Signal Processing for mmWave Communication for 5G and Beyond
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Module - 01
Wireless Channel - A ray tracing model - Part-I
Lecture - 04
General channel Model

Welcome back, today we will be talking about Channel Model in the wireless channel. It will be mostly in the RF and analog, we will also talk about the gain factor that we last time discussed. So, today's topic will be mostly based on the channel model for the wireless channel, but it will be a ray tracing model we just started it last time.

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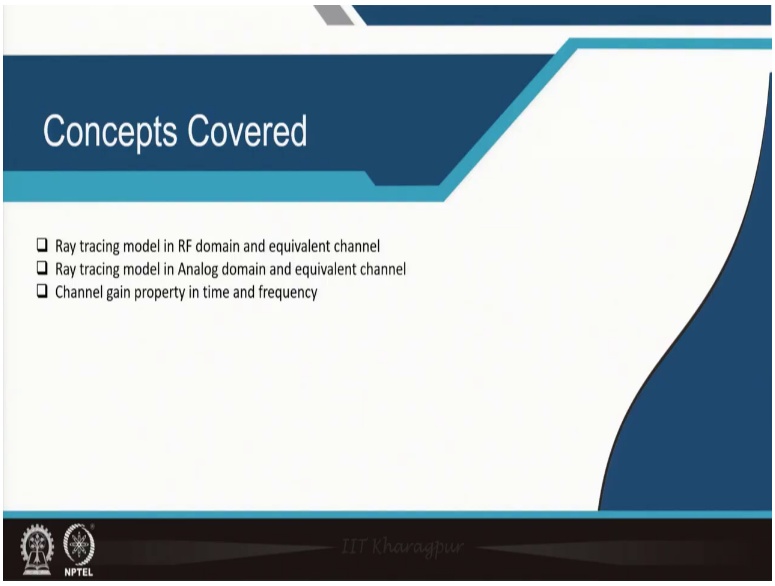

The concept that we are trying to cover today is the RF model and then its equivalent channel. At the same time we will also try to cover the channel model with analog domain and then some of the properties of the channel gains which will be covered in the time and frequency domains.

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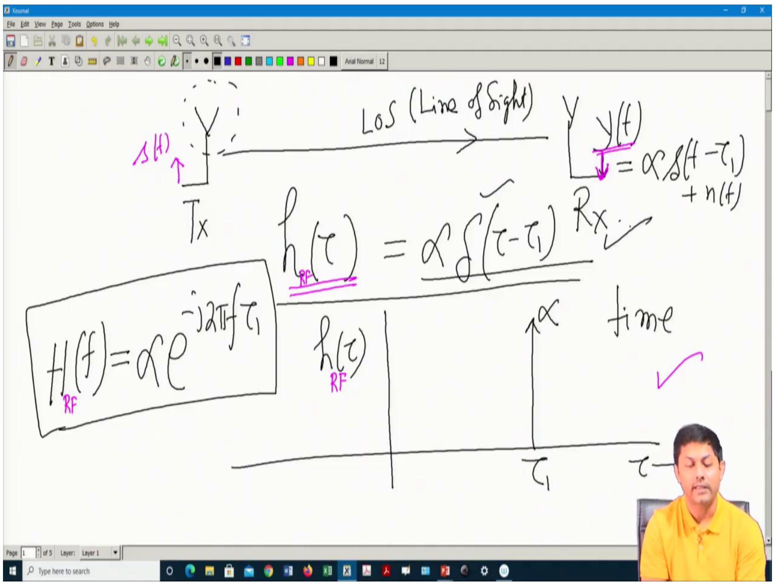

So, last time we discussed about single antenna case, we did not go for multiple antenna case. So, let us assume that we have only single antenna in this case and we also said that the complete thing is isotropic antenna for the time being. Then we will go for you know directed antennas and beam forming concept when you really enter into the millimetre wave because this is just the foundation part.

So, let us assume that this antenna is transmitting isotropically. So, this is the transmitter and this would be my receiver ok. Now, suppose I am in a space, so, what we discussed last time that if there is a space and nobody else is there to get an obstacle between the two antenna then what will be the channel model? Let us understand what is the data model.

So, data model was y t is equal to a, which or a or alpha let us assume it is alpha and then if this is what I transmitted this is what the data I transmitted there is a noise. I am not worried about the noise for the time being. So, if this is the data model at the output then what was the channel? My channel was something like that right, what was the channel? Channel was alpha into a Dirac function tau minus tau 1.

Now notice that, what is the type of channel I am creating. So, this is the time domain channel. So, what does it mean? It means if I plot it; if I plot it I will just get one impulse function having a magnitude alpha and as there is a Dirac function with delta 1. So, this part will be delta 1 part and it varies over delta. So, this is what my channel we discussed it.

Now, notice that this particular channel what we have just said this is more of a time domain data this is time domain right because this is with respect to tau. So, it is a time domain data. So, what will be the frequency domain data for this kind of channel? So that means, if this is the time domain data, what is the frequency domain data.

The frequency domain data if I call it H of that frequency domain data this will be simply a Fourier transformation of this continuous part. So, it will be alpha into e to the power minus j 2 pi f into tau 1. So, that is the one this is precisely what you will be getting for the frequency domain part, now this part was clear.

Now, let us go for multiple cases. For example, now let us see what happens when there are many other obstacle come into picture between the two antennas, but before we get into that one part you notice that this particular channel whatever we are modeling so far this is in the RF domain. So, that mean I am looking at I am standing just at the antenna. So, I am receiving the data only at that antenna level.

So, I am not getting into digital domains, I am not getting into analog domain. So, which means that this is a pure channel model which is in the RF domain I am looking the channel from the RF point of view. So, what does it mean? It means that as if like I am transmitting the data here let me put a different color code, as if like I am transmitting the data here which is in RF domain the signal is s t and I am standing here I am standing here and the signal is y t.

So, if I transmit from here and if I receive at this level, so, what is the channel, what is the signal level? It is an RF right, because I have not looked at the data from the ADC or DAC point of view or from the signal processing point of view, it is a pure RF data so; that means this channel whatever we have talked about this is a RF data.

So, let me put a simple prefix in that case h RF let us call it ok. So, nothing great about that because this is just an RF channel. So, this is the view of my antenna as if like I am an I am standing in the RF domain and this is how I am looking the channel ok this is how I am looking the channel clear.

Now, let us see what happens, I am still in the RF domain, I have not changed my domains. Now, let us see what happens when there are multiple obstacles ok.

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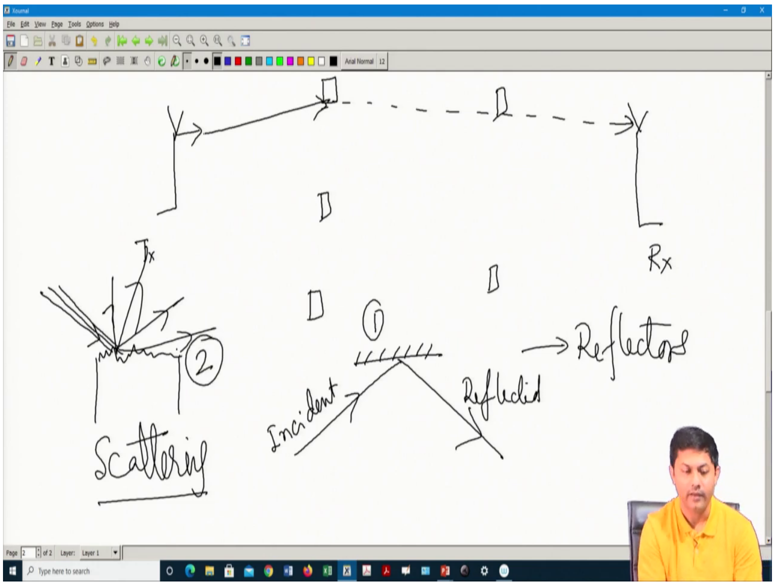

So, now, let us say I have the single antenna case. I am not changing the number of antenna. So, this is my T x again this is my R x again. So, what was our earlier assumption? Our earlier assumption was that it will be a free space moving that mean there is no obstacle between the antenna to antenna, but that is not the real case right.

If you look at you know the real world data suppose you are in a city or in a village or in a normal earth surface what will happen that the data that will be transmitted from this antenna. There will be lot of other physical phenomena that is going to happen and let us understand what are the physical phenomena because that drives us finally, the channel model. So, what are the physical phenomena that is going to happen, let us understand that.

So, number 1 phenomena that can happen is that the ray which is getting you know transmitted there will be lot of obstacles sitting here and there randomly here and there many obstacles. Say for example, you are in a room ok, you are in a conference room what are the obstacle that you can see?

The obstacle could be the wall, obstacle could be the chairs in front of you or if you are in a you know if you are in a city or in a some shopping areas what are the obstacle that you can see? The obstacle could be any object may be human being, many other objects or you know cars anything. So, these blocks are like that. So, there are different type of objects which are sitting inside just sitting between the two antennas.

Now, when I transmit this data from this antenna what can happen? So, these objects can behave differently based on their intrinsic property what is that. It may happen that some of the objects whenever a ray is incident on it just reflects, it just reflects it just reflects it ok.

So, that mean if I magnify this particular case it is as if like I have a surface where a ray is incident on that and it just gets reflected on that. So, this is my say incident wave I am not writing anything. So, this is my incident wave and this is my reflected wave, this is one phenomena that can happen ok.

Number 1 phenomena so; that means, this kind of objects I call it a reflectors. So, these I call it a reflectors. So, one such phenomena that can happen what else can be there, some of the objects it may happen that the surface of the object is very rough with respect to the wavelength of the signal.

So, what does it mean? If I magnify this say particular this particular object it may happen that the surface maybe something like this. If I just put a microscope or visually the surface may be something like that and we have several such objects right. In fact, this is the practical object every surface that we see you know in our real world case the surface are always a rough surface ok.

Now, what happens? When a ray is incident on that it will be reflected definitely, but it is not just one reflection right because a bunch of ray can happen here may be incident here and they may be reflected in different direction ok. So, such kind of things are called scattering this phenomena is called a scattering is like a splash.

You have a wall you just take a mug of water and just throw it what will happen it will hit the wall and just get splashed right this is precisely what is happening. So, these are called scatterers. So, you have a reflector, you have scatterer, is there anything else? Yes, there is one more. So, this is the second phenomena that can happen.

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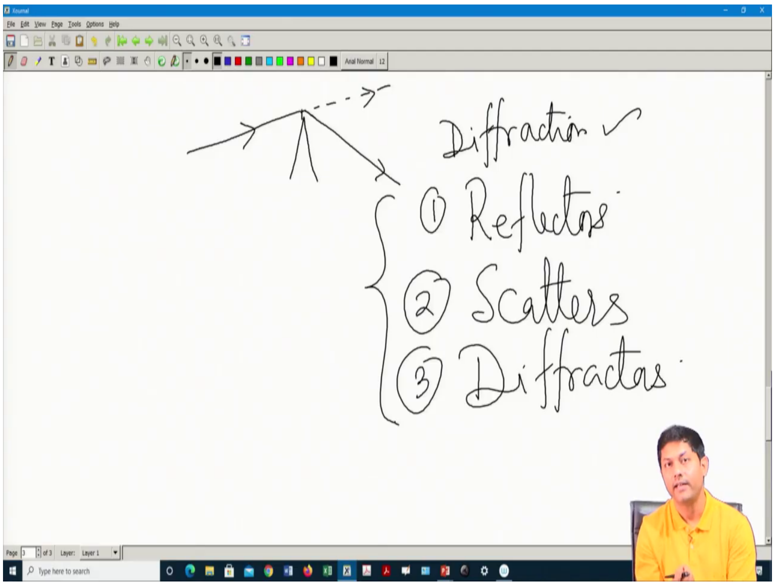

A third thing can happen where I may have an object like that it happens specially, if you have a sharp edged object ok, suppose a ray is incident on that ok. It is supposed to go it is supposed to go straight, but because it is a sharp edged object a part of it gets slightly diverted.

So, this is called your diffraction, this phenomena is called diffraction. So, you have a diffraction also; that means, there are some object which are mainly sharp edged object. For example, if you have a laptop its edges are very sharp edge right. So, if some transmitter is sitting in front of it and a antenna is transmitting a data most likely the you know the edges of your laptop will act as a diffractors, ok.

And there are many such objects like that. So, these are the 3 predominant phenomena that is going to happen when I transmit from one antenna to another antenna. So, in a summary you have reflectors, you have scatterer and you have diffractors. So, these three things are predominant in nature and there are internal activities which would going which are going to happen with respect to reflector, scatterer and diffractors.

But in one thing if I just summarize what is the impact finally, because that is what our interest is right. Because when you transmit a data from one antenna to another antenna you really do not bother about how many reflectors are present, how many scatterers are present or how many diffractors are present, because they are invisible right because the ray is invisible to you right.

So, when it comes to you, you really do not know whether the received signal is coming from a reflector or a scatterer or a diffractors, there is no way to even; I mean in fact, there is no interest for me to know that ok. Because the ray is an invisible ray so, we do not know really how many reflectors scatterer or diffractors will be present in the system.

So, to me it is to me what is the impact of such things when I am at the receiver, because we are at the receiver version we are at the receiving end. So, what will happen finally to the received signal that is what we are interested for. So, let us understand that part ok. So, whether it is a reflector, whether it is a scatterer or whether it is a diffractor, you know one thing is going to happen ok.

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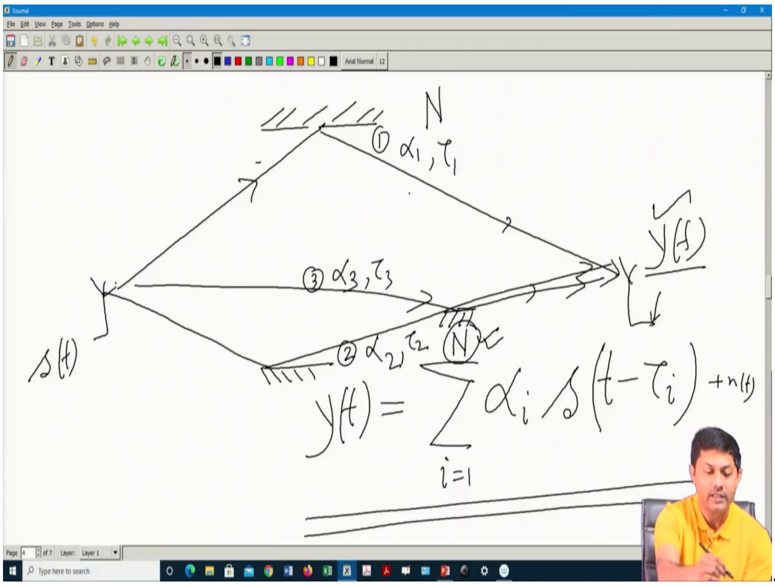

What is that one thing? Let us say this is my surface this is my surface ok. Let it be reflector, scatterer or diffractor, it does not really matter this is one surface ok. So, a ray comes here and a ray gets reflector I am not using the term specifically, for me everything is kind of a object for me ok. So, this is my transmitter and this is my receiver here ok. Let us say I have N number of total such objects total such object and they include all this thing reflector, scatterer or diffractors ok.

So, I have several such objects let us say. So, there will be a light here which gets reflected here there will be a light here, not light it could be a electrical signal for us everything is electrical signal. So, there are say in this particular case I have drawn three such cases there will be N such cases which can happen.

So, now I am receiving y because what is my interest my interest is to model it electrically. So, I am not really interested to know the physical phenomena involved here, I am interested to know what is the electrical nature that is getting reflected in my receiver that is my interest.

So, what did I transmit, I transmit s t what am I getting y t ok. So, now, I am I my interest is to model it in an electrical manner. So, what it would be y t the received signal is nothing, but summation of each and every path that is going through, right? See if there are three paths in this particular case suppose this is path number 1, this is path number 2 and this one is path number 3 in this case.

So, at the receiver what will happen, all these three paths will be added up that is all is going to happen. So, how do I represent it electrically? Now, you see that each and every path has a different path distance right. So, this first path can have a different path distance, hence it will have a different delay path number 2 and path number 3, all will have a different different attenuation factor, all will have a different different delay factor.

So, if I generalize it what will I get, that mean if I say my path 1 is having a gain alpha 1, path 2 is having a gain alpha 2 and path 3 is having a gain of alpha 3. Subsequently, let us assume the path 1 is having a delay of tau 1, it is having a delay of tau 2, it is having a delay of tau 3, why this delay comes, because the path is there right path length is there.

So, the electromagnetic wave needs some time to propagate it just the propagation delay I am talking of. If that is the case then what should be my electrical model at the receiver? Whatever I have transmitted it will now have multiple copies right because the same s t goes through multiple fellows ok. So, this same s t will go through multiple path having multiple delay limit that is the key point.

Because each and every path will show a different delay and each and every path will show a different attenuation factor. So, now, this can be i is equal to 1 to in this case 3, but let us generalize it let it be N plus N t. So, this is my final data model. So, here I am not interested to know whether it is a reflector, scatterer, diffractor, because I am at the receiver and at the receiver I have no interest to know all these.

The only thing I am interested to know what is the delayed path of each an individual ones and what is the attenuation factor that each an individual path may be showing. Now, it may be debatable do you really know N? It is not possible right because the electrical signal that is coming or rather the electromagnetic wave that is coming from the transmitter it is invisible wave right.

So, we really do not know what is the value of N. So, let us see that it is really do not have to know what is the value of N ok, but this is just from a modeling point of view. So, model wise this is a perfect model. Now let us see if this is the input output model what happens to my channel.

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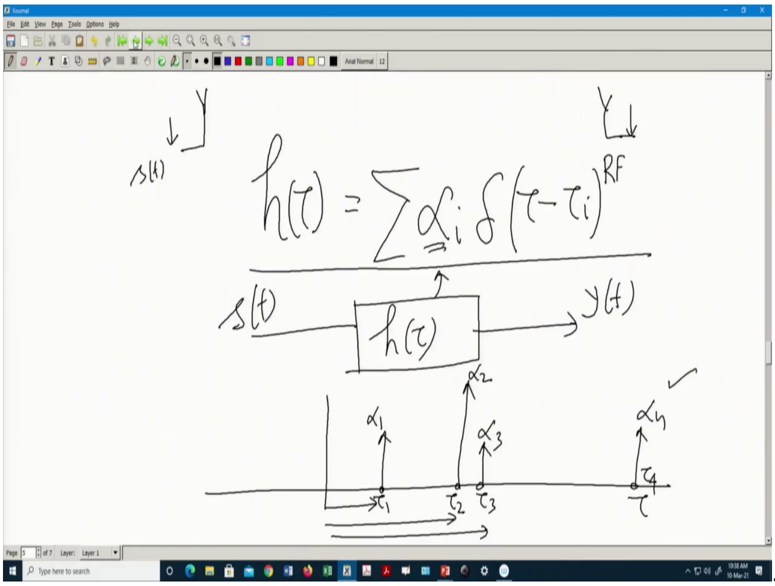

So, now I am still at RF domain. So, I am operating at RF; that means I am standing here. So, it is as if like I am sending the signal here I am standing it here ok. So, what is my channel model then, that mean if I just create a analogy here. So, what was my channel for a single case, now this part of this type of scenario is called line of sight scenario; that means it is directly going there is no obstacle in between.

So, a path which is coming from one antenna to another antenna directly without any obstacle we call it line of sight ok. Now, it was for a single case now when I have multiple such objects what is my data model? Data model we have already discussed, what is my channel model? Channel model will be a summation of all this individual paths delay and the attenuation factor. So, what it would be it would be alpha i then there will be multiple such Dirac function will be coming into picture naturally.

So, this will be tau minus tau i, this is what is going to happen. So, it is as if like i have a channel I am sending a signal s t I am receiving a signal y t and the h t is model like that ok. So, it is a summation of multiple such dirac paths, so if I plot it what is the phenomena I will observe. I will see that this is my tau ok and I will see different different values right. So, this length this height could be alpha 1, this could be alpha 2, this could be alpha 3, this will be alpha 4 and so on and so forth ok.

This part will be at tau 1, this will be at tau 2, this will be at tau 3, this is at tau 4, this should be a tau 4 if there are 4 paths existing, but notice one part that this tau 1, this tau 2, this tau 3, this tau 4 they do not occur at an uniform distance right. This is that stark difference between a discrete signal and this RF model. So, here the channel that I am seeing it; it is a dirac function summation of Dirac function, but they are not at uniform sampled space.

There are haphazardly because this tau 1, tau 2, tau 3, tau 4 they are all like independent and in fact, there could be a random variable as well ok, we will see that as well. So, this tau 1, tau 2, tau 3, tau 4 and so on so forth, they are not in a uniformly spaced, they are all you see this this is one distance, this is another distance, this is another distance and they are not in uniform spacing this is a this is a big difference here ok.

Second part is that are these alpha 1, alpha 2, alpha 3 or the gains are they complex number or real number? You can see that this will be actually a real number, why? Because where is the complex part coming into picture, I have sent a real data the alpha that is coming into picture here are just the attenuation part right. If the attenuation, attenuation is the gain it is a gain of something as if like there is a amplifier which is having a reduced gain or a attenuation.

So, the gain is less just like a real number right. So, it is a real number gain ok. So, these are the things. Now this is the view of my RF domains channel at a time domain case ok. So, what is its frequency domain? Natural question will be appearing. So, now, if this is a time domain sequence, what is the frequency domain data?

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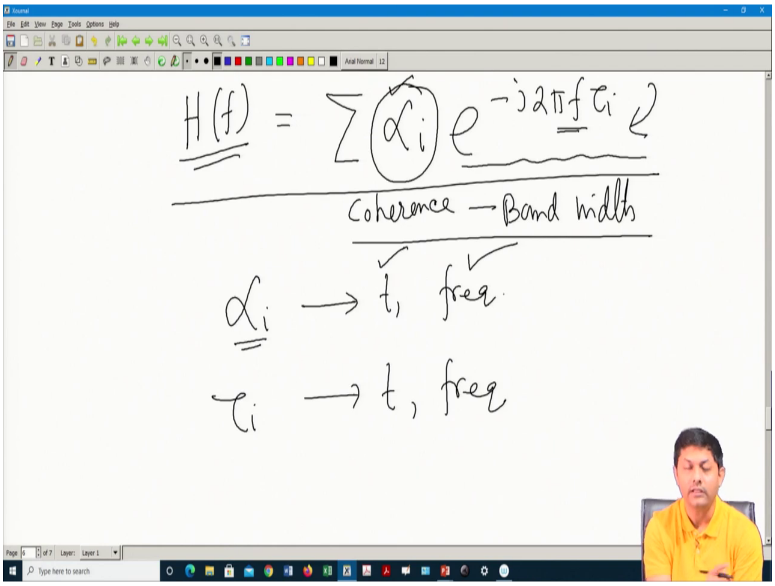

The frequency domain would be H of f ok, H of f summation of individual alpha i into e to the power minus j 2 pi f of tau i. So, this is my frequency domain. So, moment you have a frequency domain there is a concept of bandwidth and all this thing will come into picture; that means, there is a bandwidth associated with your channel; obviously, is it same as your transmission bandwidth?

No, it has nothing to do with that ok. Because transmission bandwidth can be say 100 megahertz, channel bandwidth can be say just 2 megahertz, is there a correlation? Absolutely no, because channel is channel it has nothing to do with how you transmit at what sampling that you transmit it right.

So, that this bandwidth channel bandwidth will define it mathematically this is called a coherence bandwidth. So, this has a name we call it coherence bandwidth this is a coherence bandwidth. So, this coherence bandwidth will mathematically define it, but this is a term.

So, it is a; it is a bandwidth associated with the channel and why is it happening? Because as if you look at the equation you plot it in a any simulation tool and you will see some finite value or some bandwidth value that you will get it here ok. Now this is a view from my RF and we understand that all are real this alpha is a real number, it is not a complex number ok.

Now let us see what happens to that view ok. Before I get into the definition of my view I still have not characterized this alpha, I still have not characterized it how you get this alpha ok. I still have not done that it will be part of the next lecture. So, here I am just modeling the channel pattern, but before I go to the before I go to the analog model of the channel and subsequently digital model of the channel few more comments that I i would like to have is.

This alpha and this tau i is this a function of time and frequency itself both, is it so? Let us try to understand that; that means, is this alpha and tau i; that means, this gain let me use the term gain, gain does not mean that it will be always it will always boost up the power, gain mean it can be negative gain also.

So, gain is gain covers everything, gains cover attenuation, gains cover positive also. So, let it be again common term. So, will the gain of each path will the delay of each path depends on time and frequency is a very interesting question ok and we will try to answer that ok.

Now, when you look at H f, you may see that H f which has a frequency dependent part it is only dependent through this component this component, we have not paid much attention to this alpha ok. Now we will see that this alpha and this tau are also dependent on time and frequency ok and that makes the whole thing kind of course, this is a non-linear nature, but it may not obey the LTI property Linear Time Invariant property it may not hold it.

Because each and individual term itself becoming a time dependent and frequency dependent component, but before I get into that discussion will happen next, but I would like to have a simple flavor how and why this alpha n and tau i depends on time and frequency let us just understand that part ok. Now what is this alpha, it is a gain ok. Now, how a gain appears in a channel for that particular path?

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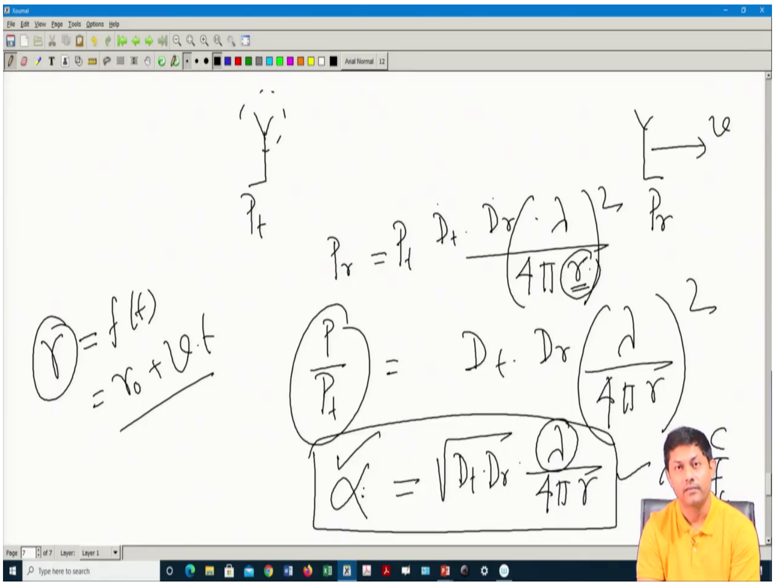

Suppose this is a simple antenna single antenna case, no in between objects are present here ok. The only thing that is present here is the free space here just a free space complete free space whatever is having. Now if there is a free space no object is present there, then how the gain happens here, how the gain appears in this particular case.

The gain appears because when you propagate an electromagnetic wave and when it goes through a free space it will start radiating the ray in all the directions right because it is an isotropic antenna, all direction it will start radiating it. So, that is a power loss happens.

So, when it reaches finally, here if I transmit a power P t I may not reach I may not receive P t I may receive P r and this relationship between P r and P t is the following this is the famous Friis equation D t into D r into lambda by 4 pi r square, D t and D r are the directivity of these antennas. So, let us assume this for us the directivity is one, but you can have a dipole antenna or any other directed antenna that is not an issue. So, these two are constant part.

But you notice that depending on the r I have a different gain. So, what is the gain here? So, gain here basically this part right, this is your gain part, this is your power gain this is the power gain, and what is the relationship with alpha? Alpha we talked about it is a voltage gain.

So, which means alpha in our case the amplitude gain is nothing, but this part is a root over of this whole quantity. So, that mean it will be D t into D r lambda by 4 pi r this is the point I am trying to make here ok so, this is alpha.

Now, you see what does the alpha depend on alpha depends on, lambda what does it mean it depends on frequency that. What is lambda? Lambda is a function of frequency right, now lambda is a function of frequency so; that means, if this is dependent on lambda of course, naturally it is a function of frequency c by f correct right c by f, f c is your transmission RF frequency so, which means that inherently your alpha depends on frequency ok.

So, one and one part is answered it has a dependency of frequency, because if I just take a simple free space equation, it gives you a frequency dependency ok. Does it depend on t? Let us understand that part, what about this r? r is the distance, is the distance time varying can it be time varying?

Yes, it is time varying why? Because so far I have not assumed that systems are moving, I have assumed that antenna is fixed each and every object; that means, this reflectors whatever we have drawn here in this case each and every reflectors are fixed we have assumed that, but that may not be the practical case, practically your transmitter can move, your receiver can move, any of your reflectors, scatterer, diffractor all can move.

If they move what does it mean? It means they are this distance this particular distance will also be a varying case with respect to time. So, what does it mean in a summary? In summary I can say that this r whatever distance we are talking of this r, this r is a function of time. If any of the receiver say receiver is constantly moving with a velocity v that that mean what does it mean?

That mean, the distance between this antenna to this antenna will also be a time varying case; that means, this will be a simple r 0 plus velocity into t something like that will come happen. So, which means that this r itself is a time varying. So, this r whatever I have drawn here I can say that is a time varying case, if r is time varying naturally alpha will also be time varying correct.

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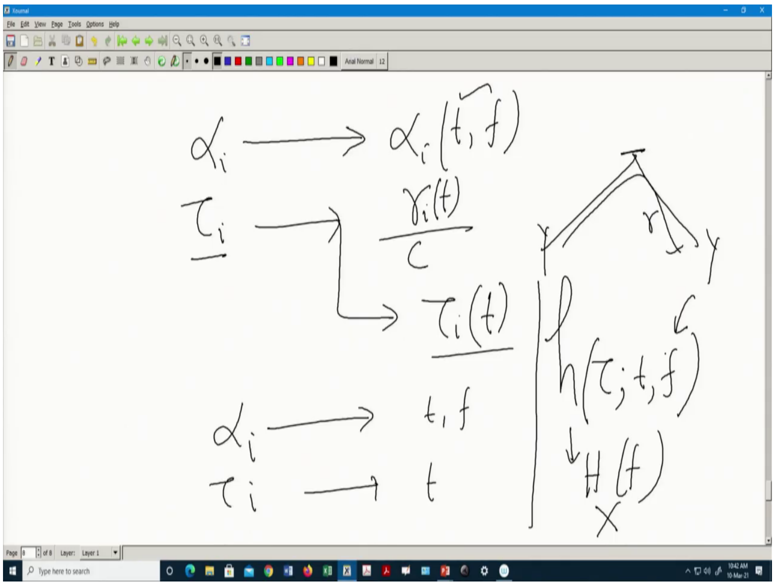

So, in summary I can say this alpha whatever we have discussed there inherently this is a function of time, this is a function of frequency. Next is tau delay part tau i, i th delay I am saying naturally this is all this will also be a function of time, what is what is the delay. Delay is nothing, but whatever distance you are going divided by velocity of light that is the delay that is what the tau is right.

So, if for a particular reflectors the path length from this antenna to this antenna and I have a reflector here. So, let us say this total r this total distance is r that is the time varying because if any of them moving is moving that becomes a timing we just discussed that. So, it means that this r i t that itself is a time varying case ok, which makes the whole tau also time varying.

So, subsequently this I can say this will also be time varying I still have not answered, is it a frequency dependent case ok. Let us understand that look at this r, does the r depend on frequency? No, it is a distance which varies over time right. So, it has no frequency dependency. So, which means that this tau t tentatively it depends on tau it depends on t it does not have a frequency dependency.

So, which means in a summary alpha depends on t and f tau depends on t. So, what conclusion I can make on the channel part then. The channel whichever I have drawn which was a tau it is also time notion will explain that what is this tau notion. Inherently, I can say this is a time varying as well as it is a frequency varying.

Now, when it is a frequency varying can I do a Fourier transformation on that? Not possible right because this is a frequency varying case. So, I cannot simply take a Fourier transformation and get an H f this is not possible, because the internal components are also frequency varying. So, it will be very tough job to get a frequency dependency frequency or transformation on that ok.

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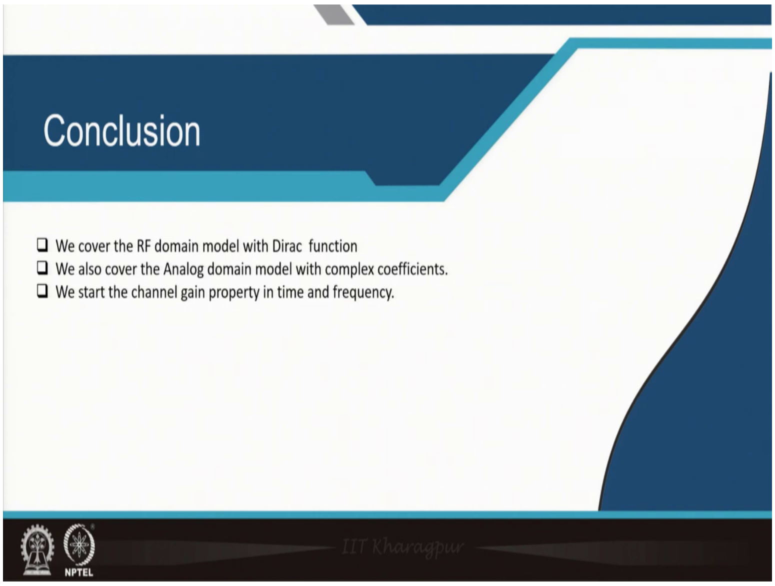

So, with this I conclude the channel model only for the RF. Conclusion, we just start the RF domain model with Dirac function, this analog domain model with complex coefficients are coming we start the channel gain property in time, it is just a basics we have not gone details into it and we just started subsequently it will be touched.

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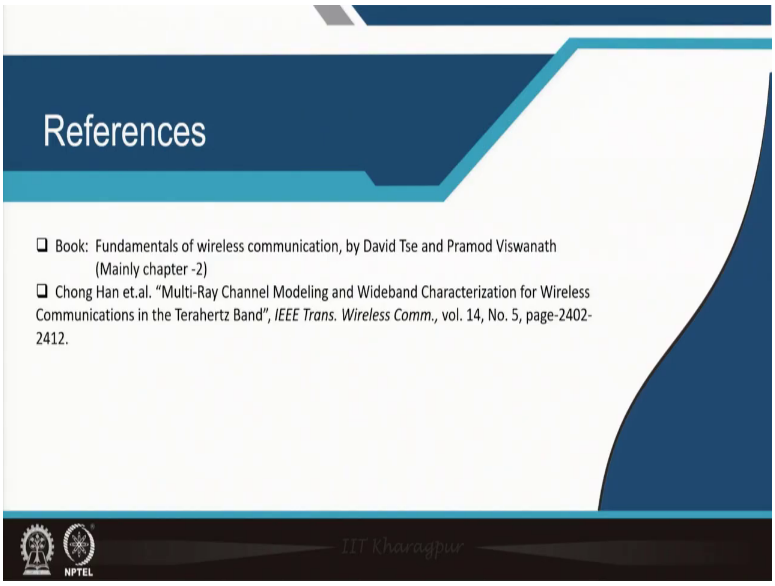

The reference I am following this book Fundamental of Wireless Communication, by David Tse, Pramod Vishwanathan and this paper I triple E paper that gives some definitions of the alpha which we discussed it.

Thank you.