

Introduction to Wireless and Cellular Communication
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Lecture – 29
Wide Sense Stationary Uncorrelated Scattering (WSSUS) Channel Model
WSSUS – Classification of Fading Channels

Good morning we begin lecture 28. We will start with a quick summary of the key points of lecture number 27, and then build up on today's material. The topics that we will be covering is to complete our understanding of the wide sense stationary uncorrelated scattering model. We will highlight all the different relationships. The purpose of deriving this model was to be able to a work with different types of channels. So, the classification or a segregation of channel is an important element. And once you segregate you must have terminology that associates with that we will introduce that terminology. Earlier when we were discussing about the different types of techniques in cellular systems like, frequency hopping, we talked about wide band versus narrow band signals, and how the channel behaves for that.

Now, whatever we have studied must correlate with what we have already studied. So, that is a very important element. So, I would like to establish that link that, whatever we have talked about earlier as wide band versus narrow band will be used. One of the good things or useful things about this course is that, whatever you study is actually what is being used by engineers who are building these products. So, standardization is very important, and for you to be able to read certain parts of the documents of standard and understand what the terminology they are using.

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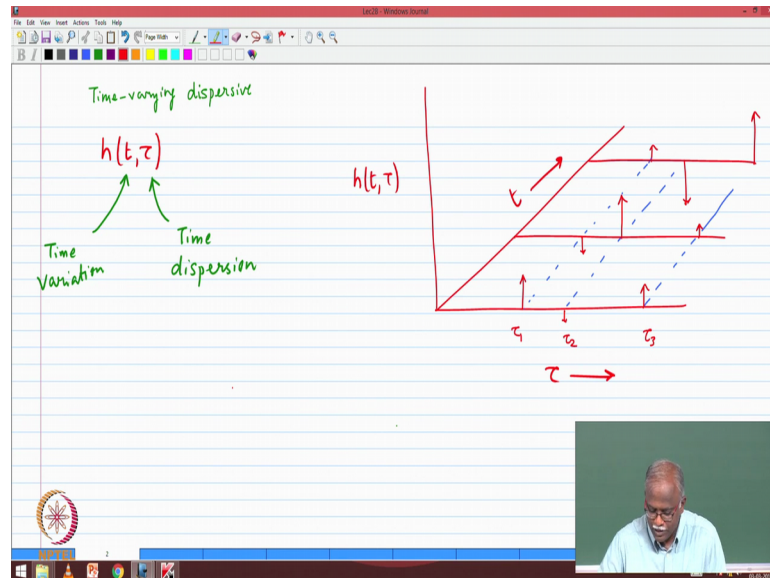
3/3/17 EE5141 Lecture #28

- Recap L27
- WSSUS Model relationships
- Classification of channels
- Terminology
- Narrowband vs wideband
- Channel models in standardization
- Fading generator
 - Clark & Gans method
 - Smith method
 - Jakes' method ✓

So, we will just mention that since we are talking about channel models in the standards 3GPP or the ITU international telecommunications union, when they talk about fading channels, what are they talking about, what terminology that they use, will just quickly mention a few of those.

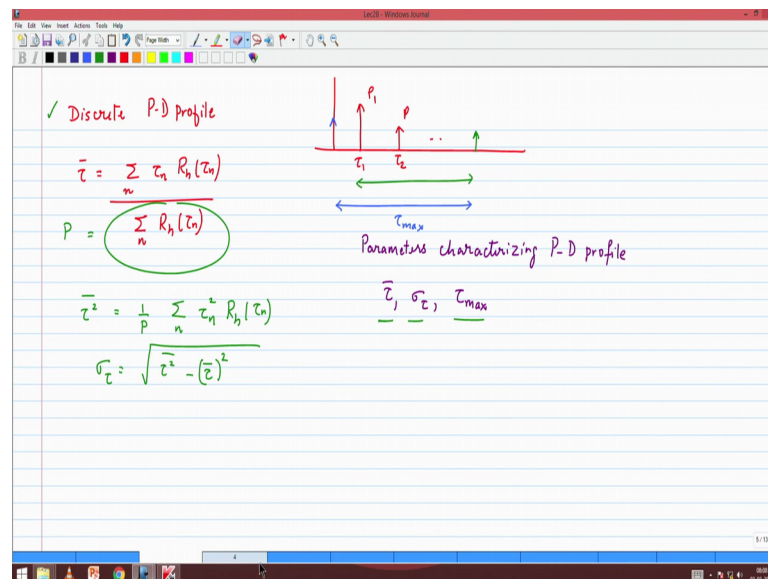
All of this gives us a theoretical framework. Now I must be able to generate this in a computer environment which then models very closely what happens in the real world. So, there are different methods that are used for generating fading, fading channels and we will indicate which of these methods. Those of you have already been exposed to a different aspects of wireless will know that the probably the most useful model is the Jakes Model, but that comes last because you are appreciated more if you know in the sequence in which these models were would develop.

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So, let us begin with a quick summary of the points that we have discussed in the last class. So, the channel model that we are working with is a time varying dispersive channel. Time varying and dispersive channel. Time variation captured by t the time dispersion captured by τ , and again the picture on the right hand side is a familiar one we have used it in 2 of the earlier lectures, just to show that there is a delay dimension there is a time dimension. How we interpret the time variation? How we interpret correlation? How do we interpret the uncorrectedness between the different delays? All of that is part of our model. So, this is keep this picture in the in the back of your mind.

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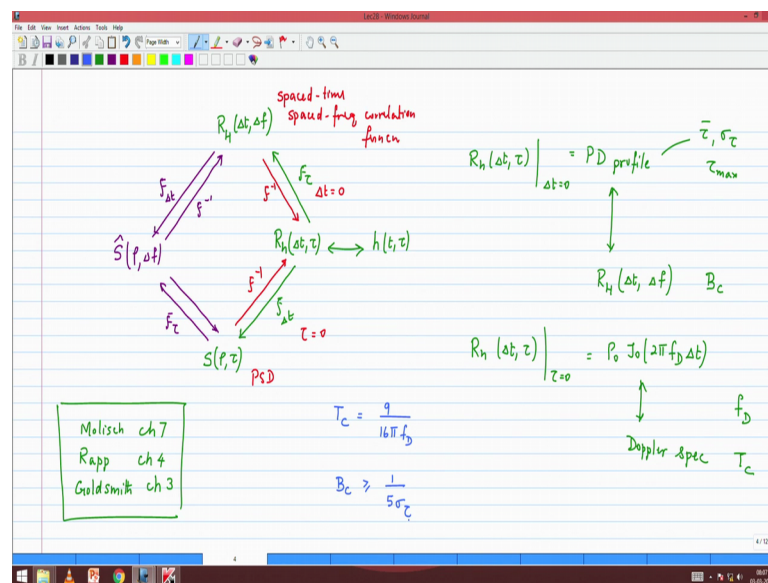


Now, the characterization of these using the power delay profile. That was something that we had looked at in the last class. We said that we could characterize either a continuous power delay profile or a discrete power delay profile. You will find that most of the time when we work in practice, we are working with the discrete time power delay profiles. The standards ask us to expect us to be working with discrete time power delay profile. So, I will just highlight that as by way of refreshing. We are interested in 3 parameters. One is the mean delay, the other one is the RMS delay and then the maximum excess delay. Excess delay is the time gap between the first arriving between the multipath and the last arriving multipath.

So, basically in terms of if there was a third multipath component, or an this would be the excess delay. Sometimes there may be a path that is considered coming almost with no delay. In that case your excess delay will start from your first multipath component. Again keep in mind that it is a first to the last arriving multipath component that is derived that is defined as tau max. Apart from that there are 2 other characterizations which tell us how dispersive the channel is. First one is the mean dispersion or the mean delay which is obtained just like a probability calculation. Summation over n tau ns the different delays times the a power delay with the power of that particular component usually power delay profiles are given in db, but make sure that this is not in db. These quantities are in the linear scale you have to may appropriately account for them.

There is a normalization which takes into account, the powers of all the multipath components please make sure that you do include the component that contributes to the tau equal to 0 component as well. So, let us take a compute tau bar you can also compute tau squared bar, and then sigma tau is obtained using our standard way of obtaining the R the square root of the variance ok.

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So, given that you are you can characterize a power delay profile. The last thing that we did in the previous lecture was to characterize that you could starting from the time varying impulse response. You could then obtain an autocorrelation function, which has got both delta t and tau variations. If I set delta t to be equal to 0 then, I can do a Fourier transform. So, basically let me just highlight that this one assumes that delta t equal to 0. Then I only have a delay dimension which if I take the Fourier transform gave me the spaced times spaced frequency function, spaced time, spaced frequency correlation function. So, that is just a remainder of the terminology that we have used correlation function ok

Now, on the other side if I took a Fourier transform with respect to delta t and mapped it setting tau to be equal to 0, or basically ignoring the tau dimension. Then I get the power spectral density because that becomes autocorrelation and then this becomes the power spectral density, PSD. Now of course, you can do the inverse Fourier transforms as well.

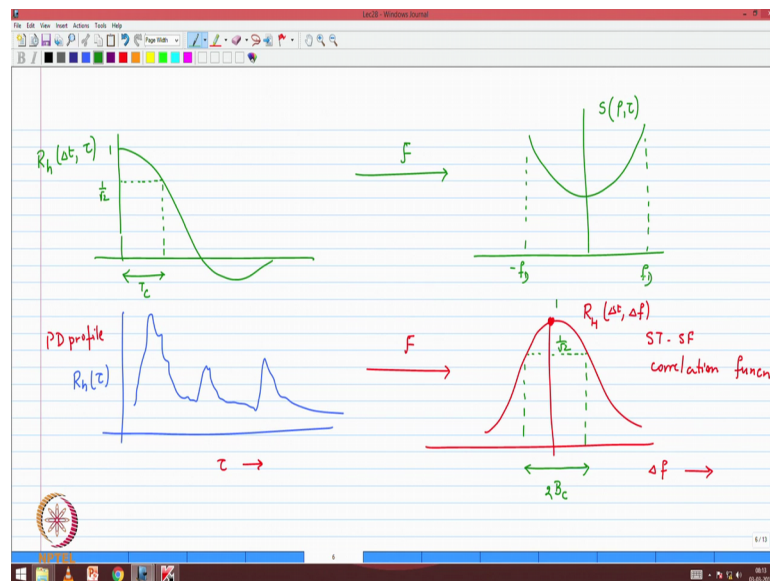
So, I will draw the arrow in the other direction, that will be the inverse Fourier transform for both of these. And maybe there is an interesting question is that you know there are 2 variables, in one side you took the Fourier transform of one, the other you took the Fourier transform of the other.

Now, what if you took the other dimension Fourier transform the second 2D Fourier transform and it turns out that yes you can do that. So, basically in this case I have taken with respect to τ , then I have to take the Fourier transform with respect to, with respect to Δt . So, you can think of another Fourier transform, Fourier transform with respect to Δt of course, the inverse Fourier transform should take you back. And so, this would be another 2D Fourier transform I will just call it \hat{s} . The Δt maps to ρ and Δf is not that variable is not affected by this transform. And likewise you could do another transformation for here instead of, since you have already done the ρ dimension do the τ dimension and, basically you can do a Fourier transform with respect to τ . And so, I would say that the, the left whatever is in purple is not as commonly used because, that is that does not giving us much more much new much newer insights. Most of the information is captured what is in green and what is in red.

So, keep in mind that there is a time varying channel response, taken the autocorrelation function. And then derive 2 very important elements from which we are able to obtain the following characterization of the channel that we are working with. The, the characterization consists of the following a coherence time which consists of T_c by which can be written as $T_c = 0.423 / \sigma_f$. So, that is depends on the Doppler side, again as we indicated that comes from the time variation which comes from R_h of Δt .

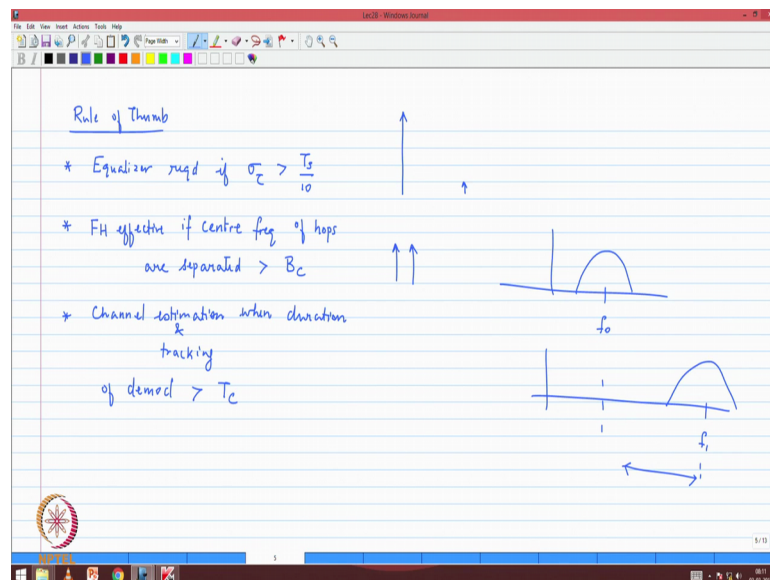
Now, on the other side when you have the space time spaced frequency correlation function, we also were able to relate it to the coherence bandwidth which is greater than or equal to $1 / (5 \sigma_\tau)$. And this also ties in very well with our understanding that as σ_τ as your time dispersion reduces, your coherence bandwidth is going to increase, which was the intuition that we also got from the Tse and Vishwanath example. So, therefore, all of this hangs together a very nicely.

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So, there are a couple of rules of thumb, which I believe will be helpful for us, I and I will just indicate those just so, that you can remember them when you come across them.

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So, the rule of thumb. The question that we ask is, when do you need an equalizer? That is, how do you deal with the time dispersive aspects of a channel? So, the rule of thumb which talks about the dispersion aspect says that equalizer is needed equalizer required if your RMS delays spread is greater than T_{symbol} by 10. So, if you have a channel that

looks like this, maximum excess delay or the may be quite large. But the RMS delay spread may still be very small, and you may be able to get away without an equalizer. On the other hand even if the channels are close by, but if you if you have strong multipath components then you may have a sigma tau which will, which we will require you to have an equalizer.

So, again the equalizer is usually good check for us to see if the if the equalizers required would be the RMS delays spread. The second rule of thumb which this is basically talks about the coherence bandwidth. So, which says that when is frequency hopping effective. Frequency hopping is effective if your hop spacing if the center frequency of the hops, center frequency of the hops and again, what we mean by center frequency of the hop? Is you may be at some carrier f_0 , next time instant you are skipping to some other carrier f_1 , the spacing between f_0 and f_1 . That is what we refer to, if the center frequencies of the hops are separated by a frequency spacing that is greater than coherence bandwidth. Are separated, we are going to write in short form greater than coherence bandwidth. And of course, that why is are we saying anything about the coherence time? Yes, you must be doing channel estimation. Channel estimation is needed whenever we exceed coherence time. When your demodulation, channel estimation and tracking ok.

When the duration of demodulation duration of demod d becomes later than coherence time because, that is when you know that the channel has changed and therefore, you must be adapting your channel estimates. This is also true if you have had a fade of course, then you have to have another channel estimate that will help you in the in the process.

So, that is sort of putting all the pieces together. So now, let us do a pictorial representation of so, what we saw in the last class? Was that the power delay profile. This is the power delay profile, power delay profile Fourier transform gets us to the spaced time spaced frequency. Power delay profile, this is the spaced time, spaced frequency function, correlation function. That is from the last class. From the lecture earlier correlation function. From the earlier lecture we have the following results. I have the time correlation which is in the form of a Bessel function. So, this is R_h of Δt

comma tau, but actually tau dimension is not focused upon here. If this is one height of 1 by root 2 is of importance to us, and that is where the coherence time comes into play, connected to the coherence time. And the Fourier transform of this relationship gave us the Doppler spectrum, Doppler spectrum had a inverted or u shaped with the peaks occurring. So, this was s of rho comma tau and, this was this was R H upper case H delta t delta f and your plotting versus the limit is of these where minus f D and f D.

So, the channel that we are talking about has got 4 sort of visualizations. One is the time variation and then at the corresponding frequency domain interpretation the tau variation along the tau dimension is the power delay profile, and it is frequency representation. From this we derive the coherence time the coherence bandwidth. So, coherence time from the Bessel function the, the coherence bandwidth from the spaced time spaced frequency correlation function, and then that helps us in terms of the complete characterization of the channel. So, this is a good way of keeping all the pieces in place.

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Terminology

flat \rightarrow constant
selective \rightarrow changing

Channel description

$y_1(t) = z_0 s(t-t_0) + \gamma(t)$ Time flat, Freq flat

$y_2(t) = z_0(t) s(t-t_0) + \gamma(t)$ Time selective, Freq flat

$y_3(t) = \underbrace{z_0(t)}_{\text{Time selective}} s(t-t_0) + \underbrace{z_1(t)}_{\text{Freq selective}} s(t-t_0) + \gamma(t)$ Time flat, Freq selective

Doubly selective \rightarrow Time-varying dispersive channel

time
freq

Now, I would like to introduce some notation. And also help you do a classification of channels. So, let us introduce some notation or terminology. Again these are probably familiar to you, but it is good for us to keep this picture in our mind when we do the classification. So, very often we have used the term flat, frequency flat, what does flat mean? It is, it is not changing, it is constant, right. It is flat. It is constant. And the

opposite of flat is something that is constant is something that is changing, something that is changing or varying which we call as selective. So, flat selective, again it can be in any context. So, the minute you see flat think of something that is constant, means you selective you say something is changing and you need to figure out what is changing. Using this information help let us write down very quickly the common notations that we will use - $R_1(t) = z_0(t - \tau) + \eta(t)$.

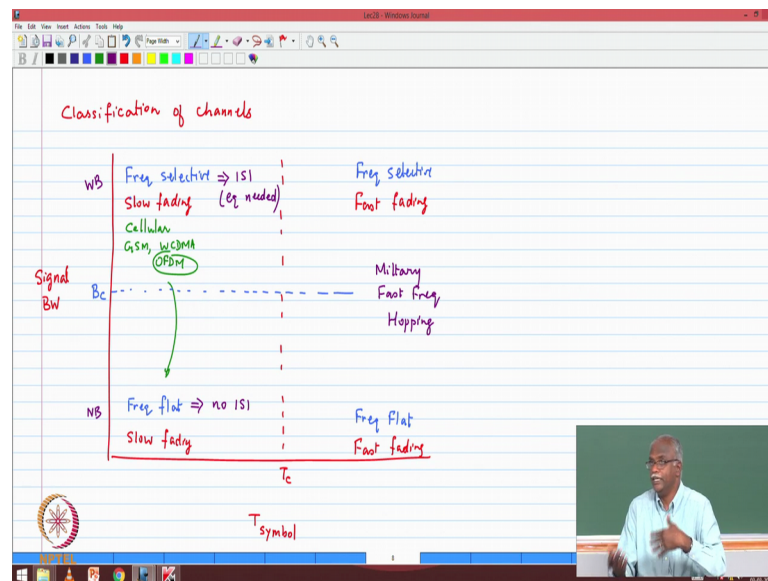
So, characterize this channel for me in time and frequency, z_0 is a constant. So, it is time flat, it is time flat. What about frequency? If there is only one tap frequency response is also flat this is frequency flat as well, the channel. I am, not I am not classifying the received signal I am classifying the channel. So, the channel description is what we are looking at, channel description. Such a channel if you have a single tap that is not changing you would describe it as time flat and frequency flat. You wouldn't call it a constant channel because constant the usage is consistent with the terminologies that we are introducing. Second $R_2(t) = z_0(t - \tau) + \eta(t)$. Time selective frequency flat, time selective frequency flat, frequency flat I will just write one more to complete my this thing.

So, third one is $R_3(t) = z_0(t - \tau) + z_1(t - \tau) + \eta(t)$ this is time flat time. Nothing is changing as far time is concerned time flat, but there is a frequency response because there are 2 taps. So, therefore, your channel will have a frequency response it is no longer flat it is frequency selective. And the last one is if these become functions of time, this one becomes a function of time, then it becomes time selective frequency selective, time selective frequency selective. Now when you repapers they will often make the following statement. The assumption is that the channel is doubly selective they do not say anything else. Doubly selective and the interpretation of that is there only 2 things that can be selected time and frequency. So, there the paper is assuming that the channel is dispersive and the channel time varying.

So, basically it is selective the doubly because it refers to time and frequency, and this basically means that you have a time varying dispersive channel, time varying dispersive channel. So, again simple notation, but you know sometimes when you read it is like doubly selective what is this you know. So, I do not want you to have that confusion you

should be able to be very clear about what the notations are. And even when you describe the channel do not (Refer Time: 20:05) z naught is constant z 1 no, no. Please use the terms times selective frequency flat whatever the combination is. So, that it is it gives us a unambiguous description of the channel.

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If you are now comfortable with the, with that part of the representation then I would like for us to do the following classification of channels. This is a very important part of understanding the wireless channel and the different systems that we work with in the context of wireless communications, classification of channels. I m going to classify in 2 dimensions 2 dimensions and again it will become very clear one is going to be the time dimension or which is going to be characterized by the symbol duration.

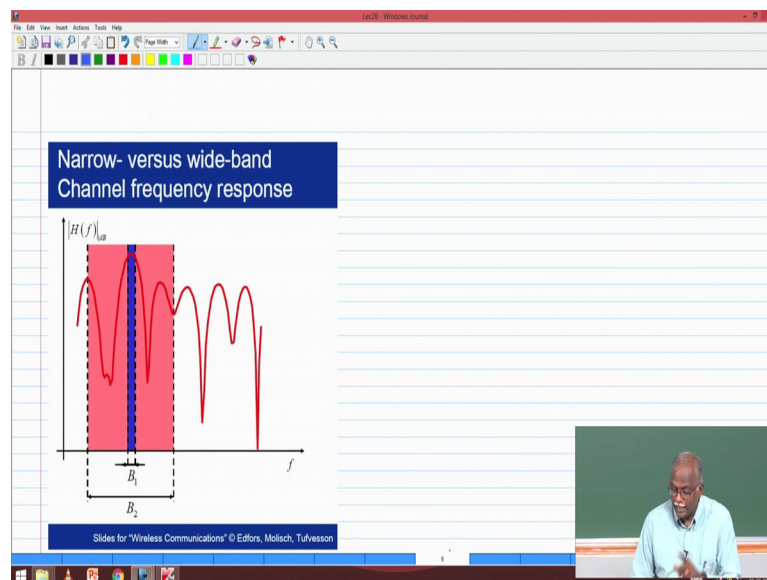
So, I have a way form I have a symbol there is a duration of the symbol. Now on the other side the signal bandwidth. So, it is a frequency characterization frequency perspective the of course, the symbol duration the signal bandwidth are related if you reduce the symbol duration bandwidth will increase. So, again keep in mind that these are a not unrelated things, but for us for the purposes of characterization this is what we would we would like to have as our in our in our understanding.

Now, when what did we call as a slow fade what is a slow fade; that means, many symbols experience the same fading pattern, right. That was what we called as a slow

fade now how would you relate the symbol duration to coherence time in the context of a slow fade. Symbol duration much slower than coherence time. So, the one that is going to divide this axis is going to be coherence time, I will put coherence time here. If you are if a symbol duration is much less than coherence time we are going to call it as slow fading. And the minute you become symbol duration crosses coherence time; that means, within the duration of one symbol your channel is changing then it becomes fast fading.

So, in this context I would like you to think about where cellular systems fall. Keep that picture in your mind.

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Now by the same token, Let us look at a narrow band versus wide band characterization. Now the red line, the red line which is the response of the channel is your actual response based on the multipath that is present in the channel. Now if my signal bandwidth was the blue one, that was we said that this would be this would this would be a narrow band signal because, it would look like the channel is almost constant in the duration of that of that channel ok.

Now, but whereas, the red signal would see channel variation and therefore, the channel is a is not constant. So, between B 1 and B 2, B 1 is the narrow band B 2 is the wide band lies the coherence bandwidth because, coherence bandwidth is a region where the frequency response of the channel is correlated. So, now, if you go back the

characterization on this on this axis is going to be the coherence bandwidth, coherence bandwidth. Now if you are much smaller than if your signal bandwidth is much less than coherence bandwidth then, what you will find is that you are going to be let me use the correct colors. Let me use blue for the bandwidth. So, this is going to tell me that I am frequency flat. Because narrow band is going to see a flat channel, frequency flat I will just change this to green change this to red. So, that there is no confusion.

So, this is slow fading, slow fading versus fast fading, slow fading versus fast fading. Frequency flat the minute my signal crosses coherence bandwidth it is going to see frequency selective. So, it is going to be frequency selective on this side. Frequency selective, but it can still be slow fading it can still be slow because that this left side of the quadrant is slow fading. Slow fading means many symbols will see the same channel. Frequency selective means that my I, I will need basically there is need for an equalizer.

So, this means that there is ISI means equalizer needed that is our interpretation of it. So, you know this complete the rest of the description. This is frequency flat, frequency flat and this quadrant is frequency selective fast fading. Now very quickly tell me, which quadrant GSM would fall into? GSM would fall into slow fading because, several symbols are say experiencing the same channel coefficients and the channel is kind dispersive so, it is frequency selective. So, most of our cellular systems will fall here. Cellular systems whether it is GSM or wide band CDMA they are all in this category and OFDM also fall into this category if you need equalization. If you do not need equalization of course, which means that your created large number of carriers. So, therefore, you have avoided equalization in your OFDM system. So, OFDM could either be here or it could be here; that means, experiencing slow fading frequency flat and therefore, the receiver is very simple. And that is one of the reasons why OFDM is very popular because you can design the system so that you do not need an equalizer.

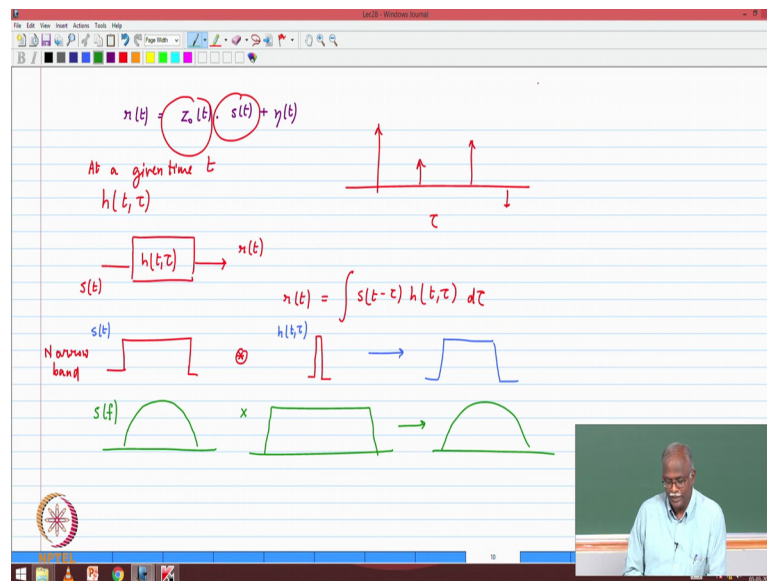
So, therefore, this becomes the. So, frequency flat means no equalizer or no ISI. So therefore, I do not need to worry about the equalization aspect. Most of our cellular systems are in the north western quadrant where it is frequency selective and slow fading. Now are there any systems that will fall into this category. That is very important right when you classify if there is some, what does this mean? In the duration of one

symbol the channel has changed, which means that some it is a very difficult system for you to track. Because you know, tracking across when even the channel is constant for many symbols is a problem. Now within one symbol if the channel changes you know it is going to be very difficult to track. So, do we have systems like that we do have and it is not used in civilian use. These are primarily military frequency hopped systems, they are called fast frequency hopping, fast frequency hopping because, they do not want the enemy to detect where you are within the duration of one symbol the frequency changes; that means, you are hopping. So, fast that within one symbol the channel will change because of your hopping of the frequency.

So, again these are very complex radios which we do not build in civilian life because you know they are hard to of course, the electronics requires required the x very extreme complexity. So, again these are used for very specific purposes. So, the right hand side is not as common, the left side is where we are, but it is good for us to sort of be able to classify and say where are we in this space. You know what are the challenges that we have to worry about. So, because it is slow fading I am with periodic channel estimation and some reasonably low complex channel tracking mechanism. If you were in fast fading that those options are out because you must have a very sophisticated algorithm for doing the channel tracking. So, this is an important element it is tied to our understanding of narrow band versus wide band. It is also tied to our classification of slow versus fast fading and the conditions under which you know you would call a system either frequency flat or frequency selective. Again, hopefully this gives us a picture of the complete landscape of what is there as far as the fading channels are concerned. Any questions?

Now, what I would like to do is spend a few minutes on one more insight that I would like you to have, and this is very important for the following reason when we talked about the time autocorrelation, the time autocorrelation. What did we what did we say the r of t was σ of t multiplied by σ of t times η of t correct.

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And we said the frequency domain interpretation is that you have to take the spectrum of z naught the spectrum of the signal and you have to convolve them, because this is multiplication in time. This is for the time variation because the channel is time varying the effect of the time variation on the channel on the signal is that there is a smearing of the spectrum. Very clear no doubt about that. Now if I freeze my time at that particular instant of time. At a given time instant, given time instant t , I have a channel which is given by h of t comma τ , I can visualize this channel as some you know some coefficients that are the channel response a coefficients.

Now, this is a function of τ , this is the delay dimension. Now if I if you were to ask me forget about the time variation, but tell me how to classify the system; I would say I am feeding in s of t there is a black box introducing some multipath components h of t comma τ t is fixed τ is the one that is a variable here. It produces for me another output signal r of t which has got different delayed versions of these components.

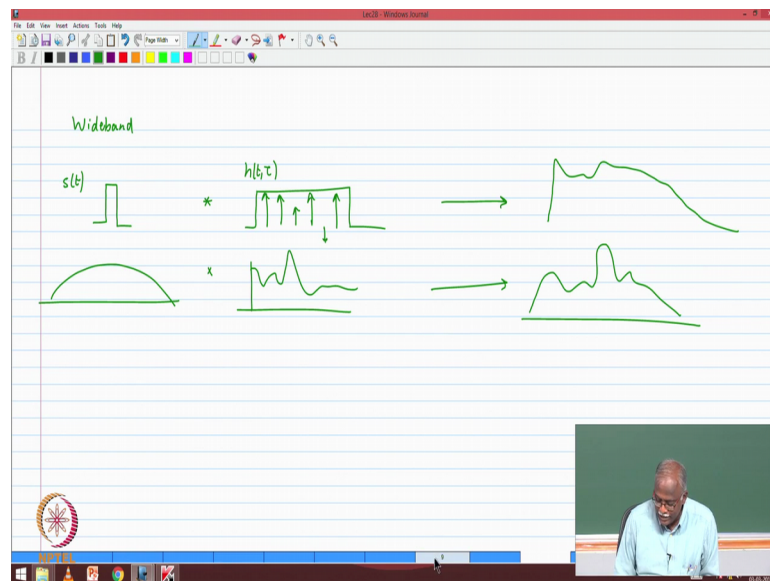
Now, this input output relationship because it is not time varying can be interpreted as LTI system and therefore, as a convolution. So, the output will be $r(t)$ can be interpreted as $s(t - \tau_h)$ comma τ_d . So, basically it can be interpreted as a convolution because I am not looking at the time variation. This looks like an LTI system just like or impulse response input output input output correlation exactly the same thing.

This is not the same as time variation because time variation when I wanted to characterize, I characterize it as a multiplicative operation this is a convolution operation. So, therefore, how do I interpret the calculations?

So, narrow band signal. Remember we talked about narrow band? How do how do I understand narrow band signal? Narrow band signal I transmit a pulse. I have to convolve with the channel, and because the pulse is very wide my channel is looks very narrow compared to the pulse. So, this is my channel response. So, this is $s(t)$ the transmitted pulse, this is $h(t)$ again the t dimension is what we are looking at. The convolution of these 2 produces for me a pulse that looks slightly distorted because of the convolution with impulse response, but it did not change much. Very clear this is the time domain convolution and operation, where the channel impulse response is much smaller than the duration of a symbol it does not affect that the symbol much. That is the intuition that we have and that is what is visualized here.

Now, the same thing can you express it in frequency. So, if this was the frequency response or the $S(f)$, frequency transform of the signal or the spectrum of the signal. Convolution in time becomes multiplication in frequency a narrow pulse is going to give me a very wide band channel. So, this corresponds to a very wide band channel. So, the resultant is I have to multiply these 2, what comes out? Looks more or less like the input because the channel did not do much distortion to it. This is what narrow band channels are and, this is the reason why this picture makes sense. Because if my channel bandwidth is small compared to the coherence bandwidth if the channel looks like it is a constant another way to visualize it is this figure.

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Now, what would be the same system for a wide band a wideband case? So, we are trying to characterize narrow band versus wide band. In this case the pulse is going to be narrow right wide band signal you must have narrow pulses that is when you get wide band. It is going to get convolved with a channel that looks much wider than the, so channel response has got many, many coefficients, but the duration is what I have shown here, that is the impulse response of channel. So, the pulse is much narrower than this. So, the convolution of these 2 produces for me a totally distorted pulse, and is much longer in duration than what I transmitted. This is why equalizer is needed inter symbol interference ok.

Now, what is the frequency domain interpretation? This is this is s of t this is h of t comma τ , sorry it is lower case h . H of t comma τ and again, the depressiveness of the channel is visible here. If I where to look at it in the terms of the frequency s of t is a wide band signal; the impulse response of this channel, now I have to multiply the impulse response or the frequency response of this channel is got some frequency characteristic. I multiply these 2 what comes out is that my input signal is now has got some effect of the, so the product of these 2 is a channel. I do not want the time domain and frequency domain to look similar to each other let me just redraw this, something. So, the product of these 2 is what is what is shown here ok.

So, the frequency spectrum has got distorted, which is exactly what you saw in the case of a wide band. If I have a wide band channel the frequency the when it passes through a dispersive channel it is frequency response will get affected. So, I just wanted you to be clear in terms of our classification in terms of our visualization in terms of narrow band versus wide band, time domain frequency domain, all of those pieces should be together. Because only then we can make clear interpretations of the classification of channels when is it narrow band when is it wide band. So, where is it narrow band here? When you are much less than you coherence bandwidth.

So, this is the narrow band portion of it, this is the narrow band portion of it. So, here is narrow band and here is wide band. Now again depending upon the depressiveness of the channel narrow band signal can become a wide band signal because you can see frequency variations. So, again keep in mind that it is a classification that requires you to understand and have the insight of how you have done come about with the classification of the system. So, again if there are any questions will be it is a good time to stop and ask, and we will then move on to the next. Any, any questions if you want just look at your notes see if you are clear about all the things that we have spoken so far.

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Channel Models in Standardization Molisch Appendix TC, TD

Appendix TC

COST 207

- Rural Area (RA)
- Typical Urban (TU)
- Bad Urban (BU)
- Hilly Terrain (HT)

PD profiles

RA

$$R_h(t) = \begin{cases} e^{-9.2t} & 0 < t < 0.7 \mu s \\ 0 & \text{otherwise} \end{cases}$$

Table 7.3

Tap #	Delay (μs)	Power (dB)	Spectrum
1	0	0	
2	0.2	-2	
3	0.4	-10	
4	0.6	-20	

Now, I want to you at the channel models that are used in standardization, Chanel models in standardization. And the best reference to read other than the standards themselves is

molisch not in the text book, but it is a online appendix 7 c and 7 d you can download it I will give the link on the web on the model page. 7 c and 7 d they give us 2 of the most commonly used models. Appendix 7 c again I just want to indicate a couple of examples so that you will appreciate that you know what ever we have done actually ties in what we have ok.

Ah appendix 7 c says that, there are 4 basic channel types. And those 4 basic channel types are rural, rural area using the acronym RA. Then there is something called a typical urban, typical urban. The difference would be that rural things would be far apart lower height of buildings not many reflectors whereas, in a typical urban you would see higher buildings lot of reflectors. And then there is a third channel characteristic there is something called bad urban has nothing to do with crime it only has to do with propagation. This is Bu which says that there are lots of very tall buildings and therefore, you can have signals just bouncing of buildings many buildings. So, it is some also refer to as a canyon effect. Because you know, the signals can propagate because of bouncing and of course, this can cause long delays in your received multipath signal. And then there is a typical urban and then there is a hilly area, HA.

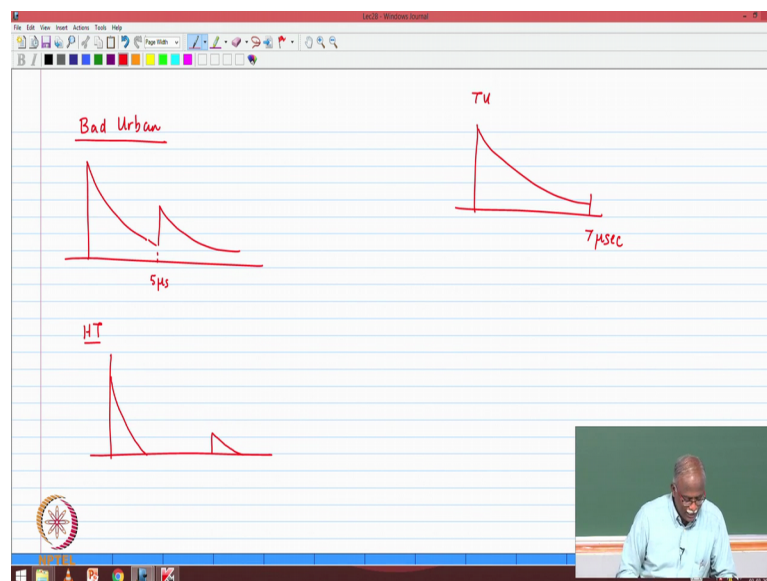
Now, interesting for us to see I would definitely like for you to go in and see the different channel models and how they are described. These are described by means of the power delay profile, power delay profiles. Let me take just 2 examples to give you that for rural area the power delay profile is given as $R_h(\tau) = e^{-9.2\tau}$ if τ is greater than 0 less than 0.7 microseconds otherwise.

Now very important, sketch this. So, the outer limit is 0.7 microseconds; that means no multipath beyond 0.7 microseconds. And it is a exponentially decaying profile and it decays very fast. Because, a exponent is 9.2 times τ . So, this is one and then it decays to by the time it reaches point 0.7 it decays to 1.6×10^{-3} . So, that is power delay profile. And now what if you wanted to sample this power delay profile then what you would do is, sample it at different points in time and then implement it based on whatever sample spacing that you want, based on your discrete time representation. So, that would be one way of understanding the power delay profile ok.

Now, the same thing using the experimental characterization they also have given it in the form of a table. So, by the way these are referred to as the COST 207. That is a project which dealt with the characterization of channels COST 207 is called COST 207 channel models for GSM and other wire/wireless systems. Now they have classified it in terms of a power delay profile you can also see in Molisch Chapter 3 there is a Table 7.3 which has the following. It says you can define it in terms of a discrete time discrete model. Tap number, delay and the power, power in dB. That is third column there is a fourth column, I will not comment on that until you read it because only when you read you will you will ask the right questions.

So, they have described the rural area in terms of 4 taps. The first tap they say comes with a delay in microseconds, second tap at delay of 0.2 microseconds 0.4 0.6 microseconds are the different delays, the power levels 0 dB, minus 2 dB, minus 10 dB, minus 20 dB. It does not follow the exponential profile exactly, but there is a reason for that because that has to do with the spectrum the fourth column. But you can understand that the description of a channel is very, very close to what we have been talking about, where you say you take the power delay profile you characterize it, and then each of these has got delay and has got a certain power level associated with that. So, please do read you will appreciate the aspects that are given there.

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Now, I would like to sort of tell you what the bad urban looks like. Bad in terms of the propagation. The bad urban and I am, I have skipped over typical urban you can look at it that is a exponentially decaying, exponentially decaying a profile maybe just does not take much time. Typical urban looks like this, it is a much slower decaying exponential. That is all because; that means, there is more multipath that is present. So, it goes all the way up to 7 microseconds, that is typical urban.

Now, bad urban on the other hand has the following behavior. It has got a decaying exponential like the typical urban, but at 5 microseconds, 5 microseconds it does this. What does this mean?

Student: (Refer Time: 44:12).

Bad urban; that means, because of the propagation environment suddenly at 5 microseconds there is a strong multipath component that is present multipath component. So, as you know you think that the multipath has almost died down, and you find that no there suddenly there is a multipath component that is springing up from somewhere.

Now, hilly, hilly terrain did I call it h a, it should be hilly no it is hilly, hilly terrain, h t. This should be hilly terrain, h t. Hilly terrain again very, very intuitive let me just sketch it for you, describe it no multipath components. So therefore, it dies on very fast, but there may be a hill or something of which the signal reflects. And that can come with the long delay much longer than you can see in an urban environment. Suddenly you know there is a multipath component not as strong as the original one, but never the less at a strong multipath component. So, again these are based on the different types of environments that people observed when they were actually deploying GSM. Somewhere dense urban therefore, you know you could see that the multipath was lingering for a long period of time. And then suddenly there was really bad propagation there was you know unexpected multipath components, again hilly terrain and rural areas are present.

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Appendix 7D

Indoor A, B
Pedestrian A, B
Vehicular A, B

ITU-R

→ Sectorized
→ MIMO
→ ...

Indoor A

Tap #	Delay (nsec)	Power (dB)
1	0	0
2	50	-3
3	110	-10
4	170	-18
5	290	-26
6	310	-32

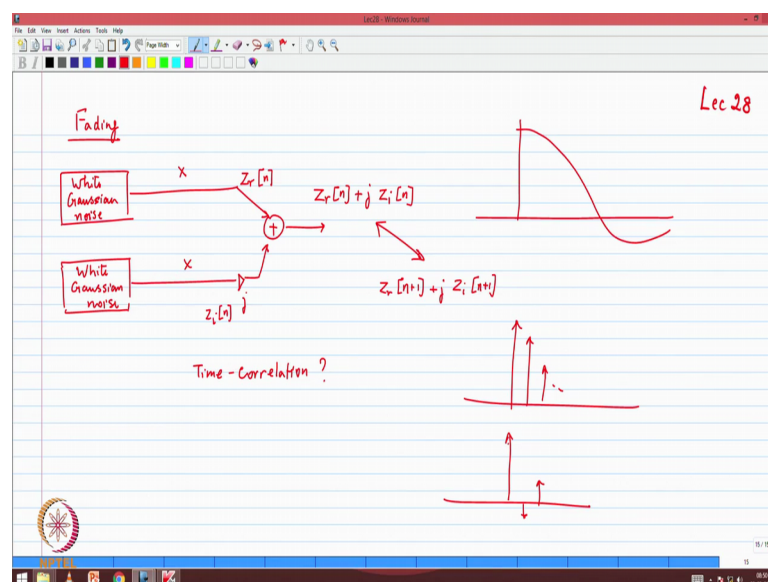
Now, appendix 7 d. 7 d is has got additional models, but I would like you to see that as well because it has something that is very useful for us. It has indoor models notice that the previous once were all out door. Rural, ya urban, AD urban all were outdoor models. Indoor models, what if you are indoor? There are indoor A indoor B. Then it has got something called a pedestrian model if you are inside of a building or just outside buildings there are 2 models and then of course, it has got vehicular models as well. These pertain to the channel models used by ITU, international telecommunications union which they specify that you have to test your system against these models. And of course, there are several variance of these, variance for sectorized antennas, variance for mimo dot, dot, dot, dot, dot. So, many variations are there, but once you have got an understanding of what are the basic models how are they classifying what are the things that they are doing then it becomes very easy for us.

So, for example, when you look at the description I want you pay attention to something. The indoor channel model, this is channel indoor a it has got 6 multipath components. Tap number this is the delay, and the power level power level. So, 1, 2, 3, 4, 5, 6, this is 0, 50, 110, 170, 20, and 310. The power levels 0 db, minus 3, minus 10, starts to look like an exponential minus 18, minus 26, minus 32. Now guess what is the unit is for the middle column. If you are outdoor was, outdoor model was 0.6 milliseconds, sorry microseconds. So, this would be definitely less than that, these are nano seconds, these

are nano seconds. So, it basically much less than a microsecond, much less than what you would see in a outdoor environment.

So, again the things for you to keep in mind are, what are the types of delays that you are seeing, what is the power levels, what is the profile look like again, that would help you appreciate what we are discussing. I will leave you with one last question. Now at the end of it we have now fully understood the wireless channel. I know you can tell me whichever way you want fading flat frequency everything, I know, I can characterize it. I understand it now I say please implement it you know go ahead and implement it show it do it on a computer.

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So, the student does the following. This absolutely no problem I know all the theory behind this. I am going to take one random noise generator Gaussian; Gaussian I will take a second Gaussian generator.

So, this is a white Gaussian, what does white mean? Uncorrelated, so basically I am generating Gaussian noise, uncorrelated Gaussian noise and in digital communications we know how to do that. So, I am I am going to take two of these white Gaussian noise, I am going to multiply this by j add this together, this I am going to call as Z_r of n discrete time. So, this I am going to call as Z_i of n . The combination of this is Z_r of n plus j times Z_i of n . Now I ask the student are you sure this is the fading channel this is

absolutely sure. Dual part is Gaussian imaginary part is Gaussian, complex Gaussian, I add the 2 together, I have got and by that this has got Rayleigh envelop, anything missing?

Student: Tap, tap, delay, delay.

Delay is not this is this, for a single tap. Frequency, frequency flat channel only one tap is needed. If I change Z_r of n to Z_r plus n plus 1 and Z_i to Z_i plus n plus 1, is there any correlation between these 2? No. Why because, independent samples were being generated. But now, if I am in a fading environment, if you suddenly tell me you know from I just moved my time observation by you know, few milliseconds and you said the channel completely change. No, no that that does not possible. Because you know that the auto correlation function is actually a Bessel function, until you reach coherence time the channel has to be remained correlated. But this is totally uncorrelated. So, the question is this is because it will generate a right Gaussian Rayleigh statistics, but it does not capture the time correlation. How do I ensure that these samples are time correlated? That is my channel at this time instant is like this, next time instant is like, this dot, dot, dot.

So, basically there is a correlation that has to be present. I cannot, I cannot get you know this at one instant this time. Next one is this, third instant is this that is not the type of channel that we are encountering. So, something is wrong with this figure. And how; obviously, what is it that we need to fix, time correlation is not present. So, we have to do something to this one think about what it is that we do we will present it in the next class.

Thank you.