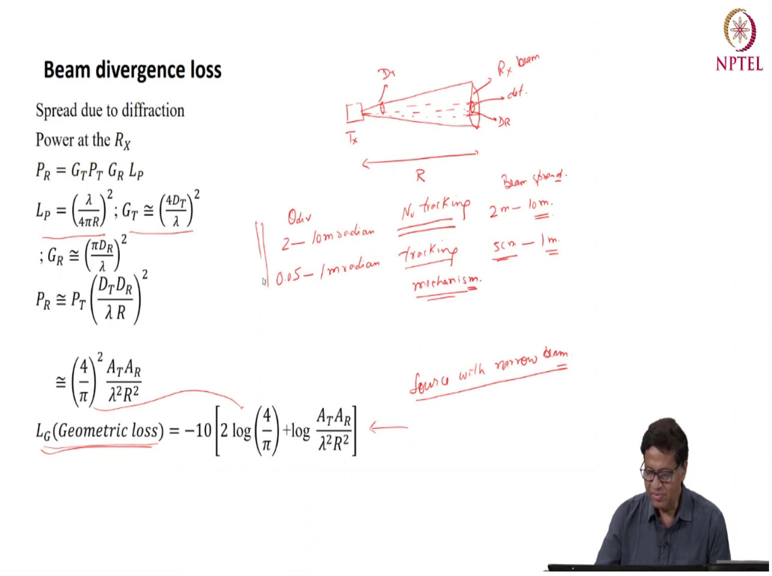
Optical Wireless Communications for Beyond 5G Networks and IoT
Prof. Anand Srivastava
Department of Electronics and Communications Engineering
Indraprastha Institute of Information Technology, Delhi

Lecture - 09
Part - 03
Range equation of FSO link...contd

Now, let us understand about the beam divergence loss because the beam is diverging and then we have a limited area where the beam is falling, thus, the optical intensity is beyond that area and it is a loss.

(Refer Slide Time: 00:42)



So, let us try to understand this beam divergence loss. So, beam divergence loss and let us assume that there is a transmitter here and I am this is a the transmit optics here. So, this will become something like this. So, my beam area is something like this and my detector area is something like this.

So, this is the receive beam, this is a receive beam and this is a detector and this let this distance be R and this transmit aperture is say D T, this transmit aperture is D T and here this receive aperture is D R. This distance this area is D R basically be between this and this. So, this is your D R and let me draw a midline as well here.

So, let us see the spread due to diffraction and then what is the power collected in the receiver. So, PR is given I am assuming other components are equivalent to 1, the neater, T R or the pointing loss or the receiver optics or the filter. So, let me use a simpler formula where I have the transmitter gain, I have the transmit power, the receiver gain and the free space loss.

So, this is a received power and we know the free space loss is given by lambda by 4 pi R square. The G T as we are discussed is given by 4 D T divided by lambda whole square and G R is given by pi D R by lambda whole square. So, if I put the values of G T, G R and L P here then what I get is P R is equal to P D transmit power into D T over D R divided by lambda R whole square.

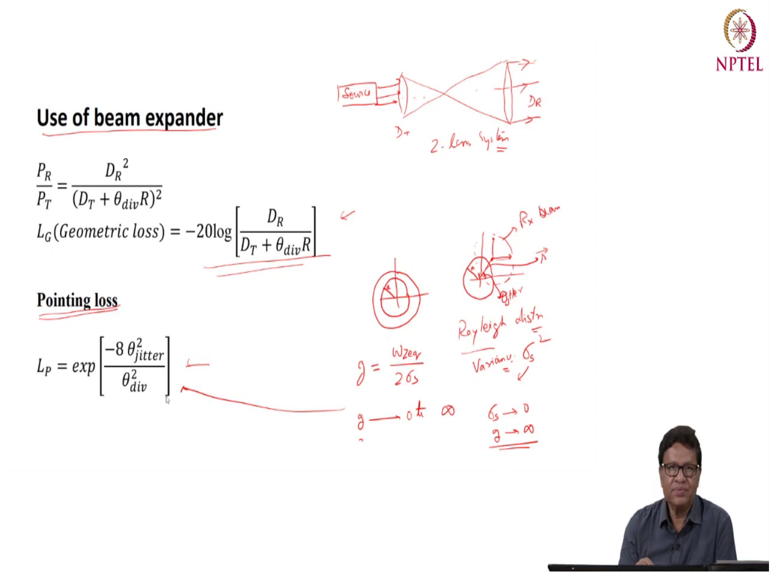
And if I convert this D T into area corresponding area using area is equal to pi r square or pi D T by 2 we have assumed so, in terms of area this is 4 by pi whole square into A T, A R divided by lambda square R square. So, the geometric loss which is actually the ratio of this taken in because I am calculating this in dB. So, this will be given by this minus 10 this because of the square comes here 2 log 4 by pi plus log et A R lambda square R square. So, this is geometric loss I will face.

So, source with the narrow beam divergence are required if I want to have this loss low. So, I required a source with narrow beam source that will change my AR source with narrow beam is required to reduce this geometric loss which is again a issue of alignment issue will come. So, just to give an idea for example, if I have theta divergence as 2 two for example, 10 milli radian, this is theta divergence it will give me a beam spread on the receiver which is 2 meter to 10 meters this is beam spread.

So, the beam spread is quite high. So, I may not be requiring any tracking mechanism. So, no tracking may be required. If I make low theta divergence because I want to make this geotechnical loss low then you know if I select for example, this kind of laser which has 0.05 to say 1 milli radian divergence it will give me 5 centimeter to 1 meter and this is quite small 5 centimeter is quite small I need strict alignment. So, I need some tracking mechanism here which makes a system complex tracking mechanism right.

So, if your beam width is low you required strict alignment and for making that strict alignment you need to have some tracking mechanism in the system built into the system. So, again there is a pros and cons of having low divergence angle. So, how do you get rid of this problem?

(Refer Slide Time: 06:56)



So, sometimes one can use a beam expander. So, beam expander actually say 2 lens system. So, you have for example, this is a source and it is emitting like this. And then you have a first lens here it converges a light here and then you have another lens which will you know collimate the beam.

So, this is a use a beam expander is a 2 lens system. And if I calculate the P R ratio of P R and P T. So, P R actually will be proportional to D R square this is D R here and P T will be D T that is this is D T plus divergence angle into R whole square. And if I calculate the geometric loss it will give me minus 20 log D R divided by D T plus theta DR. So, here you see as compared to earlier the geometric loss is less and because the geometric loss is less you get more power at the receiver.

So, the performance is improvement in the performance because you have got more power because of this arrangement using beam expander. So, this is how one can sort of handle the beam divergence loss using beam expander or a 2 lens system. The next loss is actually a pointing loss which is very important again it is related to the alignment. So, what happens actually suppose your detector area is this much this is your detector area say with say this is let me this is my detector area and say this is radius a.

Now, the beam which is arriving at the receiver if it covers this whole area then this detector gets the whole light. So, there is no pointing loss, but if that does not happen because this pointing loss may happen because of you know building little this way in the building or transmitter and receiver are because the wind they are misaligned or they may be some mild earthquake because of all these things this receive beam which you receive will be something like this.

So, this is your detector area with A and your received beam will be something maybe like this. So, only part of the received beam is available with to the detector and this is changing with time I mean this is not constant this is changing with time because of the misalignment happening. So, what basically you do?

You model this the changes happening in the X direction and in the Y direction as two independent you know processes and if I draw a you know vector R which is from this origin to say middle of this beam the received this say this is a received beam and this is a R vector this R vector is actually changing because your beam because of the pointing is changing with time. So, this R vector actually follows a Rayleigh distribution and with variance sigma square.

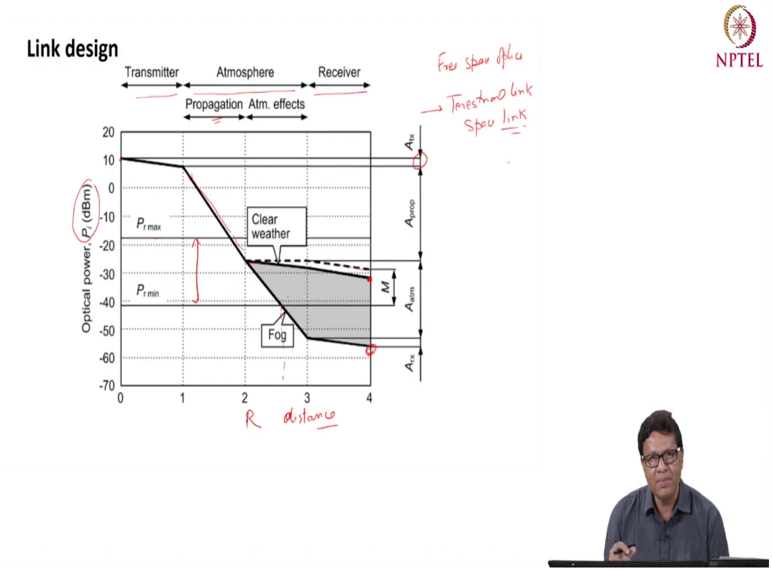
So, this has been seen in particularly studied experiment list seen that this follows this R vector follows a Rayleigh distribution with variance sigma square. So, in order to quantify this pointing loss I define a factor called g which is this is the equivalent beam width of the received beam at the receiver divided by the 2 sigma s which this is standard deviation which has come after I have assumed that you know this R follows a Rayleigh distribution with variance this is variance sigma square.

So, this g can have value from 0 to infinity 0 to infinity. So, if your sigma s there is no variance is 0. So, this g is infinity; that means, there is no pointing loss g is infinity for this case, but that is not the case. So, g has some finite value can go up to 5 6 7 8 or whatever. So, which is actually tells you the amount of pointing loss you have in the system.

So, this is what the pointing loss and this loss can be written in this form which is exponential minus 8 theta square jitter divided by theta square divergence this is a divergence angle at the transmitter and this is the angle this is making this R vector is making and this g this angle is changing.

Because as I told you follow the Rayleigh distribution and because of different conditions this alignment is changing and this beam width is changing and the R this vector makes an angle theta which is changing and then calling that angle as theta jitter. So, you can get some approximate value of pointing loss by using this expression minus exponential minus 8 theta jitter square divided by the divergence angle square. So, this is how you can get the pointing loss ok.

(Refer Slide Time: 13:59)



Now, we will start a link design for a free space optics and we will take two examples one is for a terrestrial link test and other example we will take for a space link. So, through these examples we will understand what kind of transmitter is required, what kind of receiver is required, what is the divergence required and what are the different receive aperture and transmit aperture or transmitter gain or receiver gain are required for designing these two links.

So, before we understand those numerical examples, let us try to understand using this slide what are the things which are involved in link design. So, as you know the link design consists of one transmitter, then there is atmosphere and atmosphere will have propagation loss and also loss because of the atmospheric conditions or because of the environment and then there is a receiver part which also has some amount of loss.

So, in this graph in this slide on Y axis is optical transmitter in dBm and on y axis on X axis is the actually distance you can say this is R. So, as you see here the transmit power is 10 dBm and because in the transmitter there are some lens arrangement. So, there will be some loss because of the lens arrangement.

So, this loss is depicted by ATX that is a loss because of the transmitter which could be few DV or a 2 DBs. So, that loss is considered here and then as light travels in the open outdoor see outdoor environment there will be a propagation loss which is written here and the loss falls in this fashion.

And then and as you reach some distance aj suppose there is a clear weather there are no environmental you know effect. So, in clear weather the loss which happens in clear weather is quite less. So, this will follow this dotted line and then because of the receiver there will be some loss because the receiver optics.

So, you get something here. So, your point after 4 kilometers you get something like this and if you see this power it falls in this range which I have defined as P r min and P r max. So, this is the detector range P r min is the sensitivity of the detector the minimum power it can sense for giving some particular you know performance.

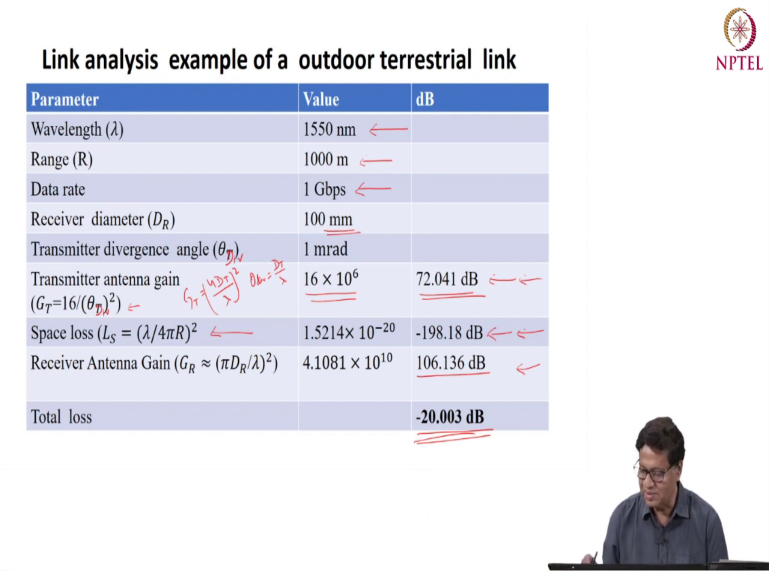
And P r max is a maximum power it can have because if you give power more than that it gets saturated you do not get any corresponding output if the power exceeds P r max. So, there is a window defined for a receiver of reciever of good receiver operation which is between P r minimum and P r max.

So, as we notice here if it is clear weather then I am able to cover a distance of 4 kilometer and my receiver power is somewhere here which lies in this range. But on the other hand if this is not a clear weather and the weather is has fog, then the fog will introduce attenuation and that attenuation is quite high that we had discussed earlier depending upon the nature of fog the attenuation per kilometer changes.

So, this value changes and if you notice here this is the received power after you have you know encountered the fog and the receiver attenuation what you get is this point which is actually falling below this range of detectors. So, it may not meet your performance, the link may not survive up to 4 kilometer the maximum bit can survive will be say somewhere here, where the light falls within this region. So, about 2.5 kilometers under foggy conditions.

So, based on this understanding let us see the different values of system parameters for a terrestrial link and a space link.

(Refer Slide Time: 18:49)



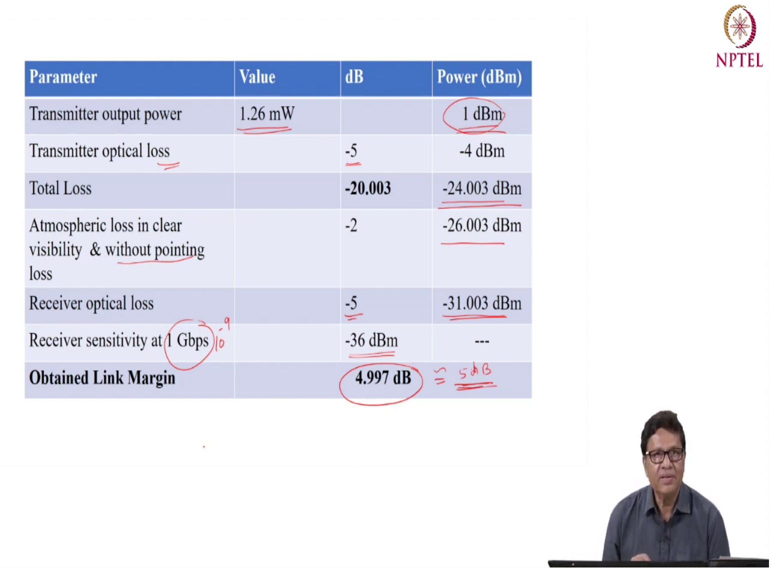
So, this is a example of a terrestrial link where I have considered 1 wavelength which is 15 nanometers this is same as used in optical fiber communication system. The distance which I am referring is 1 kilometer and I am interested in transporting or transmitting 1 gigabits per second of information. The received diameter I have used is 100 mm D R and the divergence angle theta T or you can write theta divergence is 1 milli radian.

So, the transmitter antenna gain can be calculated using 16 by theta T whole square theta div theta divergence whole square because we had seen that transmitter gain is 4 D T over lambda whole square and theta divergence we also know is approximately D T by lambda.

So, putting in this value of D T here you get expression this is 16 divided by theta divergence whole square. So, this G T is this and if I convert this into dB, it is about 72 dB. The space loss because of distance R is 1 kilometer lambda is between 50 one can calculate the space loss which is equivalent to minus 198.18 dB. This is minus because this is a loss and this is plus because there is a gain.

The received antenna gain which is given by pi D R divided by lambda whole square and D R is some 100 mm here lambda is known. So, based on this you get some gain which is 106 approximately 106 dB. So, effectively there is a loss here, but there is a gain because of the transmitter antenna because of there is a receiver. So, effective gain what you I mean still there is effective loss which is my minus 20 dB because the loss because of the space is high.

(Refer Slide Time: 20:57)



Parameter	Value	dB	Power (dBm)
Transmitter output power	1.26 mW		1 dBm
Transmitter optical loss		-5	-4 dBm
Total Loss		**-20.003**	-24.003 dBm
Atmospheric loss in clear visibility & without pointing loss		-2	-26.003 dBm
Receiver optical loss		-5	-31.003 dBm
Receiver sensitivity at 1 Gbps		-36 dBm	---
Obtained Link Margin		**4.997 dB**	

Now, if I take a transmitter output power of 1.26 milliwatt which is actually 1 dBm and I assume that there is a optical loss of point minus 5 dB as a transmitter in terms of dBm minus 4 dBm. The total loss will become because earlier it was minus 20 in the last slide, then this gets added up and what you get is minus 24.003 dBm.

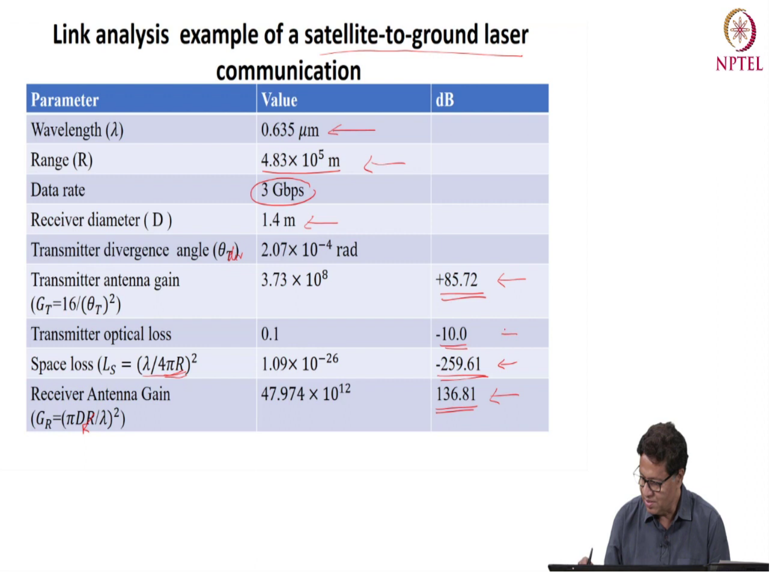
Then there is loss in the clear visibility and without pointing loss I am assuming that there is a clear weather and there is no pointing loss. So, because of that effect of minus 2 dB which makes it minus 26 dBm. And then the receive optical loss at the receiver where you have the receive aperture or some lens arrangement there is a loss of minus 5.

So, that makes it minus 31 and minimum power I require for 1 gigabits at a distance of 1 kilometer and at the you know better a rate of minus 9 is minus 36 dBm and the loss is actually minus 31. Still I am left with some 4.997 or equivalent to 5 dB which I called as a

Link margin and this linked margin is actually takes care of you know aging of the components or if some misalignment sometimes happens or some on a optical transmitter you know at some with time the power output decreases.

So, you also build some sort of you know link margin in the system which takes care of future aberrations or future issues which might come because of different reasons. So, this particular example if you have a transmit power of 1 dBm and with all these parameters the system will work for a distance of 1 kilometer for 1 gigabits per second and give you a 5 Db. So, this is an example of a terrestrial link.

(Refer Slide Time: 23:07)



Link analysis example of a satellite-to-ground laser communication

Parameter	Value	dB
Wavelength (λ)	0.635 μm	
Range (R)	4.83×10^5 m	
Data rate	3 Gbps	
Receiver diameter (D)	1.4 m	
Transmitter divergence angle (θ_T)	2.07×10^{-4} rad	
Transmitter antenna gain ($G_T=16/(\theta_T)^2$)	3.73×10^8	+85.72
Transmitter optical loss	0.1	-10.0
Space loss ($L_S = (\lambda/4\pi R)^2$	1.09×10^{-26}	-259.61
Receiver Antenna Gain ($G_R=(\pi D/\lambda)^2$)	47.974×10^{12}	136.81

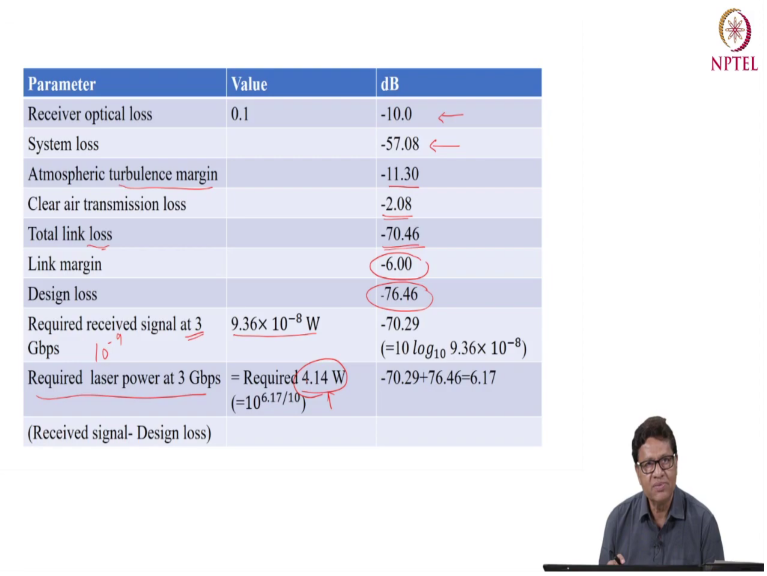
Now, let us see a link analysis example of a satellite to ground laser communication and this distance is going to be huge. So, right now I have considered as wavelength as 0.635

micrometer, range this distance is quite high of this order. This is we are talking about satellite to ground and I am also talking about high data rate that is 3 gigabits per second.

The receiver diameter let us assume this 1.4 meter, the divergence angle is actually in milli radiance or you can see 2.07 into 10 to the power minus 4 radiance. So, it is very small otherwise you cannot cover a long distance. So, and transmitter antenna gain as discussed in the last formula, you get 85.72 dB and the optical loss at the transmitter is minus 10, space loss because of the distance this is going to be huge because the distance is quite high you see the distance here distance is here.

So, this is about minus 259 dB and receiver antenna gain with these this is 5 D R, this is D R divided by lambda whole square gives a gain of 136. So, you got a gain transmit gain here you got receiver gain here, but there is a huge loss here because of this and because of this.

(Refer Slide Time: 24:50)



Parameter	Value	dB
Receiver optical loss	0.1	-10.0
System loss		-57.08
Atmospheric turbulence margin		-11.30
Clear air transmission loss		-2.08
Total link loss		-70.46
Link margin		-6.00
Design loss		-76.46
Required received signal at 3 Gbps	9.36×10^{-8} W	-70.29 (=10 log_{10} 9.36×10^{-8})
Required laser power at 3 Gbps	= Required 4.14 W (=$10^{6.17/10}$)	-70.29+76.46=6.17
(Received signal- Design loss)		

So, optical loss also there will be some as a receiver and the system loss basically if you add up all these things will be about 57 dB. I have kept some turbulence margin of 11 dB this turbulence we will discuss in detail because there will be issues because of the atmospheric turbulence. So, this I have kept a minus 11.30 because such a long distance you will encounter turbulence.

Clean air transmission loss is quite less because we are talking about space to ground and good part of the distance will be actually clean air where the loss will be very low. So, the total link loss becomes minus 70 dB and I want to keep a link margin of 6 dB. I mean this is generally kept you know for to take care of any issues which might come with time.

So, the total design loss is minus 76.46 and at 3 gigabits per second I require at least this much power at the receiver only then I will be able to decode there is some P r minimum required the receiver for 3 gigabits per second and meeting 10 is over minus 9 and that power is actually equal to minus 17.29.

So, you can back calculate what is a laser power required at the transmitter because you know the system loss you know what power you require in the receiver and then doing this simple mathematics, you can calculate what is the laser power required 3 gigabits per second which comes out to be 4.414 watts and so, this is the requirement.

So, you require every laser power of 4.14 and very very you know low theta divergence very very narrow beam in order to cover a distance of from ground to from ground from satellite to ground. So, this is some other typical values which one can use for calculating or for identifying different components for a space link.

So, with this we close this discussion on free space optics, we discussed about different you know what are the issues with a optical wireless channel in outdoor, we discussed about you know different loss and different transmitter gain and receiver gain and we also discussed about the pointing loss and we derived a range equation for calculating the what kind of power transmit power is required what kind of receive power is required and this we had discussed using two examples.

One example of range equation for a terrestrial link and the other example for a longer link which was between satellite and ground station. So, far we have discussed about the absorption part and the scattering part, but we have not discussed about the turbulence part.

So, in the next class we are going to discuss that atmospheric turbulence and how can we model atmospheric turbulence and what are the ways of mitigating atmospheric turbulence and what effects it has on the link design that we will discuss in the next class.

Thank you.