Introduction to Wireless and Cellular Communication
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Lecture - 21
BER Performance in Fading Channels
Review of Lec 1-19

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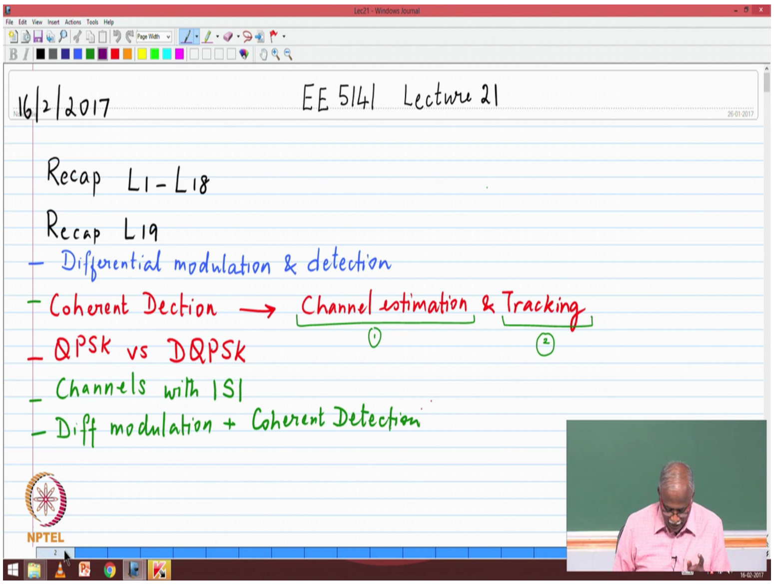

Good morning, just so that we do not lose the continuity in the last lecture we have introduced the notion of differential modulation also talked about the differential detection; differential modulation meaning differential encoding of information at the transmitter. The coherent detection requires two parts one is channel estimations the other one is channel tracking, and using those two together is what we get to get the as the aspects of coherent detection and what is the dependency is between the estimation and tracking, and how they both work together in a coherent detector we have discussed in the last class.

So, this gives us a basis for comparing the performance of QPSK versus BQPSK or any MPSK versus differential MPSK, a point that was clarified through a question at the end after the lecture was it can you do differential encoding for QAM constellations, basically you can do differential encoding of phase which is what we saw can you do differential encoding of amplitude as well. It is not common. So, most of the time when we talk about differential encoding it is only in the context of phase modulation, but there are some techniques called double differential where you have both the phase and the amplitude as differential encoding, but our reference to differential encoding will be in the context of phase.

And then the last point what we said was you know what happens with channels ISI and then you know can you have hybrid differential modulation coherent detection or coherent modulation and differential detection, again those were questions that you are ask to a founder about we will time permitting we will take up those questions.

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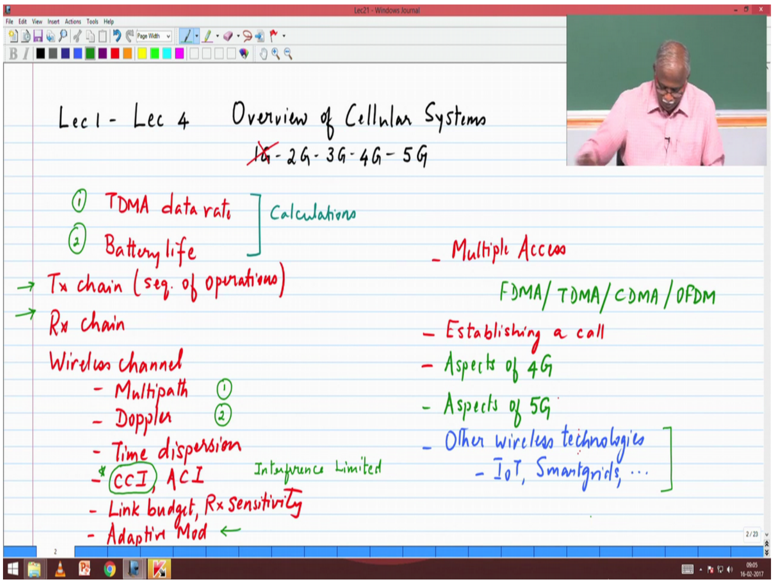

So, lectures 1 to 4 where more of a review and again some elements I hope you are able to keep in mind and apply and more in terms of the concepts and the information. So, we basically went all the way probably did not do much on 1G except to say that it was an analogue system most of our discussion has been 2G to 5G, and in terms of calculations the only two calculations that we really sort of did as part of this review was one when we calculated the data rate of a TDMA system and so that is how much user rate that you can carry per slot and the other one was the with respect to battery life you know given the mill ampere hours of a battery, what is the different modes in which you how much you will the battery lasts.

So, again in terms of actually calculations these were the only two, but there are several concepts that that emerge. So, let us just sort of run through to that in a way this sort of refreshes your memory and also gives you a contexts on what we are the building the course upon. We did make a only introduction to what are the sequence of operations in a transmitter and also in the receivers.

So, basically the information source, the error correction coding the modulation and all the basically the that changing, then we also looked at several aspects of the wireless channel which are important for us the notions of multipath which we are going to use extensively in the coming lectures, again the notion of Doppler what happens in the presence of the Doppler in the combination of some multipath and Doppler, we just said intuitively we said that there is special distribution of troughs and peeks which will affect the performance of the signal. We also mentioned that when these multipath components arrive with different delays then we will have time dispersion that is going to be an important element.

Then we spend some time looking at the sources of a impairment in a channel of course, noise being one, the second one is the interference which is the more dominant. So, basically our cellular systems are interference limited. So, we need to have a good characterisation of the impairment and among the two the co channel interference is going to be the one that is more dominant or dominant that we have to be worried about the adjacent channels is taken care of through the received filtering.

Then as part of the overview we also did a quick very simple link budget calculations introducing the notion of receiver sensitivity, this also told us that if you have a buffer in terms of the signal strength you can go for adaptive modulation changing your constellation size if you have better SNR you can go to higher constellations. From there we also went into a differentiating the different generations through the method of multiple access that they have utilised also made a few statements about what are some of the advantages, disadvantages, why generation shows that particular multiple access talked about establishing a call and then some aspects of 4G, what are some unique elements of 4G and then aspects of 5G ok.

So, again over a period of probably three little more than three lectures, this is what we covered and then last part was we also touched upon non cellular technologies, again just to understand things to Bluetooth, wireless lan and several emerging standards in the context of internet of things, smart guards, smart metering several applications which will requires densities requirement of the transmitter receiver units. So, this was lectures 1 to 4 I hope you had a chance to look at the slides and should be fairly easy to follow from the overall context ok.

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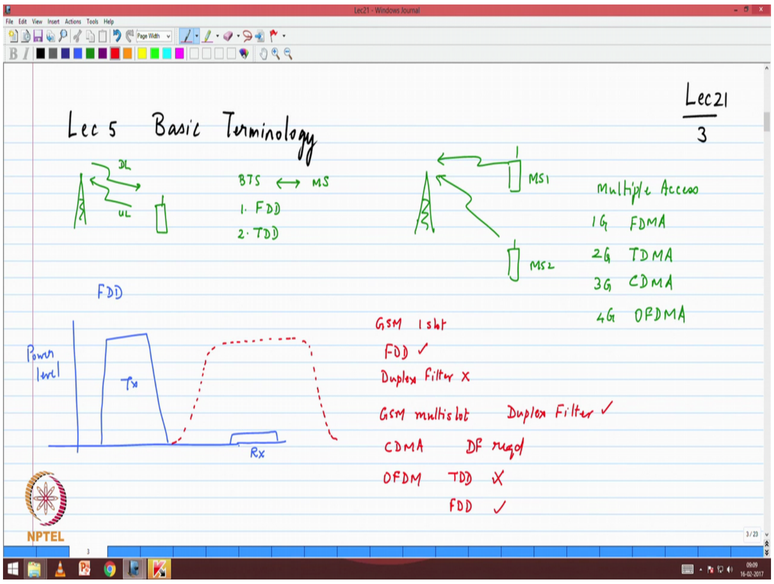

Then starting with lecture 5 we introduced the basic terminology, again let me just run through. So, that your familiar with it in the context of a. So, we have introduced the following notation of uplink and downlink. So, downlink is always from the base station to mobile uplink is from the mobile to the base station and the link between a base station; and a mobile station can be through the following duplex operations frequency division duplex which means uplink and downlink are on different frequencies or it can be time division duplex which case there is only a single frequency uplink and time link are time division multiplexed.

Now, the difference between duplexing and multiple access several times that creates little bit of confusion. So, here is a base station I have mobile station one mobile station two this is MS 1 MS 2 now how does mobile station one and mobile station two access the or connect to the base station that is multiple access or base station talking to mobile station 1 and mobile station 2. So, multiple access comes when multiple newses are trying to access the system. So, multiple access multiple access again based on the generation could be FDMA that was 1G, TDMA in the second generation CDMA in the third generation and OFDM in the fourth generation O F D M A do not forget the a at the end it multiple access orthogonal frequency division multiple access. We also said that when you have an FDD system you have to be careful with the transmit and receive powers.

So, FDD systems there is a transmit that is happening at very high power. So, this is power level. So, this is the transmit spectrum little bit away from that is the received spectrum, and that is your received signal. You do not want your transmit signal to affect. So, therefore, we introduce a duplex filter which basically will cut off the transmit signal and allow the received signal, and usually it is a band pass filter that allows the received channel to come in without the impacts of the transmit.

Now, there are some unique situations such as in GSM, GSM is an FDD system, but does not required duplexes if it is single slot. So, GSM one slot operation, it is FDD it is correct duplex filter no and that is because you have use the advantages of the TDMS system duplex filter duplex filter does not require. GSM multi slot that is a same user asking for more slots this case the duplex filter will be needed because it is a FDD system duplex filter. So, it is not always true that an FDD system will require a duplex there are exceptions and this happens to be an exception.

On the other hand CDMA. CDMA duplex filter I will call it as DF required always because it is continuously transmitting continuously receiving. Now OFDM does it require or not OFDM does it require duplexes filter.

Student: No

No why.

Student: (Refer Time: 10:01).

It is a TDD system by that keep in mind that 4G has got 2 d 2 flavours, one is TDD OFDM and then there is an FDD OFDM. So, this one this one does not require this one will require a duplex filters. So, again the notion of why is required when is it required again something that I would like you to be comfortable with.

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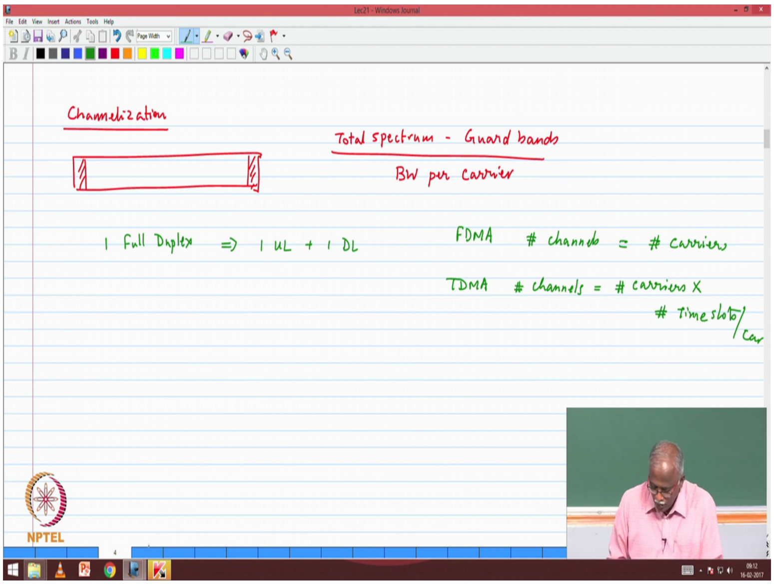

We also talked about may be one couple of more points in the early stages in terms of the we talked about channelization. How given a spectrum you will estimate the number of channels available and that is typically by taking your spectrum your told what is the guard band, you have to remove the guard band do not forget to do that and then it is total spectrum that you have minus the guard bands remove the guard bands and then divide by the bandwidth of a carrier band width per carrier ok.

And keep in mind that one full duplex channel must have both uplink and downlink. So, there is uplink spectrum downlink spectrum do not count it as double the number of channels you have to pair it is a paired channel. So, always we talk about full duplex channel. So, basically this must consists of one uplink channel plus one downlink channel. So, always give the number of channels in terms of full duplex channels not half duplex channels. So, basically it would be the total bandwidth minus guard bands divided by bandwidth per carrier.

Now, if it this carrier happens to be a TDMA system. So, if it is FDMA number of channels equal to number of carriers correct; because each carrier represents one channel number of carriers. On the other hand TDMA systems I think there were a few questions regarding this, in TDMA the number of channels that is number of physical channels when you say channels it is always physical channels, physical channels one time slot is considered as a one physical channel. So, that would be equal to number of carriers into number of slots number of time slots per carrier time slots per carrier. So, please make sure that you do count the channels appropriately for the TDMA systems and FDMA systems, for CDMA it is based on the number of codes again it is not counted the way we do it for these other systems.

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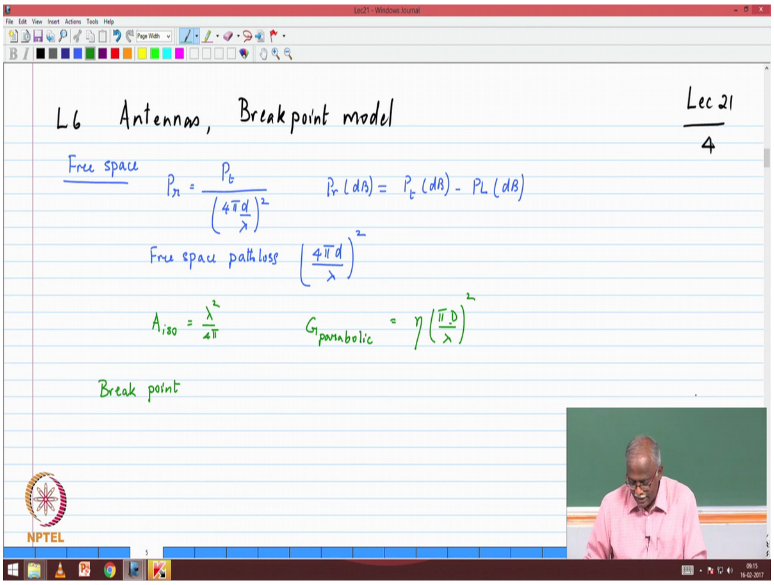

We move on to the lecture number 6 where we introduce the concepts of antennas break point model and the other. So, let me just sort of a quickly run through again most of this is the review, but hopefully it will help put all the pieces together as you prepare for the test. So, one of the key things is we look at free space propagation; we spent a quite bit of time understanding free space propagation from an isotropic at source, isotopic receiver and based on that the relationship that the received signal power is equal to transmitted signal power by 4 pi d by lambda whole square; that is the free space equation can be written in terms of the received signal power in dB equal to the transmits signal power in Db, minus path loss in dB which basically tells us that the free space path loss that is a very important quantity which we use in several calculations, free space path loss is given by 4 pi d by lambda whole square ok.

And we also looked at some aspects of antennas did not spend a whole lot of time because that is not our focus, but just to for complete the sake the effective area of an isotropic radiator is given by lambda square by 4 pi. It is dependent on the lambda of the of the transmitted frequency and we also looked at the gain of a parabolic antennas we used for back hole in the number of wireless applications, this is given by the antenna efficiency times pi D by lambda whole square. D is the diameter of the approached. So, basically have a circular cross section they diameter of that is what we are utilising.

The combination of these two basically gave us a break point model and let me see if I can pull up that particular portion from the corresponding lecture.

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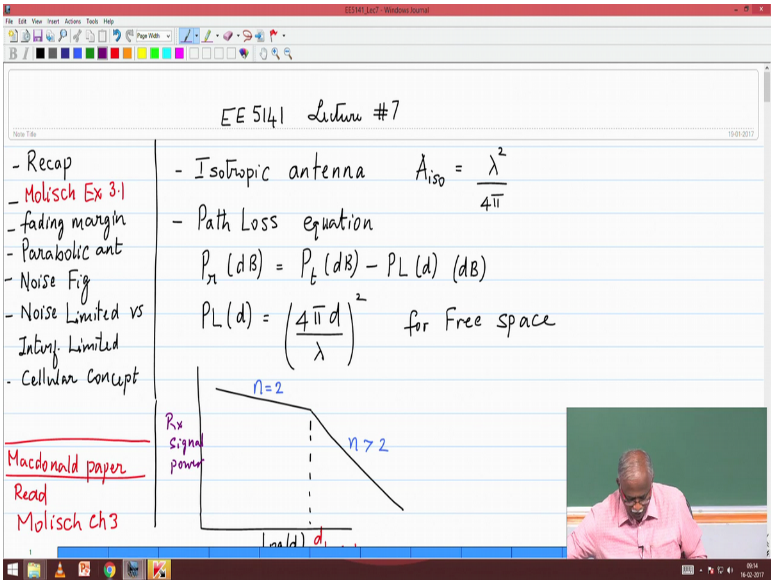

So the summary that came from lecture 6 break point model states I will take free space propagation up to the break point; that means, from the source antenna radiation point up to break point, and then go at a slop that is greater than two because of a higher path loos. So, basically this is receive signal power as a function log d logarithmic that that is when you get the straight lines. So, this is the break point model and we looked at some calculations using the break point model.

So the break point model is something that you should be familiar with it is one of many path loss models happens to be the simplest of the path loss models again we made the statement that you know some of the more complex path loss models we will be looking towards the end of the course, but again it is to keep in mind that there is a model that tells you what the received signal power is and the break point model is one such method.

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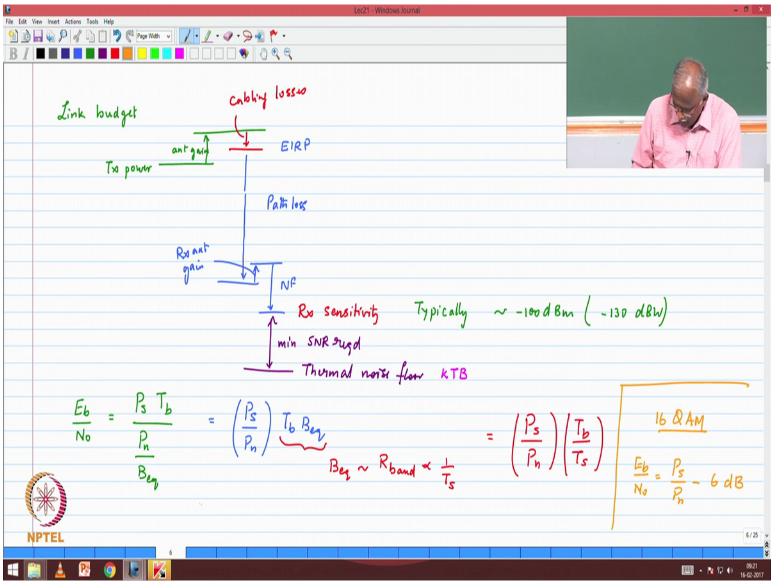

The second aspect that we started to look at was the element of the link budget I would like you to remember it in the following fashion link budget. So, there is a transmit power that is coming out of the power amplifier, then there is antenna gain that raise it higher. So, this is antenna gain and then there is a cabling losses. So, this is cabling losses, resultant is ELRP the effective isotropic radiated power. So, EIRP very important because that is one of the starting points, then from EIRP we allow the path loss based on the exponent. How much distance I can go depends on the exponent, but basically there is a received. So, this is at the receiver then there is received antenna gain sometimes it could be loss which means that you careful how you do that receive antenna gain that will boost your signal up then noise figure is going to cause you a degradation that is the noise figure and this is a very important value that is receiver sensitivity ok.

Depending upon the modulation scheme that we have used you have a minimum SNR required, minimum SNR required and that must be given must be maintained with respect to the thermal noise floor. So, that is in a sense a link budget in a noise limited environment and the thermal noise floor is given by K by both plans constant T ambient temperature B the bandwidth of the received signal again the effect of bandwidth we have looked at in a couple of examples and in the assignments to say that you know when does this noise floor move up or down based on the bandwidth of the signal that we are working with ok.

Now, in this context I believe we also may be let me just mention receiver sensitivity for most of the systems that we are looking at is typically of the order of minus 100 dB m typically of the order of minus 100 dB m, how much that will be in dB w? So, it is always dB w plus 30. So, again you keep that in mind. So, the numbers that we are talking about are small. So, make sure your doing the calculations carefully. In this context and also in the context of the computer simulation I believe we have also looked at this relationship the way you link E b by N nought to the transmitted signal power or received signal power. So, this P s times T b divided by the noise power divided by the equivalent bandwidth of the receive filter.

So, this can be written in the following fashion as P s by P n times T b times B equivalent and a for systems that employee a root rise cosine type system filter at both the transmitter and receiver, we have a very good relationship because B equivalent is approximately equal to R b the baud rate the or the bandwidth of the signal. So, this is baud rate or the symbol rate of the system symbol rate is proportional to 1 over t s. So, this proportional to 1over t s. So, basically this relationship will become P s by P n, T b by T s. T b by T s because equalent bandwidth is approximately is inversely proportional to the or the proportional to the symbol rate and it is inversely proportional to the symbol duration ok.

So, if you were doing a 16 QAM example I know we have not done this before. So, I though this good to just mention this 16 QAM the relationship between E b by n nought and P s by P n would be equal to E b by N nought would be equal to P s by P n minus T b by T s is 1 by 4 because it carries 4 bits per symbol. So, if I convert that into log it will be 6 d B. So, E b by N nought would be. So, again this is something that you should be familiar with something that we have discussed.

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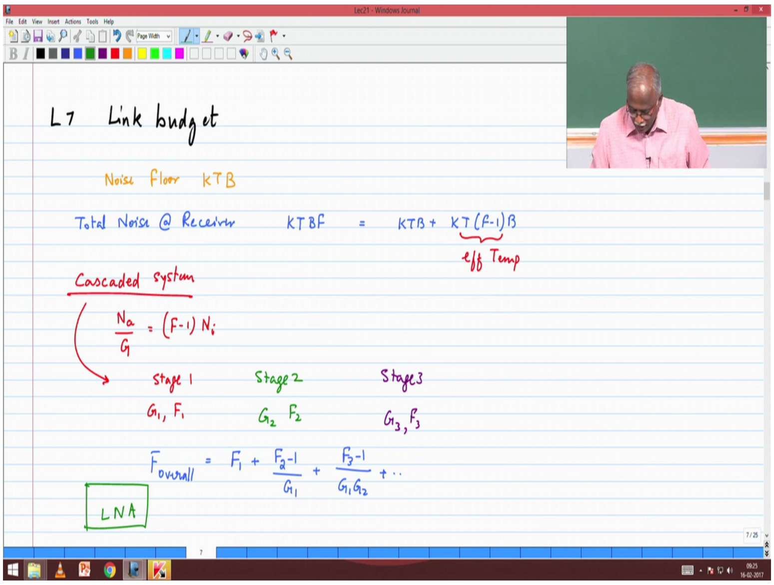

Now, another aspect of the link budget is the understanding of the noise. So, the noise floor is KTB the equivalent bandwidth. The total noise at the receiver that will include the noise figure of the receiver. So, it would be KTB times F and we give two interpretations to this one is KTB plus KTBF minus 1 times B. Where f minus 1 into t is called the effective temperature of the receiver. So, and based on higher the noise figure it looks like the electronics is at a higher level and therefore, adding more noise to your system ok.

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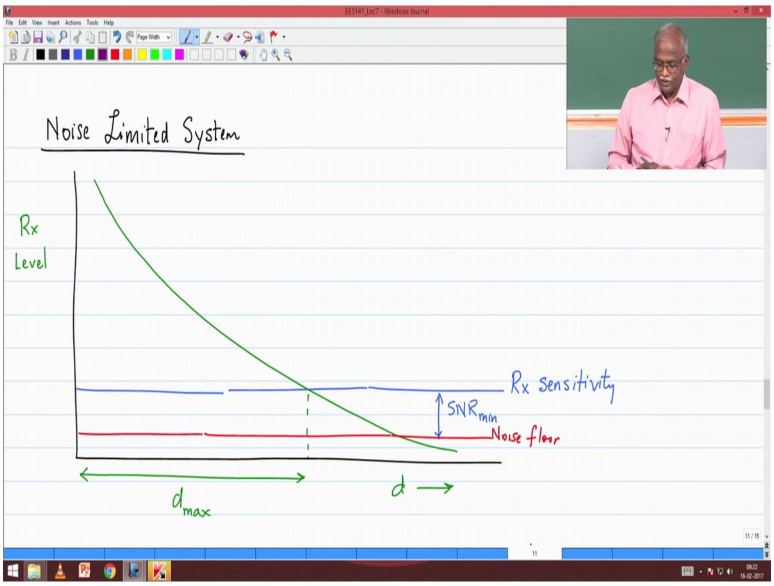

And this also give us a way to look at the noise limited systems where we said that the our understanding of the noise limited system the path loss will decrees or this received signal will decreased, there is a noise floor that is a constituted by KTBF and then there is a receiver sensitivity that we have to allow for and the minima received signal strength and that will more or less determine where my maximum range of my signal to which my maximum range my signal can travel in a robust manner. So, this was an figure that we have used in lecture 7.

If we go back to our discussion, we are also looked at most of the time or systems are not single devices it is a cascade is antenna coupler. So, there are several elements in that. So, we just think of it as a cascaded system and all we are interested in is a how does the noise figure get affected. So, the first element of that is that you have to be able to reflect the noise added by that particular system to the input side, always the noise which is introduced by that particular node divided by the gain is equal to f minus 1 times N i where N i is the ambient noise value that is or the input noise like to density ok.

So, now if you have a cascaded system where stage one consists of a gain N 1 and noise figure F 1 that is stage one stage two is gain G 2 noise figure F 2 and then stage three G 3 F 3 again there are several interesting observations that we have derived from it, but the most important one is our ability to write down the overall noise figure. F overall is given by the noise figure of the first system plus F 2 minus 1 divided by G 1 plus F 3 minus 1 divided by G 1 G 2 dot dot dot ok.

So, that tells us that the noise figure of the first stage is very important and the gain of the first stage of the earlier stages help suppress the effects of the subsequent stages you know the subsequent stages are not very good in terms of noise figure, it does not affect us because the first stage has to be and this is the reason why we have low noise amplifier as the first stage in most of our receivers. Low noise amplifier because you want to amplify with low noise so that you can get the benefit of low noise figure of the front stage, and also the gain to suppress the noise figure of the succeeding stages ok.

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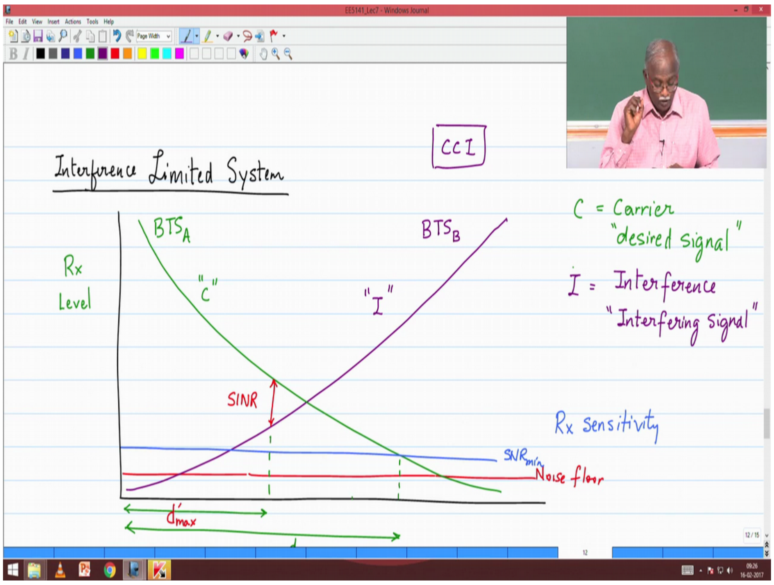

This also let us to another diagram when we start talking about systems that are interference limited. So, the situation changes in the following fashion now we have the noise floor, we have the receivers the receivers sensitivity still, and we have the signal from base station a the signal station from the base station of b which is interfering base station co channel interference make sure that you keep that in mind, this is a co channel interferer CCI, and we cannot have negative CCI we cannot have an 0 dB CCI. So, we have must have a positive signal to interference ratio which means that your the maximum range to which you can use the desired signal from base station a is from is the max, notice that it could be substation ally smaller than what d could have been. So, the once it becomes an interference limited system we have to change our method of thinking. So, that now we start looking at SINR and not at SNR that is something that we have discussed ok.

So, that was lecture 7; then we move into the next part where we introduce the cellular concept.

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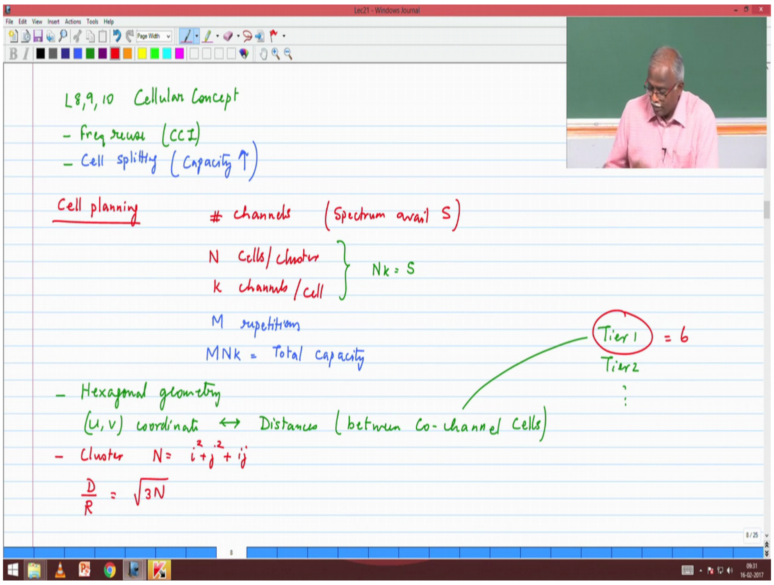

So, lectures 8 9 and 10 address several aspects of the cellular concept. Let me just run through again most of it is review the cellular concept consisted of two things one was frequency reuse this is McDonald concept. So, that give us co channel interference that is a very very key. So, that was one aspect of it the second one was that you could do cells splitting to increase your capacity this is for increasing capacity ok.

Now, we did do couple of examples on cell planning; cell planning very important which tells us how to designs the system the key elements that we are looking for first and foremost is the number of channels number of channels that are available to us that would depend on these total spectrum spectrum minus guard bands divided by the channel band width is gives us the number of channels. So, this is based on the spectrum available this is the calculation that we have already done before and if you have n cells per cluster N cells per clusters and K channels per cell per cell channels per cell the relationship that we have is N times K must be equal to the total spectrum the basically you take the total spectrum divided by the number of cells in the cluster and say that this is the number of channels that you have it per cell.

We then looked at the tessellation where there are M repetitions of the cluster. So, the overall capacity is given by MNK. So, number of channels per cluster multiplied by the number of repetitions. So, this is the total capacity of the system total capacity of the system, we talked about what are the ways in which we can increase capacity decrease improve the C over I robustness all of that where link to these elements. The underlined frame work or the foundation for this discussion happened to be the hexagonal geometry; hexagonal geometry which has several simple, but important elements one was the u, v coordinate system and in the u v coordinate system we have to be able to compute distances, usually we were computing distances between co channel cells and that is a necessity because of we want to characterise the co channel interference.

So, co channel cells.

And the co channel cells also we said are divided into tier 1 tier 2 and so on and very often we would be focusing on tier 1 as the most important elements, and that would always E b equal to 6 for the hexagonal geometry that we have assumed. The cluster size was another important outcome from the tessellation process, the cluster sizes the valid cluster sizes N is given by I squared plus j squared plus i j where i is the index along the u axes j is the index along the v axes in the u v coordinate system, but in if you consider a normalised latest then the i n j are just integers there for easy for us to calculate.

The important parameter in the hexagonal geometry happened to be D by R where d is the distance of the co channel cells tier 1 co channel cell, in most cases R is the dimension of your hexagonal. So, basically you can think of it as radius or the size of the side of the hexagonal D by R we showed was equal to root 3N. That is a very useful result because that tells us how to estimate the co channel interference approximately for any of the cluster sizes that we will be work with that we will be work with.

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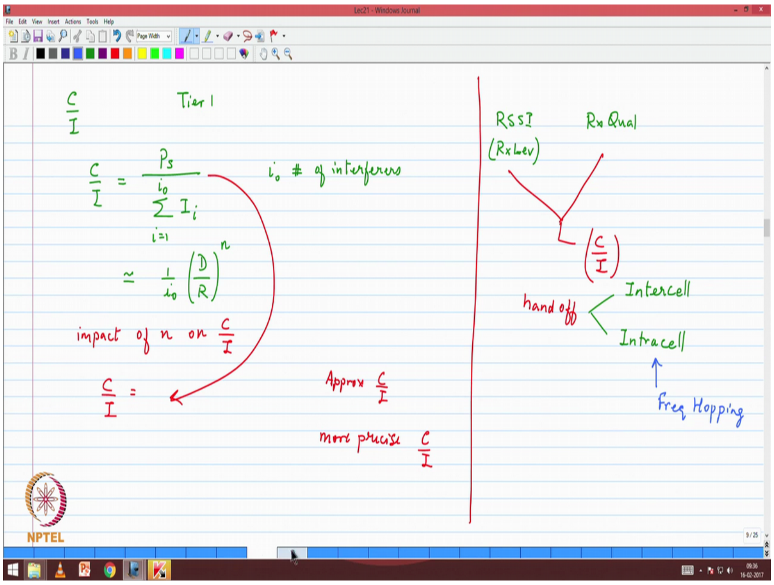

One of the elements that we are interested in is an estimation of C over I and whether we want to include tier 1only or tier 2 also again that would impact our calculations. So, C over I the definition would be the signal power divided by the total interference power. I is equal to one to i naught times i i. I naught is the number of interferes number of significant interferes you could restricted to tier one or you could restrict to less than tier one if you are doing sectorization, but the important one is that you have to make sure you have estimated the number of interferes that interferes.

Now, there are several approximations that we have done one of the approximations is that we can approximated as 1 over i naught that is the total number of interferes the desired signal strength is proportional to R power minus n, the interfering interferes proportional to D power minus n. So, therefore, this is comes as D by R rest to the power n one by n naught this is an approximation, but it gives us a first order very quick estimate whether the cluster size will work based on the D by R ratio that we have. We also did indicate what is the impact of the path loss exponent on C over I, it is a different impact with respect to a in a noise limited environment where n would be larger n would be undesirable, but in the case of a interference limited environment it actually you know improves our C over I.

There are several times when we would have to estimate C over I more accurately than one what we have done in the previous formula. So, that those are examples that we have looked at. So, basically C over I using exact distances or at least the this would basically go back to the form and then calculating the distances for more correctly for each of the interference interfering signals. So, we have done approximate C over I and more precise not I would not say completely precise more precise C over I again based on how much of the geometry that you are willing to use and there thereby get the desired effect.

At the end of the day we are interested in the signal quality, and we did talk about the following two measures of signal quality one is RSSI also known as R x Lev. R x level and there is another one which is R x qual (Refer Time: 33:01) x quality that tells you how many frame errors are occurring this is just a signal strength measure. Keep in mind it is the received signal. So, it could be mixed with noise interference basically whatever comes into the receive filter is what is measure.

Now, using a combination of these two we have to find a estimate of C by I and we also make decisions whether the user requires a handoff again it is a interaction between the the results and observations from RSSI and R x qual and you also make a further decision whether you need to have an inter cell handoff or an intra cell handoff would be and as we mentioned if you are close to the base station, but seeing the lot of interference intra cell is the right thing to do, but if you are at the boundary and you seeing a lot of interference from the others then better to do an inter cell handoff because your own signal is week and that you should derive from a combination of what you have seen in the RSSI and R x qual.

Intra cell handoff can also be visualised as frequency hopping because what you do in intra cell handoff is to change the frequency, but stay connected to the same base station that is exactly what you do in frequency hopping you change the frequency, but still connected to the base station; however, you did not wait for a measurement of RSSI or R x qual, but you are constantly changing these centre frequency that was lecture up to lecture 10.

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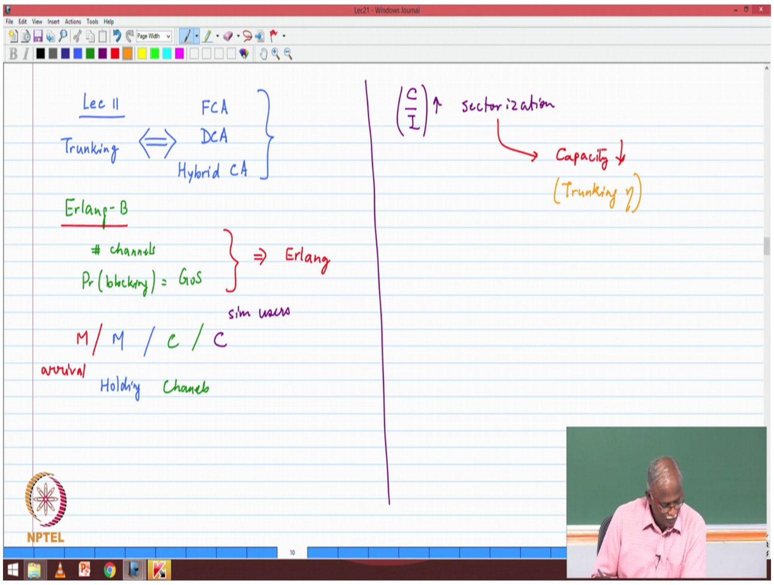

Lecture 11 gave us a new perspective into the cell planning and it is capacity. So, this was the part where we talked about trunking. What is the advantage of having more number of channels in a pool and this also told us that once you do the frequency planning you could do fixed channel assignment, you could do a dynamic channel assignment which would probably be the mostly beneficial or you may want to do something which is a hybrid channel assignment. These are different channel assignments and again all of these are related to the Trunking efficiency.

And the trunking efficiency was the Erlang B discussion that we had again not going into the derivation of the erlang B, but the just use that to given the number of channels and the blocking probability probability of blocking which is grade of service G o S. Usually we use these two to come up with what is the erlang traffic that you can load the system with off ward traffic that you can load the system with because this amount of traffic would result in the would satisfy the grade of service for the given number of channels; again there are three values given to you can compute the third a that is the essential discussion.

The basis of the erlang B was you assumed that it is memory less arrival memory less holding time, then you have C channels, and C carriers, C simultaneous calls simultaneous users simultaneous user basically your using all of your available channels based on this assumption the erlang B has been derived and that give us a ability to get a field for what is the blocking probability and how much we can load the system

In the earlier discussion we always said that C over I will improve if I do sectorization because I naught decreases and therefore, I get read of some of my tier one interferes, but erlang B tells us that this is going to result in capacity loss, because of reduction of trunking efficiency. So, again and the loss is because of the trunking efficiency, trunking is always better if you have more number of channels available to you because it is a statistical multiplexing technic, which says that the more channels you have the more users you can except to be able to multiplex.

If the channel conditions are not good then we must go for handoffs and lecture 12 we did take a or part of lecture 11 we also had a discussion on the aspects of handoff.

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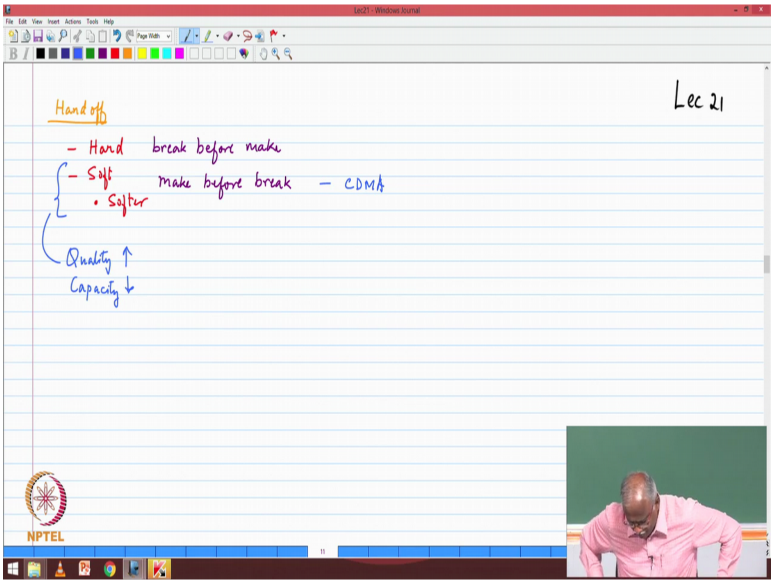

Now, handoff has got several aspects, but we did touched upon on the following there are three types of handoffs hard handoff, soft handoff and a under that a something called a softer handoff. And again the hard handoff belongs to the category where you break before you make break before make, and the other once correspond to make before break, the once the system that lends itself to soft handoff nicely is CDMA all others will be hard handoffs and the price that we will pay is that a soft handoffs means quality improves, but your using more resources. So, capacity will go down that is the trade off with soft handoff we talked about that, we talked about when you do soft handoff sorry when do you handoffs when you do ok.

Now, let me ask you an interesting question, you saw this graph for when your talking about interference limited system. We also saw this graph when we did handoff if you remember in the case of handoff we were going all the way up to the cross over point or very close to the cross over point whereas, here we are saying cannot even go close to the cross over point what is the difference why.

Student: (Refer Time: 40:48).

Did you understand the question? The same graph is saw into two scenarios one case it was I have to stop well before the intersection point, the other case you know I sometimes go even as long as I am I know I can even go beyond the cross over point and then change over my base station and get better signal.

Student: (Refer Time: 42:11).

Thank you excellent this is an when it is interference limited it is co channel interference. So, which means you can at this at the point of intersection it is 0 dB signal to signal to SINR is 0 d B. So, there for you must stop before you reach that point; however, in the case of handoff these were orthogonal they are not interfering with each other. So, you can go all the way till you hit the noise floor and that is the reason why you are able to go beyond the intersection point, this not a mistake it the in one case it is co channel which is also adding to the interference impairment, the other case it is an orthogonal frequency which is not adding to the interference all it is doing is it is helping you to get better signal to noise ratio through the handoff process good.

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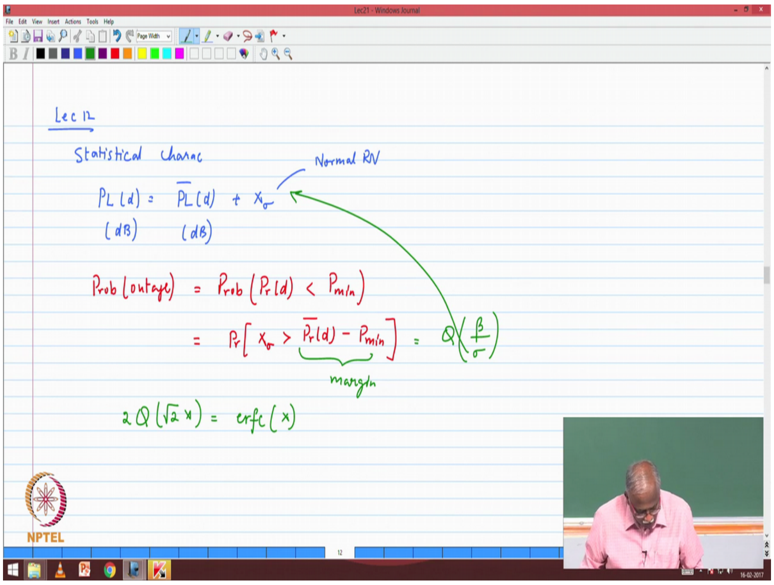

Let me quickly summarise the rest of the topics that we have we have covered lecture lecture 12. So, lecture 12 the topics that were covered was a statistical characterisation of shadowing; statistical characterisation where we said that the path loss at a distance d can be represented in terms of the mean path loss plus normal random variable. So, this is a normal random variable this is a equation that is written in the dB form, and it is a normal perturbation around on a dB value.

So, the underlying random variable is a log normal random variable and we looked at the characterisation of that. The reason this was useful is because it helped us to calculate the probability of outage. Probability of outage depends on the probability that the received signal at a distance d is less than the threshold P min whatever threshold that you have done maybe it is a sensitivity and this we related it to the probability that x sigma is greater than the mean path loss minus P min; that means, your shadowing a loss is more than what you have allowed and so which means that this quantity represents your margin.

So, what is the minimum that will that you can tolerate and what is the mean path loss that where will the signal will come with the min path loss and that means, your if the shadowing exceeds the margin it will go into outage and this we related to the Q function Q of beta by sigma and this sigma is related to the standard the variance of the normal random variable.

The Q function can be you can use it as a Q function or the complementary error function. So, Q of two times two Q of root two x is the same as the complementary error function of x. So, you can look it up here in the Q tables or in the complementary error function tables.

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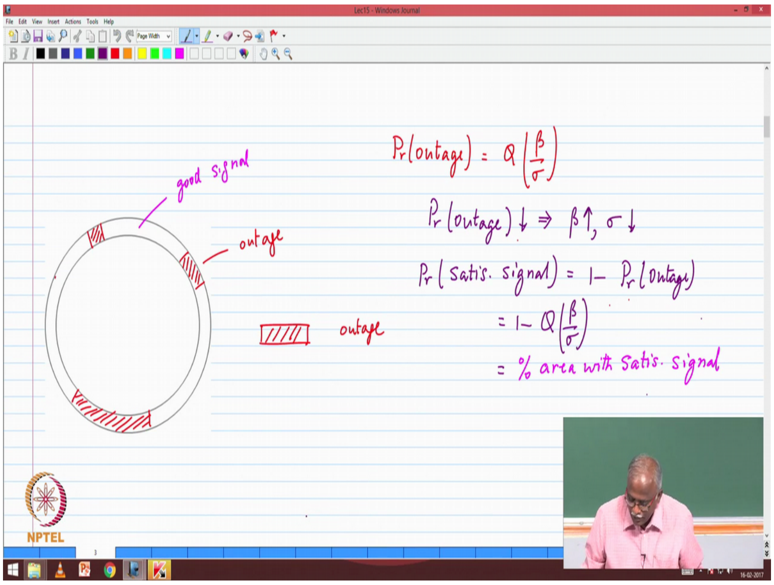

And one of the important interpretations of this statistical characterization came when we used that to interpret the percentage of area that at the cell boundary that will be affected by the outage ok.

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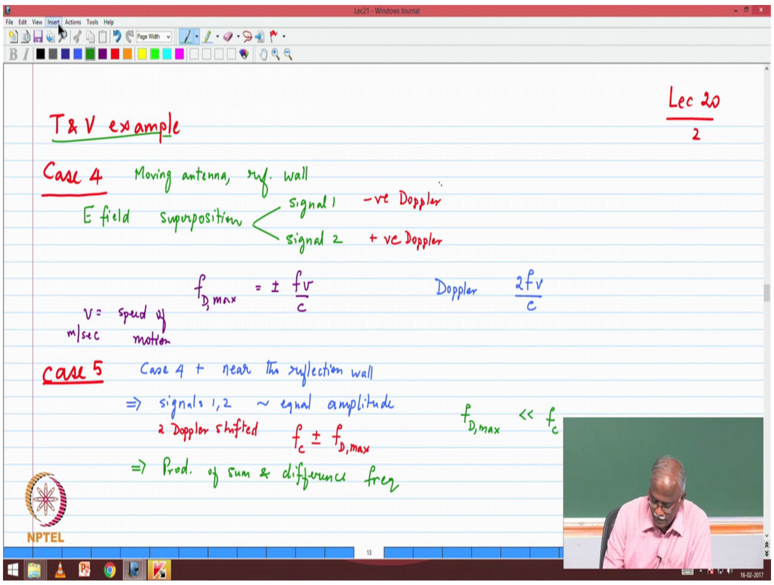

Then we moved into from the from there the next few lectures, we talked about the classification of large scale versus small scale large scale versus small scale effects small scale effects.

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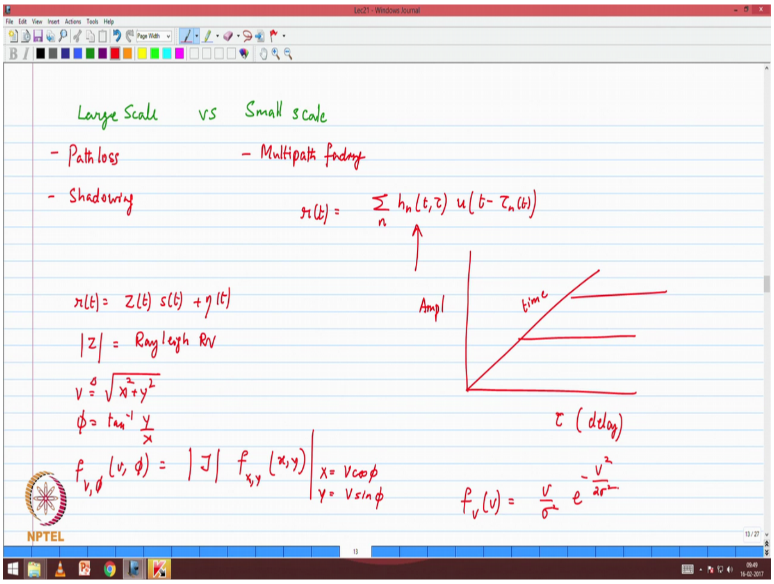

So, we listed path loss under large scale we listed shadowing under large scale and this one would be multipath fading. So, or first entry into the small scale effects was to understand the model for multipath fading multipath fading which we derived using our understanding of the impacts of Doppler the delays that are happening at the different time, instance of time and we said that the channel can be characterised in the following fashion r of t can be characterised as some number of multipath components h n t comma tau u of t minus tau n of t, u represents the transmitted signal h n is the channel responsive not using the word impulse response it is a channel response.

And the best way to characterise this was through a three dimensional plot, where this was the tau dimension this was the time dimension and this was the amplitude dimension and again we have given the interpretation of why we want to keep it as time in and the delay dimension a separate because the channel response can change at different instances of the time and for each instance of the time of time that is snap short has to be interpreted appropriately.

And the interesting derivation that followed said that if I want to characterise my received signal in terms of single multipath, where all of them are merging into single one z of t, s of t plus eta of t; then the modulus of z is a Rayleigh distributed random variable Rayleigh EIGH Rayleigh random variable again I would very much. So, the way we did it was we said v is equal to square root of x squared plus y squared x and y are i i d 0 means a Gaussian random variables with a given variance v is equal to tan invers of y divided by x. So, that gave us a joint p d f of v of pi equal to the Jacobean.

Please make sure that you are comfortable with the Jacobean derivation, f of x comma y that is joint distribution of x and y in this case it will be a product of two Gaussian p d s and then you have to substitute x is equal to v cos pi and y is equal to v sin pi that will give me the joint p d f of v, and then we from that we obtain the marginal p d f which said f v of v is v by sigma squared e power minus v squared by 2 sigma squared.

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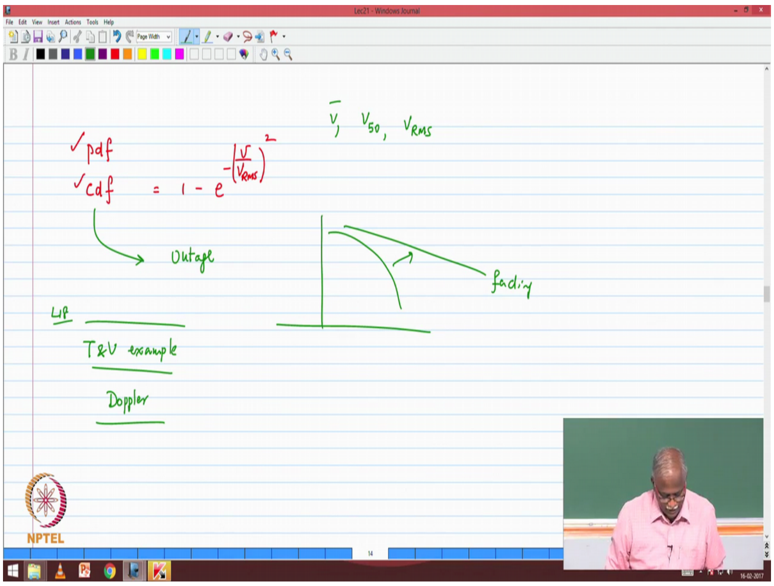

And using that relationship we also derive. So, now, we have the p d f we also derived the c d f, which is given by 1 minus e power v by v r m s the whole square. And this also helped us in terms of interpreting outage due to small scale fading there is outage that happening ultimately there is a net outage, but there is outage that can be caused by small scale fading and that is something that we were able to characterise in terms of that ok.

And the last class was which was lecture eighteen we introduce the say N. Vishwanath example. So, that we could get a feel for what are the effects of Doppler was primarily what we had discussed up to that point, and then subsequently we introduced coherence time coherence distance, but that was in lecture 19. So, this is the point at which the lecture 18 ended, we also gave some interpret or intuitive feel for this is AWGN performance, this is fading performance and how did it go from here to here because of the fluctuations in your SNR. For the Rayleigh p d f we did calculate the mean value we also calculated the median value and of course, a V RMS was also computed as part of the overall characterisation.

Again this was not scheduled part of the lecture there was other lecture scheduled as a lecture twenty one which we will have to makeup after the quiz some time ok.

Thank you very much.