Wireless Communications

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Lecture No. # 19

Mobile Radio Propagation - II (Continued)

Welcome to the next lecture on mobile radio propagation.

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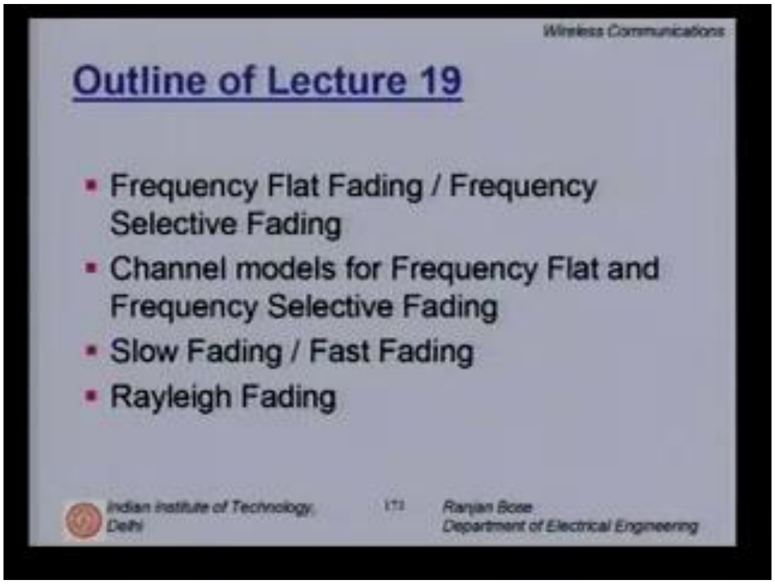

Outline of Lecture 19

- Frequency Flat Fading / Frequency Selective Fading
- Channel models for Frequency Flat and Frequency Selective Fading
- Slow Fading / Fast Fading
- Rayleigh Fading

Today we will start with frequency flat and frequency selective fading. We will today talk about channel models for frequency flat and frequency selective fading. Then we will look at another aspect of how fast the channel changes vis-à-vis the signal itself. So we will then talk about slow fading verses fast fading. At the end if time permits, we will briefly have a beep at Rayleigh fading and Ricean fading. Of course, as always we will start with a brief recap of what we learnt last time.

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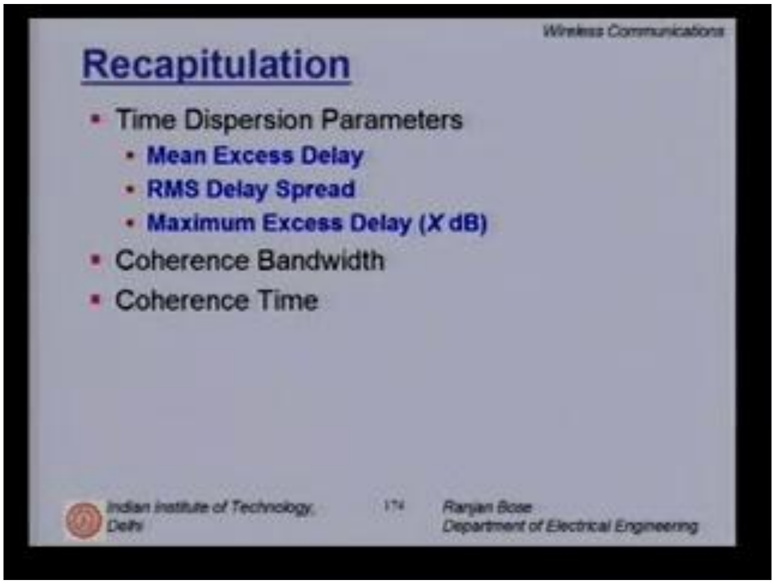

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Recapitulation

- Time Dispersion Parameters
  - **Mean Excess Delay**
  - **RMS Delay Spread**
  - **Maximum Excess Delay (*X* dB)**
- Coherence Bandwidth
- Coherence Time

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In the previous classes, we have been talking about time dispersion parameters of your fading channel. If you remember, we have a transmitter and a receiver spatially separated and the propagation occurs through the wireless medium. We are working in a wireless channel environment. It is possible that the transmitter and receiver are moving with respect to each other as is the case in mobile communication. In such case, we have various time dispersion parameters to characterize the channel. We learnt last time that the power delay profile which we can measure is useful in obtaining the three important time dispersion parameters namely; the mean excess delay, the RMS or the root means square delay spread as well as the maximum excess delay. We also learnt last time about coherence bandwidth. How broad or wide is the channel bandwidth with respect to the signal makes a difference in terms of fading. We learnt last time that if two signals are separated by more than the coherence bandwidth fade independently. We also learnt about coherence time which has to do with how fast the channel is changing with respect to the symbol duration. today we will play with these parameters with respect to the signal and see what do we mean by frequency selective fading or frequency flat fading, fast fading verses slow fading, can we have a combination of these, what does it matter, etc. we will also look at some examples.

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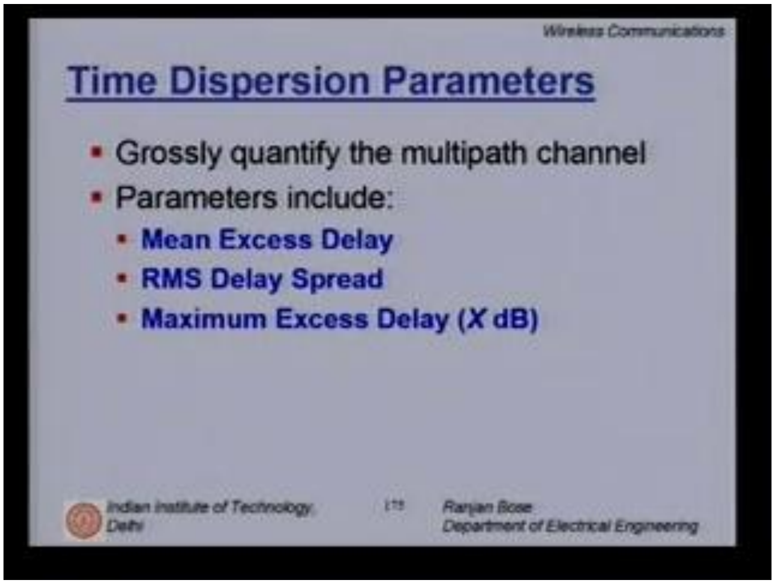

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Time Dispersion Parameters

- Grossly quantify the multipath channel
- Parameters include:
  - **Mean Excess Delay**
  - **RMS Delay Spread**
  - **Maximum Excess Delay (*X* dB)**

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So continuing with our notion of time dispersion parameters, we recall that they grossly quantify the multipath channel and the three most important parameters that we will revisit are the mean excess delay, the root means square delay spread and the maximum excess delay.

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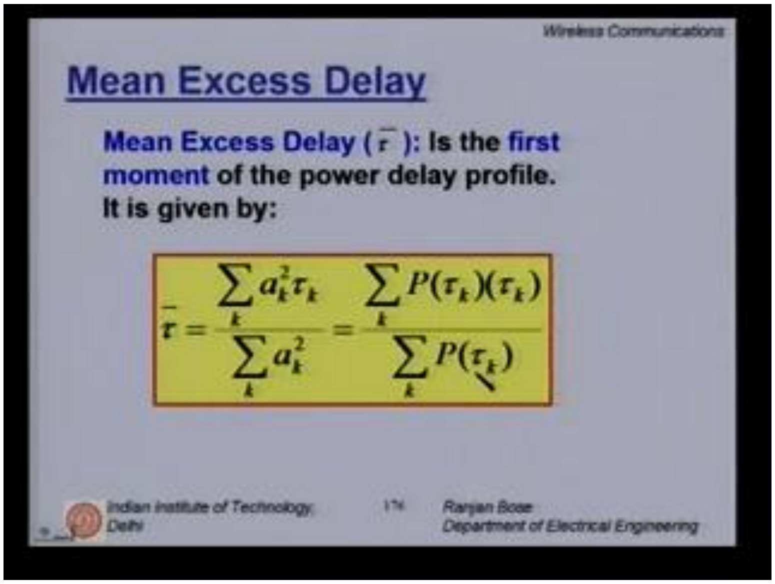

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Mean Excess Delay

Mean Excess Delay ($\bar{\tau}$): Is the first moment of the power delay profile. It is given by:

$$\bar{\tau} = \frac{\sum_k a_k^2 \tau_k}{\sum_k a_k^2} = \frac{\sum_k P(\tau_k)(\tau_k)}{\sum_k P(\tau_k)}$$

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So if you recall the mean excess delay represented by tau bar is the first moment of the power delay profile. it is given by the following formula tau bar is equal to summation a $_k$ ^{2} tau k divided by summation over k a $_k$ ^{2}.

Please remember the small k represents the number of multipath channels. If we are in a room environment with their several multipath components, then k can range from 1 to 20 or more whereas if we are in the outdoor environment where we do not have very many buildings or other reflectors, k can be a smaller number. There could be 6 or 8 significant reflections and hence multipaths. Now the moment we measure the power delay profile which is p(tau), we automatically square the received strength. So a $_k$ represents the channel gain for the k^{th} path. the equation for tau bar which is the mean excess delay turns out to be summation over k P (tau $_k$) which is nothing but the power delay profile times tau k divided by summation over k P (tau $_k$).

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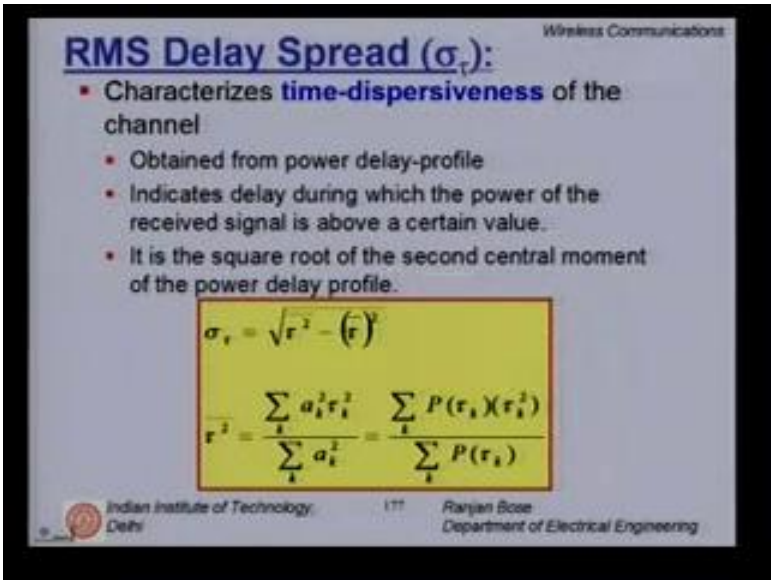

RMS Delay Spread (σ_τ):

- Characterizes **time-dispersiveness** of the channel
  - Obtained from power delay-profile
  - Indicates delay during which the power of the received signal is above a certain value.
  - It is the square root of the second central moment of the power delay profile.

$$\sigma_\tau = \sqrt{\overline{\tau^2} - (\bar{\tau})^2}$$

$$\overline{\tau^2} = \frac{\sum_k a_k^2 \tau_k^2}{\sum_k a_k^2} = \frac{\sum_k P(\tau_k)(\tau_k^2)}{\sum_k P(\tau_k)}$$

The root means square delay spread signified by sigma tau characterizes the time dipersiveness of the channel. It is directly obtained from the power delay profile. It indicates delay during which the power of the received signal is above a certain value. It is the square root of the second central moment of the power delay profile. Mathematically sigma $_{tau}$ is equal to under root tau ^{2} bar, the average value minus tau bar ^{2} which is the second central moment of the power delay profile. Again tau bar ^{2} which is used in this equation is nothing but summation over k P (tau $_k$). This time tau $_k$ ^{2} divided by summation of P (tau $_k$). So given a measured value of a power delay profile, it is easy to compute tau bar. It is easy to compute tau ^{2} bar and hence it is relatively easy to compute sigma $_{tau}$ from this equation. Please recall that RMS delay spread will have a limit of how fast you can send the data bits over an unequalized channel. Today we will learn that these parameters come into play when we talk about the frequency selectiveness of a channel also.

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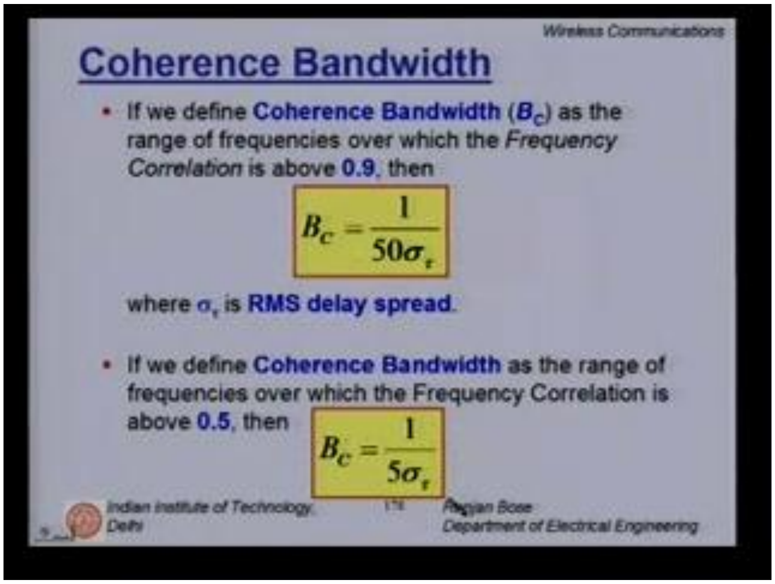

Coherence Bandwidth

- If we define **Coherence Bandwidth** (B_C) as the range of frequencies over which the *Frequency Correlation* is above **0.9**, then

$$\boxed{B_C = \frac{1}{50\sigma_\tau}}$$

where σ_τ is **RMS delay spread**.

- If we define **Coherence Bandwidth** as the range of frequencies over which the Frequency Correlation is above **0.5**, then

$$\boxed{B_C = \frac{1}{5\sigma_\tau}}$$

We learnt about coherence bandwidth. We define coherence bandwidth B $_C$ as the range of frequencies over which the frequency correlation is above 0.9. This is one of the two popular definitions if we define it, then B $_C$ comes out to be 1 over 50 sigma $_{tau}$. Sigma $_{tau}$ if you recall can be calculated directly from the power delay profile. The other popular definition of coherence bandwidth is the range of frequencies over which the frequency correlation is above 0.5. If we go by this definition, then B $_C$, the coherence bandwidth is nothing but 1 over 5 sigma $_{tau}$. Sigma $_{tau}$ is the RMS delay spread.

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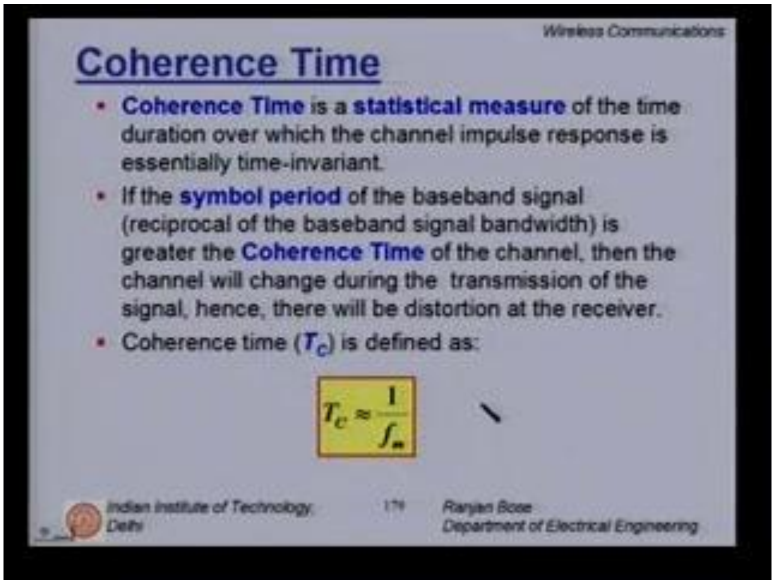

Coherence Time

- **Coherence Time** is a **statistical measure** of the time duration over which the channel impulse response is essentially time-invariant.
- If the **symbol period** of the baseband signal (reciprocal of the baseband signal bandwidth) is greater the **Coherence Time** of the channel, then the channel will change during the transmission of the signal, hence, there will be distortion at the receiver.
- Coherence time (T_C) is defined as:

$$\boxed{T_C \approx \frac{1}{f_m}}$$

The third notion was of coherence time. Coherence time is a statistical measure of time duration over which the channel impulse response is essentially time invariant. So we are talking about how fast your channel is changing. Again how fast or how slow is relative to how fast is your signal duration. if the symbol period of the baseband signal which is approximately the reciprocal of the baseband signal bandwidth is greater than the coherence time of the channel, then the channel will change during the transmission of the signal. We have to be careful about it. Hence there will be distortion at the receiver. The coherence time T_C is defined as 1 over f_m where f_m is the maximum Doppler shift. We learnt that the Doppler shift depends on the velocity of the mobile. The lambda or the wave length of the frequency that we are using and also the relative angle at which the signal impinges on the mobile. Now we will talk about the small-scale fading.

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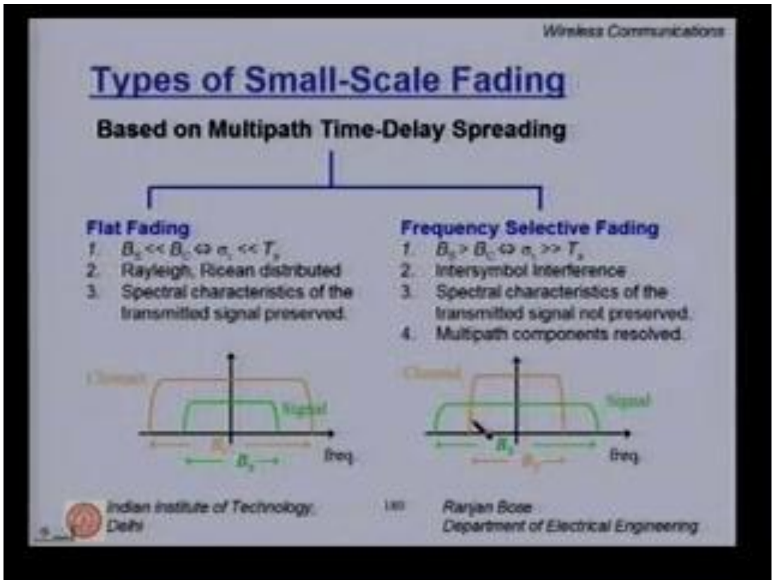

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Types of Small-Scale Fading

Based on Multipath Time-Delay Spreading

Flat Fading

1. $B_S << B_C \Leftrightarrow \sigma_\tau << T_s$
2. Rayleigh, Ricean distributed
3. Spectral characteristics of the transmitted signal preserved.

Frequency Selective Fading

1. $B_S > B_C \Leftrightarrow \sigma_\tau >> T_s$
2. Intersymbol Interference
3. Spectral characteristics of the transmitted signal not preserved.
4. Multipath components resolved.

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Based on the multipath time delay spreading we can classify the multipath time delay spreading into two parts. First is the notion of flat fading. The complete expression is frequency flat fading. So we are trying to comment something about the nature of distortion that we get vis-à-vis the frequency of transmission. So frequency flat fading occurs when B_S which denotes the bandwidth of the signal is much smaller than 'B_C' - the coherence bandwidth. This implies that sigma tau which is the RMS delay spread is much less than 'T_S' - the symbol duration. Now sigma $_{tau}$ is only a function of the environment. It has nothing to do with the signal. So if in a small room environment with lot of reflectors, if sigma $_{tau}$ is much smaller than tau $_S$, then in that case we will experience something called as a 'frequency flat fading'. In these scenarios, we typically find that the received amplitude to be statistically distributed either as a Rayleigh or Ricean. At the end of today's talk, we will introduce both the Rayleigh and the Ricean distribution.

The spectral characteristics of the transmitted signal is preserved in the case of flat fading. The other part based on the multipath time delay spreading is the frequency selective fading component. This is the compliment. So in this case, B_S which is the signal bandwidth is greater than B_C. please note it is not much greater than (check) just greater than. Starts you into the domain of frequency selective fading but in many cases, we consider B_S greater than B_S. it equally implies that sigma $_{\text{tau}}$ should be greater than 'T_S' the symbol duration. in this case intersymbol interference occurs. Please note we are trying to distinguish the effects caused by flat fading channel and frequency selective fading channel. again both these are coming from the time dispersiveness of the channel that is, multipath time delay spreading for the same signal that we are sending if the time delay spread increases. In that case, the channel will tend to become more frequency selective. The other features of a frequency selective channel is that the spectral characteristics of the transmitted signal is not preserved. This is the major impediment but it can be also viewed from the other side of the coin which is, you can have uncorrelated fading for one part of the signal with respective the other part of the bandwidth.

So in a frequency selective scenario, I can have inherent ways and means to overcome or reduce the effects of fading. The good part is if your B_S which is the bandwidth of the signal is much greater than B_S, you tend to resolve the multipath components. This we have seen in the case of ultra-wideband UWB communication where each multipath is resolved. Clearly UWB falls into the second category which is frequency selective fading. Usually it is unfair to comment without the knowledge of both the signal duration and the delay spread whether the channel is frequency flat or frequency selective. However in the case of UWB communication, even if you go into the room environment, you tend to encounter frequency selective fading because of the large bandwidth for ultra-wideband scenario. Graphically, let us look at what is happening in the first case which is the flat fading scenario. On the x axis, we have plotted the frequency. Here you can see that the signal bandwidth is represented at the baseband in green and the coherence bandwidth in orange. You can see that the coherence bandwidth is much larger than the signal bandwidth. If such a situation occurs, you encounter flat fading. In such a situation you will also find that the received signal is not distorted whereas on the frequency selective situation, the signal is clearly the bandwidth of the signal and is larger than that of the coherence bandwidth. I do expect that my received signal will be distorted when I look at it from the frequency domain perspective.

Conversation between student and professor: The question being asked is: in the scenario of flat fading, the entire signal bandwidth is faded. Identically there is a correlated fading going on here for the signal. So if the signal fades, it fades. You cannot say that the part of the signal will undergo fading and the other part will not undergo fading or you cannot have a mitigating effect for fading. So how do we resolve or overcome the problem of fading?

For that clearly we have to resolve to other measures. We go for the next dimension which is the time dimension. If my channel is slowly fading or fast fading, I can transmit copies of the same signal at different time durations separated by more than coherence time so that they will undergo independent fading or maybe I can use multiple antennas and use some kind of a spatial diversity so that I can overcome the effects of frequency fading. Clearly, frequency diversity will not work in this case. We will talk at length about two dimensions. One is the frequency dimension and one is the time dimension as we go along in today's talk. We can have a mix and match of a frequency selective channel or a frequency flat channel, a slowly varying channel or a fast fading channel.

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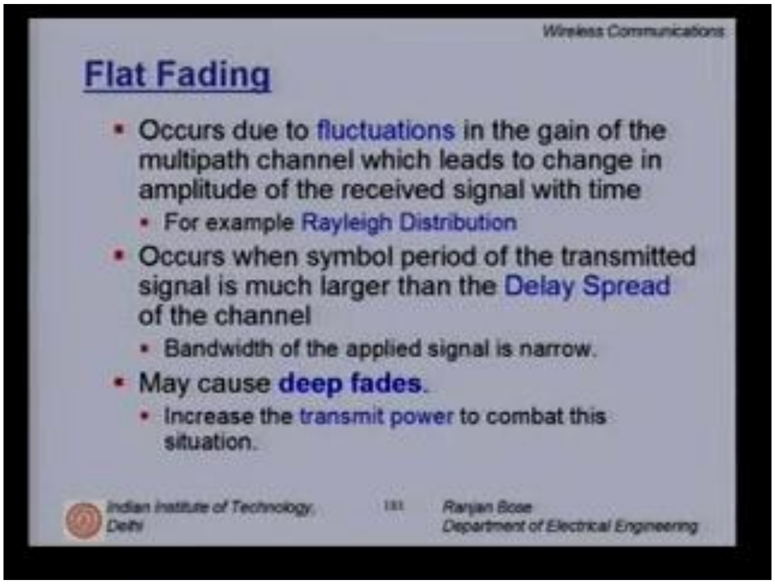

Flat Fading

- Occurs due to fluctuations in the gain of the multipath channel which leads to change in amplitude of the received signal with time
  - For example Rayleigh Distribution
- Occurs when symbol period of the transmitted signal is much larger than the Delay Spread of the channel
  - Bandwidth of the applied signal is narrow.
- May cause **deep fades**.
  - Increase the transmit power to combat this situation.

Let us talk a little bit more about flat fading. Flat fading occurs due to fluctuations in the gain of the multipath channel which leads to the change in the amplitude of the received signal with time. A good example is Rayleigh fading. If you do have a line of sight, also you tend to get Ricean fading. Flat fading occurs when the symbol period of the transmitted signal is much larger than the delay spread of the channel. Clearly, these effects start vanishing if your multipath component reduces. For example, if we use a highly directional antenna, both at the transmitter and receiver, we wipe out most of the multipath components. In those cases, your delay spread of the channel starts going down. Just for the selection of the half power beep of the antenna can affect your delay spread and hence whether the channel is flat fading or frequency selective fading. When you design a communication system, all these things will come into the picture. The bandwidth of the applied signal is narrow as compared to the coherence bandwidth of the channel. We are talking about the flat fading scenario. Flat fading may cause deep fades out of which we have to only come out using some other technique like using time diversity or antenna diversity. The other way to come out of this deep fades is to increase your transmitted power. This is a poor solution because usually, we do not want to solve the problem of fading by increasing the transmit power. There are the other smart techniques to overcome the effects of fading without resolving to the increase in the transmit power. However it still remains one of the possibilities.

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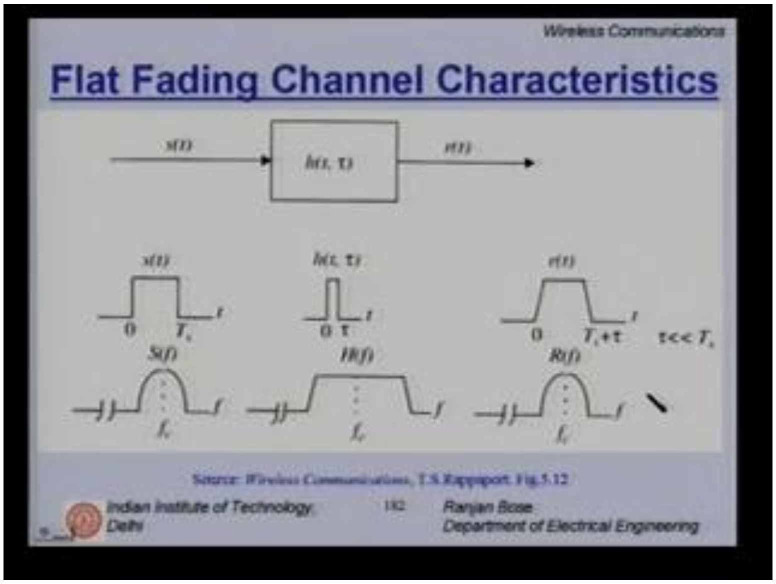

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Flat Fading Channel Characteristics

Source: Wireless Communications, T.S.Rappaport. Fig.5.12

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Let us now look at certain flat fading channel characteristics. Assume that S(t) is a signal being sent. It passes through a frequency flat fading channel described by h (t, tau) and the received signal is r(t). So if you want to represent s(t) in the time domain, it may look like a pulse. Now for a flat fading channel, clearly we do not have multiple pulses coming out. The h(t) is a single impulse. On the other hand, if we were talking about frequency selective channel, the h (t) would be either spread or you will have several pulses here. So it’s a simple way to explain whether the channel impulse response is frequency flat or frequency selective. Now clearly what you receive here is a convolution of s (t) with h(t, tau) and you get a slightly spread pulse like this. Let us see what happens in the frequency domain.

Let’s say the approximate frequency domain representation of s(t) is given by this. It is just a representation. It may not be the exact Fourier transform. An exact Fourier transform would be an impulse here. h(t) is in the frequency domain. h (f) probably can be represented like this. What is important is that h(f) is much larger than s (f).

So ‘B_S’ the bandwidth of the signal is smaller than the coherence bandwidth of the channel approximately. What we get is a product of these two here and as expected, there is hardly any distortion. This is exactly what happens when we work in a flat fading scenario. However suppose I would like to decrease my signal symbol duration, I can do that today. We are pressing for faster and faster data transmission which forces us to reduce t $_S$. in that case, we will have a much broader h(t, tau). It may be multiple impulses here and then you will see that the situation changes. We will talk about it.

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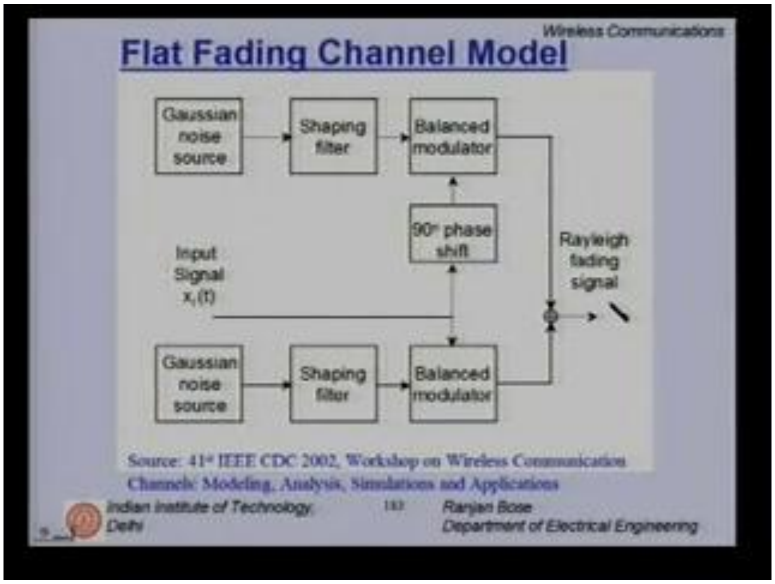

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Flat Fading Channel Model

Gaussian noise source

Shaping filter

Balanced modulator

90° phase shift

Input Signal $x_i(t)$

Rayleigh fading signal

Gaussian noise source

Shaping filter

Balanced modulator

Source: 41st IEEE CDC 2002, Workshop on Wireless Communication Channels: Modeling, Analysis, Simulations and Applications

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Now suppose we have to generate or synthesize a flat fading channel, we can do so either in software or hardware using something like this. Here we are trying to explain how to generate the Rayleigh fading signal. Rayleigh fading signals if you look at the PDF can be obtained by square root of the squares of the two Gaussian random variables added in quadrature. So this is exactly depiction of that. So we have a Gaussian noise source and another independent Gaussian noise source here. Here we have a shaping filter, a balance modulator with a 90 ° phase shift. So cosine and sin and then multiply here. This is nothing but your Rayleigh faded signal.

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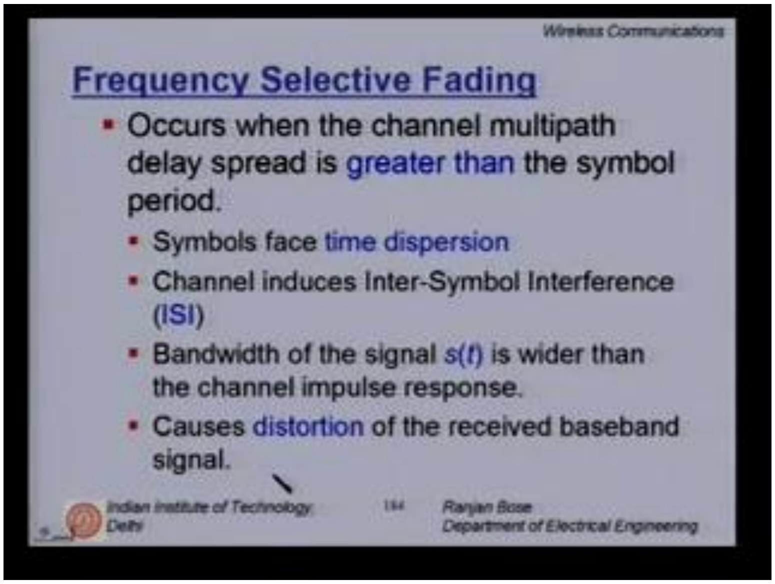

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Frequency Selective Fading

- Occurs when the channel multipath delay spread is greater than the symbol period.
  - Symbols face time dispersion
  - Channel induces Inter-Symbol Interference (ISI)
  - Bandwidth of the signal $s(t)$ is wider than the channel impulse response.
  - Causes distortion of the received baseband signal.

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The other part is the frequency selective channel. Let us now talk about it. Frequency selective fading occurs when the channel multipath delay spread is greater than the symbol period. The same channel will behave as a frequency selective channel. If my ‘T $_S$’ - the symbol duration goes down, symbols clearly face time dispersion. The channel will introduce intersymbol interference because now I have a delayed response of several impulses being represented by the h (t). The bandwidth of the signal S(t) is wider than the channel impulse response h (f) which will be the transfer function. This frequency selective fading causes distortion of the received baseband sector. If we look at in the frequency domain, it will become much clearer.

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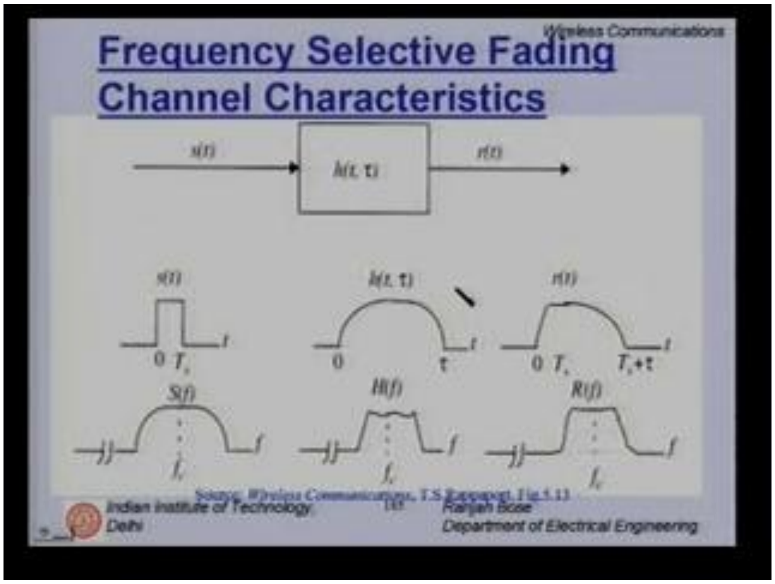

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Frequency Selective Fading Channel Characteristics

Source: Wireless Communications, T.S Rappaport, Fig 5.13

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Let us look at the frequency selective fading. Again, we have a frequency selective channel represented by h(t, tau). The signal that we are sending is s (t) and what we receive is r (t). Please note s (t) much smaller in terms of the width of the symbol t(s). Here for the sake of simplicity, we have drawn a continuum but in most cases, you will have lots of peaks and troughs as you have seen in most of the profile measurements. What we receive here is a convolution of s(t) with h (t, tau). To get r (t) which will be a distorted form, this is clearer in the frequency domain. Let us say s (f) represents the frequency domain representation of s(t). h(f) can be given like this and if we multiply s (f) with h(f), we get a much distorted version of s(f). Clearly the frequency selective fading has introduced distortions and hence the name frequency selective fading is justified. It selectively fades some of the frequency components and let’s go of others.

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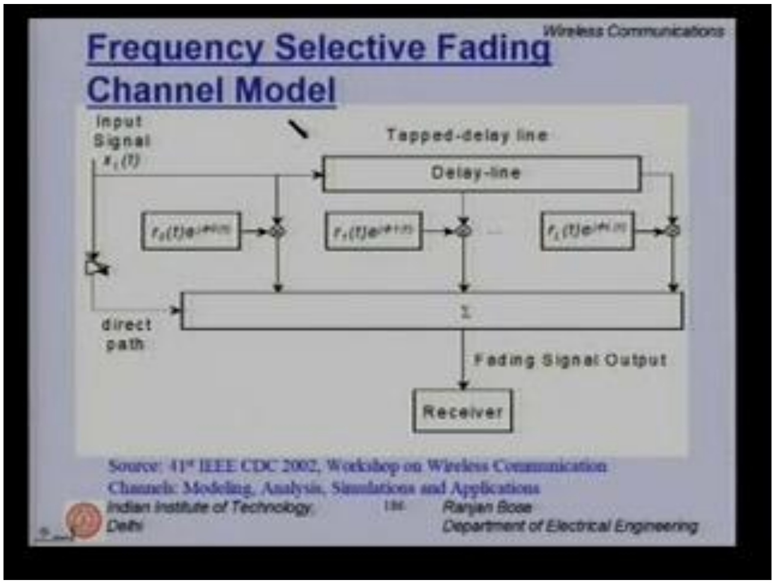
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Frequency Selective Fading Channel Model

Source: 41st IEEE CDC 2002, Workshop on Wireless Communication Channels: Modeling, Analysis, Simulations and Applications

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If we were to draw the frequency selective fading channel model, it can be represented by a tapped delay line. By far, this is the most popular model for a frequency selective channel. Here we have an input signal say x (t). Now we can have either a direct path or several multipaths to this channel model. It is almost intuitive what happens for the various multipaths. We introduce a delay term which will be resulted by a phase shift and an amplitude multiplicative factor. So we take this first version and multiply it with r $_0$ t e raised to power j phi t. then these corresponds to the second multipath so on and so forth up to ‘l’ multipaths. This is represented by tapped delay line model. Then we add them up. That is what we get at the receiver and we get the faded signal output. If we have to generate in the lab scenario or by a simulation frequency selective fading, then we can deploy this kind of a setup.

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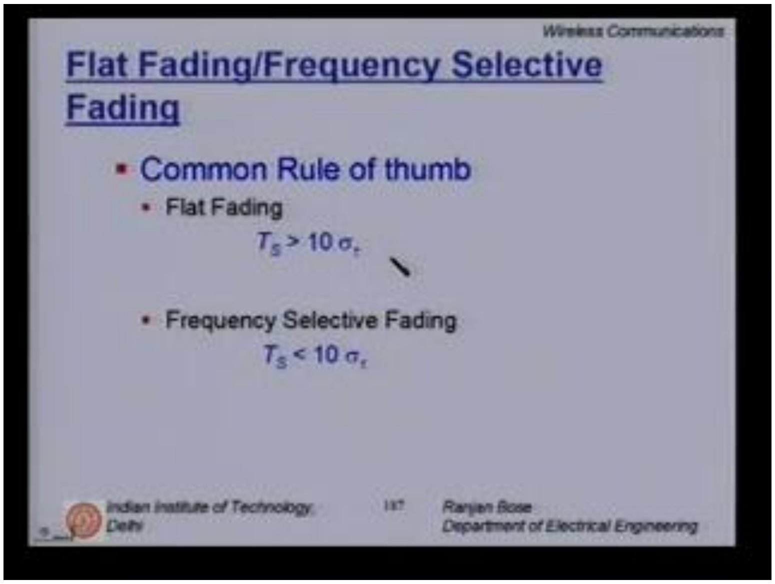

Flat Fading/Frequency Selective Fading

- Common Rule of thumb
  - Flat Fading

    $T_S > 10\,\sigma_\tau$
  - Frequency Selective Fading

    $T_S < 10\,\sigma_\tau$

Now the question is: what is flat frequency flat fading or frequency selective fading? What are the common rules of thumb? How big is ‘big’? Clearly by saying T_S much greater than sigma $_{tau}$ doesn’t give us any definitive answers. Remember we defined flat fading when T_S, the symbol duration is much larger than sigma $_{tau}$, the RMS delay spread. So a rule of thumb is an order of magnitude. So if T(s) is greater than or equal to 10 times sigma $_{tau}$. Sigma $_{tau}$ is the RMS delay spread. Then we will say that the channel is behaving as if it is flat fading. On the other hand, if T (s) is less than 10 times sigma $_{tau}$. You can say that the channel is frequency selective. Sigma $_{tau}$ has nothing to do with the signal. So the same channel, the same room can behave either as a flat fading channel or as a frequency selective channel depending upon what my symbol duration is. Conversation between Student and Professor: the question being asked is: what happens to the case when Ts is less than 10 sigma T or greater than this one? Clearly, these two cases should cover all the scenarios if you are in between may be T_S is approximately equal to sigma T. what do you do? So those are clearly the grey regions where your signal will behave somewhere in the middle. So distortions will start coming in but though not significantly. You’re absolutely safe. No matter what happens, this is absolutely no distortion. In this case there will be distortion and you can confidently overcome the effects of fading. There is no way out that you cannot overcome fading by using frequency diversity. Somewhere in the middle, the frequency diversity technique will not work effectively. You will still have some defects and you will have signal distorted. Those are the cases when T_S is approximately of the order of sigma $_{tau}$.

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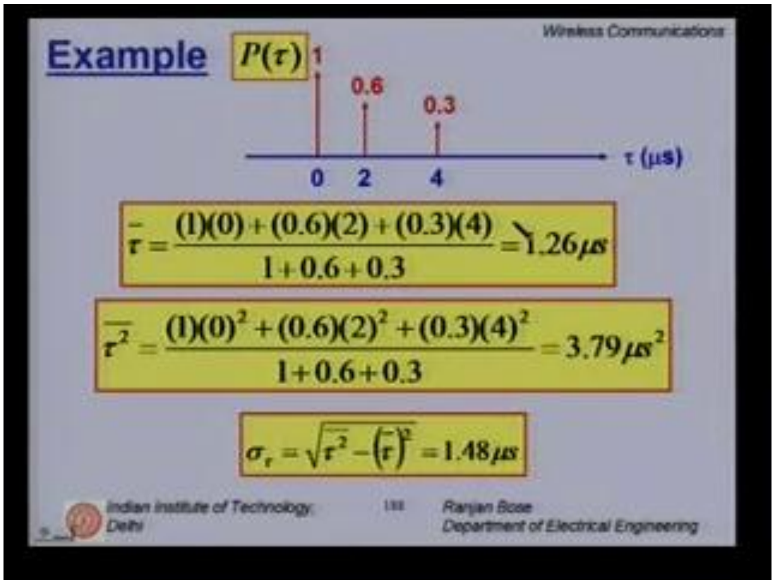

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Example

$$\bar{\tau} = \frac{(1)(0)+(0.6)(2)+(0.3)(4)}{1+0.6+0.3} = 1.26\mu s$$

$$\overline{\tau^2} = \frac{(1)(0)^2+(0.6)(2)^2+(0.3)(4)^2}{1+0.6+0.3} = 3.79\mu s^2$$

$$\sigma_\tau = \sqrt{\overline{\tau^2} - (\bar{\tau})^2} = 1.48\mu s$$

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Let us look at an example. Let us consider a multipath channel where by measurement, the power delay profile looks like this. There are three impulses received. One clearly coming from the line of sight and two from reflections. Now for this, if you calculate tau bar, it comes out to be 1.26 ms. the tau ^{2} bar comes out to be 3.79 ms^2. These are using the formulae discussed before and the root mean square delays spread sigma $_{\text{tau}}$ is 1.48 ms for this channel.

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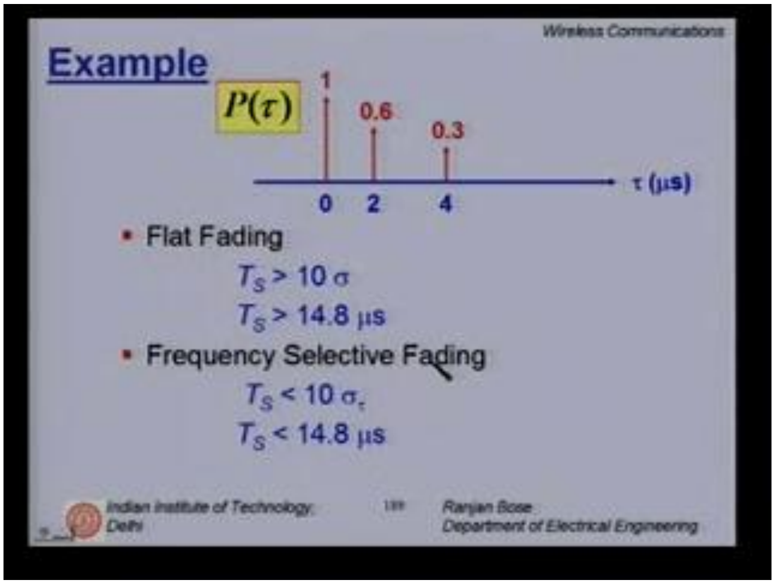

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Example

- Flat Fading

  $T_S > 10\,\sigma$

  $T_S > 14.8\ \mu s$

- Frequency Selective Fading

  $T_S < 10\,\sigma_\tau$

  $T_S < 14.8\ \mu s$

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Now the question is: what is the case when you will experience flat fading or when will you experience frequency selective fading? so using the rule of thumb T_S greater than 10 sigma T which is greater than 14.8 ms will lead us to flat fading scenarios whereas for much less than this one, you will have frequency selective scenarios.

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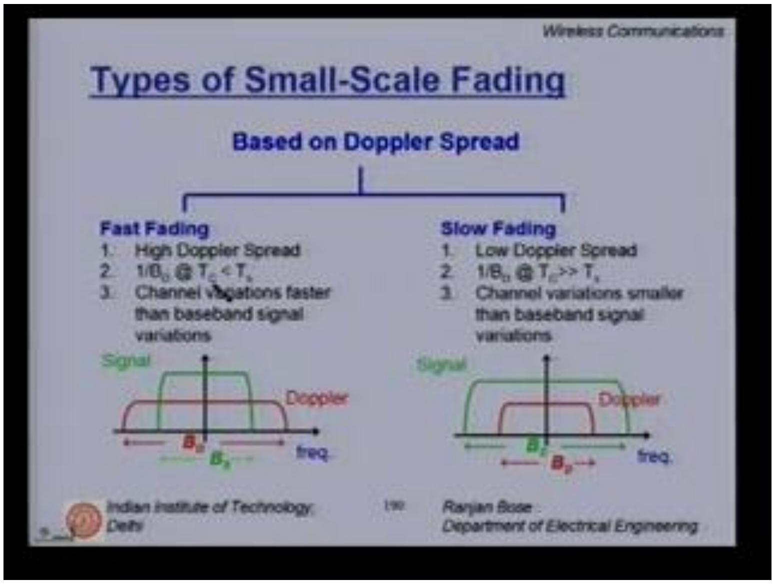

Wireless Communications

Types of Small-Scale Fading

Based on Doppler Spread

Fast Fading

1. High Doppler Spread
2. $1/B_D \approx T_c < T_s$
3. Channel variations faster than baseband signal variations

Slow Fading

1. Low Doppler Spread
2. $1/B_D \approx T_c >> T_s$
3. Channel variations smaller than baseband signal variations

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Conversation between Student and Professor: the question being asked is: for intersymbol interference, we can overcome the effect by using something called as a ‘Nyquist criteria’ where I can overcome the effects of intersymbol interference. It doesn’t say that intersymbol interference will not occur but we can sample the signal in such a manner with at the sampling instances, only the effects of the other symbols are almost zero. The same is the case here. ISI or intersymbol interference will occur but we have to resort to some kind of pulse shaping which will be required to satisfy the Nyquist criteria and then when we sample it, yes, we will overcome the effects of ISI but in frequency selective channel, symbols will run over the subsequent symbols. There will be interaction between the symbols. Pulse shaping is required to overcome the effect. Similarly equalization can be done to undo the effects of the spreading. Nyquist criteria is related to how much sampling time and how was sampling time intersymbol related to overcome a fading.

Conversation between student and professor: the question being asked is: does intersymbol interference always occur? How Nyquist criteria can help it overcome? The answer is: for this given channel, intersymbol interference is the part of life. You will get ISI. ISI can hamper your performance? It can limit your data rate. It can distort or breakdown your subsequent symbol with respect to others. however if we want to satisfy the Nyquist criteria which is the pulse shape design, then if you sample at the correct instances, the effect of the subsequent symbols will not be seen. That has nothing to do with the channel. The channel will introduce intersymbol interference.

So while designing many wireless communication systems, the first thing is to understand the channel model. Then you have to understand the effects for example, for multipath spread, you have to understand the intersymbol interference and then accordingly design this. Sigma table tells you till how many symbols your ISI will be lost and that will help you to design a pulse shape which will help you overcome. Those are the inputs. We can take from the channel. Otherwise the Nyquist criteria has to be satisfied independently. Now let us look at the types of small scale fading. These are clearly based on the Doppler spread. Doppler spread we know comes from the relative motion of the transmitted and receiver or even if the transmitter and receiver are fixed, the channel might be changing. Again we can classify the types of small scale fading based on Doppler spread into two parts. One is the fast fading scenario. Here there is high Doppler spread and it occurs when T_C is much less than T_S. T_C is the coherence time of the channel. T_S is the symbol duration. The channel variations are faster than the baseband signal variations.

If this occurs we say that it is a fast fading scenario. The counter part is a slow fading scenario where we have low Doppler spread. The relative motion of the transmitter with respect to the receiver is much slower than how fast the signal is changing. Here we have the 'T_C' the coherence time much greater than the symbol duration T_S. the channel variations are smaller than the baseband signal variations. Again we are talking about two types of classifications. The fast fading and the slow fading. Both of them depend upon how big or small is your T_S. let us look at it graphically. In the frequency domain, the x axis represents frequency in the green. We have plotted the signal and in the red is Doppler spread. If the Doppler spread is much larger than B_S in that case, we have fast fading. This can occur when the vehicle is moving very fast. On the other hand, if we have the other scenario where the green representing the signal bandwidth is much larger than the Doppler spread. Then the motion is slow or the transmitter and receiver are almost static and the channel is not changing very fast. In that case, we have slow fading. Clearly this will have an implication if you are going to use time diversity to overcome fading. We are dependent on T_C. This time for our definitions, T_C being the coherent bandwidth ,$T_C < T_S$ gives us fast fading. T_C much greater than T_S gives us slow fading. Please note this has nothing to do with frequency flat or frequency selective channel. We are talking about a completely different dimension. The only link if you must try to connect these two is a T_S. what makes them independent is a T_S. It has nothing to do with B_C. T_C is the coherence time. B_C is the coherence bandwidth.

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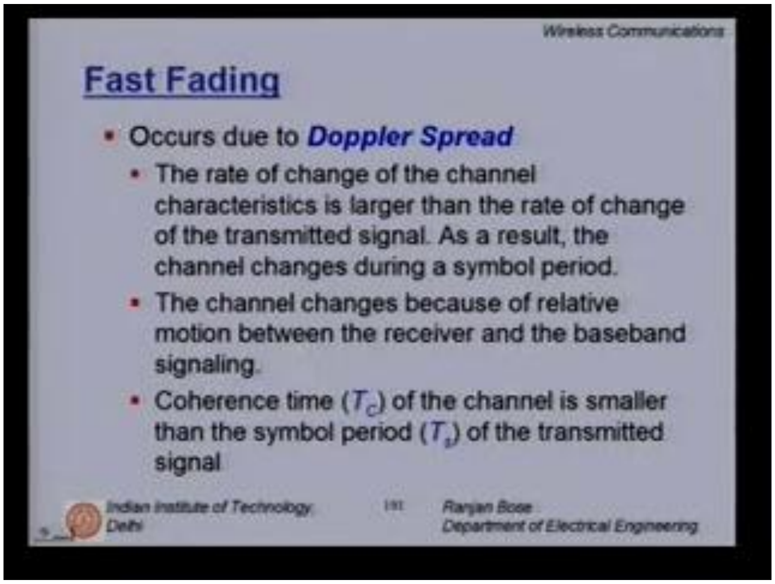

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Fast Fading

- Occurs due to ***Doppler Spread***
  - The rate of change of the channel characteristics is larger than the rate of change of the transmitted signal. As a result, the channel changes during a symbol period.
  - The channel changes because of relative motion between the receiver and the baseband signaling.
  - Coherence time (T_C) of the channel is smaller than the symbol period (T_s) of the transmitted signal

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So let us talk a little bit more about the fast fading scenario. Fast fading occurs due to Doppler's spread. The rate of change of the channel characteristics is larger than the rate of change of the transmitted signal. As a result, the channel changes during a symbol period. The same symbol may undergo a different kind of fade in the start of the signal and by that time, the symbol duration is over. The fading characteristics have changed. Inherently this kind of a symbol can overcome parts of fading. The channel changes because of the relative motion between the receiver and the baseband signal. The coherence time T_C of the channel is smaller than the symbol period T_S of the transmitted signal. You can intuitively understand the concept of fast fading by assuming that you are moving with respect to the transmitter and you are passing through the troughs and the peaks of a fading channel. Since you are moving so fast that within the symbol interval, you go from a faded point to a non-fading region. So within the symbol duration you get in and out of fade. The fading environment changes within the duration of the symbol. This is fast fading.

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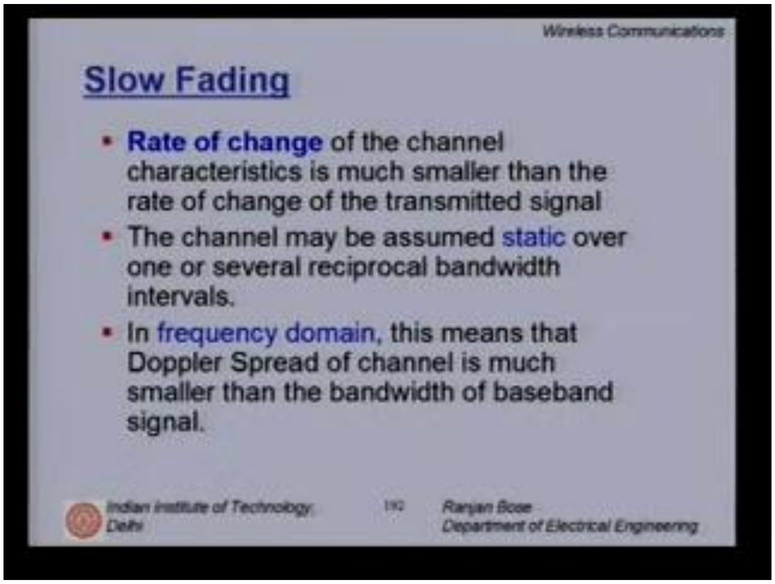

Slow Fading

- **Rate of change** of the channel characteristics is much smaller than the rate of change of the transmitted signal
- The channel may be assumed static over one or several reciprocal bandwidth intervals.
- In frequency domain, this means that Doppler Spread of channel is much smaller than the bandwidth of baseband signal.

The other part is the slow fading scenario where the rate of change of the channel characteristics is much smaller than the rate of change of the transmitted signal. Here the channel may be assumed to be almost static over one or several reciprocal bandwidth intervals. In frequency domain, this means that the Doppler spread of channel is much smaller than the bandwidth of the baseband signal. Now there was a question raised earlier with respect to what happens in between the frequency flat and the frequency selective channel. A question may be asked as to what happens in the scenarios where it is in between fast fading and slow fading. Well, the researchers have come out with a term called a ‘quasi static channel’ where it is somewhere in between. It is not a slow fading scenario or a fast fading scenario but it is a quasi-static channel. So in that scenario, you can assume that your fading is fixed over one symbol duration but will change on the onset of the next symbol. It doesn’t change within the symbol but it also doesn’t stay same for several symbols. That’s a quasi-static channel.

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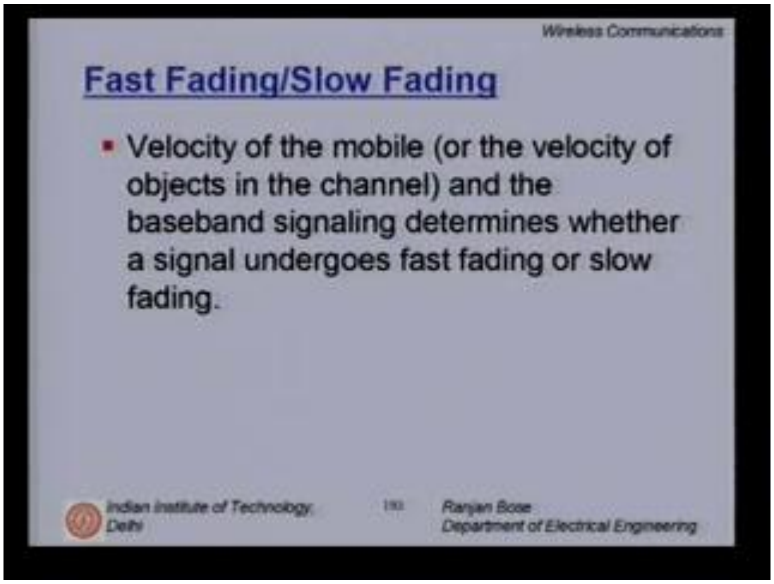

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Fast Fading/Slow Fading

- Velocity of the mobile (or the velocity of objects in the channel) and the baseband signaling determines whether a signal undergoes fast fading or slow fading.

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On fast fading versus slow fading, the velocity of the mobile or the velocity of the objects in the channel and the baseband signaling alone determines whether a signal undergoes fast fading or slow fading. If I was moving and I stop at a red light, I come into the domain of slow fading and then when I see a green light, I pick up speed and accelerate. I again get into the fast fading scenario.

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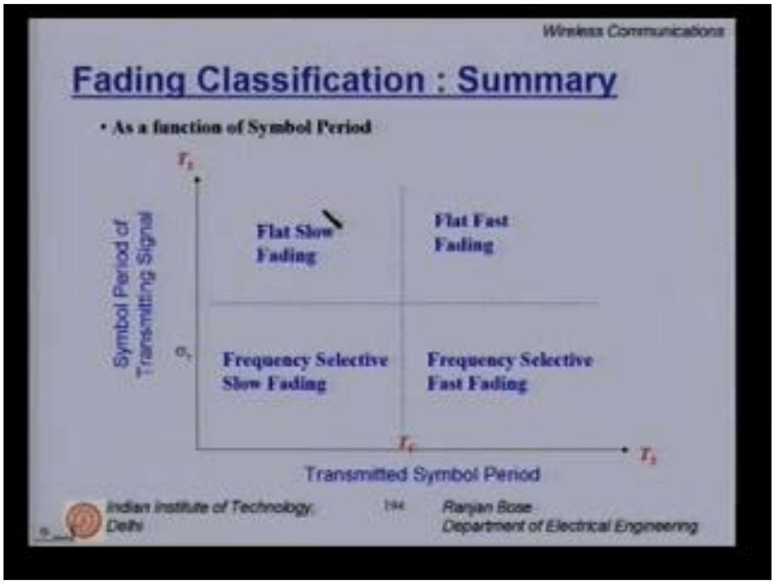

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Fading Classification : Summary

- As a function of Symbol Period

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Now let us try to summarize the fading classification using these two orthogonal axes. Please note here we have put four components. The flat slow fading scenario, the flat fast fading scenario, frequency selective slow fading scenario and frequency selective fast fading scenario. Since the coherence bandwidth and coherence time are orthogonal and are independent. They have nothing to do with each other or influence each other. I can have a combination of flat versus slow flat fading versus frequency selective fading, slow fading versus fast fading and choose a combination. There the only link as mentioned before is T_S. Now if on this axis we have T_S as also on this axis somewhere we draw these lines. These lines on this axis is a 'T_C' the coherence time and on this axis is the RMS delay spread sigma $_{tau}$. Sigma $_{tau}$ and T_C can vary independently and hence it can lie in all these places. Clearly these are all fading scenarios and will require one or a combination of fading counter measures to overcome the effects of fading. So if you are in a frequency selective environment, then frequency diversity will be useful. If you are in a fast fading environment, you have to use time diversity. If you are in a flat slow fading situation, then maybe you have to resort to increasing the transmitted power to overcome the effects of fading. It's a bad situation to be here.

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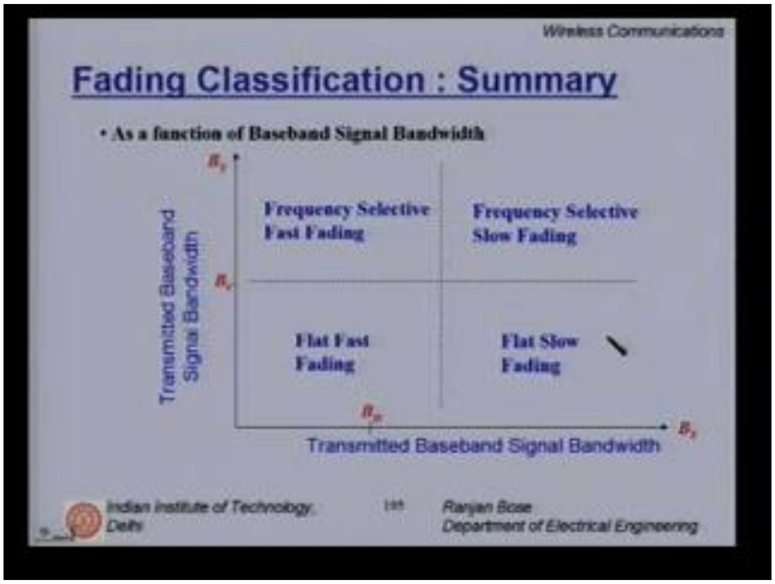

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Fading Classification : Summary

- As a function of Baseband Signal Bandwidth

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Now you can flip the coin and look at the other view point which is fading classification as a function of the baseband signal in terms of its bandwidth. Here again I have two axis. But on these axes, I have the B_S. B_S represents the bandwidth of the signal. Again I have four quadrants. But the lines that we draw are 'B_D' the maximum Doppler spread and B_C the coherence bandwidth. Since B_D and coherence time B_C and the RMS delay spread are inversely related, we have these four scenarios again. Whether you want to look it from the frequency domain perspective or time domain perspective, you have these four types of combinations passes. Clearly you can be close to these grey regions where it is somewhere in between fast and slow fading or frequency selective versus frequency flat fading. Grey regions exist. These lines are not clear demarcations. It is not a black and white scenario. Now let us talk very briefly about fading distributions.

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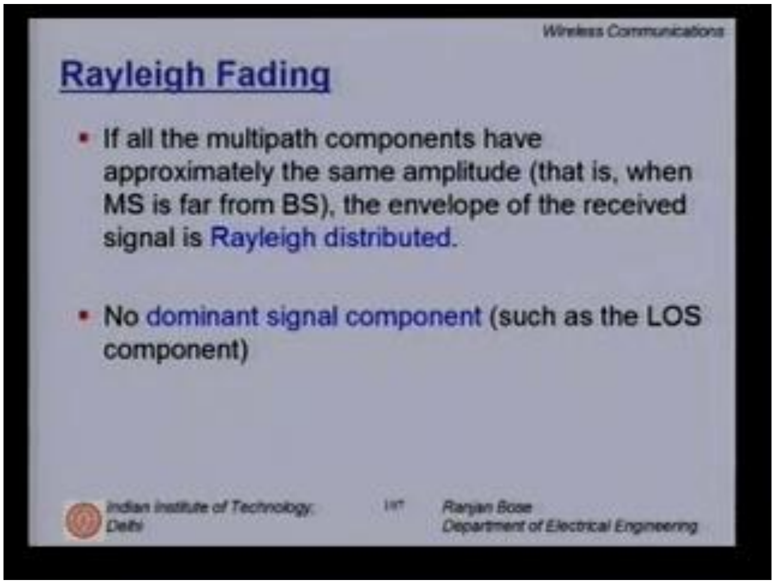

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Rayleigh Fading

- If all the multipath components have approximately the same amplitude (that is, when MS is far from BS), the envelope of the received signal is Rayleigh distributed.
- No dominant signal component (such as the LOS component)

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We must talk about fading distributions at length. in subsequent lectures, statistical characterization of the variation of the envelop of the received signal over time leads us two fading distributions. the two most common distributions that we counter are Rayleigh fading which happens when we have a lot of multipath components similar to one another but no direct line of sight or we can have the Ricean fading which is occurring when we have a clear line of sight as well as multipath components. If all the multipath components have approximately the same amplitude that is, when the mobile station is far from the base stations and there are several reflectors, the envelop of the received signal is approximately Rayleigh distributed. No dominant signal component must exist even if there are no line of sight. One or two reflections should not be much stronger than the other reflection. Otherwise you will not have Rayleigh fading. This assumption is generally true for mobile scenarios when the mobile station is far away from the base station. Whereas as you start moving closer to the base station, you tend to have a line of sight. In that case, it will degenerate into Ricean fading.

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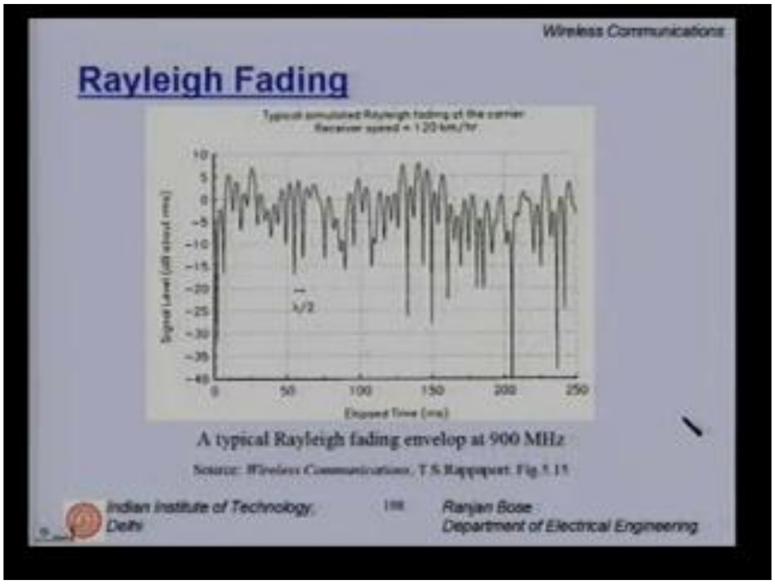

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Rayleigh Fading

A typical Rayleigh fading envelop at 900 MHz

Source: Wireless Communications, T.S Rappaport, Fig 5.15

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If you look at the Rayleigh fading profile on the x axis, we have the elapse time in millisecond suppose a vehicle is moving along this axis. The distance will translate it to the elapse time. on the y axis, we have the signal level. It's in dB. So it's a logarithmic scale. Hence you have well rounded profile. Otherwise you will get a much jagged received signal strength. So the dB rounds it off. This is the typical Rayleigh fading profile. If you plot and look at the histogram, you will find that it actually has the Rayleigh distribution. What is interesting to note is the presence of various deep fades if you see the deep nulls here. This is a typical characteristic. The Rayleigh fading situation coming from multipath components. This is a measurement obtained at 900 MHz. the scenario will change at a higher frequency. These fades will become much more frequent if we go and do the measurement at 2.4 GHz.

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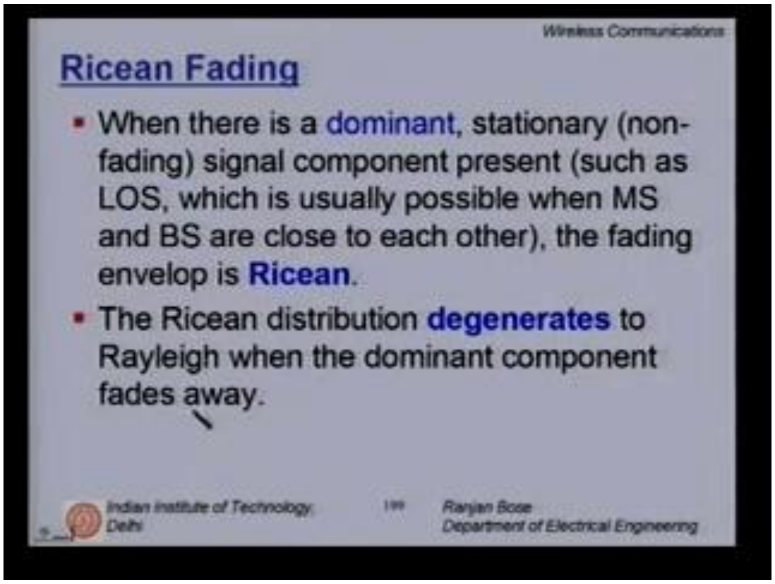

Ricean Fading

- When there is a **dominant**, stationary (non-fading) signal component present (such as LOS, which is usually possible when MS and BS are close to each other), the fading envelop is **Ricean**.
- The Ricean distribution **degenerates** to Rayleigh when the dominant component fades away.

When there is actually a dominant stationary signal component present such as a line of sight or a very strong reflection which is usually possible when the mobile station and base station are close to each other. Then the fading envelop is not Rayleigh but Ricean. The Ricean distribution degenerates to the Rayleigh when the dominant component fades away. This would be a logical place to stop. Let us summarize what we have learnt today.

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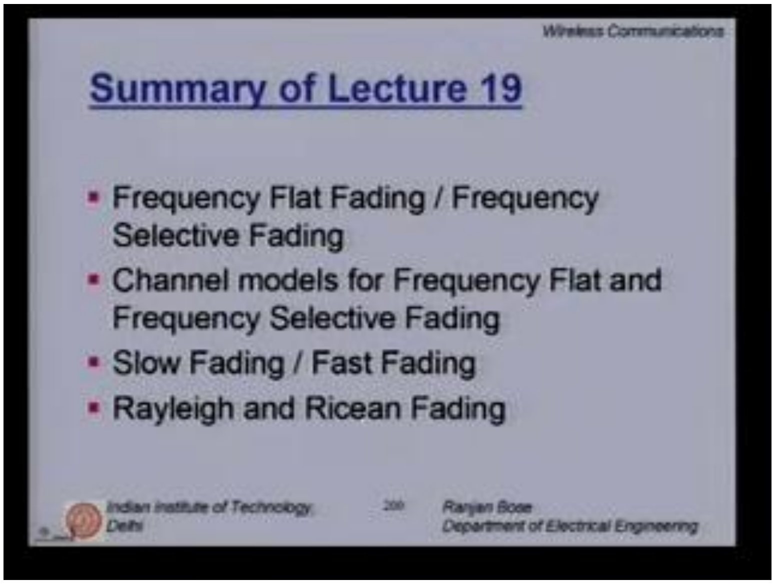

Summary of Lecture 19

- Frequency Flat Fading / Frequency Selective Fading
- Channel models for Frequency Flat and Frequency Selective Fading
- Slow Fading / Fast Fading
- Rayleigh and Ricean Fading

We spent some time discussing the frequency flat versus the frequency selective fading channels. We looked at it both from the time domain as well as from the frequency domain perspective. We then discussed the channel models for frequency flat and frequency selective fading. Then we focused our attention on slow fading scenarios vis-à-vis fast fading scenarios and then finally we had a beep at how a Rayleigh fading looks like and what is meant by Ricean fading. We will talk about the Rayleigh and the Ricean distributions and more about fading in the subsequent lectures. Thank you!