Signal processing for mmWave communication for 5G and beyond
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Module – 04
Detection, Estimation and mmWave channel
Lecture – 19
Basic ISI channel

Welcome to the session again. So, today we will be talking about the module 4 which is the Detection, Estimation and the millimeter Wave channel more details into millimeter wave channels. So, today we will first talking about the Basic ISI Channel.

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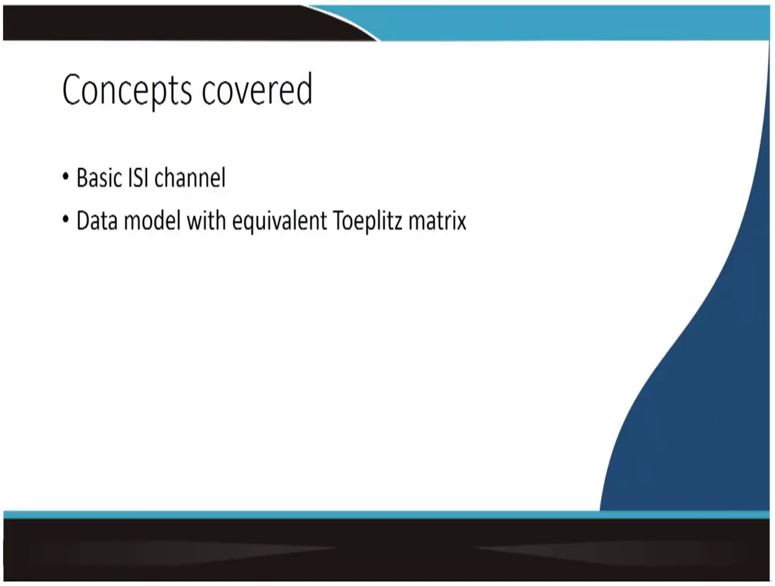

The concept that will be covered today is the basic ISI channel model and then what is the data model with the equivalent Toeplitz matrix. So, last class we have talked about the coherence time part and we did not give any formal definition, we just gave a flavor of what exactly coherence time means. So, I go back to my earlier diagram here.

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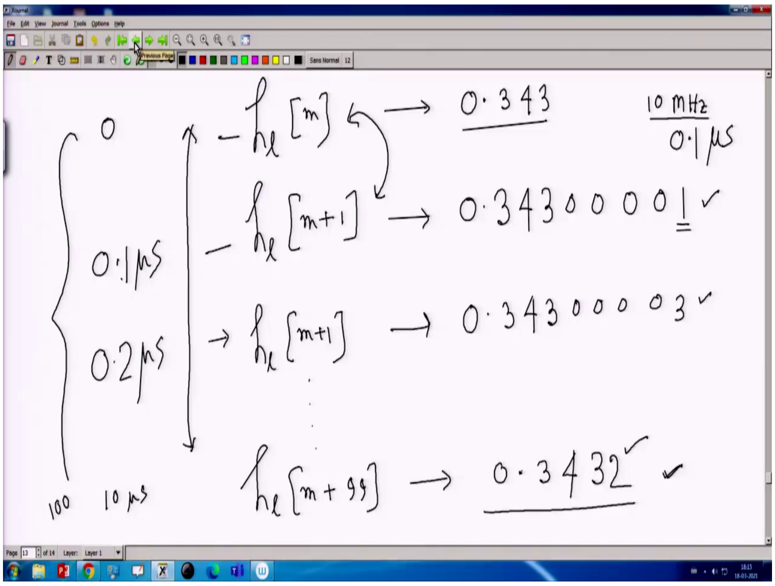

So, if you look at it here I think I have already re-explained I am let me go through again. So, here what I am saying is that channel say I am sampling the data at 10 megahertz sampling and I am seeing my channel is changing because of the Doppler then we said that is the change significant ok. If the change is not significant I should not even care.

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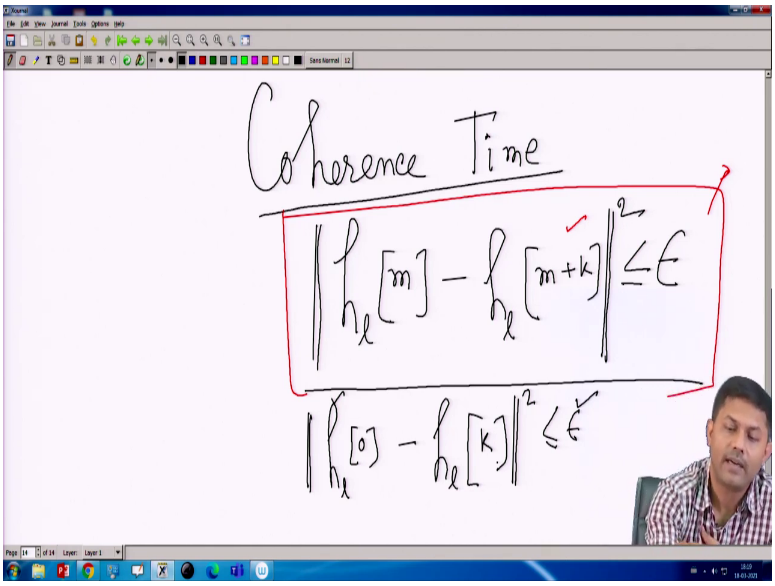

Now, when I say if the change is not significant with respect to what ok that should be a definition, because significant or not significant is not a mathematical definition; you have to mathematically define what is significant right.

So, can I says can I make this kind of definition say I have h l at a particular m at mth point whatever the definition whatever the m value mth time whatever the channel value. Let us say m plus k, can I define this as a parameter it is a mean square error. That means, how much the it has to (Refer Time: 02:16). So, can I define that as a measurement quantity by which I can say channel has changed this much amount because this is a measurable quantity.

Now, can I bound it? So, let us say this is less or equal to some epsilon ok what is the value of epsilon that comes from your application right. If it is audio it may be very large value because what does it mean? It means that I can tolerate a larger change in channel without doing a reestimation. If it is a like a 4 k or 8 k video 8 k streaming video probably epsilon can be even smaller number.

I cannot specifically say what value needs to be taken, but you can guess the number can be very small say 10 to the power minus 8 or 10. But it can be some small number right depends on application whatever it is.

Is this a reasonable quantification of my changes of channel right, so that means when I say from m to m plus 1 m plus 2 m plus 3 and so on I say up to 100 my channel do not change significantly. It simply means that take any of them from the first to any of these values their mod square does not cross my limit epsilon ok, moment it crosses epsilon I would say at that point my channel has changed significantly.

That mean if I take the first one so obviously the change will be from first to the last. So, if I say my h l 0 minus h of l k. So, you keep on increasing your k and observe with respect to the first one how much the data has changed and you define your own epsilon and see whether channel has cross the limit, that moment at a particular value k has crossed the limit I would say till k my channel did not change significantly because my application does not care anything beyond epsilon changes ok.

Now this is a big it now it becomes kind of a fuzzy because I do not know. So, that mean for every time you have to bring in the applications right, because unless you specify the application this does not have any meaning to me right coherence time because different application needs a different coherence time because that is what it comes to me.

But can I generalize it independent of coherence time independent of the application, that mean no matter whether it is audio or you know video. But more or less I can say if it goes by if it goes beyond this time the channel do not change. Now what is that do not change probably just 1 percent or 2 percent. So, can I have that kind of definition which is irrespective of any application yes there is a definition for that? So, that definition is basically this one.

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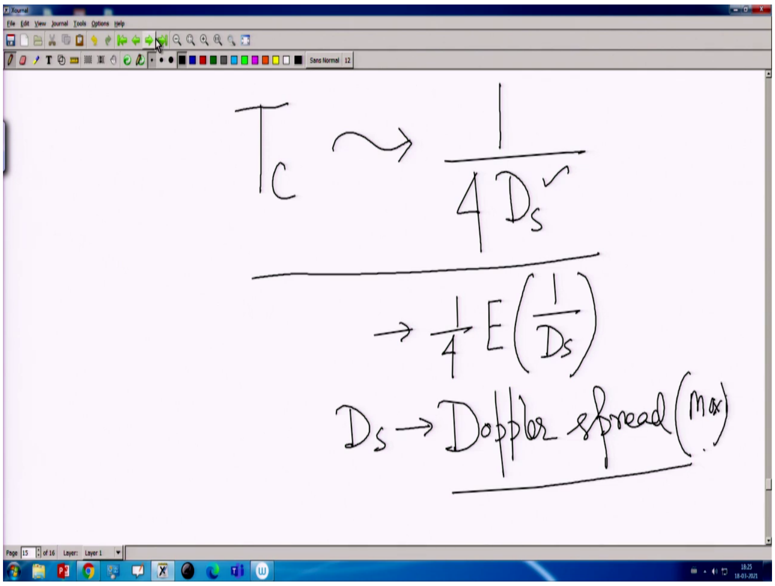

So, your coherence time is defined as 1 by 4 of your Doppler spread ok, that is the real definition. So, this is in this is also a coherence time definition, but this is more of an well accepted definition which does not take into account the application specific case. Now using this definition we have seen say different cellular standard or whatever, it kind of satisfied most of the applications ok some may be impacted some may be not impacted, but on an average this is a good definition ok.

Now, here if D s is a random number naturally we have discussed this that this would be again expectation will come into picture. So, this is your Doppler spread. So what is this D s? This is your Doppler spread this is your Doppler spread this is a good definition of a coherence time, see the Doppler spread is say 1 hertz that mean you have 1 second time to 0.25 second time for which channel do not change significantly do not change significantly meaning, it may be just one percent or two percent for which most of my application run almost perfectly ok.

Now, what is the Doppler spread? I think we may have defined it, but for the benefit of this class I redefine it again. The Doppler spread is basically you know the delay spread right it is the maximum delay from the lowest point to the highest reflectors point right. So, similarly there is a Doppler spread also it is the let me first define what is called Doppler frequency that has already been defined I believe.

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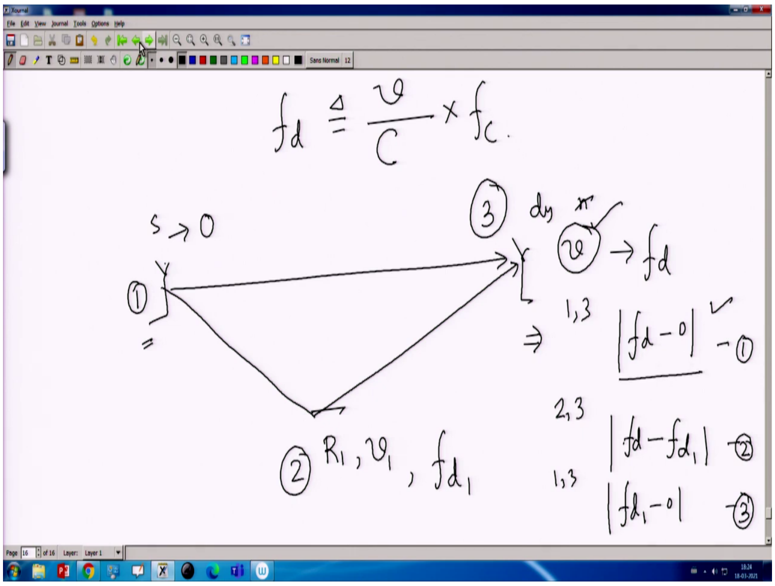

So, let us say f d is the Doppler frequency it is just a definition this will be v of the element divided by speed of light multiplied by rf frequency ok. Now Doppler and the difference in the Doppler so basically; so what is the Doppler spread ok. So, you if you have a transmitter here if you have a receiver here and let say you have one reflector here and let us say this is the one; this is just one data point right and there may be a more data point ok.

Take again the similar way we have done for the other one. So, take each and every pair of points and see what is the Doppler frequency coming into picture for individual points. Suppose this is static, this is static and this is dynamic say this has a velocity v ok. So, for this the Doppler frequency would be 0, for this the Doppler frequency would be 0, for this the Doppler frequency would be some f d right ok.

Or if this one say reflector is also moving with some other velocity some other velocity say v 2 velocity so this is moving at a speed of v 1 velocity then it will have some other Doppler frequencies. So, let us say it will also have a Doppler frequency associated with it.

So, every component will have a Doppler frequency; now spread meaning it is the difference between that ok. So, you take each and every pair that mean; this is say node 1, this is node 2, this is node 3 ok. And take each and every pair say for pair number 1 and 3 you see the difference between them ok. So, its a take the mod of that the positive definition positive difference only f of d minus 0 because this has a Doppler 0 the first one has a Doppler 0.

So, you take each and every pair and try to get the difference between their Doppler frequency with a positive magnitude take this, then you take the pair 2, 3 you will have some f d 1, f d minus f d 1 and so on. And similarly you have for 1 and 3 you will have f d 1 minus 0 like that so we have 3 points.

So, 1 2 just the way we have done the delay spread same thing we are also doing it here that is the Doppler spread. Take the maximum of them I do not know which one will be maximum depends on; what is f d1 what is f d 1 let us say this is the high frequency. So, this component will be the highest.

So, which means my D s whatever we have defined it here this D s is Doppler spread, but of course the maximum of all the doppler spread is a max of the Doppler spread. So, you take the max of it ok. So, take this take 1 2 3 and see what is the max of it ok and that max.

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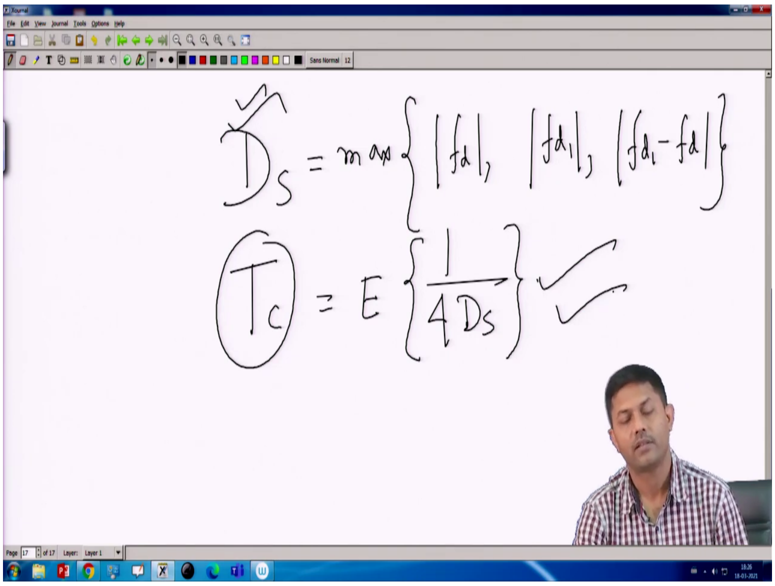

So, your Ds is basically the max of all the Doppler frequency different. So, it would be mod of f d mod of in this particular example and then this would be f of d 1 minus f of d like that. Take the maximum profit and whatever comes that is your maximum Doppler spread.

So, your coherence time is a fairly good definition your expectation of 1 by 4 of this Ds number. Why it is an expectation? Because this D s is a random number right because every v is a random number, velocity is a random number we have discussed this. Nobody moves at a constant spread everybody moves in a different random direction and random velocity. So, your Doppler spread will also be random and this will also be random ok. So, that is the point here ok.

So, this definition is quite popular and we if we know what is your Doppler spread then you can tentatively find out what would be the you know what is the time range for which my channel remains almost constant. It should I should not say the term constant it is like it does not change significantly. Significantly again it is application dependent it is a context dependent, but more or less I mean no matter what application you take it I it covers most of it. So, this is the classic definition.

So, now if I summarize what we have so far learnt; I would see that we have now we are now moving to the millimeter wave part, because this is the pillar of understanding from here the actual millimeter wave or millimeter definition will start here. So, what we have learned let me summarize it.

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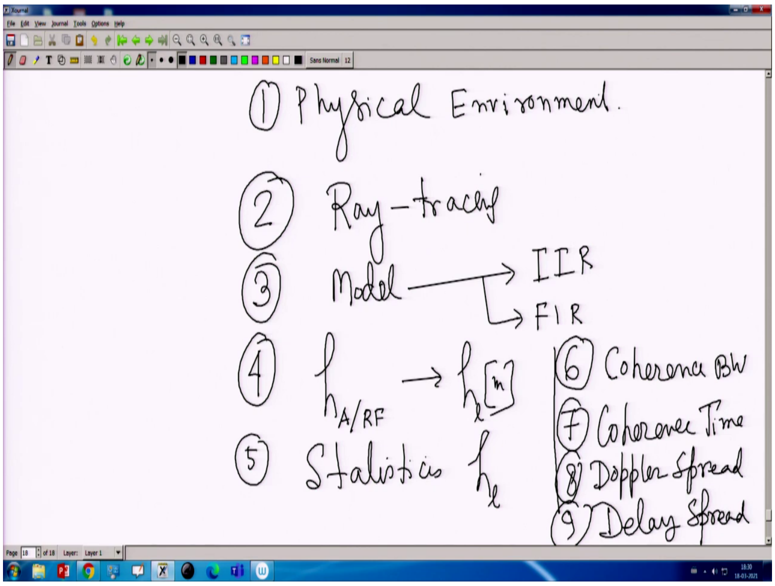

So, in summary we have learnt the physical environment over which the transmission happens like; reflector, scatterers, what is the reflector there are three type of physical usually these are the three physical blockage will be there. Then what we have learnt? We have learnt how you can model the channel using ray tracing. That means, just if a ray goes from one point to another the point to point ray tracing ok.

Then what we have learnt? We have also learnt using the ray tracing how I can finally model the channel model the channel using IIR filter and subsequently an FIR filter. How do I get IIR to a FIR? You just take a window you get an a FIR filter. Then we have learnt how the channel models vary from analog to the digital part right, because that is where our another interest was so channel by channeling analog or RF and this is your channel model digital h l m; this is what you have learnt it.

Then we have learnt some of the parameters; what are the parameters that you need to consider for channel. So, before parameter the statistics part statistic. Statistic of what? Statistics of individual channel tap and we have we have shown that if I follow more or less the central limit theorem there will be 0 mean Gaussian cyclic symmetric 0 mean complex Gaussian noise complex Gaussian channel.

Then we have learnt the parameters, parameters in the sense that; we have learnt what is called coherence bandwidth. coherence bandwidth is what? It is the actual bandwidth of the channel that comes into picture.

Then we have also learnt what is called a frequency flat fading and frequency selective fading channel. That mean if it is a coherence bandwidth is more than your actual system bandwidth I will just see one tap it is a flat fading. That means, as if like my channel has infinite bandwidth.

So, every frequency component of my data is facing a equal amount of gain from the channel it is a flat. Then we have learnt the coherence time, then we have learnt what is called Doppler spread, similarly we have learnt what is called delay spread because these are the parameters which will be left and right used in the channel.

So, far these are the parameters that we have learnt, but as we move along there are some more parameter which will appear they call they are called angle of arrival angle of you know departure those will come into picture, so far that we have not considered; but these are the basic models that we have considered.

So, in summary there are nine points that we have discussed this here and we have also discussed the time series part. So, I am should not write 10 th model, because that is like a mathematical tool by which you can model the Doppler or a time varying case here ok.

Now, let us move to the millimeter so this is the foundation. Now this foundation works for most of the channel case, but then what will be the different scenarios when I change my RF from just 6 10 gigahertz to say 40 gigahertz 60 gigahertz or 100 gigahertz or even more ok millimeter wave or terahertz kind of what exact changes that appear here we need to now understand it ok.

Now, before we get into that let us understand step by step, because this is the first foundation. A second foundation is that; why should I go into millimeter wave? Why should I go into the higher RF ok?

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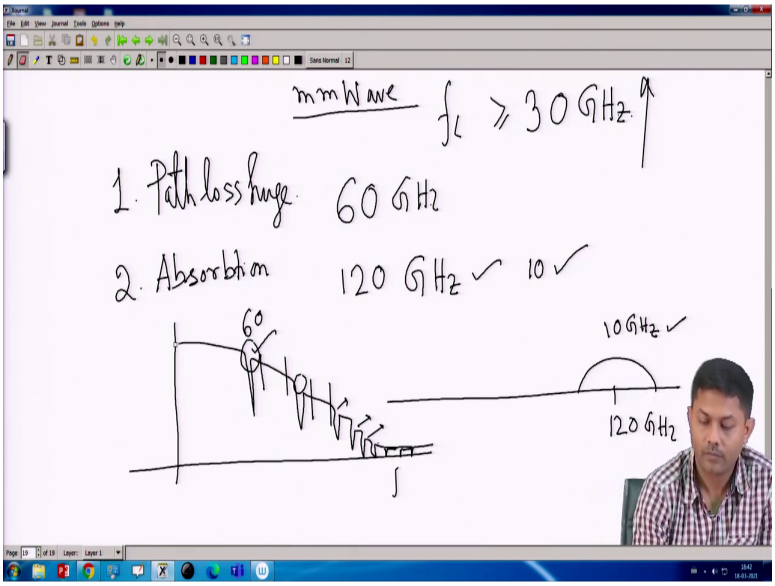

So, let us start that part. So, whatever parameters we have defined whatever methods we have defined they all hold good equally good probably better for any RF they do not change over and above some extra thing comes into picture that is the reason we have so far covered this foundation part. Now we are getting into the millimeter wave models.

Now, before I get into the millimeter wave model let us understand what is the physical point or the physical systems that it offers. The physical system in the sense the environment you know the reflector scatterer those things what they offer to us ok, because unless you know them there is no question of modeling right. And if I do not model I cannot do I cannot do a signal waveform generation or do a signal processing. So, let us understand that physical part of it.

So, that mean when I say millimeter wave it essentially says that my f c is greater or equal to 30 gigahertz ok. So, what is millimeter in this case? It is the lambda. So, for 30 gigahertz what is the lambda ok? It is sub centimeter sub 1 centimeter; that means, you can you have to express it in terms of millimeter that is why it is a millimeter wave concept ok.

That means it will be less than 1 centimeter ok. So, I have to say it is a 5 millimeter 2 millimeter so I have to express that lambda in terms of millimeter ok, because it is no more a centimeter it is a sub centimeter lambda. So, that is what is a you know it is a millimeter wave concept.

So, now suppose I change my RF and why people want to change it. I think we have discussed this part why people want to go for higher order. The higher order advantage is that the availability of bandwidth that is fine that is the first key aspect that comes to us right, because if you look at the 10 gigahertz space that is available in a particular region you see that most of the places the up to 10 12 gigahertz it is auctioned fully ok. So, it is not available space is not available for any more transmission.

Now, we need to go for a 5 G or even you know after 10 years 6 G and so and so forth. So, what is the what is the spectrum? The spectrum is not available right, because spectrums are completely auctioned and they are utilized. So, if the spectrum is not available there is no question of bandwidth also available, because you may get some spectrum here and there but the bandwidth may not be available right.

Suppose you may get something at say 9 gigahertz and the amount of bandwidth that you get say just 2 to 2 megahertz bandwidth that you get. So, what is the use of it ok because we are talking of 5G we are talking of 1 Gbps 10 Gbps data link. So, if you have that level of data link I mean using that small amount of bandwidth is not good enough we have to increase your bandwidth as well right, because it has your capacity of your system has to increase unless it increases there is no point.

So obviously, I need a larger bandwidth ok. Now when you say larger bandwidth the concept comes that; where is it available? Because up to 12 [Laughter] or you know some 6 gigahertz I do not have any higher bandwidth available so then obvious natural push is that you have to go for a higher RF. So, you increase RF increase your RF so 30, 40, 60, 100 whatever I mean sky is the limit you can go as much as you can go and that is what the push is for.

So, now what is the advantage of going so up going so high? Advantage is that bandwidth itself is available. Say for example I am at 60 gigahertz RF or I am at say 120 gigahertz RF ok. How much bandwidth available around 60 gigahertz? Plenty probably 1 gigahertz 2 gigahertz bandwidth is available at 120 gigahertz.

How much bandwidth is available? To the best of my knowledge I do not know if anybody has ever utilized that bandwidth for commercial transmission in a cellular or any Wi-Fi no; nobody has used it so it is available fully. So even if I take say 10 gigahertz or 5 gigahertz bandwidth probably it is ok even that.

So, that mean; if I go for a higher RF as it is not auctioned people do not use that except some places military and all radar and all, but most of the time and most of the places the higher RF is unutilized. So, I can utilize a higher bandwidth as well. So, that mean I can go at 120 gigahertz RF and I can create a signal which is almost 10 gigahertz ok.

I can have it because nobody has done it. Now is it as simple as that? Is it as simple as just going to the higher RF and utilizing the whole bandwidth; probably no, what are the bottleneck here? The first bottleneck here is that moment I increase my RF what are the channel model changes that come into play effect?

If you remember the way we have done a channel model ray tracing model it is a very generic model. So, even if you go for terahertz or whatever frequency go whatever we have explained so far that same thing holds true there is no difference. The only thing is that if I increase my bandwidth some of the things will break down and what is the remedy for it.

But in a some sense or the other the same model whatever you have discussed the same thing I can utilize it ok. Now we need to understand where something I just said [FL] that what something breaks we need to see that where something breaks. But if something breaks cannot I use that model whatever we have discussed? I would say yes, you can still use that model whatever I have discussed, but with some sort of a small modification that I will explain.

Now, let us see if I go for a higher RF what is the problem was that; obviously, your range will not come into picture, because if it is a 6 gigahertz your range was very high right. If you look at 3G or 4G base station he has a very tall base station and what is the range some kilometer it can go right range.

But if it is 120 gigahertz or say 60 gigahertz forget about it no way it can go up to kilometer probably few 100 meter few 100 meters. I do not know probably 200 300 meters or even it can even maybe it is 120 gigahertz it can go even for few meters. If you can calculate how much it can go. So, that is a big problem right.

So, if I go for higher RF the problem is that my path loss is very huge. So, this is the problem for millimeter wave a second bottleneck which appears to us is that path loss is used fine; what about the absorptions? Because if the if it increases the frequency the environmental components will do a worst I would say I mean it will create an havoc in terms of the absorptions. I think I have I may have shown you some of the absorptions scenarios, if I look at the gain received gain versus other frequency there was a famous diagram which will show like that. If you go higher RF the deeps will be much more ok.

So, these are around 60 this is I think around 80 90 I am not sure, I need to check that and there are many there are many such radar laundry list of points where you know the deeps are there ok.

So, these deeps will now come into picture if you go into higher RF these deeps are very frequent. So, even if you want to utilize say larger bandwidth you have to careful you have to be careful that you are not into any of the deeps. So, why this deeps happen? These deeps are due to the resonance of the material through which the RF is going on ok.

Say for example, if there is materials are I mean here may have different material carbon dioxide, oxygen, sulfur dioxide, water vapor, all these are there were certain resonant frequencies and they are like a different resonant frequency we have. So, if RF comes out to be of one of those resonant frequencies that whole RF will be completely killed. So that means, that particular metal will absorb the whole RF that is why this deep comes into picture right, so this is one issue.

Now, apart from even a deep this deep comes whenever there is a resonant frequency, but apart from that what about these? What about these? They are not just due to the path loss they are also due to the absorption.

It means that if you increase the RF the absorption by a normal material will also increase. That mean a material which probably do not do much absorption at say 5 or 6 gigahertz, but it will show some sort of a larger absorption when it goes up to say 100 120 or 200 gigahertz RF.

It is the property of the material I think I may have shown you when you when I was characterizing the you know the alpha part the gain part of the channel it has three components right; one is a path loss one is a absorption coefficient another one is the phenomena dependent right. So, this absorption becomes very prominent when I increase my RF second part. A third part, a third one and which is also another issues.

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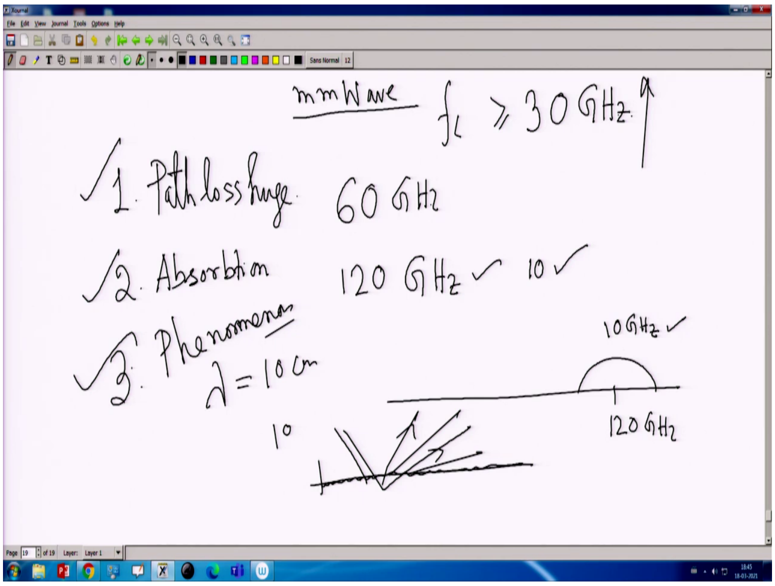

Third one is third one is what about the number of reflectors and scatterer. So, on what basis some object acts as a scatterer or a reflector or a defractor, it depends on the dimension of the material or the object with respect to the lambda.

Suppose my lambda is say 10 centimeter then I am sending an RF which is whose lambda is 10 centimetre. But I have an object which is just say 2 millimeter object small 2 millimeter wave object will it create any trouble for this particular RF? Not much, because its dimension itself is very small with respect to lambda, does it act as a reflector?

Well, may not; does it act as a scatterer; what it will scatter? Because it is it is dimension is so small it just only a small blockage will be there you do not create much hindrance to it. But what if I have an object which is of the order of 10 centimeter, will it act as a reflector? Yes now it will act as a reflector; will act as a scatterer? Well, it depends if the surface is smooth or not.

Again we have also explained the smoothness again is a relative parameter ok. Say for example, I have a surface like this and this surface is something like this slightly rough. Now whether it will be a rough or not again it will be decided by lambda. If the lambda is large probably this small ring would not create any problem, this will just act as a reflector. Whereas, the same surface will act as a scatterer if the lambda is small suppose the if you look at this wrinkles small small small small deeps what is the dimension? Probably fraction of a millimeter probably 1 or 2 millimeter.

Now, if the lambda is of the order of also 1 or 2 millimeter then each and every you know deeps will act as a individual small small small small what? Reflector. So that means, as a whole it will act as a scatterer. That means, if the ray falls here every fellow will now start to deviate the data from all directions. So, this is becoming a scatterer; scatterer is more dangerous than the reflectors right.

So, these issues now come you may see more and more reflector more and more scatterer probably I will say more and more scatterer because every tiny object now becomes a scatterer every surface which you did not think that can be a that can be a rough surface you may think that is a very smooth surface. But now that will become a rough surface whenever you decrease your lambda, so those issues now come.

So that means, the phenomena related issues are now becoming; now this phenomena dependent issues are now becoming again propaganda. And I mean every point whatever we have discussed for the gain part all now become very worse when I increase my RF ok.

So, I will stop it today in the next class we will take these points and try to see what happens in the millimeter wave, how these points can be tackled ok all increases but how we can tackle this. And finally what will be the right model for the millimeter wave. And if I increase the RF say terahertz or so on how the modeling will be come into picture.

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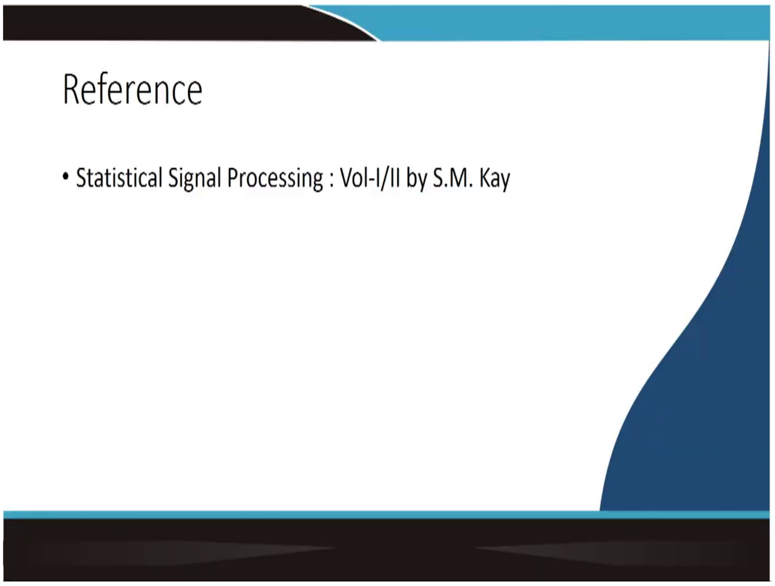

This is the reference statistical signal processing volume 1 and 2 by S.M Kay ok; with this I conclude the session here.

Thank you.