 1/2 A_c squared 1+ P_m. you have seen this before where $P_c = A_c^2 / 2$ is the power in the carrier and P_m is the power in the modulating signal. k here is the modulation index.

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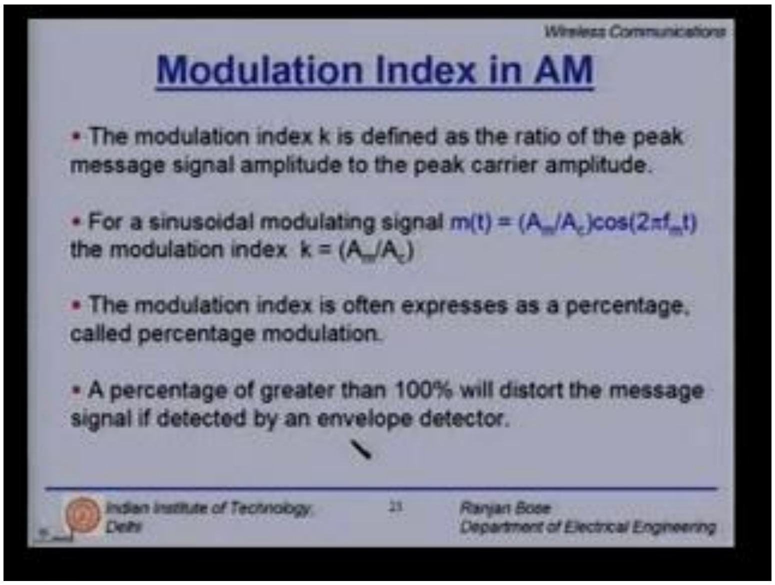

So the modulation index k is defined as the ratio of the peak message signal amplitude to the peak carrier amplitude. For a sinusoidal modulation, modulating signal m(t), the modulation index k is given by A_m/ A_c. the modulation index is often expressed as a percentage called the percentage modulation of A_m. a percentage greater than hundred will distort the message signal if detected by an envelope detector. When we talk about detectors we will find that envelop detector is one of the cheap popular ways for detecting Am signals in the absence of the carrier frequency.

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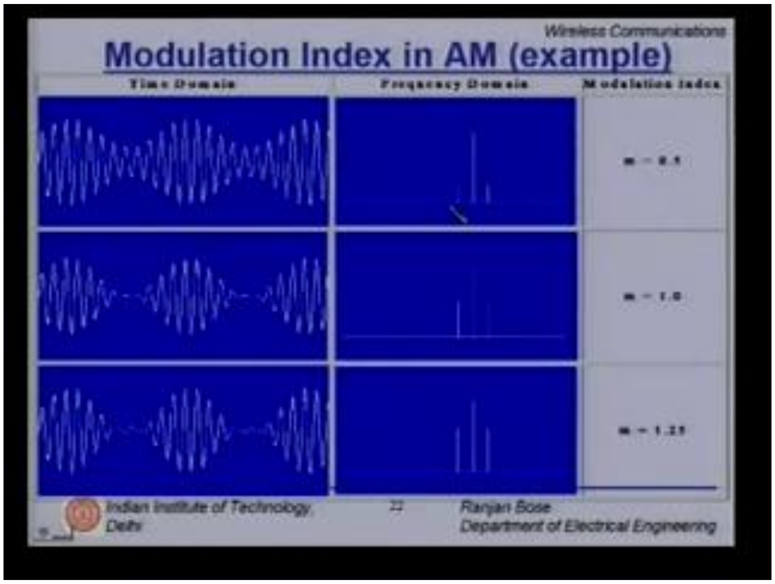

Let us look at an example where we have different kinds of amplitude modulated signals with respect to the modulation index. So on the right most columns represents the modulation index. The first one is for m =0.5 or 50 %. Here you can see that there is a carrier and the message signal modulates the carrier. In the frequency domain you have a very strong carrier signal and relatively weak message signal. If you go back, you see that k is nothing but the ratio of A_m message to 'A_c' - the carrier amplitude. So as I increase my modulation index, my A_m increases. So let's see what happens when we go at 1. Here we are just about there. We have not yet distorted our message but anywhere above 1, at m =1.25, you see the message crosses over and starts distorting it. If you just use an envelope detector to detect it, you will have severe distortions at these cross over points.

Conversation between student and professor:

Student: Here m = 1. So does it mean that Am = Ac?

Professor: that's right. Here the power of the signal. In this diagram, k = Am by Ac. so this is the peak amplitude. Here if you see in this diagram, there is an upper sideband and lower sideband. Together they compete with this Ac. so the total power is split between the carrier which is a single impulse here and for the maximum frequency at two, so that half and half, they add up to one. So Am over Ac is actually one here whereas if you see here, in the last diagram you have gone beyond this 0.5 level and both the upper and lower bands are greater than that and so your modulation index is greater than one. Here it is much smaller. So the point to be observed in this diagram is that if you have a modulating index greater than one, your signal gets distorted if you use an envelope detector at the receiver.

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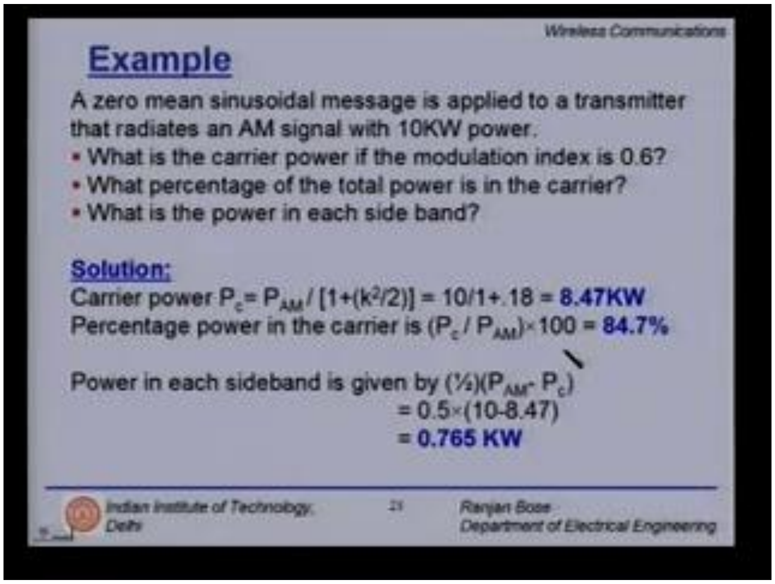

Let us look at another example. A zero means sinusoidal message is applied to a transmitter that radiates an AM signal with 10 kW power. The question is: what is the carrier power if the modulation index is 0.6? The next question is: what percentage of the total power is actually in the carrier because that is not conveying any message. So in a sense it is wasted power. Now what is the power in each sideband? So carrier power is given by this formula P_c is equal to $P_{AM}/1+K^2/2$ and if you plug in these values, you get for a 10 kW. A total power 8.47 kW is in the carrier. The percentage power in the carrier is P_c divided by P_{AM}. It is close to 84.7 %. The power in each sideband is given by 1/2 P_{AM}-P_c because that's where the remainder of the power will be once you subtract out the power in the carrier. This is given by 0.675 kW. So the carrier is hogging most of the power which is not a good sign.

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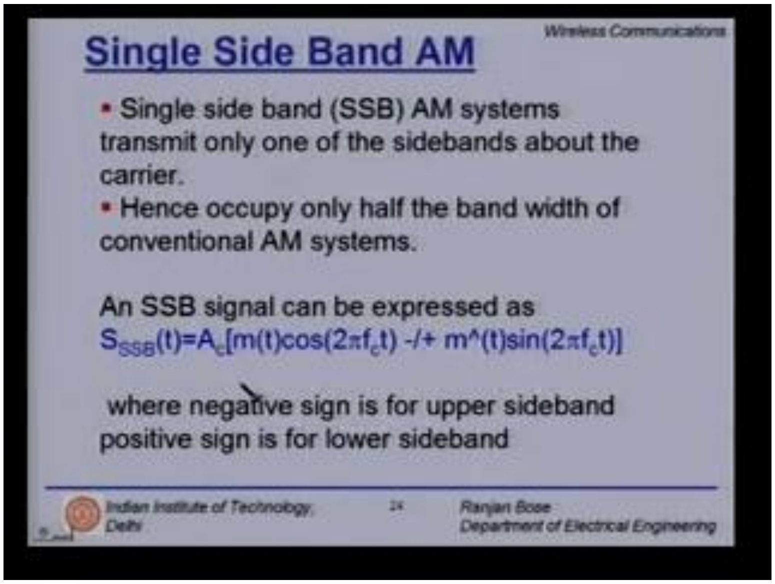

Now let us try to do something about that excess frequency being used by AM systems. Remember we said that the AM system normally would require 2 FM where FM is the maximum frequency of the message signal. So you have the notion of a single sideband AM or SSB. What does a single sideband AM system do? An SSB system transmits only one of the sidebands above the carrier. Not both. Hence they occupy only half the bandwidth of the conventional AM systems and SSB signal can be expressed as follows. S $_{SSB}$ in time domain is A_c m(t) cosine 2 pi $f_c t$ +/- m hat t sin 2 pi $f_c t$. What is m hat? m hat we will talk about it later. It will be given by one of the Hilbert transforms. The plus and the minus sign cater to whether it is an upper sideband or lower sideband. Plus will be the upper sideband whereas minus will be the lower sideband. So in this method, you have a single sideband AM signal.

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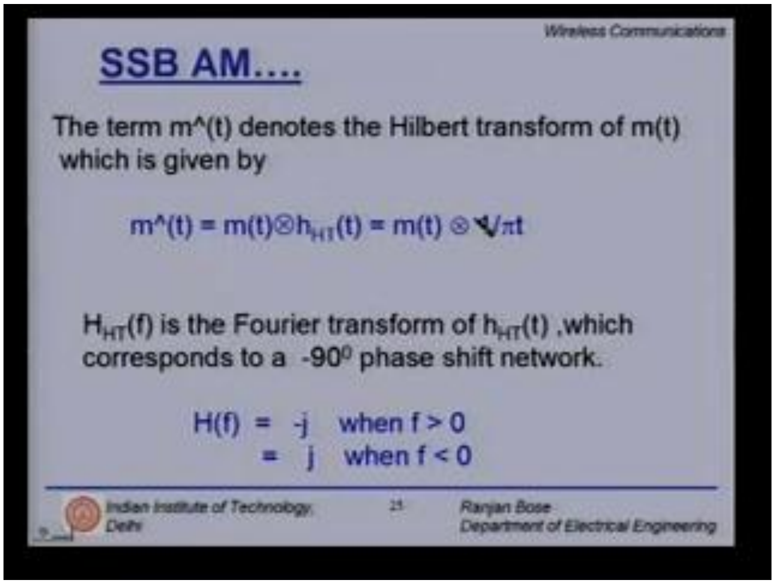

The term ‘m hat t’ denotes the Hilbert transform of m(t). We will just define what is Hilbert transform. m hat t is m(t) convolved with h Hilbert transform. the impulse response of a Hilbert transform which is given by 1 over pi t. ‘H’ Hilbert transform in the frequency domain is the Fourier transform of impulse response. $h_{HT}(t)$ which corresponds to a 90 degree phase shift network. H (f) is given by - j when f > 0 and j when f < 0. So this is the famous Hilbert transform. It is very useful for SSB in signals.

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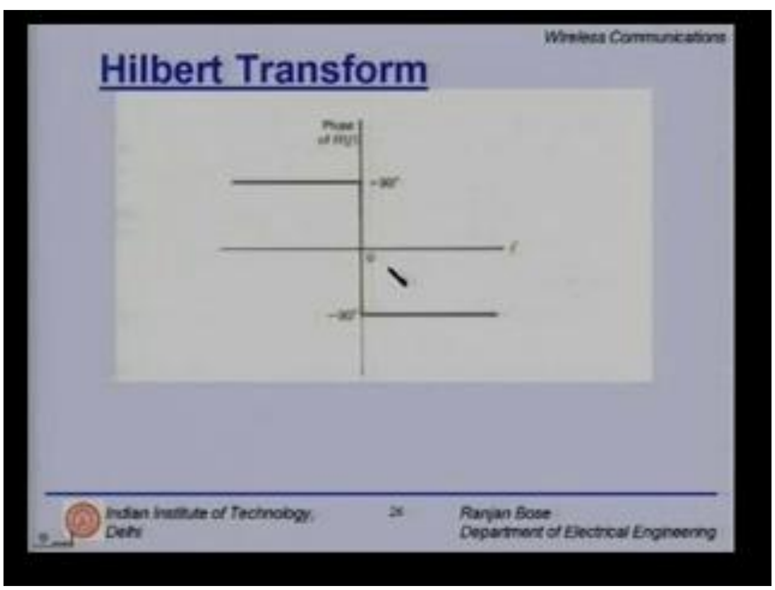

So in the frequency domain, you have for f > 0, - 90 degrees phase and for f < 0, it is + 90 degree.

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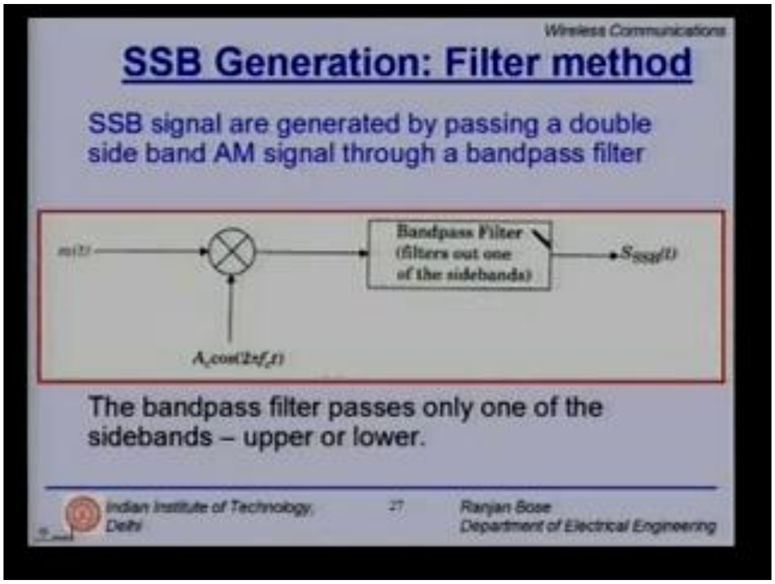

Now let us look at the SSB generation. Using filter method SSB signals are generated by passing a double side band AM signal through a band pass filter. Clearly filter out the section you do not want. How is it implemented? ‘m(t)’ which is the message signal comes and is fed into a multiplier. On the other side we have A_c cos 2 pi f_ct which is the carrier. You multiply, pass it through an appropriate band pass filter whether you want to remove the upper sideband or lower sideband and you have the single sideband fairly simple. The band pass filter passes only one of the sidebands; either upper or lower. So the onus is on designing this band pass filter. How sharp should be the cutoffs, that you only transmit the desired signal other than that. The rest of the portion in the transmitter is fairly simple.

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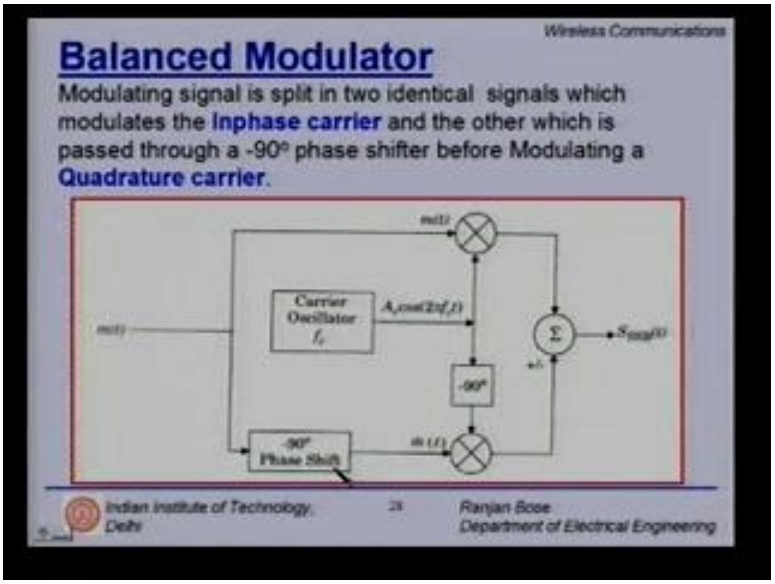

The other way to generate an AM signal is to use a balanced modulator. How does that work? the modulating signal is first split in two identical signals which modulates the in-phase carrier and the other which is passed through a 90 degree with a negative sign phase shifter before modulating a quadrature carrier. So in-phase is cosine 2 pi f_ct. Quadrature is sin 2 pi f_ct. So the original signal is first split. One is passed through a - 70 degree phase shifter trying to mimic what Hilbert transform is doing. How does the block diagram look? You have a message. You take the same message here m(t) and then in the next leg, you have a - 90 degree phase shift. You have this m hat t. on the other hand; you have the carrier A_c cos 2 pi f_ct. Pass it through a – 90 degree phase shifter to get the quadrature component on this side and in-phase component on this side. Multiply, add and you get the single side band. You do not have to worry about any band pass filters or how sharp the cutoffs are. So both the methods either using a band pass filter or a balance modulator has their pros and cons. here the errors will creep in if the phase shift has a drift.

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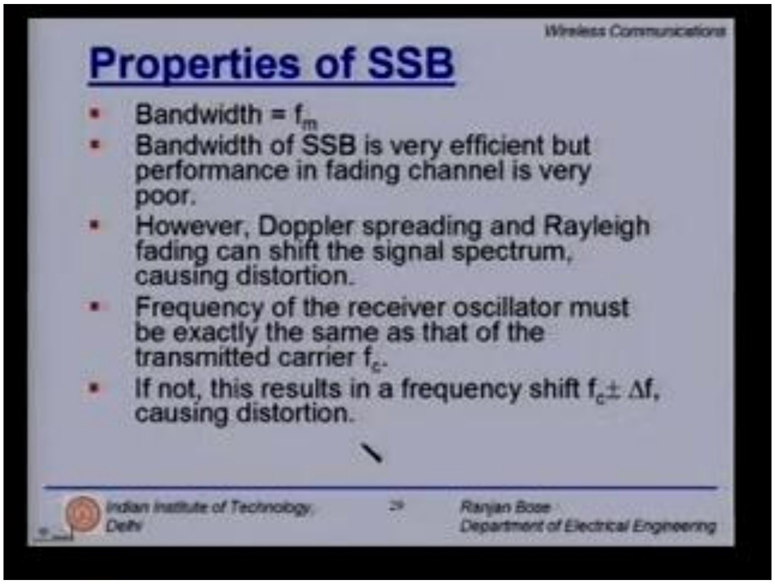

Now let us spend some time looking at the properties of single sideband. AM modulated signals bandwidth is clearly FM by design. I have cutoff half the bandwidth and retained only that is required. The maximum bandwidth of the message. The bandwidth of SSB is very efficient but performance in fading channels is extremely poor. Doppler spreading and Rayleigh fading can shift the signal spectrum thus causing major distortions. Please picture the SSB in the frequency domain. Any shift because of the Doppler frequency shift will cause a distortion at the demodulator side. The frequency of the received oscillator must be exactly the same as that of the transmitted carrier. The point is you have to have a proper match between the carrier frequency that is sent and one that is used for demodulation. Otherwise you introduce distortions. If not if there is not proper matching at the carrier frequency and the local oscillator, then it will result in a frequency shift f_c +/- delta f causing distortion.

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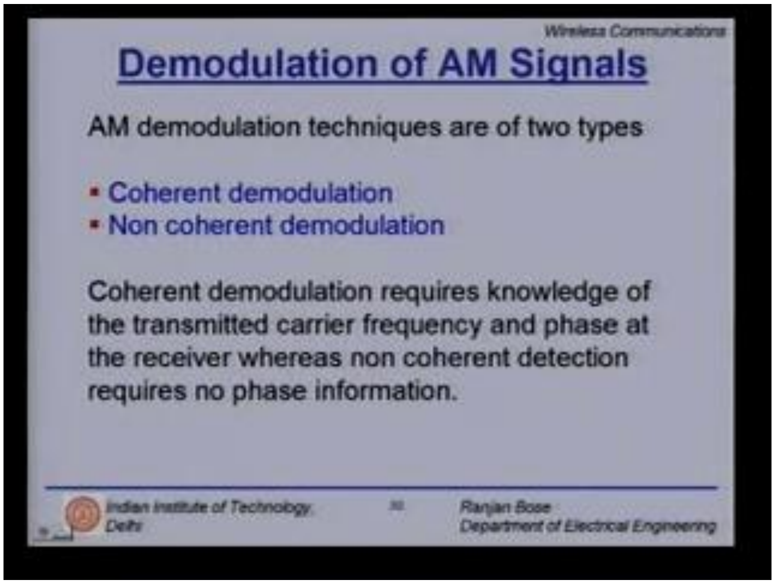

Now let us look at the other perspective of demodulation of AM signals clearly you can have a coherent demodulator or the incoherent or non-coherent demodulator. The AM demodulation techniques are of two types either you have a coherent demodulation or you have a non-coherent demodulation. Coherent demodulation requires knowledge of the transmitted carrier frequency. That’s a must and also the phase at the receiver whereas non-coherent detection requires no phase information.

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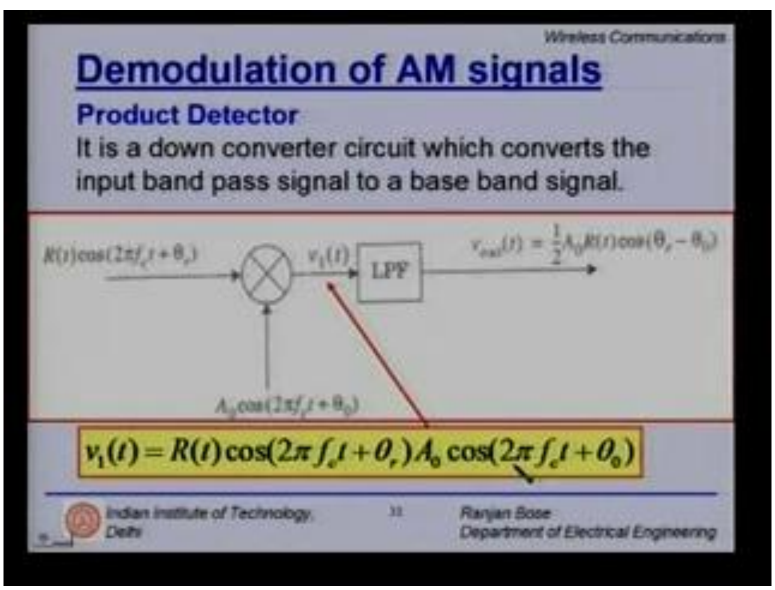

First let us look at the product detector. It is nothing but a down converter circuit which converts the input band pass signal to a base band signal. It's just a down converter and then passes it through an LPF. So let us look at the block diagram. You have this received signal R(t). This signal R(t) cos 2 pi f_ct + theta r. here you have a local oscillator. Again A $_0$ cos 2 pi f_ct + theta $_0$. You multiply. Once you multiply, you will get something. This is the v $_1$ t given by R(t) cos 2 pi f_ct + theta r. here simply multiplied by A $_0$ cos 2 pi f_ct + theta $_0$. Now what is this quantity? As we will see, in the next slide, this has a low pass component and a higher frequency component.

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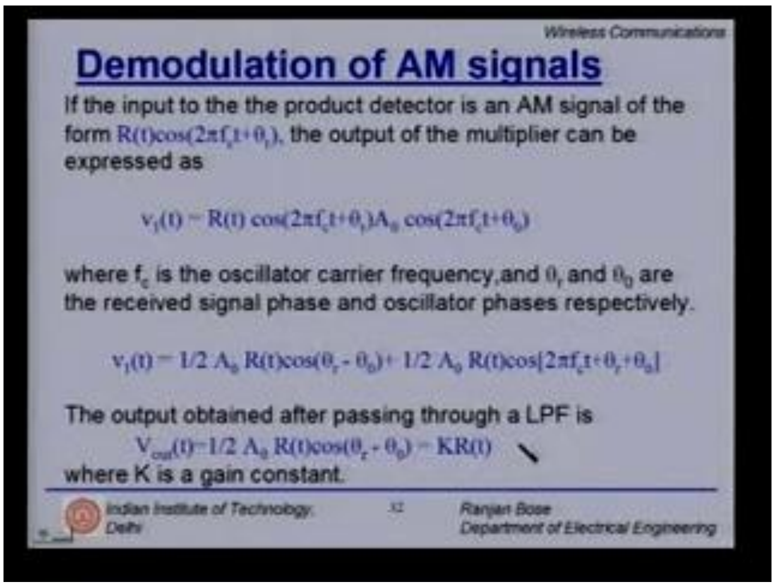

So if the input to the product detector is an AM signal of the form R(t) cos 2 pi f_ct + theta r, the output of the multiplier can be expressed as this. We saw just now where f_c is the oscillator carrier frequency. theta $_r$ and theta $_0$ are the received signal phase and the oscillator phases respectively. If you do a basic trigonometric simplification, you get v 1 t as 1/2 A $_0$ R(t) cos theta $_r$ - theta $_0$ + ½ A $_0$ R(t) cos 2 pi f_ct + theta $_r$ + theta $_0$. Now if you pass this through a low pass filter, what you obtain is just this first term '1/2 A $_0$ R(t) cos theta $_r$ - theta $_0$. Here this 2 pi f_ct makes it high frequency component which is filtered out by the low pass filter. So in effect, you are left with K times R(t) as long as your theta $_r$ and theta $_0$ are fixed though unknown. Your K is a constant. So I am in business. I can take this, amplify it and I get back my R(t). K is a gain constant.

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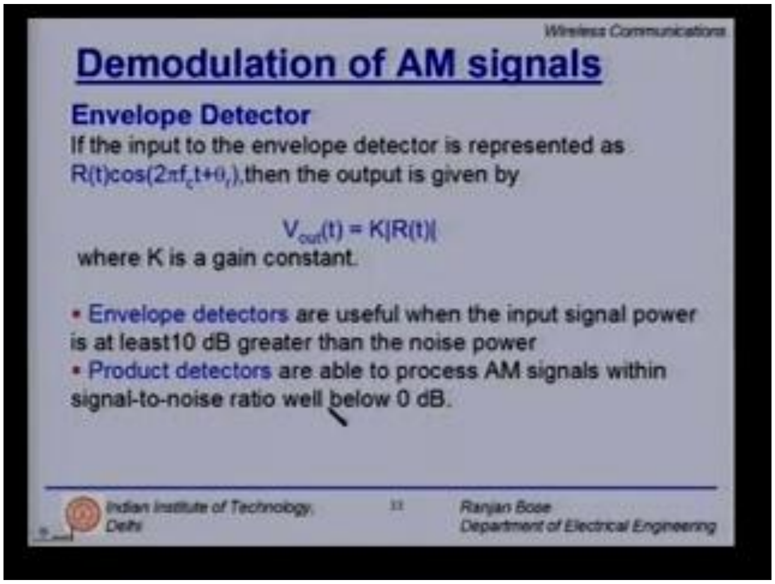

Now suppose we do not have the luxury of the carrier being known with its phase, then all we do is an envelope detection. if the input to the envelop detector is represented as R(t) cos 2 pi f_ct + theta $_r$, then the output is given by V $_{out}$ as K absolute value R(t) where K is a gain constant. That's about it. Envelop is where the information is. If you have an envelope detection you get the amplitude modulated information. Envelop detectors are useful when the input signal power is at least 10 dB greater than the noise power. It doesn't work in low SNR's. That's the major problem. On the other hand envelop detectors are extremely easy to design. It's just a capacitor and a resistor very easy to design. On the other hand, the more complex product detectors are able to process AM signals within signal to noise ratios well below 0 dB. So extremely poor conditions, very low signal to noise ratio also you can make the product detectors work but your envelop detectors will fail.

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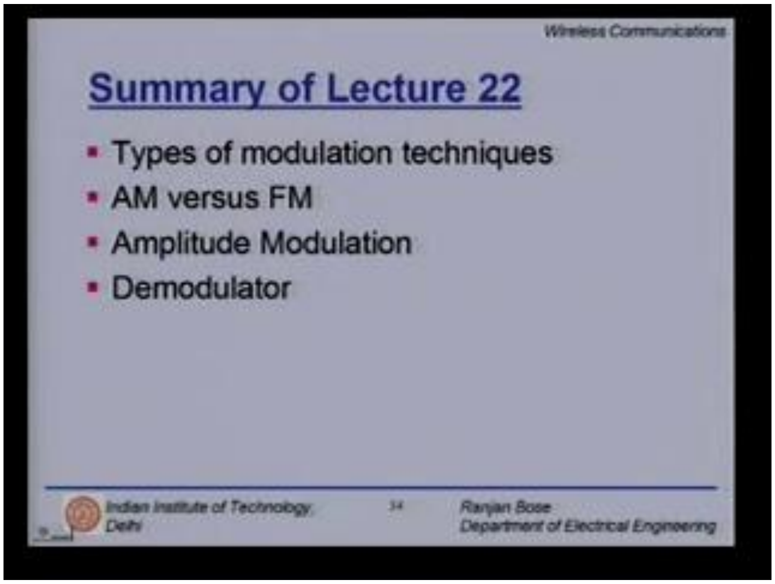

Let us now summarize what we have learnt today. We started off with different kinds of modulation techniques that can be used for wireless communication systems. We looked at the analog modulation techniques and the digital modulation techniques. Then we started off with a rough comparison of FM versus AM: the two most popular analog modulation techniques. We then looked at AM modulation in detail. How you make the modulator, what is a product demodulator, what is the envelop demodulator, etc. these are the two kinds of demodulators we have studied for AM and what are the relative advantages. In the next lecture, we will have a look at FM and then in the subsequent lectures, we will look at the advanced digital modulation techniques and try to correlate them with what standards use what modulation techniques. Thank you!