Signal Processing for mmWave Communication for 5G and Beyond
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Module - 01
Communication System
Lecture - 02
Rx Structure

So, welcome. Welcome to the signal processing class for 5G in the context of millimeter wave. This is the module 1 lecture number 2 where we will be talking mostly about the RF part the basic Rx structure along with it; it will also contain the analog and RF part. At the same time this is the first lecture where the basic part of the channel will be introduced compared to the earlier one.

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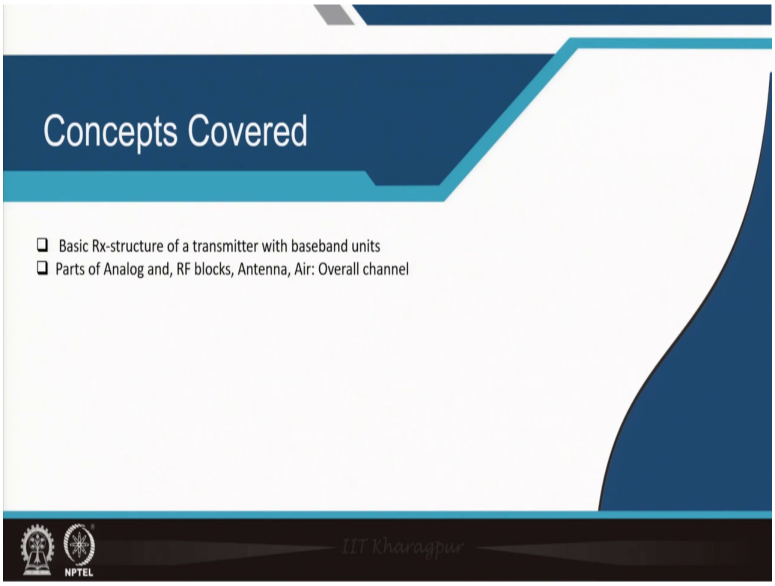

So, these are the concept which will be covered tentatively by today; the basic Rx structure of the transmitting block with baseband unit. And then various parts of analog RF blocks, antenna and the air and the concept of the overall channel and subsequently how it enters into the channel part.

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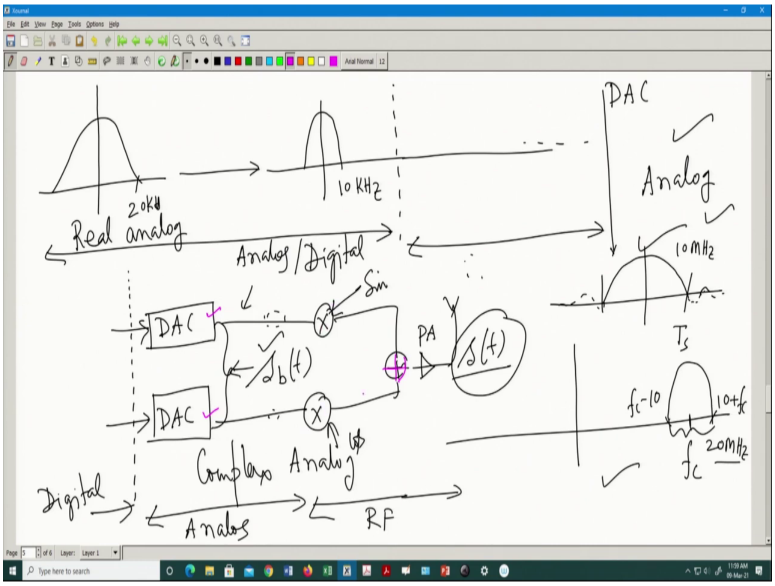

So, in the last lecture what we have discussed is that, we have received analog waveforms. It is a spectrum and that spectrum was 20 kilohertz spectrum and then we did some signal processing and we squeeze the spectrum to say 10 kilohertz spectrum due to whatever reason ok.

Now, till here this is your till here I would say. So, this should be so may not be this is not correct this part. So, till here I tentatively have analog and digital both ok. Then it goes through bunch of signal processing and finally, it reaches there are lot of modules here and finally, it reaches the DAC ok.

During this digital time, sometimes the spectrum does not even appear because when you do the channel coding there is no concept of spectrum there. Because it is a stream of bits when the spectrum again appears when the concept of single mapping comes into picture before that there is no concept of spectrum.

So, sometimes the spectrum will be lost here and then you bring back the spectrum again, but that time the spectrum has no correlation with this fellow the first one whatever you are you started with that is the voice signal. So, what will happen? At this stage the spectrum can suddenly increase this is my sink pulse.

So, the spectrum can suddenly increase to the band of occupancy that you need. So, it could be say 10 megahertz also depends on what should be the sampling time at the tack. So, you had 20 kilohertz, 10 kilohertz in between suddenly it stretch to 10 megahertz ok. Now you can understand why exactly this spectrum changes happens because this is mainly your sampling time because of the DAC sampling time and you may require high bandwidth because you may not be given a complete times for transmission.

So, you may be given a very small fraction of time for transmission. In that case you have to use a very larger bandwidth to pump more and more data otherwise you may not meet the data requirement at your application. So, this is what we have learnt it ok, but now again your analog domain starts. So, this is your analog domain.

So, you started with analog in between digital and then you are back to analog then what are the other component? So, you have a DAC here, you have this DAC here you have two DACs why 2 DACs? Because your signal is a complex signal, but when you view it we do not view it separately it is from a mathematical point of view these are at a complex signal. So, it is a complex analog signal can I write it like that? So, this is a complex analog.

So, what you started with? A real analog this is a real analog ok, then it goes through digital suddenly there is a symbol mapper which converts to a digital complex signal then; obviously, when you put a DAC, it becomes a complex analog signal and then individual row you can modulate it there will be internal some other modules I am not getting into that then you modulate it with sin and cos.

And then what you do? You add up send it through antenna this is how the jobs are ok. In between there is one more module called power amplifier because that gives you the gain required power gain for transmission. In between there may be some filter here some filter here just for spectrum shaping and those kind of things, but this is tentatively what your system will look like.

So, at this stage this one we call it s b t this signal. So, this is an analog complex signal and b refers to the baseband ok. This one which is a RF signal we call it s t just for our simplicity ok, and how the spectrum look like? So, the spectrum here will look like this one whatever I have drawn here its say I am my sampling rate is 0.1 micro second.

So, you say 10 megahertz, 10 megahertz positive and negative both side it will come at the RF after the RF what how the spectrum will look like? The spectrum will look like somewhere my RF say f c is my RF. So, it is a 6 gigahertz or 10 gigahertz or 30 gigahertz. And now I am slowly entering into the channel part how exactly the channel appears here and what are the components involved here and then the same spectrum will be appearing here.

So, this will be my total you know 10 megahertz here, this is 10 megahertz this will also be whatever 10 megahertz. So, f c so, this will be 10 plus f c and this will be f c minus 10 that is the spectrum here. So, this total it will occupy 20 megahertz spectrum in the RF terminal this is how it will look like ok at the antenna level. Say antenna level this is how the spectrum look like.

Now, if you look at exactly what is your interest of signal processing. So, your signal processing actually ends here. So, you are basically dealing with the digital stuff ok the rest of the thing should be analog this part this part is the RF this we call it RF this we call it analog, this we call it digital.

The question come where exactly you stand to recover the data? Obviously, you have to go through digital, analog RF and then finally, at the receiver. It will first RF then analog then digital the reverse process will start right. So, it matters where you want to view your system. Now as you know in a real modems the actual signal processing happens in the digital part.

So, we will be interested as if like we are sending a digital signal and finally, we are getting back a digital signal right. So, this is what how a transmitter look like and obviously, when you go to the receiver opposite things will start. Now, let me give you a brief about what exactly happens in the receiver because we are now entering into the channel model very slowly.

Now this is how the spectrum look like now let us get into the point where receiver how exactly a receiver look like. Now what is the relationship between s t and s b t? It is important to know because this is RF, this is the base band ok and you know the actual signal if it is an RF it is just a matter of shift. So, what is the relationship between s t and s b t? It is just a matter of shift right. It is a frequency shift right.

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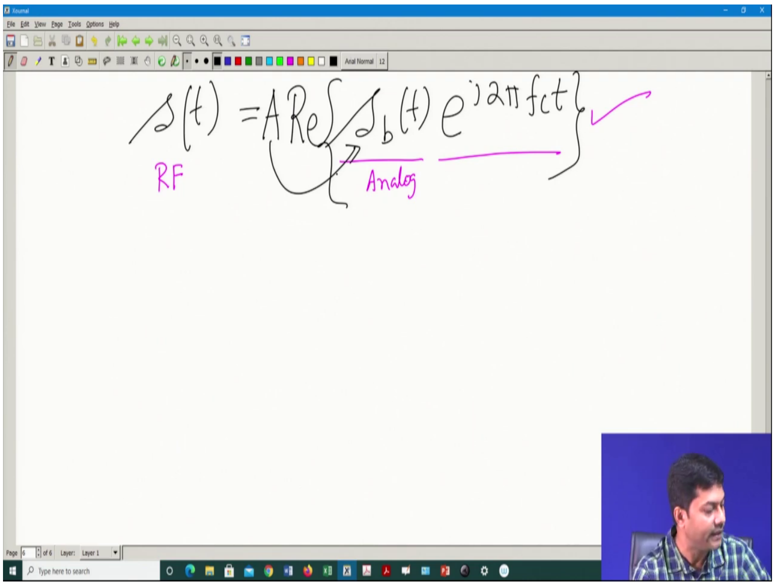

So, the relationship would be it is a very famous relationship between the RF signal and the equivalent baseband signal will be this. This is your s b t baseband signal multiplied by shift in time and I take the real part I take the real part of it. If I take the real part what will happen? The spectrum will be always in one sided spectrum.

So, that is ok, but this is important that is s b t e to the power j 2 pi fct. So, that is the relationship between your RF domain to your analog base back domain. Now, if you notice very carefully your analog s b t is a complex analog signal why? Because it is output of two DAC one DAC is the real part another track is the imaginary part.

Then what I do? You notice very carefully that I finally, add up here I finally, add up here right. So, now, this will be real, this will be also real I just add up. So, it is like a one real signal that I am transmitting it ok. So, now, here when I am in the actual antenna once I am in the air basically I am now just throw that signal from the antenna point of view, this is what comes into picture that this is my RF which actually gets transmitted from the antenna.

Now, this comes into picture now there are some more stuff that will be here which I have not drawn that this particular signal will go through some gain changes. What are the gain changes? If you notice there is a power amplifier gain changes there are some impairment gain changes and we need to understand that part as well.

Because here if you notice DAC will give you some gain right naturally the DAC has its own gain which may or may not be equal all the time because of the system you know inaccuracies then this modulator part this multiplier. They also have their own you know gain mismatch then finally, there is a power amplifier.

So, what we will get is that I am not modeling that part naturally because our intention is not to model all the impairment at the first stage. But in this course at the end when you go to the impairments modeling for the millimetre wave communication, I will come back again here. Why because now in that case I will be modeling each and individual points gain mismatch, phase mismatch and then we will see how exactly it impacts our transmitter and receiver in the context of millimetre wave system we will come back here.

But at this stage let us assume that the gains are perfectly fine; that means, this DAC and this DAC have equal gain, this fellow and this fellow have equal gain, this power amplifier is not showing any nonlinearity. So, everything is in a very real I mean good, good word. So, where impairments are not there except that some you know thermal noise otherwise gain mismatch is not there.

So, that is why I am not so, interested in the gain part, but you can assume very safely there might be a overall gain here, but that is ok you can engulf this whole point here it is as if like this part of s b t. So, I am not explicitly writing that particular a part it is assume that this s b t will engulf that individual gain part ok.

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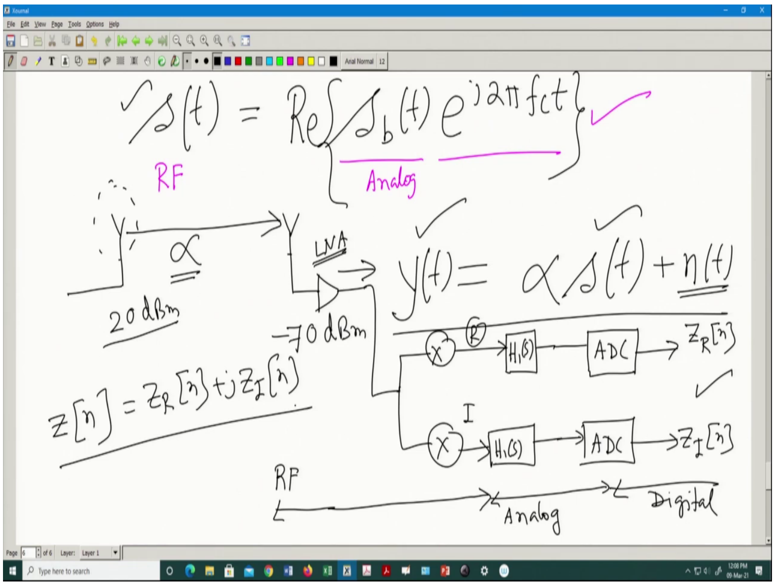

Now, this is what I have transmitted ok at the receiver what will happen? Let me not go very detailed into it, but there is a brief about it. So, in the receiver what will happen? So, this was my transmitter let us assume that I am in a very simple world or rather I would say I am in a space ok.

So, when you are in a space you are just transmitting say isotropic manner. So, in all direction this antenna is transmitting. Let us assume for the first case then it is receiving the data here ok and there is only one path from this transmitter and receiver. Now, as it is just one path this there is a path loss because when RF signal travels through a space it will lose its power.

So, let us say that power is called alpha that power gain is called alpha it is not a gain rather it will be an attenuation. So, finally, what I receive here is that. So, if I call that I receive y t I that means I sent s t and I am receiving y t at this antenna and what is the nature of this y t? Is it RF? Is it analog? Is it digital? No, because it is just an antenna because I am modeling step by step. Because I have to model the complete channel never think that channel is just RF.

I will show you the channel composites it consists of everything it is a composite part of RF, analog and digital mismatch everything will come into channel ok. So, now this is my received signal at my antenna. See if this is my received signal and my antenna. So, what should I get? Whatever I got or whatever I transmitted from the transmitter antenna s t multiplied by this gain say alpha this is a voltage gain this is not a gain.

But rather you can think of some attenuation plus some thermal noise will come into picture which is an additive in nature ok. And subsequently we will put more attention on the channel part on this not channel part on this noise, but as well will characterize it, but this is what you will be receiving it that what you transmitted multiplied by again it is a very simplistic model.

This is a very simplistic transmission and transmissions model transmitter and receiver model where you are just transmitting a signal in an isotropic antenna and at the receiver you are receiving in a very simplistic manner that means that antenna does not pose too much problem does not show any non-linearity in the system in a very simple manner you have received it ok and just a simple additive Gaussian noise.

Let us not put the question ok whether it is a Gaussian or something, but it is an additive noise in this. So, this is what you receive it at the antenna ok. Now, I assume that there might be some component called LNA here ok Low Noise Amplifier what is this noise what is this amplifier called? Why is it called low noise amplifier?

Because the signal that you receive will be very small power that will be that you may be receiving at the transmitter you probably transmitting at say 20 dBm power. There is a huge power, but what you receive? Very very low power probably this is a typical number minus 70 dBm.

So, that mean huge loss you see. It is a 90 dB loss almost. Because 90 dB in a log scale that mean you can say most of the power is lost as a very fraction of power will be received here now you cannot decode such kind of power. So, you need an amplifier ok. So, there is an amplifier.

So, that amplifier may have a gain, now this alpha whatever I am talking here that comprehends this gain ok so; that means, this alpha is having a broader notion which is not just again between antenna to antenna. Now, I just let me write the complete chain so, that it will be easy for me to explain the channel part subsequently.

Now at this stage this antenna will be going through an LNA again because the received power might be very low then what will happen? Then you do earn demodulation ok then what you do? After demodulation filters all these things will be there. So, let me not write all the component, but at least some filter say H 1 and this will be predominantly an analog filter.

So, what does it do? It will take away all the extra component and gives you only the baseband signal then what will happen? After that this will go through a sampling because I have to now get back my digital signal. So, I send to ADC now you notice that I am creating two you know two physically two physical line here.

So, one line will be the real part that I part and another line is my imaginary part or the q part. So, it is I q component that is because this is what I have transmitted right if you notice what I have done this is what I have done right this is what I have done. So, I have transmitted in a real and imaginary part separately, but I have combined them together. So, obviously, when I you know reconstruct the signal I have to get them back real and imaginary separately now this is what my data which is a digital data ok. Let us call it say let us call different notion different notation.

Let me use Z R n say real part this is my imaginary part ok. Again few understandings what I receive here at the antenna? What I receive here at the antenna is a RF signal it is an RF domain. So, this is RF. So, from here this is the RF, till here this is RF from here to here this is analog, from here it is digital.

Now, let us say this component I call it Z n. So, Z n will be my simple Z R n plus j Z I n. So, that is my signal which I receive it ok. Now, how do I reconstruct the signal that is not my point here because the course mainly deals with the channel part. Now, let us understand that what exactly we mean by the channel then we will start the modeling part.

Once we start the modeling part then we will start millimetre wave terahertz whatever that all will start subsequently, but first you have to understand what exactly I mean by the channel in my physical layer system. So, that has to be made very clear. So, in a summary what we have done?

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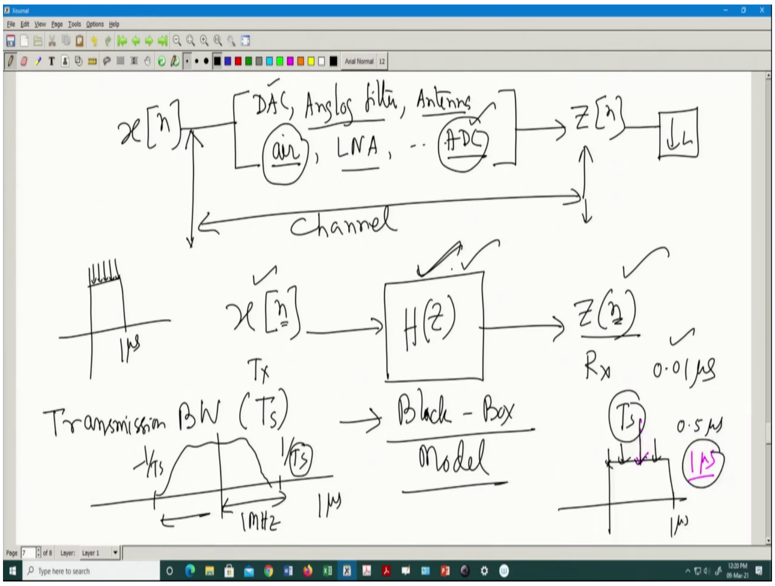

We started. Let us not get back to our voice signal we have or we are trying to transmit x n digital that is my symbols right.

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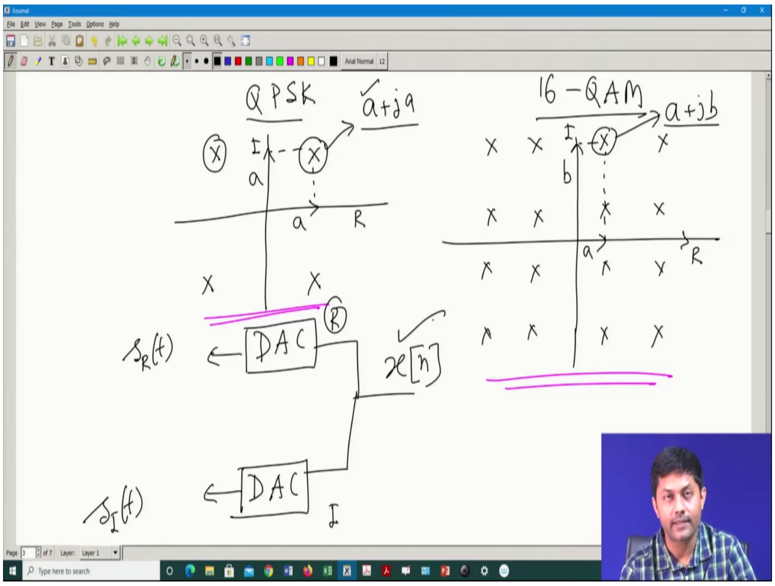

So, that is exactly my symbol I am talking of this part here. This one; see they are my symbols ok. So, this is where I may start point then it goes through bunch of path which contains DAC, some analog filter, then what antenna, then gain or attenuation in the air, LNA. So, many analog components RF component and finally, it goes through ADC, then again I got back my z n this is what I do this is what exactly I have done right.

So, this is where I stand that mean to me the signal is x n, to me my received signal is z n anything in between I call it channel got it? So, channel does it mean that it is just air ok because air is one part of the channel the other part of the channel that mean the filtering effect, all your phase problem, noise problem, amplitude variation, you have lot of analog filters right they have their you know nonlinearity every whole thing constitute your channel ok.

Now, we may model these components specifically very well why? Because we are the designer we are meaning the person who has designed the model they know the models very well. So, you if you ask a person who has done the design for DAC, LNA, ADC all components he can tell he or she can tell you what should be the model of that part what about the air we are not designing air part, ok got it.

So, this is where the physics come into picture. So, when I say channel, my channel is actually all together is my channel all together in my channel ok. Now from a signal processing point of view what do I think? So, it is as if like I give x n as an input, it goes through some system in a z domain. Because I am because my view is from here, I am standing here I do not care in between whether it goes through RF, whether it goes through analog nothing comes to my mind to me it is a system where I give x n and I observe Z n that is all my job is.

So, I am this is my transmit part, this is my receive part in between everything I will call it a black box can I think of it like that? Yes. So, now, this is what the black box is. So, I am in a black box. So, this is my black box. So, my transmission point is x n, my receive point is z n ok this is my black box.

Now, my job is now to model this part this is what my modeling part this is my job my job is to model it ok. Now, let us before I go into the model part of the black box, one part of the story is the bandwidth part where the bandwidth coming into picture we have to make it very clear this bandwidth x n side bandwidth is called an input bandwidth or a transmission bandwidth.

So, let us call that as a transmission. So, what should be my transmission bandwidth sorry? Transmission what was the transmission bandwidth? That depends on my DAC speed. So, let us say my sampling speed was T s at the date of T s I am sampling my DAC.

So, how do how what is the transmission bandwidth? Transmission bandwidth was from a DSP point of view or a baseband signal processing point of view, I will get a bandwidth of 1 by T s here minus 1 by T s here that is also from here my signal will be occupied ok. Now, if this is say 1 micro second that mean my actual signal bandwidth is 1 megahertz here and 1 megahertz in the negative side total band of occupants will be 2 megahertz in the Rx side but my baseband will be 1 megahertz, clear?

But, when I receive it try to understand and this concept is extremely important because this is where finally, we will be modeling your channel part ok. Now, when I receive it there is no necessity that at that ADC level I exactly have to sample at T s time there is no such necessity right. Say for example, this stage is 1 micro second what does it mean?

It means that the pulses my DAC sends it this is just 1 micro second pulse, but at the ADC level at the receiver level there is no necessity that I have to resample the signal at 1 microsecond ok I may sample it; obviously, I should not sample at lower frequency because I may miss some of the data, but I can sample at even higher frequency I can sample at say 0.01 micro second also.

So, which means that there will be 10 samples here essentially I am doing. So, I have drawn 5 here, but you can imagine that may be 10 samples here or 5 samples depends on what my sampling speed. So, this n is not correlated with this, but only thing I can say that this sampling rate should be at least more than my input sampling rate otherwise what?

Otherwise I will I mean it will violate my nyquist state right if I send at 1 megahertz signal baseband signal and if I sampler less than 2 megahertz; obviously, I will see aliasing. So, at least I have to sample at 2 megahertz that is the bare minimum. Then I will you know I can, but I can sample it at 10 megahertz, I can sample even at 100 megahertz also sky is the limit.

So, I am not getting into the sampling part, but this concept is important because that defines how exactly I view my channel; that means, depending on what my sampling rate add my receiver will determine what should be my channel view and that is the reason why I bring this point here ok. So, make sure that I need not to have a any binding that my receiver my sampling rate would be exactly matching with my transmission rate ok got it ok.

Fine, but naturally I can match it here. So, I can have a T s sampling rate here also because this is digital. So, I can create a nyquist by two rate because if it is a digital signal usually if it is a nyquist state ok. So, try to understand that suppose my sampling rate at the transmitter is 1 micro second.

So, at the receiver what will happen? I need to have a 0.5 micro second sampling for my nyquist state. So, what does it mean? It means that within 1 micro second, I need to have a two samples ok. So, that is what nyquist state mean, but as it is a digital signal and it is a it is assumed that throughout my total time of you know the transmission my data will not change.

Now, this one can make something changes, but at least my data side will not change right. So, it is enough to have just one sample here ok. So, which means that instead of having a 0.5 micro second sampling I can come back to 1 micro second, but that does not happen initially. So, that will be done with some with some intermediate single person.

So, that mean at the ADC I may use a very high sampling rate then what happens usually after this one I can do some sort of a down sampler here. So, at a rate of L such that I get just one sample during my whole micro seconds.

So, effectively I can create a 1 micro second and 1 micro second sampling rate. So, that is ok. So, that part is clear here. Now my job here is to now model this part. Now, in a very simple manner can I think of it like that. So, if you think that how exactly the components are. So, they are all serially tagged right.

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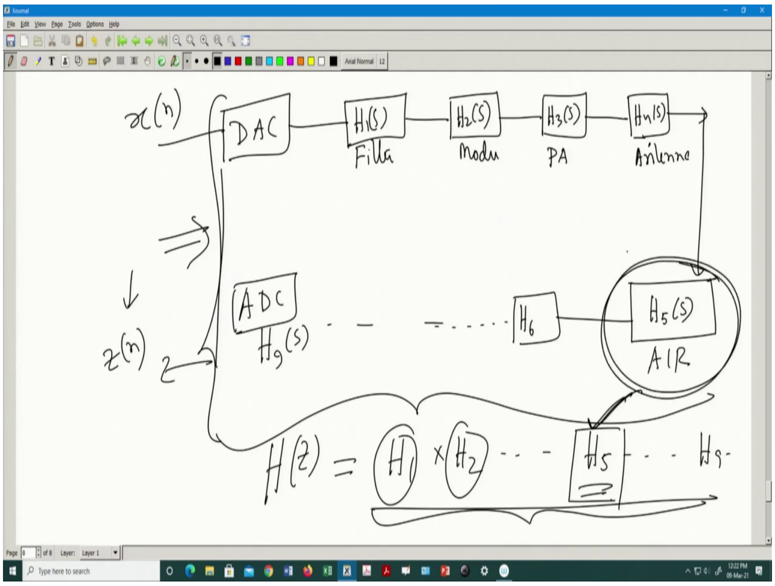

So, you have a DAC, I can think of it like that then there are some analog filter, then there is a you know modulator let us say that is also some sort of a linear system ok let us call it H 2 S ok. So, if it is a you know RF modulator you can think that this is nothing, but some sort of a multiplier of course, it is multiplying with the sin or cos, but I can think of it as a filter.

Anything that is going through the system I can think of it as a filter right even if it is a simple multiplier of course, I can think of it as a filter having just one flat gain right I can think of.

So, every component you can think it of a filter. So, this is my DAC as a filter ok. So, this is could be some other normal filter which is used for you know spectral shaping, this could be that modulator part you have a power amplifier I have shown that can also be thought as a filter, if it is a plane gain you can think about a filter right.

So, ok so that is also a filter. So, let us call it H 3 s. Antenna; antenna you know very well that antenna has a filter characteristic right. So, this is antenna. So, let us call it H 4 s what about the air? It is also going through some gain loss right. So, if you just you know send the signal from one antenna to another antenna in between what happens between the two antenna and this is our key job how do you model the you know gain part between the two antennas.

That is also filter you can think of it as a filter right because you send a signal at the receiver you receive something; that means, it is going through some you know some process. Whether it is a linear or non-linear secondary question, but you can think it up as a filter some filter right. So, that mean this is also another filter the air part.

So, let us call it H 5 s this is my AIR, then what happens? Then the reverse process will start again it will go through LNA and then you know demodulator. So, there is a bunch of filter that comes into picture. So, I am not drawing as. So, you can think of as many as filter you want. So, what was my job this was my input part and when it comes here this is my ADC part right everything is a filter. So, let us call it some I do not know what is the indexing.

So, let us call it H 9 or something. Everything is like a filter because this is what I said my channel is. So, this whole thing is a cascade of filters right cascade of filters that mean that this part whatever I have drawn here this part what you what do you think of it from a dsp point of view?

Now, this whole H z now be careful somewhere I am using s suddenly I am bringing z why? Because my view is digital I am at digital level. So, everything else so that mean from here I think that is nothing, but a some digital system I do not know whether it is internally analog digital all conversion I do not know to me it is like a digital system why because I am sending a digital I am receiving digital internally how internal conversion happen I do not care.

So, for me the whole thing together is a digital system. So, I can think of this whole H z is some equivalent of H 1 multiplied by H 2 dot, dot, dot say H 5 this is where my interest is H 9 and so on. So, all the filter effects will be just cascaded I can think of it like that.

Now, these characteristics are kind of known to us, but this is the one which is very important the correct characteristic at the AIR. But all together is your channel, never think the channel is just air that is wrong channel is everything. From DAC to ADC whatever component is there all components individual points constitute my channel effect and this is how my channel is now ok. Now, our job is to mainly model the H 5 part or the AIR part.

This is our key part the rest of the things we tentatively know how the model could be done because we are the designer. So, we have fair idea about it, but this is the one which do not happen. We will next you know next class we will be explaining the characteristic at the H 5 or the AIR part how the channel is modeled there.

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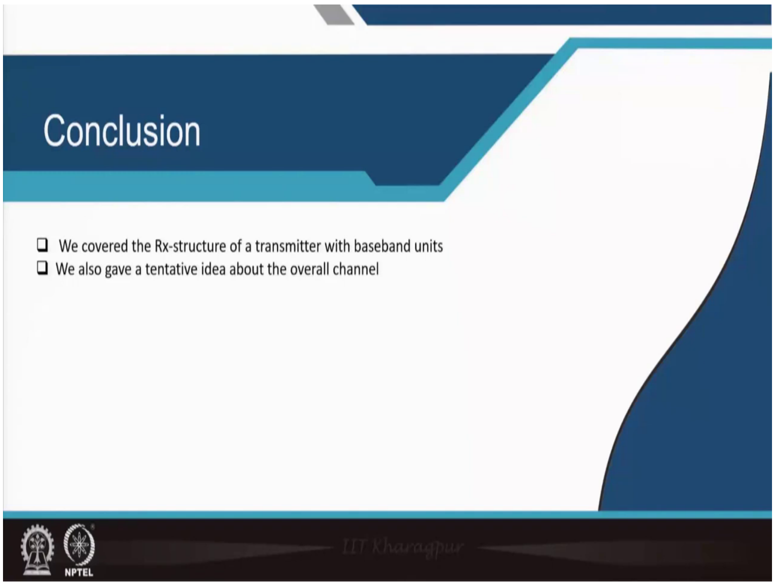

So, today we covered Rx structure along with all the baseband and analog RF components and we also gave a very tentative idea about the overall channel what it contains like. Like the baseband inaccuracies, then air part, the RF part and all these things overall whatever the channel means the overall filters cascading is what the channel means so, that what we have covered. Even the references are same compared to our initial ones.

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Thank you.