Signal Processing for mmWave Communication for 5G and Beyond
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Module - 02
Wireless Channel - A ray tracing model-Part-II
Lecture - 08
Wireless channel - A ray tracing model part - II (cont)

Welcome. Welcome to Signal Processing for millimeter wave for 6 G and Beyond. So, far we have talked about the channel model in the RF analog and digital modems right. Now, today we will continue the digital parts, we have just concluded the channel model in the digital, but we have not gone too details into it. So, let us do more characterization on the digital side. So, this is the module 2, where we will be continuing the wireless channel model, but it will be more on the ray tracing model and this should be the part II and lecture number 8.

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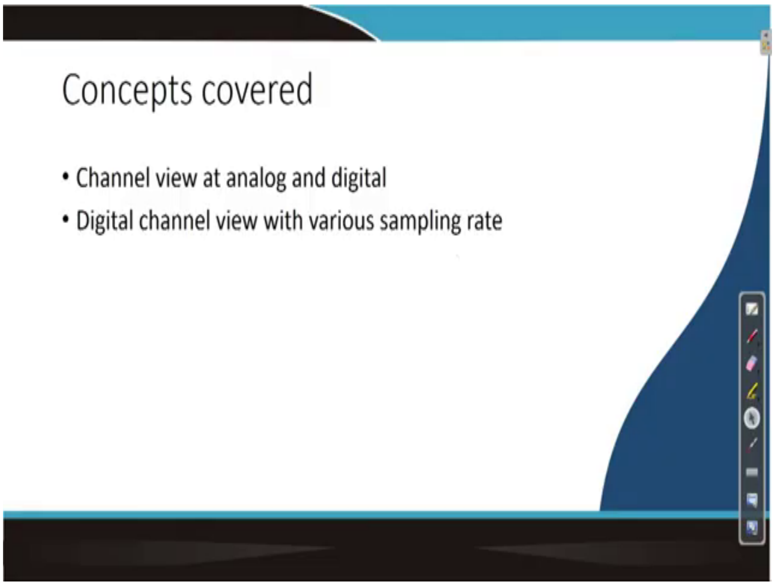

So, the things that will be covered today is the following various channel view at analog and digital levels and then the digital channel view with various sampling rate ok. So, let me just summarize. So, when you go for a digital, your channel model or rather I would say your.

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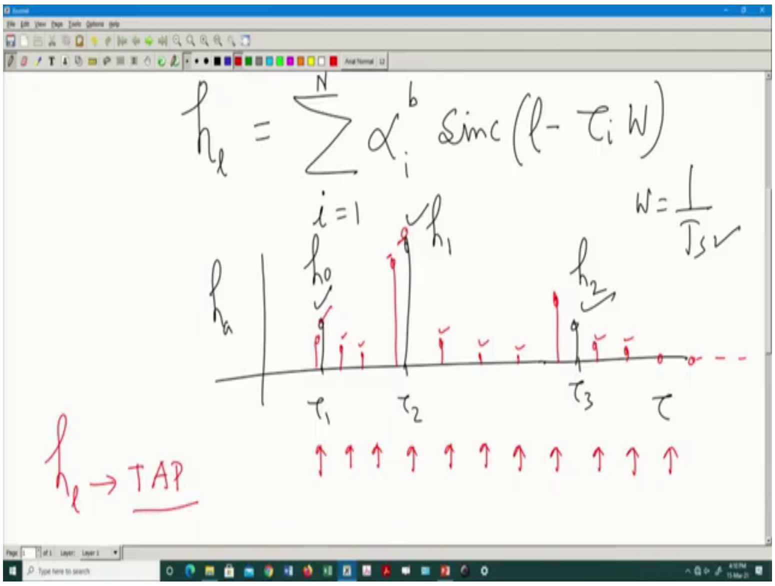

Let us look at the channel model itself your channel model was like this. If you have n number of reflectors or scatterer whatever path you have, then we have alpha i this is the baseband part and then you have sinc l minus tau i and this is your sampling frequency. So, 1 by T s.

So, here I would say W is equal to 1 by T s that is the, that is the sampling rate at which you are doing the sampling at the ADC or the receiver. So, if you change your T s you have a different view of your channel today we will explain that part, how exactly the you know digital side the channel the view of the channel at digital completely changes from sampling point to sampling point ok. This is the struck difference between the analog view as well as the RF view ok. So, this was the complete channel the lth channel.

What do you mean by lth channel? lth channel meaning it is basically the channel component of the suppose you have multiple channel component you are seeing. So, in analog what component you are seeing analog or RF you are seeing something like that right tau 1 at tau 2 let us assume at tau 3 you have some values that you are seeing it depending on the tau 1 or the delay 1 right. So, this was the analog or the RF view of the channel. So, these are called my channel components individual channel.

So, I would say this is my first component, this is my you know second component, this is my third component whereas, in digital same concept similar concept, but the times at which I may see those values may not be exactly at that. So, I may see it here, I may see it here, I may see it here all will be uniformly sampled right it all depends on at what sample at what frequency I do the sample. So, at these points I may see the value. So, I may see some values like this, I may see the values something like that, some value is like that again some values like this just giving an example and so on and so forth.

So, if you look at the difference between the blue colored the black colored you know channel components and the red colored channel components, you may see that they exactly do not match right in time domain wise right. They may not they may not match exactly because there may be extra components that you may see it you see this? This extra component that you may see it and also the values that you are seeing it may not be same as where the earlier one is its all; it is the interpolation that we have discussed last time ok.

But there is a correlation. So, wherever there is a higher values, you see there may be an higher value there, but gradually it goes down if there is no more components here, but the digital view of the channel is like a uniformly spaced channel that you can see. So, this h l we call it TAP.

So, next time onward I may just refer to as a channel taps. So, you have so, many taps. So, it is called a channel tap. So, in the analog front these black points were taps. So, here in this case we have 3 taps in the analog or RF, but when I convert it to digital I may see many such taps uniformly spaced ok.

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So, now move on let us move on. We have also seen that ultimately what we may see is completely different way of interpretation right because the original channel would have been here, would have been here or let us say somewhere around here. So, let us say this is my at tau 1 delay I have a tap in analog at tau 2 I have a tap at tau 3 I have a tap. So, what does this equation refer to? This equation refers to it says that there is a sinc. So, that mean at every tau i point I have a sinc right. So, getting into that.

So, which means that at this point I have a sinc and so and so forth right at this point I have one more sinc ok. Similarly, I have one more sinc here like that ok and what I am doing digitally? I am just sampling it I may be sampling here uniformly sampling this is precisely what we have done ok. And what is the width of each and every sinc pulses? That depends on what time I am sampling it so; that means, whether the sinc pulse will be wider or you know narrower that depends.

So, the gap I would say. So, the gap between the 0 and the peak of the sinc is 1 by T s. Now, I mean the frequency at which you are sampling it right. So, now, you can see there are lot of interesting explanation or rather interesting interpretation that you can make it from this diagram. So, which means that when we sample it I think we have discussed it already, at any point it is basically mixture of you know all the sinc pulses right.

So, suppose for example, I am sampling somewhere here, there is a sample point here. So, this sample point probably it may be prominent here. So, the value that I will see it at this point is the value where the red you know touches plus the value this you know this orange color touches. So, this plus that; that whole double will be is added up here. So, I may see a value like that. Similarly, here if you see it all three points value will be added up I think this is what the particular this equation is referring to right.

So, which means that at a particular lth point lth sample point the channel value depends on the contribution from all the taps which were seen in the analog and RF. So, you can think in one sense that all these lth taps any taps l equal to say 0 to say whatever value can I say they are all correlated naturally right because if say I have only 3 analog taps and digital wise I may see so, many taps right. So, what does it mean? Each and every tap you can think that these are all correlated taps.

Now, how much the correlation would be? That depends. That depends on the gaps, that depends on the sampling time and all these thing, but they are all correlated practically because here if you look at here the tap value here depends on what? Depends on this value, this value and also depends on the green. It may be have a very small contribution, but it will have some contribution you take any points let us say I take this point. So, it will have a contribution from green, it will have a contribution from red, it will also have a contribution from yellow.

So, which what does it mean? It means that, when I digitize it after I view the channel from ADC all my channel taps are somehow become correlated taps and that is a very important you know important aspect of my channel. So, never assume the channel taps are all uncorrelated independent that may not happen that really may not happen when you do a digitization.

But for all practical processes probably we can make some sort of those assumptions, but in reality they may not be it all depends on how the sampling rates will be existing ok. So, let us draw more diagram and try to understand how exactly the correlation can impact you. Let us say I am having a different level of sampling let us say this is one sampling point right.

Let us say increase my sampling frequency that mean I have an ADC, I just sample at a very high speed say for example, my transmission bandwidth is say something like 10 megahertz transmission bandwidth that may from transmitter say the DAC speed I am talking DAC sampling rate is a 10 megahertz. Now, to recover the signal at the receiver side what should be my sampling frequency? 20 megahertz right. Let us say I sample at say 100 megahertz what will happen? Or may say I sample at even higher 200 megahertz and that is practically what is done in the receiver.

So, at the ADC you first sample at a very high speed and there is this different purpose for it and then you adjust your sampling rate. So, when you sample such things at a very high rate what exactly get impacted here let us understand that. So, let us say my channel taps remain exactly at the same point because they do not change whether you sample at a high speed or low speed the reflector the scatterer and they do not change their positions right. So, they remain as it is ok. So, the second point was somewhere here the third point was somewhere here ok.

So, this was my tau 1, this was my tau 2, this was my tau 3. Let us say I sample now at a very high speed ok. So, let us say this green one becomes very sharp, this is my sampling. So, it is goes on ok. The red one also exactly the same level of sampling because ok and let us say I have the third one where you have almost the same point here ok. Your what is your sampling speed now? Your sampling speed would be somewhere here, here, here, here, here all very faster sampling rate right you see there are much faster sampling rate ok.

So, what does it mean? What type of channel or what type of view of my channel happens? You see analog and RF they remain as it is they do not change what changes is the way you see that channel in a digital view right. So, what is the channel that you see it here?

In the digital case in the first case you see a channel which will look like that you may see a tap like this exactly because whatever value it comes that value will be there whatever value it comes that value will be here, you may see a tap like that you may see a small tap here probably a significant tap because this value is significant plus some you know some more tails here and there comes into picture.

And here I may see some significant tap again some significant tap it will die down finally, because I may not see anything like that. So, this color this one is the digital view. So, this is my h 0, this is my h 1, this is my h 2 and so on so forth ok. So, this is my channel term that h l whatever we have written as an equation whereas, in the second case, I must completely see a different view of my channel right channel remains the same from analog and RF.

But just because I change my sampling rate I completely see a different level of taps how the view of my channel now? The view of my channel will be the will be slightly different. So, let us draw let us draw a line here for the lack of space because I want to put it in the same diagram. So, here I have some tap like that ok. Next I have something like this.

So, it will be here something like this, something like this, then immediately I will be having some almost like a 0 taps again I may have something something again I have something something again almost 0. This is the case number 1, this is the case number 2 for the digital view. The analog remains the same the actual physical system remains the same just that you sample you know differently, I see a totally different view of my channel.

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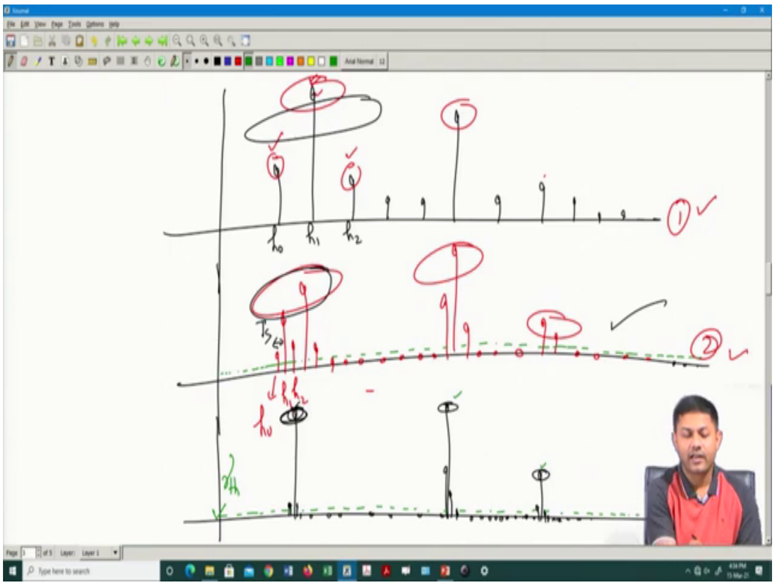

So, in summary I can say something like that. So, depending on how I sample it, I may see like this some taps will be like that or I may see like this something like that this is that was that case number 1, case number 2 I just I have just drawn you know separately. So, this is an interesting view. So, that mean this is the same channel same physical system just because I sample at higher speed I may see a totally different channel ok. Now, this will be the h 0 for the first case this is the h 1, h 2 and so on and so forth. This is the h 1, h 0 I will start from here this is the h 0, then h 1, h 2 and so and so forth ok.

So, this view difference will be there the based on my sampling rate ok and all the components are complex number right because this alpha i b whatever we have shown it here this was in fact, a complex number right. So, my drawing here I have only drawn the amplitude mod square the modulus of the amplitude. So, that or I have I may be just drawing the real part or the imaginary part so, that some negative part may not appear, but ultimately these are all complex number ok.

So, now one interesting again a continuation. Suppose I increase my sampling rate I increase my sampling rate ok. I just keep on increasing say instead of 2 megahertz 200 megahertz I make it say 2 gigahertz. So, what exactly the effect? So, can I say if I increase it very high or rather before I get into it. Now, from diagram number 1 and from diagram number 2 can I guess who gives me the correct picture of the physical points of the reflection reflectors and scatterer?

Can we guess which can give you the better introspection? Look at equation look at the diagram number 1, it is slightly a lower sampling rate, but you know what, there is a bigger fellow sitting here, but there are some significant components ok and there are slightly lower here and then suddenly again something goes up and then again some low again up and ok.

So, there is a guess that probably something actually something sitting there; there may be something sitting here, but you cannot make it so sure why? Because these significant components are also contributing so much that it is as if like there is already a reflector sitting here, reflector sitting here, sitting here. sitting here.

So, you cannot make that conclusion if the you know if the sampling rate is lower, but look at what happens when I make a very high sampling rate ok. So, what does it mean? You see that this the reflectors at least it creates kind of a zone or I can say well there will be some reflectors in the vicinity exactly do not know which one gives me the exact tau 1 value because tau 1 may not be the integer multiple of my sampling rate.

So, I do not know where, but I know for sure that there is something there. I can make some conclusion there is something here, I can make some conclusion there may be something here make it even fine tune make even make the make even a T s smaller and smaller and smaller. So, what does it mean? It means that you are increasing the sampling rate even increasing what is the impact of it? So, the impact of it would be, I may eventually see that there may be a large path here there may be a small path in because I am just increasing my sampling rate.

This is what is going to happen. So, I can further you know specify your time region that my tau 1 will fall somewhere here right this time this particular time will be your T s time. So, you know for sure that tau 1 will be somewhere you know somewhere in this circle, but you do not know where, but if I make it even fine tune it what does it mean? I make my sampling rate even faster then I suddenly see that there will be a very large peak 1 or 2 can be smaller, but it dies down very quickly dies down very quickly ok.

So, I know for sure my tau 1 is now you know concentrated within this timing within this timing my tau 1 would be within this timing my tau 1 would be. So, earlier I was guessing my tau 1 could be somewhere here with higher sample, I make my tau 1 that region gets even smaller with higher sampling rate now I said my tau 1 should be somewhere within this. So, that just increases your resolution of guessing the tau 1, tau 2, tau 3 and that is precisely what happens ok. Got my point ok.

So, now let us move on here, you know this is the impact of your sampling rate increment let us see what happens next? So, let us define some more mathematical parameters or rather I would say what happens to the delay spread that we defined in the earlier case what is the impact here? So, what is the impact in the digital case?

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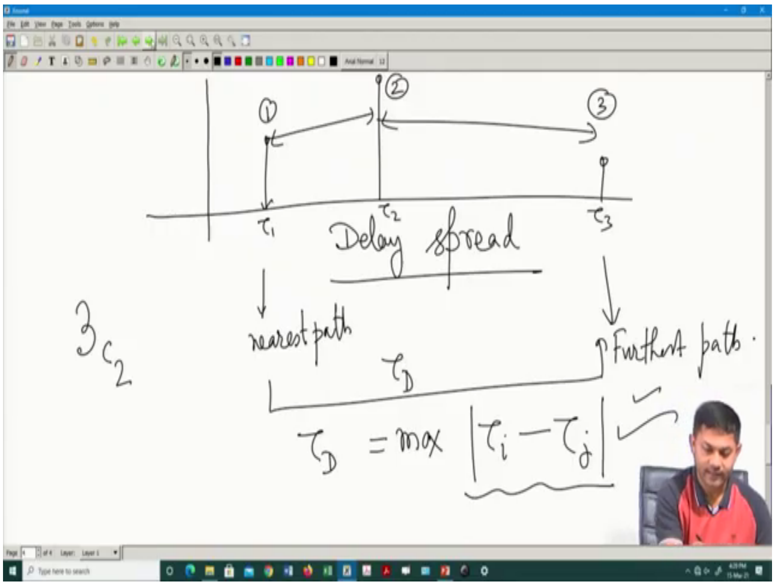

So, what happened after digitizing? So, this is where say I have a you know the first reflectors, this is my second reflector and this is my third reflectors ok let us define a term called delay spread ok.

So, what is the definition of delay spread? Delay spread is basically defined as the maximum spread of my delay; that means, this is the nearest path I would say the nearest path and this is the I mean the farthest path.

So, the delay between these two is your delay spread. So, let us call that as say tau D let us define it like that this is the parameter this is the parameter which is which plays a very important role in channel characterization ok. So, when we say delay spread its basically says that it is the time delay simple time delay or the tau delay between the nearest path and the farthest path.

So, can I mathematically define it? Yes, I can mathematically define it. Tau D what it would be? Take every point every reflector or every scatterer every you know every point I am talking take every reflector scatterer or refractors take the delayed difference between them. So, let us say I have the ith path minus I have the jth path. So, let us take the absolute value of this two and take all these points any two points you take it and the maximum of this difference is what your delay spread right.

See if in this particular case this above example you have totally 3 paths. So, how many such pair that you get for delay element? You will get 3 c 2 total you know delay elements you will get. So, you will get. So, this is my first path, second and third. So, you take the delay difference between 1 to 2, then 2 to 3 and then 1 to 3 and see which is the highest number. So, that is your delay spread. So, essentially it boils down to the fact that it is looking for the delay between the nearest path and the farthest path ok.

So, this is the definition of delay spread in the analog and RF. Now clearly what is the delay spread or what happens to the delay spread when I digitize it? Does it hold true this definition ok? So, let us understand that. Now, as you know when I sample it; it is an interpolation of my RF data RF channel or analog channels it is an interpolation and by interpolation why this interpolation because you have an ADC say ADC is kind of doing a sample and hold right. So, here hold is nothing, but some sort of a low pass filter.

So, you have the high speed or you have the sample data uniformly space data and then ADC will make a uniform sample and then it will do a LPF and that creates the that creates the interpolation. So, that part is kind of explained. Now, what we want to know is that because it is a interpolation.

So, what does it mean? So, it means that the channels that we have just shown here it is basically coming due to the sinc pulses right. So, this is these are all sinc pulses right will they be all 0 the ones which I have drawn at the end they need not be 0 right because there is a sinc this path is there so there is a sinc here.

So, there is a sinc here this equation. So, sinc is infinite pulses right. So, it will it has still throughout right. So, no matter what you when you sample or where you sample it, you will get some value; however, small it is. So, what does it mean? It means that the channel impulse responses or I can say the taps it is kind of an impulse responses can I think of it like that? Yes it is a system of linear equation I can think of it as like a impulse responses.

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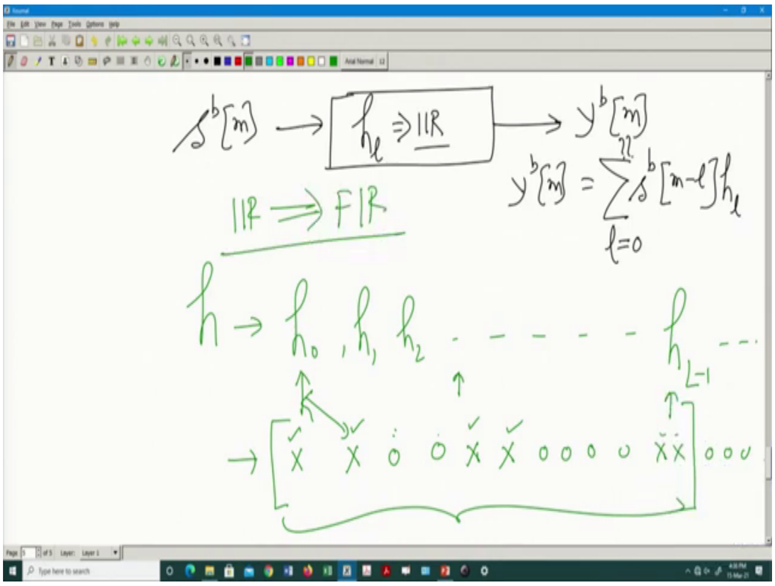

So, what does it mean? You have given S b n it is as if like that and it goes through some sort of a you know filter some sort of a filter and I get Y b n this is what we have seen probably I put the different input m notation.

And then this is what your different channel is. This precisely what are the different channels here right. Now, the number of such h l what was the linear system of linear equation? We have shown it to be something like that this varies over all the l, you have S b m minus l and then you have h of l.

A very simple system of linear equation and we have seen that this is nothing but the filter it could be FIR or it could be IIR filter, but what we have not conclude earlier is that what is the maximum value that this summation can take? Ok; that means, how many taps I really see.

Typically, this should be infinite that is precisely we have shown it here. It could be infinite because it can go on it is a sinc pulses it can go on right if it can go on then can I say this filter this h l this filter is some sort of a IIR filter infinite impulse response it is coming out to be like that ok.

And these data's these values are nothing but the impulse responses because I am doing a convolution with these values whatever values are shown here all these discrete values along with the data. So, I am nothing, but doing a convolution here, but the number of such values are infinite.

So, can I say that this infinite response or this filter is a IIR filter? Yes, logically it is, but practically what happens? You can see that is the values which are coming after the you know after the last path ok I may not see much value after sometime practically. So, which means that if I create some sort of a thresholding, if I say any values beyond this point I do not consider to be any value at all ok.

Say for example, I put some sort of a thresholding said thresholding meaning I just put a some sort of a thresholding. I would say that anything below the threshold value I consider the tap value as a 0 value. Here also I create the same thresholding how much that thresholding would be? That depends on the system design, how much you consider it as a contributing factor? If this power is say 0.1 percent of any of these peak values I will say probably does not impact my system.

So, something like that. So, after this say some sort of a gamma th some thresholding I would seen I will not see any more taps. So, what type of channel I would see? The kind of channel that I will see here is something like this kind of channel I will see I will see h 0 ok I may see h 1. So, let us say these are my value whatever it is L minus 1 and so on, but let us say practically I have a tap here, some taps here just 3 taps and practically I have a tap here actually physical taps meaning actual physical presence of reflector or scatterer.

So, I may see that this channel in after digitizing I may see some value here some complex number, some value here because it is close to then because of the thresholding this channel tap could be 0, then 0, again some values will be there, again some value, again it will start 0 0, again some value, some value again some 0 0 0 and all will be 0. So, that mean I may say practically h 0 can be a tap, h 1 can be a tap, but h 2 these two elements do not have any tap.

Again, I can see some you know some non zero value again I will see some 0, again some non zero and finally, I will get a 0. So, when I say finally, I get a 0 finally, meaning if I even if I wait for say infinite time, I will not get any more 0 because I have a threshold I have you know I have put some sort of a cut off. So, I would see my channel tap is not going beyond this point. So, that mean it is a typical windowing a typical windowing how do you convert an IIR filter to an FIR filter? This is an IIR filter right. I mean you have infinite impulses.

So, typically you will see some sort of a FIR consideration when you do some sort of a window you just you know you just use some sort of a thresholding and do not consider anything beyond that point. So, see after sometime you will see that taps just becoming 0. So, that whole concept this IIR now gets converted to some sort of a FIR filter using thresholding ok. So, today we end the session we will go more into the next class.

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And the reference will be same as what we have said in the earlier class Fundamental of Wireless Communication by David Tsee and P. Viswanathan.

Thank you.