Optical Wireless Communications for Beyond 5G Networks and IoT
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Lecture - 09
Part - 01
Outdoor Optical Channel Modelling

Hello everyone. So, today we are going to start about Outdoor Optical wireless Channel. In the last few classes we have discussed about indoor optical wireless channel. Today we will see how optical wireless channel is modeled in outdoor conditions.

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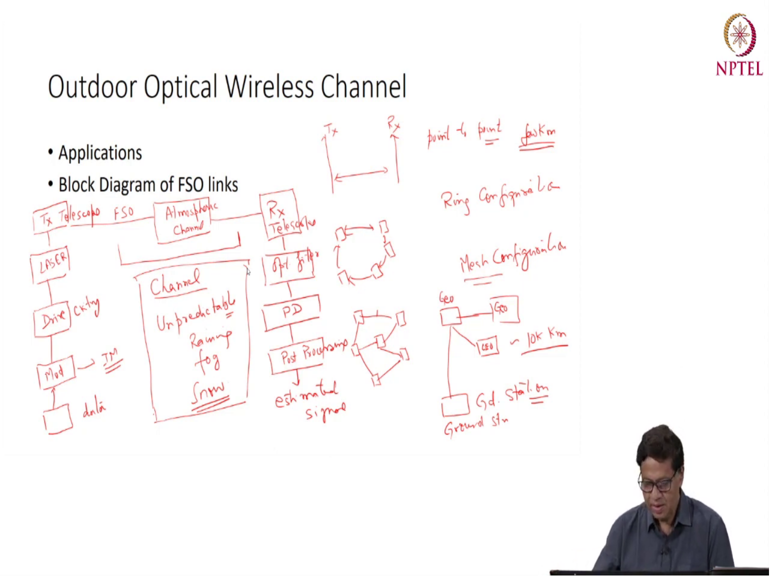

So, first let us try to understand, what are the different applications of outdoor optical wireless channel. So, first to the immediate application can be you know connecting two points. This is T x, this is R x, suppose you are not able to lay fibers here or it is difficult to lay fiber. For example, in a metropolitan city, so you can put a transmitter here, laser based transmitter and the receiver and communication can be established. So, this is one application which is called as point to point.

You can have different configurations of this, you can have ring configuration for example, ring configuration where the systems are connected in the ring fashion. So, these are optical wireless channel, this is optical wireless channel, this is optical wireless channel all are optical wireless channel.

Other could be a mesh configuration, where you connect the different nodes which are the optical trans-receivers. So, that whenever one link is down you have some different paths, so that is the idea of having mesh configuration. So, all these systems can be stalled in all possible configurations point to point, ring configuration or mesh configuration.

Now, let us understand what are the; this is application in the test here. For example, you can have also use optical wireless communication channel in space. For example, connecting two GEO satellite or connecting one GEO satellite with a ground station or from GEO satellite to a LEO satellite. So, you can have connectivity for example, from a GEO to another GEO satellite these are satellite terminals or you can have connectivity with a LEO satellite.

So, these lines which I am drawing here, they are actually optical wireless channel they are in space in free space. And they can also be a connectivity with ground station for example. I mean these distances are very large 1000s of kilometer. So, this is a possible from geo to ground station.

So, you have examples or applications both in terrestrial as well as in space link. And these terrestrial links are of the order of few kilometers whereas, these space links are going to be of the order of you know 10 k kilometers of that order. So, now let us understand the block diagram of a optical wireless channel in outdoor applications.

So, you will start with the say input data here. This is a information or data and then you do some sort of modulation. It could be for example, intensity modulation, this we have discussed in earlier classes. So, the data is modulated by changing the intensity of the optical source.

And then you have some sort of drive circuitry and then you will have generally for outdoor applications you have laser. And then you will have some sort of lens arrangement, which is called as T x telescope, we will understand more about this later. And from here you have a FSO channel Free Space Optics.

And let me denote this as you know atmospheric channel. And on the receive side you have again some optics, let us call that as receive telescope. And then you have optical filter to remove certain noise which are not in the band of transmission and then you convert the optical signal received using a photo detector.

This could be a PIN diode or a APD diode or any advanced detector. And then you do some sort of post processing to recover your signal. So, here you will get your estimated signal. So, this is the basic block diagram, so we will understand more about this channel.

How do we model this channel? And how do you mitigate the effects of the channel? Suppose you want to increase the length, how do you mitigate the effects of channel? So, this is what we will study in outdoor channel. And this channel by the way is very unpredictable. It is a time varying channel unlike your indoor channel which was sort of deterministic. This is unpredictable.

And it depends on what kind of environment conditions you have. Whether is it raining or there is some fog or snow, you know depending upon this, your channel characteristic will change and your receipt power at the receiver will also get changed and your performance may go up and down. So, this channel is normally this is modeled as a statistical channel.

So, we will study in detail about how do we model different aspects of this atmospheric channel.

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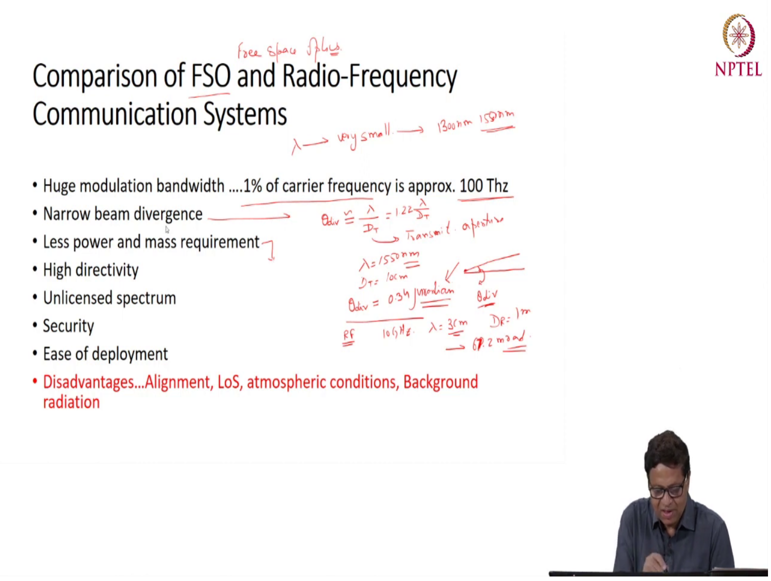

So, let us now briefly understand a comparison between a free space optics. This FSO is Free Space Optics and radio frequency communication system. So, the basic difference which comes from the fact that the wavelength of optical channel is very very small; it is very small as compared to RF channel, as we have seen in traditional systems the wavelength is of the order of you know 1300 nanometers or 15, 50 nanometers, right.

Whereas in RF the wavelength is very large, if the order of centimeters or you know it can be millimeters now. So, it is of that range, whereas it is in terms of nanometers here. And we understand from information theory that as you increase the carrier frequency your information carrying capacity increases.

So, if I; even if I use 1 percent of carrier frequency in the optical domain I get about 100 terahertz of bandwidth. I mean this is the bandwidth is available to me, whether I can use it that depends what kind of transmitter components or receiver components and things like that. But the bandwidth is available to me. So, it has huge modulation bandwidth.

The second is narrow beam divergence. We know that the laser for example, emits light it can emit light in a very narrow angle. So, theta divergence actually is equal to lambda by D T this is transmit aperture. I mean this is generally the approximation taken to be exact this is actually equal to 1.22 divided by lambda by D T.

So, if I try to calculate for example, for lambda is equal to 1550 nanometer, which is a typical wavelength used in optical fiber communication systems. And if I have this D T of the order of say 10 centimeter, then I get theta divergence this angle this is for example, this is source, this angle theta divergence is of the order of 0.34 micro radian it is very very small.

Whereas, if I see in case of RF for example, in RF for 10 gigahertz this is a on a higher site and gigahertz and the wavelength will be about centimetres, 3 centimeter. And if I assume DR for example, typical value of 1 meter this angle becomes 67.2 milli radian. So, you get in milli radians whereas, in this case it is in micro radian.

So, narrow beam divergence; that means the beam can go a longer distance, it is not diverging. So, and most of the power is in the beam I mean which is actually depends on the size of the detector, but as the beam travels it is not diverging. So, you need a very small detector which are conventional detector and you get good amount of intensity or good amount of power at the receiver. So, that is another advantage.

It requires less power and mass requirement. Just to give you one more feeling about the narrow beam divergence. Let me explain this in giving some typical example of you know beam from say planet Mars to Earth.

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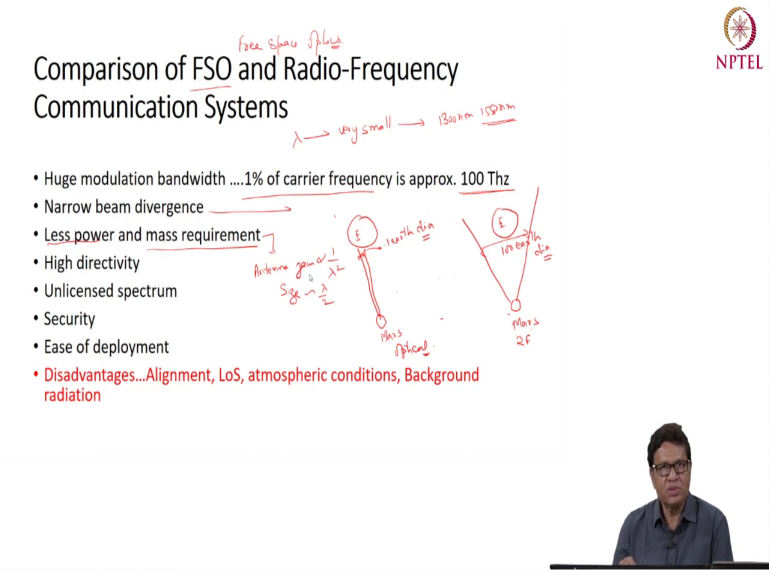

So, in that case, so suppose you have a laser beam and this is your Earth and this is your say Mars. And then you suppose you have a optical beam here and then the divergence which it has traveling from Mars to Earth is actually 0.1 of the Earth diameter 0.1 of the Earth diameter. Whereas, if you see for example, in RF case this is Mars, this is Earth. So, this will diverge much more and this is distances of the order of say 100 times earth diameter.

So, that is the main difference this is for example, for RF and this is for optical. You require less power and mass requirement. So, the components which are used in optical wireless communication in outdoor they are small in size the antenna used here they are small in size as compared to the systems which are you used using RF, where the size actually depends on the wavelength.

So, the size of the equipment or the antenna transmit antenna or the receive antenna is much higher. And you require huge power for transmitting RF signals, if you want to transmit over a long distance. But whereas, the amount of power required for transmitting optical signal is quite less. So, the equipment which are used for optical wireless communication is it consumes less power and also their compact and light.

We also know that antenna gain for example, is proportional to 1 by lambda square. So, smaller the wavelength high will be the antenna gain. And size of the antenna which are used is of the size of lambda by 2. So, from there from here you can get an idea that optical wireless communication system free space optical wireless communication systems require, they can give you more antenna gain and the size of the equipment used is very small.

Let us now understand about the high directivity.

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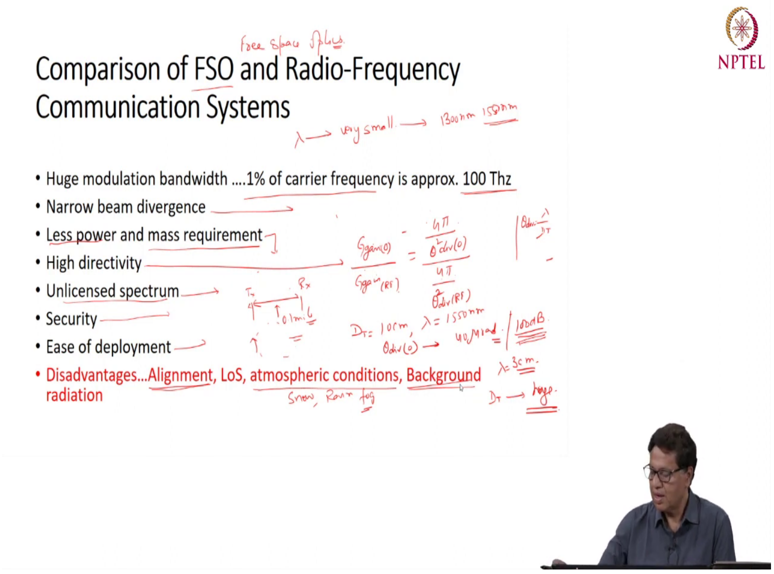

So, high directivity the gain in optical, if I take the ratio of gain optical versus gain RF. This is actually equal to 4 pi, the gain is defined by theta square of divergence in case of optical, divided by 4 pi theta square this is divergence in case of RF. Because we know theta divergence is lambda by DT.

So, the gain is defined by this and if I take some example. For example, I use this for example, DT as that is a transmit aperture as say 10 centimeter and again operate at wavelength 1550 nanometer, then theta divergence for optical I get is about 40 micro radian and I can get a gain of 100 dB which is huge.

And getting same amount of gain in RF for example, at wavelength say lambda is equal to 3 centimeter which is the RF frequency equivalent to RF frequency is in gigahertz. So, in order to get this 100 dB gain this DT in the transmit aperture which I require of the antenna size is actually huge and which is impractical.

And then this also gives you high directivity you can focus the beam onto a very small area, whereas, the RF actually as it travels its spreads around a large area. The other big advantage is that there is no license required for optical wireless communication system. Whereas, in RF it is licensed one has to take permission from the authorities, one has to pay a huge amount of money for buying spectrum whereas, the spectrum in the optical domain is actually unlicensed and there is no cost involved here.

So, that is a one of the very big advantage of using optical wireless communication as compared to radio communication. Other advantage is security, if you want to tap optical wireless channel you have to come very close to each other. For example, this is your T x and this is your R x and this is generally point to point communication.

So, you have to be very close of the order of 0.01 mile you know close to the beam only then you can tap some information, right. And whereas, in case of RF, as it spreads over a large area one can tap the information from a large distance. So, in a way it is more secure transmission as compared to RF and ease of deployment you do not have to lay fibers. For example in free space optics, simply install the transmitter, install the receiver, align them and you can have the communication.

So, ease of deployment as compared to RF where the equipments are bulky and they are not they are not light. Of course, it comes with certain disadvantages; you require a alignment point to say LoS essentially a line of sight technology. So, you require a precise alignment, if you want to have the communication with the transmitter and receiver.

And it is; it the it gets affected because of atmospheric conditions. As I mentioned earlier, the conditions of the attenuation of the signal or the scattering of the optical signal depends on the environment. For example, if you know snow will have some effect, rain, fog. So, all these conditions are going to have effect of absorption or scattering happening here.

So, the channel is actually dependent on the atmospheric conditions in a big way. Whereas in RF it is one can say it is not entirely independent of atmospheric conditions, but the dependence is much less? And also one has to handle the background radiation, which is coming from solar, from other sources they are contributing to the receiver and they are actually noise in the system.

So, this is another issue because you cannot block and that happens to be in the same wavelength range where your communication is taking place. So, this is another issue with the free space optics. So, it has some advantages also you know there are a couple of disadvantages which are there in free space optic system.

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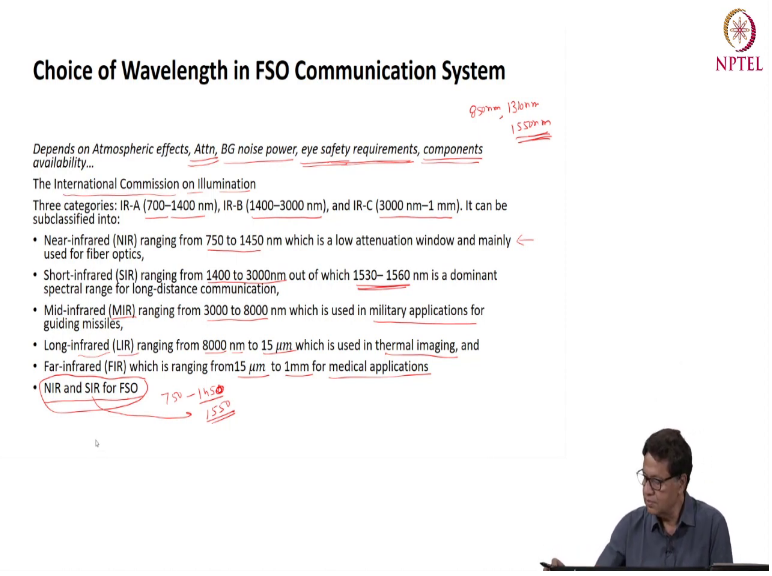

Now, let us understand what is the choice of wavelength in free space communication system? I mean what wavelength should be selected in the optical spectrum for free space optical communication. Actually it depends on variety of factors. It depends which wavelength has got less attenuation because you can cover a longer distance.

Background noise power you can use a wavelength where you may not have background noise. So, removing background noise becomes easier simply use a filter and you will be able to remove the background noise. So, it depends on the background noise. And also another factor which is important is eye safety, because not all wavelengths are eye safe.

So, there is a table defined which actually you know discusses or describes, what is the power I can tolerate, which wavelength, what is a maximum exposable exposing limit all those things are defined in eye safety requirement. So, you have to select a wavelength which is s harmless to for example, eyes or the tissues.

So, so this is another criteria which will decide what kind of wavelength we should select for free space optics and also the important thing is the components availability. You may not be able to get components at all the optical wavelengths. So, there are only few wavelengths where you know component industry has matured.

For example, when I am talking about optical fiber base systems, normally the systems are around 850 nanometer or 1310 nanometer or 1550 nanometer the reason here is that they it has less attenuation at these wavelength. And there are other advantages. And so, the component industry is quite matured in terms of making components around these wavelengths.

So, and for free space optics the immediate you know thinking will be that let us why not use same components, which have already been you know developed. So, component availability, I should there may be a wavelength which gives me all the advantages, but I may not get a component for that wavelength. So, so these are some of the if; you know criteria for deciding the choice of wavelength.

You know the International Commission on Illumination is an international body. They have defined you know three types of band mainly. IRA which goes from 700 to 1400 nanometer.

IRB which goes from 1400 to 3000 nanometer and then IRC which goes from 3000 nanometer to 1 millimeter. They are further classified into near infrared and this is the wavelength range for near infrared 750 to 1450.

Then short infrared this is the wavelength range, for the short infrared 1400 to 3000 nanometers and MIR mid infrared which goes from 3000 to 8000 nanometers. And from long infrared goes from 8000 to 15 micrometers. This is nanometer this is micrometer, 8000 nanometer to 15 micrometer and far infrared ranges from 50 micrometer to 1 mm.

And they have different applications for example; this particular IR in NIR is actually used for in optical fiber communication because the attenuation is quite low for example, in 1310. So, this is generally used for optical fiber communication, optical fiber based communication. Short infrared is used for long distance because it covers this 1550, which I have mentioned here.

So, 1530 to 1560 which is actually a window, which has the other least attenuation. And most of the amplifiers which are developed for example, EDFA erbium doped fiber they work on these wavelengths. So, this is a wavelength of choice for optical fiber communication which comes in comes under the subcategory of short infrared. And then you have mid infrared this is high 3000 to 8000. Generally they are used in ability applications, so it is a dedicated use in military applications.

Long infrared used in thermal imaging and far infrared is again used for some medical applications. So, so based on all these factors, what kind of attenuation, background noise, eye safety requirements, the choice of wavelength for free space optics is NIR, SIR that is near infrared and short infrared.

So, the range is basically near infrared, if you see 750 to 1450. This also by the way is same as optical fiber communication wavelength, where one can use 1310 as one of the wavelength. And in the SIR region that is short infrared you have 1550 which is again a communication bandwidth. So, most of the FSO system are based in this region. So, this is a choice of wavelength in free space optics communication system.

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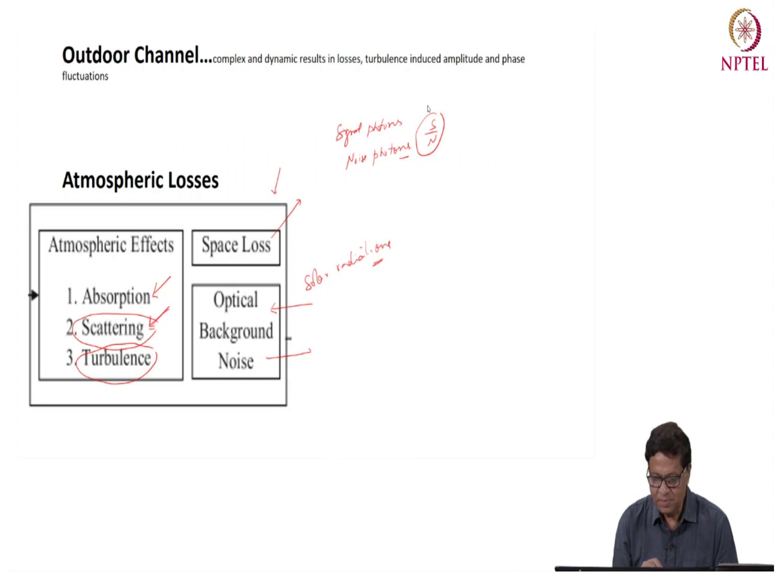

So, outdoor channel as I mentioned is quite complex and dynamic. It is changing with time. So, and it will result in losses, there will be a space loss as the light travels from one place to another place. And there is a turbulence in the atmosphere and this turbulence will actually induced variation in the amplitude, variation in the phase which is actually noise.

So, these fluctuations and channel changing with time also environmental effect makes a outdoor channel very complex. So, and if you see in this table atmospheric losses, the three things, one is atmospheric effect where you know light is absorbed or absorption, absorption happening. The light may be getting scattered from the particles which are there in the atmosphere.

And this scattering actually depends on the size of the particle. If it is very small it is a different kind of spectrum. It is; if it is little large it is a different kind of spectrum. If it is still large you have you know diffraction kind of scattering. So, depending upon the size, because atmosphere has all molecules or gases or aerosols, so they all have different size, the concentration is different.

So, this is going to have a important role in the free space optics and then turbulence. So, all these things we will study in quite detail, absorption scattering and turbulence. So, these are the atmospheric effects. And how do we model these things and how do we mitigate the effect that also we will be studying under this outdoor channel.

And then there is a free space loss which is happening when the light is travelling from one place to another place. So, for example, if you are a terrestrial link, there will be atmospheric loss. If you are going from you know space link, it will have both the loss atmospheric loss. And then in the space where there is no atmosphere, probably there may not be that much loss.

So, one has to consider you know what environment; for what environment you are making the system. And also we need to worry about the optical background noise, which I said solar radiation for example, it has wide spectrum. And it may also fall in the region, wavelength region of interest and light coming from any other source. So, these are the atmospheric losses, absorption, scattering, turbulence and space loss will be there and one has to worry about the optical background noise.

So, basically if the receiver I have to see, I have to find out how much photons I am getting, signal photons. And how many are which are coming from background or let me call them as you know noise component or noise photons. So, basically this defines my signal to noise ratio, right. So, so this is about properties of the outdoor channel.

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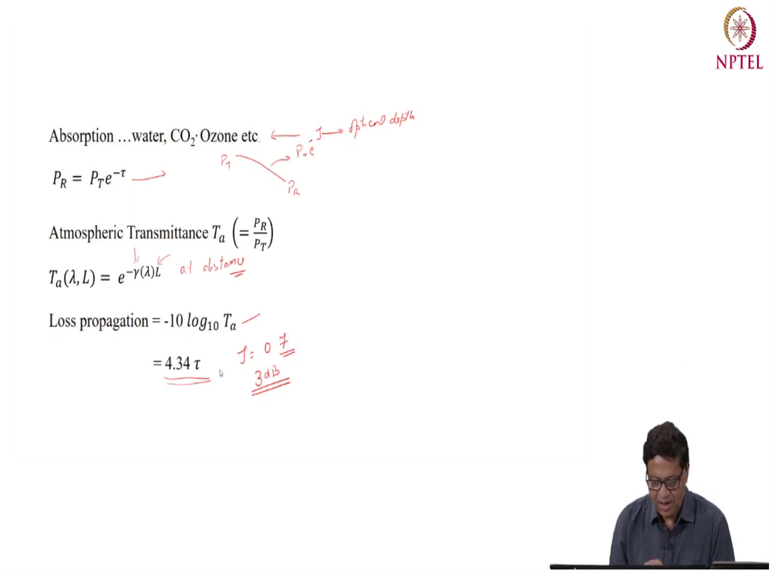

So, absorption because in the atmosphere you have water molecules or carbon dioxide or ozone, so they basically absorb the light so, the light which is received, the intensity or the power gets reduced because this is the absorption. Let us also now understand as it travels, how can we model the light traveling from transmitter receiver.

So, this received power actually varies in this form. If this is your transmit power, it actually follows or decay. So, this was say P T, this is P R. So, it follows in this fashion where tau is called as the optical depth. Let us define atmospheric transmittance T a which is ratio of received power to transmit power.

So, this T a the atmospheric transmittance is changes as e raised to power minus gamma. This is the attenuation coefficient and it is a function of wavelength into the distance at distance L and distance L. So, this is how atmospheric transmittance is defined with the function of wavelength and the distance.

So, if you calculate the loss propagation, it will give you minus 10 log to the base 10 T a and where T a is defined as P R by P T ratio of the received power to the transmit power. And if you put all these values here, what you get is 4.34 tau. So, if your tau is say for example, 0.7, so the reduction in the power is actually 3 dB or the power has reduced by a factor of half. So, this is the concept of optical depth.

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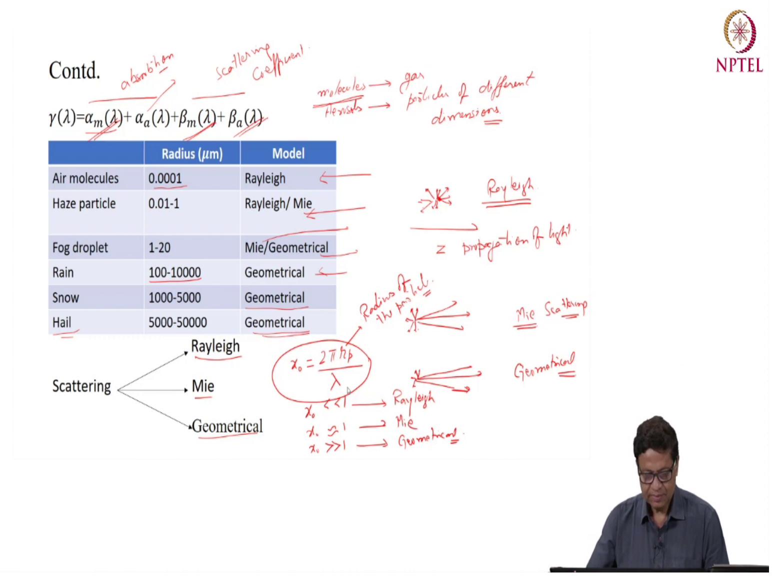

So, now let us understand this gamma lambda. What are the different components of attenuation coefficient? So, it has actually the attenuation happens because of molecules in the atmosphere or the aerosols. These are you know gas gases, they are present in the atmosphere and these aerosols can be some particles of different dimensions, particles of different dimensions.

So, the here m stands for molecular. So, this is you know absorption, the alphas are the absorption and these are scattering coefficients. So, this is scattering coefficient betas. So, alpha m lambda is actually absorption molecular absorption or the gases, which are present in the atmosphere. So, this coefficient is for molecular part of the atmosphere and this is aerosol, that is, different particles.

So, this absorption coefficient because of the aerosols, this is absorption coefficient because of the molecules. And similarly, you have scattering coefficient because of the molecules and scattering coefficient because of the aerosols. So, beta m and beta a are the scattering coefficients for the molecule and the aerosol respectively.

So, total gamma lambda which is a function of lambda has these four components, two because of the absorption, two because of scattering and each absorption is scattering have molecular attenuation coefficient and because of the aerosols, the other is because of the aerosols, particles of different dimensions.

Now, absorption we have understood because of CO2 or ozone or because of water content, the light gets absorbed. So, scattering actually depends on what is the size of the particle or dimensions or the cross section of the particle, what is the volumetric density of the particle? So, scattering will depend on these factors.

So, if your particle size is very very less of this order point 0.0001 micrometer, it will suffer Rayleigh scattering. If the size is between 0.01 to 1 micrometer, it will suffer on the lower side, it suffer as a Rayleigh, but little on the higher side, it will suffer a Mie scattering and if you have a particle size of ranging from 1 to 20 micrometer, for example in a fog droplet.

So, on the lower side, it is going to be Mie scattering and if the dimension of the fog droplet is little higher, it might suffer a geometrical or diffraction kind of scattering. Rain, if the size is large, 100 to 1000 it is geometrical, snow again 1000 to 5000 that is the typical size of the particles is going to be geometrical and hail their bigger in size 5000 to 50,000 micrometer. So, this is geometry.

So, basically scattering is Rayleigh and Mie and geometric depending upon the size of the particle. So, what happens actually in Rayleigh as if this is a propagation of light, Z direction, this is a propagation of light. In the Rayleigh what happens, you have side lobes they disappear. So, suppose the light is scattered from this point, the side lobes which are here, they get disappear whereas, you have light scattered in all other directions. So, this is the property of Rayleigh scattering. So, this is Rayleigh.

In Mie scattering, there is a front lobe is keeps on increasing and the background lobes here, they are sort of symmetrical. So, this is typical Mie scattering. And the third one where you have small background lobes, this is small and a higher amount of forward lobe. This is actually term as you know diffraction or geometrical.

So, basically Mie and Rayleigh, so one can also define depending upon the size of the particle. So, if I define size of the particle as x naught, which is equal to say 2 pi R p divided by lambda, this is say radius of the particle. And lambda is the wavelength. In scattering actually it is redistribution of optical energy in different directions, not necessarily change in wavelength. So, this lambda will remain the same.

So, this x naught is defined by 2 pi by lambda into R p, R p is radius of the particle. So, if this x naught is very very less than 1, then you have the Rayleigh scattering. And this will be less than 1, when you have r p is very very small. And when x naught is equal to 1, you have Mie spectrum, Mie scattering.

And when you have x naught greater than 1, then you have geometrical or diffraction kind of scattering. So, it can also be modeled based on this x naught figure, which is which has this radius of the particle built into this formula. And also it depends what volume of particles you have in the atmosphere, whether it is dense or light. So, it depends on those factors as well.

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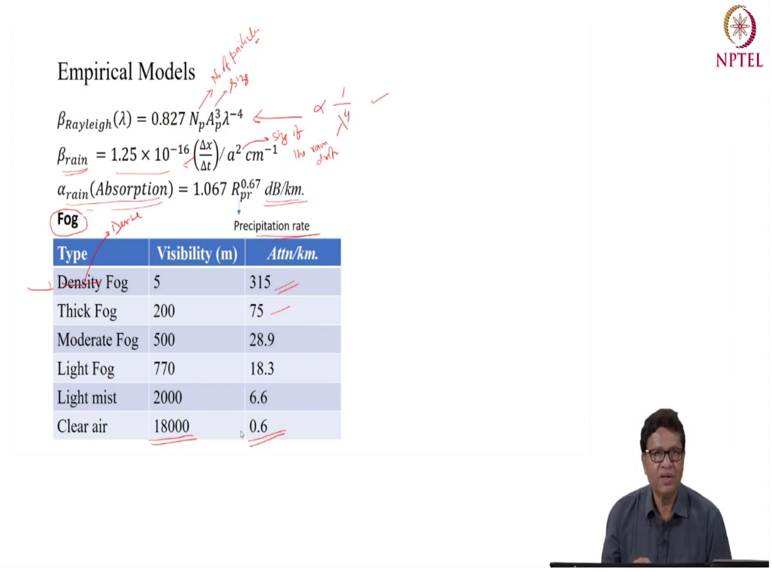

So, these are some of the empirical formulas. For example, this is for Rayleigh, so one thing to note here is that coefficient is actually proportional to 4th power of lambda, inversely proportional to 1 4th power lambda. This is the number of particles, this tells you the area. Sorry, this tells you about the size. This is the number, basically the volume part, number of particles in a unit area. And it goes as 1 by lambda 4.

So, higher the wavelength, lower will be the coefficient, beta Rayleigh. So, this is also one of the criteria for selecting a you know choice of wavelength for free space communication system. The coefficient because of the rain is given by this. This is size of the raindrop average. And this actually basically is the velocity of the rain.

So, this coefficient is given basically by delta x by t, which is the velocity divided by the average size of the rain droplet. And then this is actually because of the absorption happening in the rain is given by this formula, where R pr is actually precipitation rate. So, this is in terms of dB per kilometer.

Another factor which is; which will play a very important role is actually fog. And fog can be classified into different parts, the density fog, the thick fog, moderate fog, light fog, light mist clean air. And it basically depends, what kind of visibility you get? Suppose you have a 5 meter visibility classified under density fog, you know dense fog. This is dense fog actually.

And then if the visibility is up to 200 meters, it is thick fog, similar so on and so forth, for clean air, the visibility can be about 18 kilometers. So, it is quite high for clean air. And under for different categories of fog, if you see that innovation for dense fog, for example, is 350 dB per kilometer, whereas, for thick fog, it is 75.

In a clean air, where the visibility is up to 18 kilometers, the attenuation is because of this is of the order of 0.6 dB per kilometer, it is quite low. So, these are some of the models which are used in calculating the loss which will happen in the atmosphere.