Optical Wireless Communications for Beyond 5G Networks and IoT
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Lecture - 11
Part - 2
Underwater OWC Channel Model…contd

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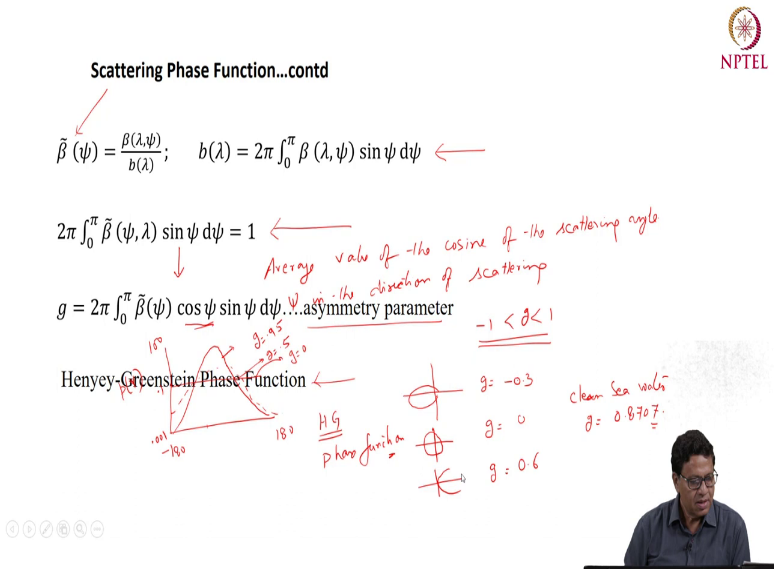

So, define yet another function which actually is scattering phase function now which is ratio of beta lambda psi divided by b of lambda. And b of lambda in the last slide we have calculated like is given here 2 pi 0 to pi beta lambda psi sin psi d psi. So, this if I put this use these two equations, then I get this equation which is 2 pi 0 to pi scattering phase function into sin psi d psi which is equal to 1.

Now, if I take you know average value of the cosine of the cosine of the scattering angle psi in the psi in the direction of scattering. Then it will give me a parameter which is called g which is called a asymmetry parameter which is given by 2 pi from here beta tilde psi cos psi and sin psi d psi this is called as asymmetry parameter g.

And this g basically decides how the light is scattered, a negative value of g will tell you the light is scattered backwards positive value of g will tell you that it is scattered forward in the forward direction. And the absolute value of g if you see which tell you the amount of light scattered either in the backward direction or in the forward direction.

So, this g the value of this g is between 1 and minus 1 and if for example, if I have g is equal to say minus 0.3; that means, the light is reflected backwards something like this. If I take g is equal to 0 you know the light is in all the direction; so, this is some sort of isotropic scattering. If I take g value as little more high say 0.6 and plus value, the light is reflected in the forward direction.

So, basically the value of g tells you sin tells you whether it is backward reflected or forward reflected and the magnitude tells you how much amount is scattered in the backward direction or in the forward direction. So, for example, the value of g in clean sea water clean sea water that value is 0.8707. And also, for different values of g if I want to draw a plot between say angle which is the psi angle 180 this is and suppose this is starting from 0 0 1 to say 100, this is say some power p psi with respect to the angle.

Then if I have you know 0.1; so, somewhere here then if there is a straight line this corresponds to a grid g is equal to 0. So, in all the angles there is a equal amount of power and if I take very high value of g it is for example, it will have a distribution like this. So, this is g is equal to 0.95 for example, this is equal to g is equal to 9.95.

So, most of the power or lot of power is in the forward direction and it is confined within these angle the angle which is for example, you know within these angles. And if I take somewhere g is equal to 0.5, it will give me this is g is equal to 0.5. So, basically this g value tells you about how the power the scattered power is scattered at different angles and in what direction.

And so, using this g value a scattering phase function has been defined which is called as Henyey Greenstein phase function which is in short also known as HG phase function.

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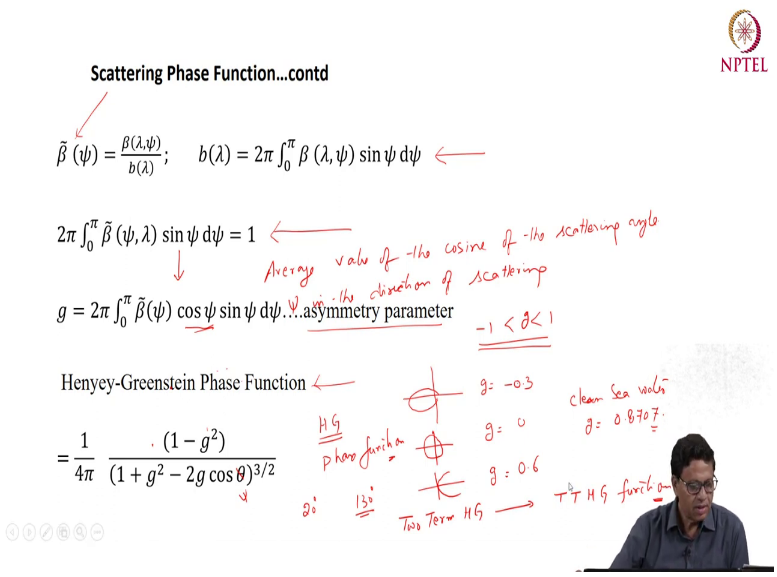

And this is let me remove this from here; this HG function is given as 1 by 4 pi 1 minus g square divided by 1 plus g square minus 2 g cos this is psi actually here, psi to the power 3 by 2. So, this is the Henyey Greenstein phase function and this actually basically deals with the you know angles when you have that psi angle between say 20 degree and 130 degree.

Any angle more than 130 degree or less than 20 degree this may not be entirely valid. So, for that another function is defined which is called as two term HG function or in short this is called TT HG function; so, this is how the scattering is modeled.

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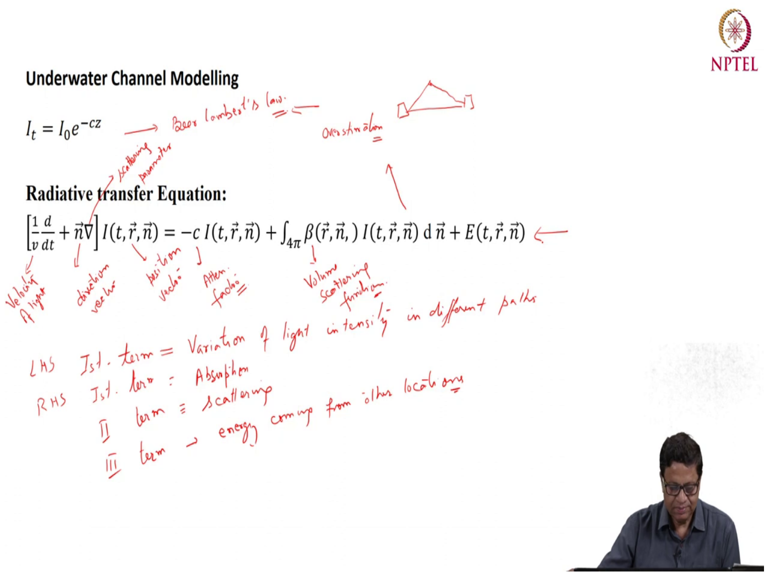

Now, let us try to understand the underwater channel modelling. So, I had explained you that the intensity the transmitted intensity is equal to I 0 that is the initial intensity and after it travels a distance of z, it is attenuated and it is given by beer Lambert's Law. This is same this is simple Beer Lambert's lamberts law and it actually does not assume that the light is also see for example, this is a transmitter it assume that all the light is traveling like this.

But there may be a possibility that some light can get reflected from some obstacle and the photon or the light can come back to the receiver and it adds to the receiver. So, this is not assumed in this simple formula which is given by I t is equal to I 0 e raised to power minus c z.

So, this basically overestimates the intensity at the at distance r; so, this does some o estimation. So, in order to have a correct estimation of the received power, we need to deal with a equation which is called as radiative transfer equation which is given by this. So, here if you see let me first explain what are the symbols here; so, this is velocity of light.

This is velocity of light and this is the direction vector and this is the scattering parameter scattering and r tells the position vector position vector. And so, intensity at position r and in this in the direction n this is how it is defined at time t. And this is the attenuation constant attenuation factor and this is your Volume Scattering Function VSF, volume scattering function.

So, basically if you see this consist of three terms the first term in this expression is variation of light intensity in different paths; so, let me write this this is variation of light intensity in different paths. And the second this is on the LHS, and in the RHS first term actually gives you is the attenuation part, it gives you the absorption part rather absorption. And the and the and the second term deals with the scattering part the scattering and if you see the third term this is the energy coming from other locations.

So, as I mentioned there may be energy coming from some reflection, not necessarily that all the energy comes from line of sight from other locations. So, this is how it has to be modeled in order to you know get correct picture of how the energy is scattered or absorbed inside the optical medium. So, very difficult to find out the close form equation, because it has integrals and differentiation and all that; so, basically it has to be solved numerically.

And if you take the limiting case of this like assuming that there is no reflection happening there is only line of sight. And all the all the light which is collected by the receiver is coming from the transmitter, it will reduce to Beer Lambert's law. So, r t reduces to Beer Lambert's law this is Beer Lambert's law.

So, it assumes that the light is monochromatic and there are no reflection refractions. And so, basically in order to get exact the this has to be numerically analyzed and calculated to get the behavior of light inside the water.

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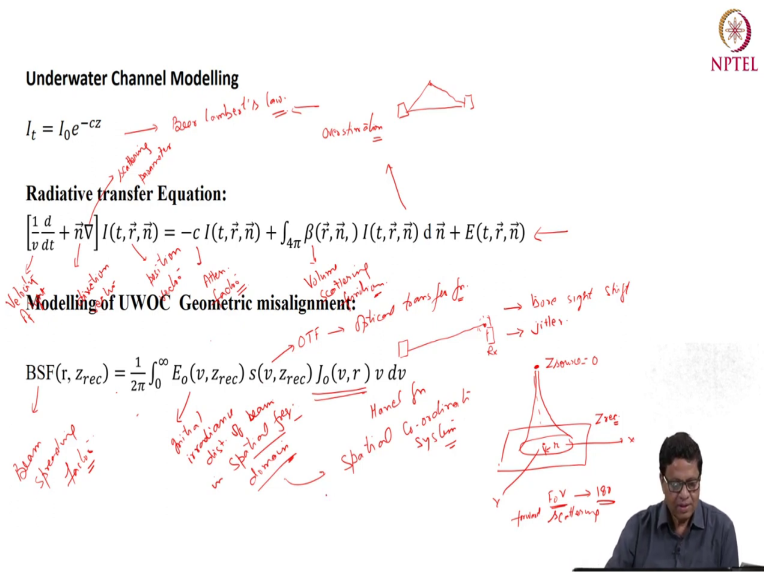

Another thing is how do you model geometric misalignment? So, what normally happens when the light travels from point a to point b inside the water. The two effects will occur, one of them is that if you have say this is transmitter this is your receiver. There may be a possibility that you will get this light which is at an angle and which is not you know in alignment with the receiver.

So, this is called as bore sight shift bore sight shift; so, basically the beam the center beam is away from the center that is a fixed displacement of beam away from the receiver this is called as bore sight shift. And the other is that the beam is jittery along a around a middle position; so, it is not constantly in this position, it is varying around this; so, this part is called as the jitter.

So, the beam is affected both by the bore sight shift as well as jitter. So, this can be modeled using this equation which is called as beam spreading factor this is beam spreading factor. So, the to understand this formula let me draw a diagram here; so, this is your source; suppose, this is your source this is z distance of this is source, say this is 0 and when the beam travels.

So, this is the receiver plane for example, this is the receiver plane; so, let me write this as the z receive. And this is the beam here and this is say r this area is referred as r, the radius is referred as r and say, this is x direction and this is you know y z y direction. So, this beam spreading factor at point r anywhere in the circle at z receive plane is given by 1 by 2 pi 0 to infinity, E 0 v z r is z receive this actually is initial irradiance distribution of beam in the special frequency domain.

So, this is irradiance initial the start initial irradiance distribution of beam in the special frequency domain. And this S v z receive is the optical transfer function optical transfer function optical transfer function which is the Fourier transform of impulse response. And this is you know converting the whole thing from special frequency domain to special coordinate system, I require a Hanel function which is given by this.

So, this is use Hanel function to convert this special frequency domain to special coordinate system coordinate system. So, this is how beam spreading factor can be defined or can be modeled, but again this is a quite simple explanation of beam spreading factor. Because, it assumes that F o V of the receiver is 180 degree I mean it is collecting lights coming from anywhere.

And it also assumes that there is only forward scattering which may not be the case scattering. So, under these limitations you know this may not be a highly accurate you know expression for beam spreading. So, there are more advanced modelling for beam spreading which assumes some particular F o V angle and also assumes that there are light coming from other sources as well.

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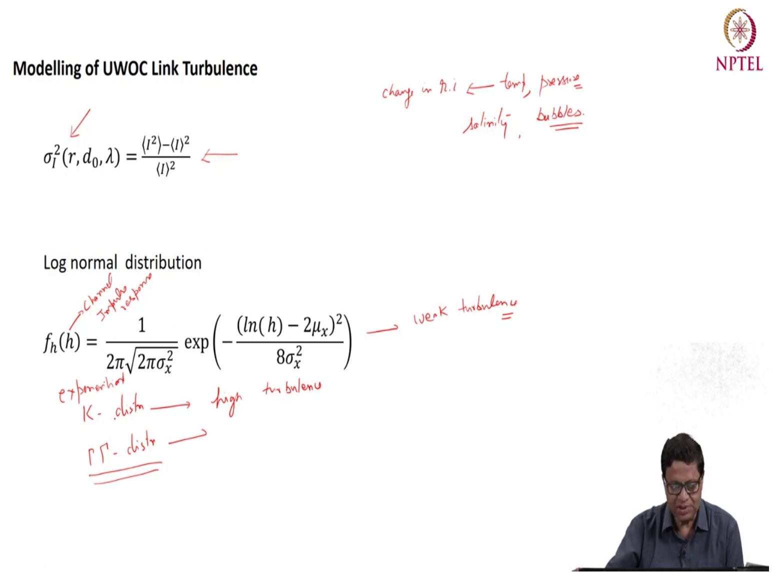

So, now let us discuss about the modelling of underwater link turbulence. As we had done when we are modelling outdoor channel, we had to discuss in detail about the turbulence part; so, we will discuss the turbulence modelling inside the water. So, during turbulence actually there are changes in the refractive index, change in a r i the water refractive index and this happens because there is a change of temperature or there is change of pressure or there are salinity, they are there are some bubbles inside the water.

So, this is going to effect the propagation inside the water, because of these factors because they all result in change of refractive index; the factors are temperature, the pressure, salinity of the water and formation of bubbles. So, as we had defined the turbulence factor by a scintillation index at some point are these you know this is the position where I am defining the scintillation index is defined as this.

This is you know same definition we have taken from outdoor channel modelling. So, one of the simplest modelling for turbulence we had considered was log normal distribution. And it is something given by this where h is your channel impulse response, this is the PSD channel impulse response and mu x and sigma x square are the mean and the variance.

So, this is a simple log normal distribution and we also discussed that this is only valid for weak turbulence. When the scintillation index is very very low that is weak turbulence and may not be valid for high turbulence. And then we considered another type of distribution which was K distribution which was valid for only high turbulence and we also studied about gamma and I K distribution.

So, gamma distribution was basically it is valid both for weak as well as high depending on the value of alpha and beta which we had considered those are the scattering parameters. So, in water we normally do not use these expressions because of you know salinity or bubbles or different temperatures, we need you know hybrid distribution or a mixture of two distributions.

We also consider exponential as well, exponential which was for again you know high turbulence. So, for modelling underwater we consider you know mixture of these two mixture of these distributions which we had discussed in the outdoor modeling.

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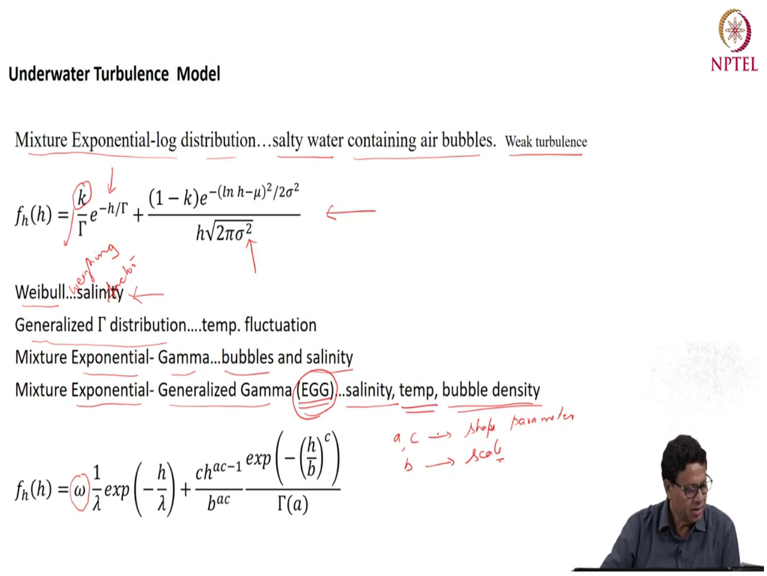

So, for example, if I use hybrid PSD of exponential and log normal distribution and this is valid where the water is salty and has some bubbles and under weak turbulence this this model shows good results. We can use I mean this is how it is represented here where this k is the weighing factor weighing factor, if it is too much salty or there are too many air bubbles.

So, this basically tells you the this is the exponential part and this is the log normal part. So, a water which is salty and has bubbles and weak turbulence this is a very good approximation for turbulence model inside the water. If you use a Weibull distribution, it is good for salinity; so, if the water has no bubble, but has lot of dissolved salt content this model is good model. And then we have generalized gamma distribution; so, this takes care of the temperature fluctuation inside the water.

So, this is a valid model when there is a lot of temperature fluctuation happening and then there is another mixture hybrid model of exponential and gamma takes care of both bubbles and salinity. And there is another model which is Exponential and Generalized Gamma which is also called as EGG model. It is quite popular, it takes care of salinity that is dissolved concentration of salts inside the water, takes care of the temperature fluctuation takes care of the bubble density.

And this model is actually represented like this, this is the distribution of the power spectral density omega is the weighing factor and you see here a b c. So, a and c are the shape parameters of the bubbles and b actually tells you the scale parameter what kind of scale large or small. So, this model which is EGG or EGG model mixture of exponential and generalized is a very good model takes care of all you know impairments of in the inside the c which is salinity, temperature and bubbles, density.

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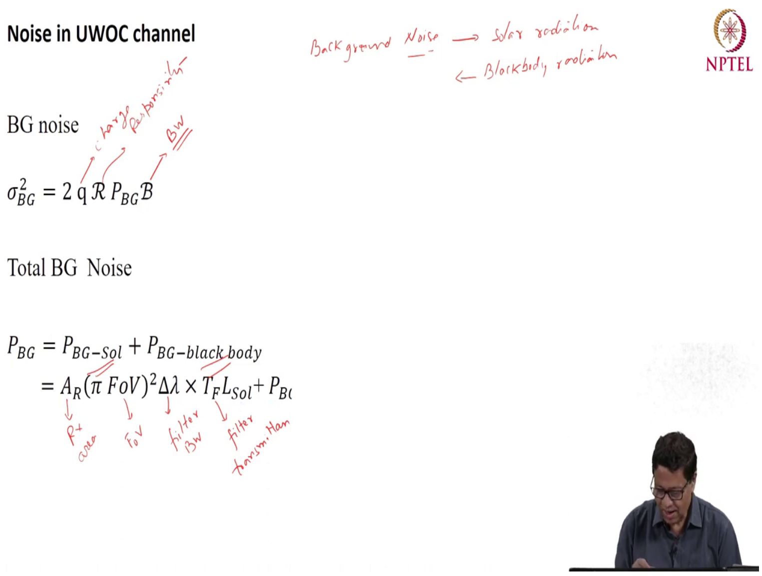

Now, we will see about the noise in underwater optical communication channel. So, one of the main noise is background noise, background noise; it has two parts, one part which is coming from the solar radiation the solar radiation which go inside the water. So, one part is solar radiation, the other part is because of light which is inside the water which is called as black body radiation and this is body radiation with bioluminescence.

So, this is the another contribution to the noise and the background the background noise can be written as we had seen earlier when we were discussing about the noise part is 2 q, q is charged and R is responsivity of the detector and P BG is the background noise and B is the bandwidth. So, as I mentioned it has two parts, one is solar radiation which is coming in the water and the black body radiation which are from inside the water; so, this is a combination of two parts, one is solar other is black body.

So, if you see the expression for background solar noise is given by A R, A R is the receive area R X area and this is field of view of the receiver and delta lambda is the filter bandwidth. So, this is field of view F o V and delta lambda is a filter which i may be using as the receiver filter bandwidth.

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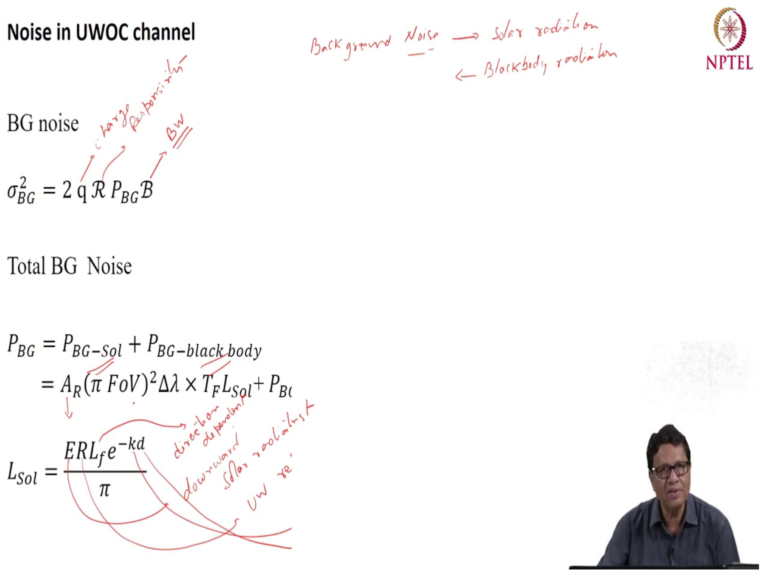

And this T F is the Filter Transmittance filter transmittance and this is the component loss because of the solar radiation and the other part is black body radiation. And if you see this L solar is defined as ERL f into e raised to power minus kd divided by pi. Where e is the downward solar radiation and ER is the underwater reflectance and L f basically tells about the direction of the solar which is falling on to the device inside the water.

So, this is something in direction and direction dependent quantity and k is the diffusion attenuation constant, diffusion attenuation constant and d is the depth at which you are trying to see the effect of solar d is the depth. So, this is how this L sol is calculated and then the other part is black body radiation; so, this is the background noise consisting of solar radiation and black body radiation.

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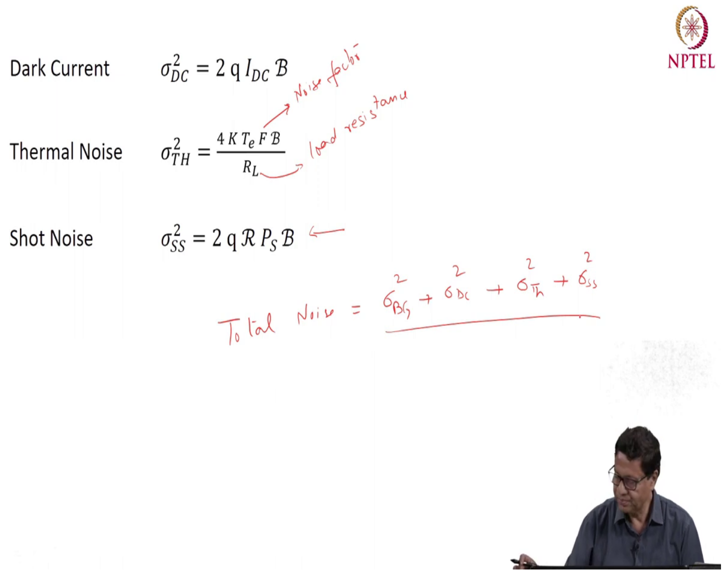

The other one is dark current which again we have studied in when we were discussing about the sources and detectors. So, this is given by 2 into q charge I DC there is a dark current in the photo diode and B is the bandwidth. Even if there is no light at the photo diode there is some current flowing which is called as the dark current, because the thermal agitation of the electrons inside the device.

The other one is the third noise is thermal noise which is 4 K T e B by R L and R F is the noise factor. If you are using pin diode or APD depending upon that you put the value of F, R L is the load resistance and K is the Boltzmann constant and B is the bandwidth. So, this is how thermal noise is calculated and the short noise which basically depends on the signal received or the power received is given by 2 q R R is responsivity P S is the received power, B is the bandwidth and as usual, E is the charge; so, this is the solar part.

So, the total noise inside the receiver the total noise will be some of these quantities total noise. So, which is equal to sigma square background plus sigma square direct current plus sigma square thermal plus sigma square short noise; so, that is the total noise in the system.

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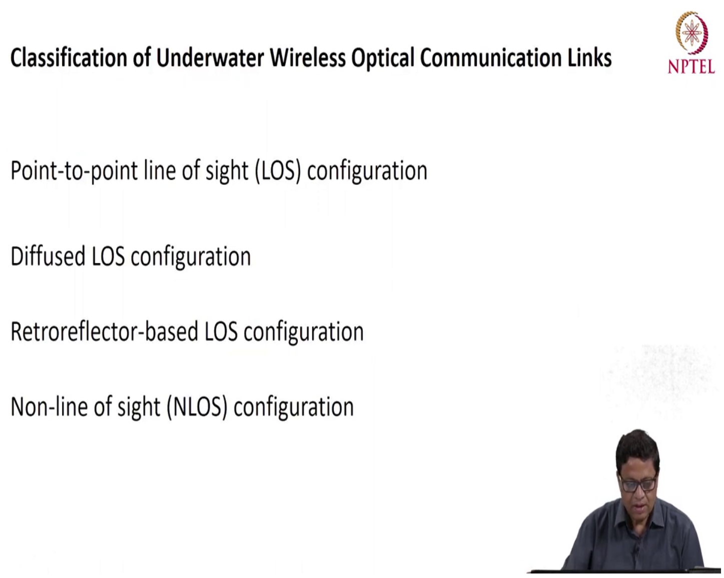

Now, let us try to understand how the beam optical beam propagates inside the water. So, there can be four options one is point to point LOS configuration, the second one is diffused line of sight, and the third is retro reflector based line of sight configuration and the fourth one is non-line of sight. So, we will now understand you know these four ways of transmission of optical propagation and links.

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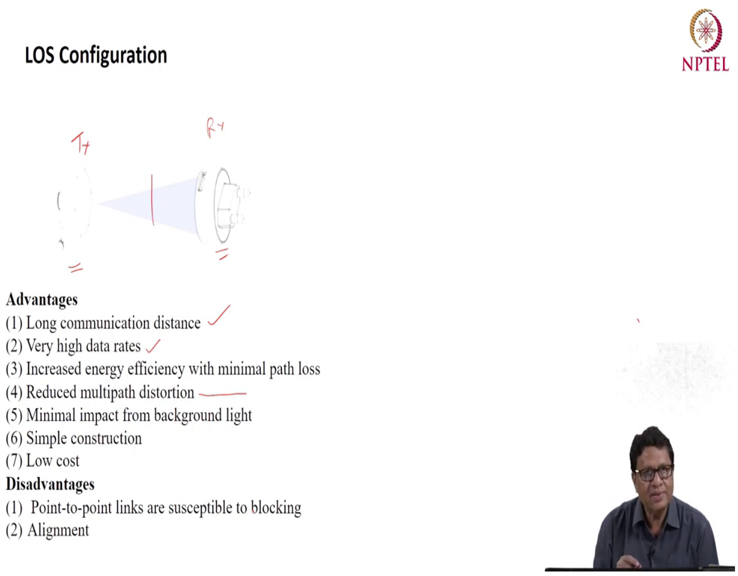

So, this is the first one is line of sight configuration where this is your T X, this is your R X. So, there is a line of sight communication and then this is you know beam is spreading as it travels inside the water and this is the receiver which is collecting the light which is transmitted.

So, the advantage for line of sight configuration is that you can have long distance communication, because the light is the total light is aligned or the transmitter receiver they are aligned it is you know line of sight; so, it gets a maximum light. So, we can have long distance communication and you can have very high data rates.

So, increased energy efficiency because the path loss is much less, because if the light is getting reflected from objects there will be you know decrease in the strength of the signal and this reduced multipath because there is not many multi paths here. So, this is mainly line of sight; so, reduced multipaths distortion. So, the effect of ISI will be minimal here and minimal impact from background light and simple construction and this is a low cost.

The issue with line of sight configuration is that if there are you know any obstacle here; for example, then there is no communication happening. So, this is one of the main issue it is susceptible to blocking, the second requirement is that both transmitter and R X they have to be aligned. If they are not aligned then line of line of sight is not happening; so, these are the few advantages and disadvantages of line of sight configuration.

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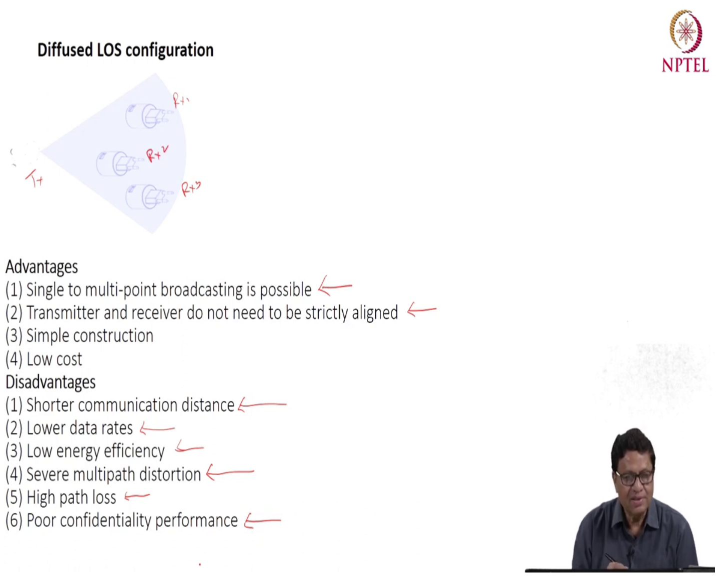

The second option could be diffuse line of sight configuration; so, here the light this is your Tx again these are different R X's R X1, R X3, R X2. So, the light is diffuse and it can cover many receivers, the advantage is that you have single to multipoint broadcasting. The data can go to different receivers which fall into this cone and transmitter and receiver they do not have to be aligned, because anywhere you put the transmitter you will get some part of the light.

So, that is alignment requirement is not require, this is a simple construction as a low cost. The issue is because the light is getting spread over large area; so, the intensity which falls onto the receiver gets reduced; so, this is therefore, the link distance may not be very high. The lower deteriorate because the power received by different receivers is low, low energy efficiency and it will have because the light is spread over a larger area.

So, there is a possibility that it will suffer multipath reflections from different objects. So, this will result into severe multipath distortion, high path loss because of multipath distortion and since it is being shared by different receivers. So, there is a security concerns or there is a poor confidentiality performance of such a equipment. So, these are the some of the you know pluses and minuses of diffuse line of sight communication.

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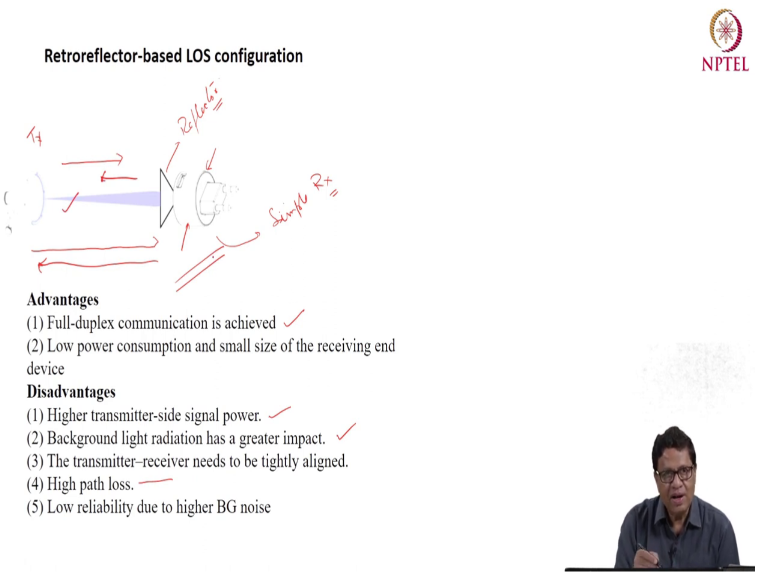

The third option is retro reflector based line of sight communication; so, here you have the receiver here and you have a reflector here. So, this is this is used when you have want to make a simple you know receiver which may not require lot of power. So, what actually happens, there is a high power beam which goes from transmitter this this is the darker line this line is actually the high power beam which is falling onto the reflector.

And what happens then the data is decoded here and also the data which is coming from this device is impinged on the light which will be reflected back to the transmitter. So, it is some sort of this transmitter is interrogating this receiver; so, the light is the high frequency light at the receiver is decoded. And then any information from this receiver is encoded and after reflection it goes back to the transmitter.

So, here this is a very low cost receiver which may not require enough power because there is no source required there is power which is getting reflected from the reflector. So, these are there may be some requirement where you want to have a device for a longer time or should have a long lifetime; so, you require you know less power consumption.

So, for those applications retro reflector based line of sight configuration is used. So, the advantage for with such configuration is that this is full duplex both the directions and then low power consumption at the receiver because of small size of the receiving and device. Because the receiver there is no transmitter it is that light which is it is getting received is getting reflected back into the same transmitter and it may be encoded or modulated.

The issue with retro reflector is you require a very high transmitter sight signal, because this power has to be very high because it has to travel you know twice the distance; so, this power has to be high. The background light radiation has a greater impact, because already the signal strength is very less after it traverses you know the complete distance, the onward distance, and reflected part the noise may dominate; so, this is another issue with retro reflector.

The another one is the transmitter receiver needs to be tightly aligned, they have to be aligned this does not use non-line of sight use a line of sight high path loss because of distance travelled in both the directions. And it is low reliability system because of you know more background noise which is coming into the system.

And sometimes you know the light which is going onward towards the receiver here and the same is reflected back, it may result into some sort of noise which adds further to the overall noise of the system. So, this is a less reliable system the only advantage is that you use a very low cost which uses very less power receiver device.

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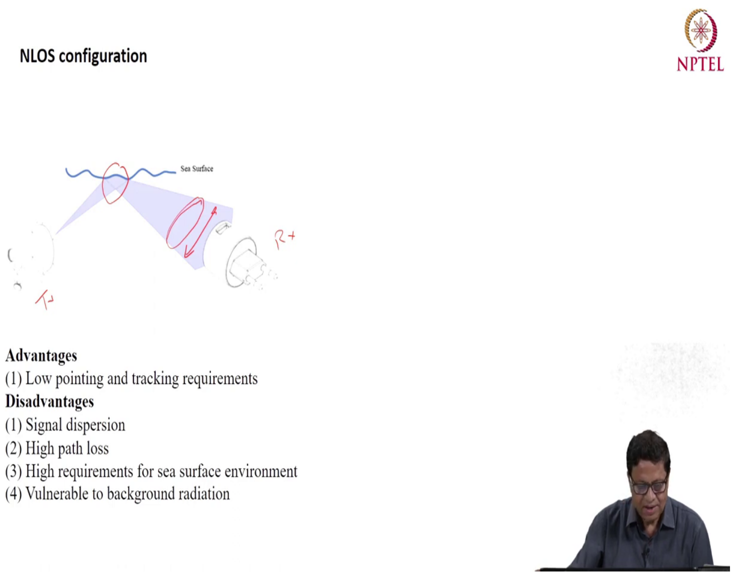

And the third the fourth part is non-line of sight configuration where you have the transmitter and the light gets reflected from the sea surface and collected by the receiver. So, there is a annular cone which is received by the receiver from a transmitter x. The advantage of this is low pointing and tracking requirement because there is a cone here; so, receiver can be any position here to capture the light. The disadvantage is signal dispersion, because it travels a longer path and there are various rays travelling.

So, it travels a longer path which results into some sort of dispersion high path loss because the reflectivity here is not very high at the sea surface; so, there is a high path loss. And then high requirement for sea surface environment; so, you require you know a calm water not turbulent water.

So, that you get ample amount of light and the receiver. And it is of course, vulnerable to background radiation, the solar radiations or other radiations like black body radiation; so, this is vulnerable to background radiation; so, this is non-line of sight.

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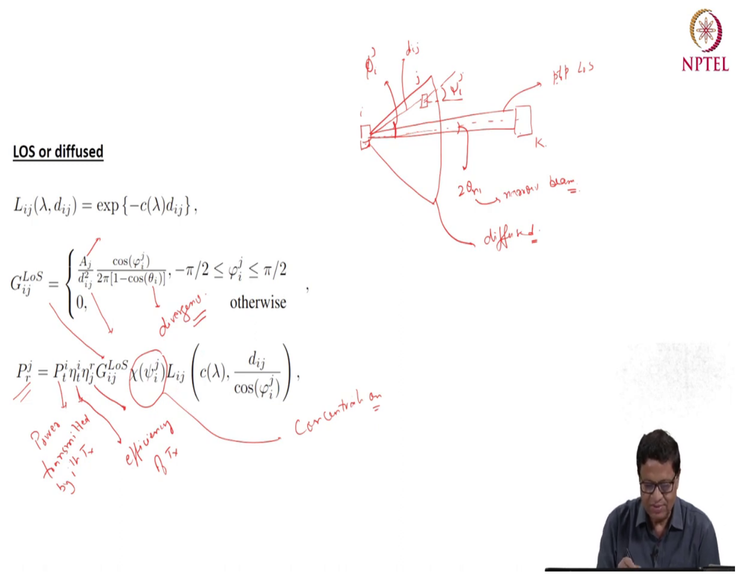

And now let us try to calculate what is the power received in line of sight or diffused system. So, let me draw for a line of sight or diffuse system suppose this is your transmitter i and there are two options one is you know a line of site; so, this is the receiver here.

So, this is line of sight this is point to point to point LOS and the other is diffused and diffused is say something like this and say suppose your receiver is somewhere here. And this is the normal part here and this is say this is K th receiver i is the transmitter and this is say j jth receiver and the light can be collected like this.

And the angle which it makes with the normal let us called as this angle which makes the normal let us call as the theta ij theta ij. And this distance from the ith and jth receiver is dij and this angle which is highly directional we can call this as 2 theta narrow beam. This is narrow beam which is point to point, and this is the diffused and this angle which it makes with the normal is say psi i j.

So, the loss which is function of lambda and the distance is given by simple beer Lambert's law which is exponential minus c lambda d ij, d ij is the distance. And the gain in the system is given by G ij line of this is for line of sight A j is the area of the receiver, d ij is the distance. And this phi theta ij or phi ij this is this is phi ij is given the is the angle between the normal and which it makes with the receiver j and this is the divergence angle of the beam divergence angle of the beam.

So, this is how G ij the gain in the LOS path is defined and it is 0 if the angle is away from minus pi by 2 and plus pi by 2. So, and if I calculate the power which is received at the jth receiver by the ith transmitter this is a received power is the power transmitted by the transmitter ith transmitter. This is the efficiency of the transmitter, this is the power transmitted by ith transmitter, and this is the efficiency of the transmitter of T X and this is efficiency of the receiver.

And this G ij line of sight is defined by this factor here and this is concentrator gain, because at the receiver we are using concentrator. Because, if I do not use concentrator, I require a wide lens receiver and using a wide lens receiver or photodiode will have more capacitance which will limit the data rate; so, I am using some sort of concentrator. So, this is defined this gain is defined by this factor and then L ij is the loss which is a function of c lambda iteration coefficient and function of d ij and cos phi ij.

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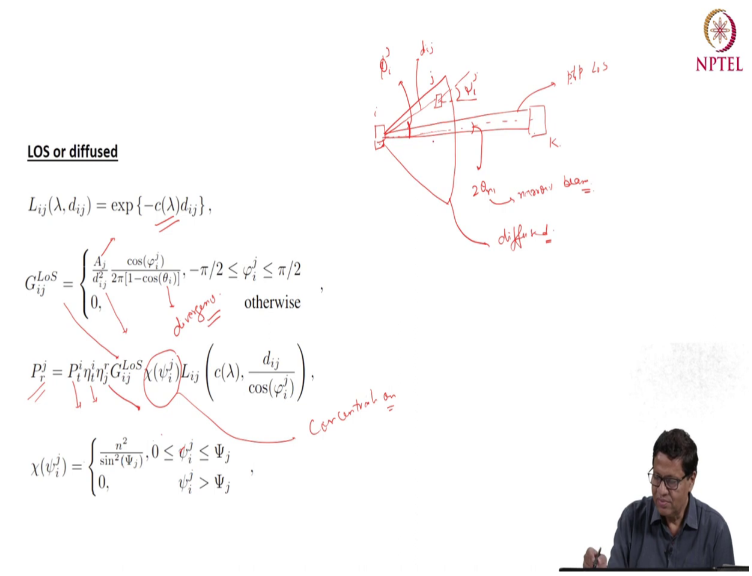

And if I see this concentrator gain which we also studied when we were studying the indoor modelling is given by n square sin square psi j, psi j is given here and n square is the n is the refractive index. So, this is how the received power for line of sight or diffused system this is this s I have given an example of a diffused system, but similarly one can calculate for a line of sight system.

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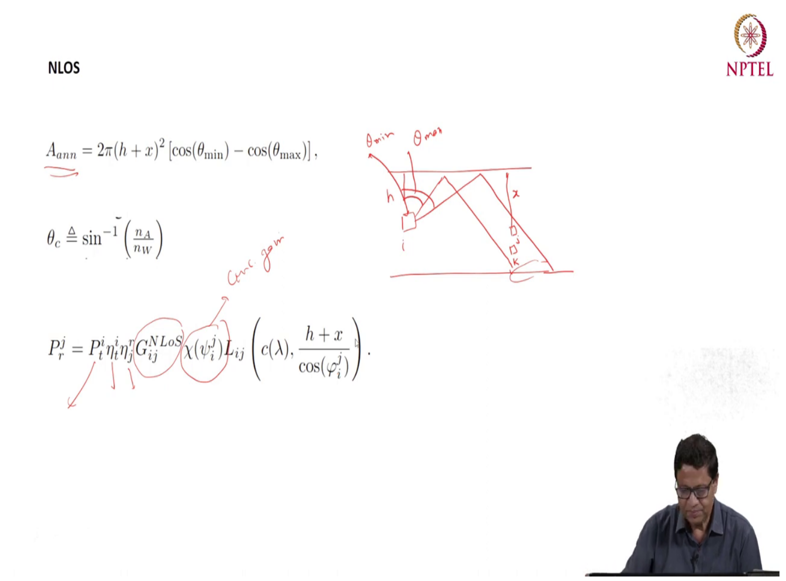

The next one is non-line of sight; so, in order to understand this non-line of sight. So, let us understand you know it is actually the light is getting reflected from the water surface. So, suppose this is your transmitter say i and this is at depth h; so, and your receiver is somewhere you know this light will get reflected like this.

The other light which get reflected will be like this and other light, they will be refracted they follow a simple Snells law at the surface at the boundary there is a air on this side, there is a water in this side; so, there is a difference of refractive index.

So, it will be only a annular portion of the light which will be reflected here also your receiver has to be somewhere here or somewhere in this region in order to capture the light. So, let us call this K this is J and this distance for example, j the receiver from the surface water is x.

So, it has been shown that if you have h plus of h plus x sphere radius that is 2 pi r square that area where the light is available for the receiver.

So, this A annular is given by 2 pi h plus x whole square into cos theta min; so, this is the vertical line and this angle and this angle this angle is theta max and this angle is theta min. So, this annular area is given by 2 pi h plus x whole square into cos theta max cos theta min minus cos theta max and we know the critical angle is refractive index of the air divided by the refractive index of the water sin inverse.

And if I calculate the power received by the jth receiver in this annular ring, this is actually annular ring is given by the transmit power by the ith transmitter, this is the efficiency of the transmitter i, this is efficiency of the receiver i. And this is the gain coming from the non-line of site component and this is the concentration concentrator gain this is concentrator gain. And then the attenuation L ij is function of c lambda at initial coefficient, h plus x that is height and cos phi ij.

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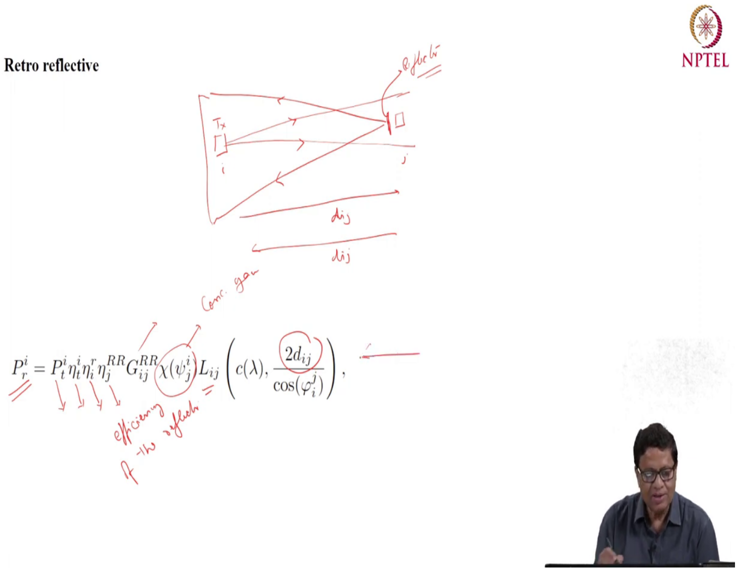

The third one is retro reflective, for retro reflective let us understand this is your transmitter here it gives a high power beam narrow beam high power. So, this is a high power beam narrow beam and the receiver is something here and then at the receiver side there is no transmitter. So, the rays are reflected; so, there is a reflector here; so, let me write like this is a reflected here reflector.

Here where the rays are whatever optical beam is received it is demodulated and then whatever data the receiver has is encoded and transmitted by the reflector. So, this is collected by this transmitter, this is the reflected beams in this direction and this is the transmit high power transmit beam and I had explained why we want to use retro reflective.

So, there are special requirements where you want to have receiver of low power long life. So, in this configuration you know using the we are using the reflector for sending the information back to the transmitter and if I want to calculate this is i this is j and if I am interested in calculating the power which is received by the ith transmitter.

This is the transmitter transmitted power, this is the efficiency of the transmitter element or transmitter, this is the efficiency of the receiver and this is the reflectivity or the efficiency of the reflector, this is this is the new term here efficiency of the reflector. And this is the gain which is added by the reflector G ij RR and this again is our concentrator gain and Lij is the loss as it travels.

Now, it is traveling two distance two twice the distance this is you know di j for example, and it also travels another di j. So, this is there therefore, this is 2 2 d ij and of course, function of cos phi ij; so, this is how the power can be calculated in the retro reflective. So, with this we come to we come close to we close our discussion or underwater optical communication systems.

So, in this lecture we have modeled different disturbances of underwater like turbulence, what is the background noise, what is absorption, what is the scattering, misalignment, the background noise all other things we have seen. And we have also modeled you know different turbulence where we need to have a mixture of two turbulent models which are ideal for modelling underwater turbulence.

And then we also discussed about different configurations, the line of sight, non-line sight, retro reflective. And diffuse and we also calculated the power received in all these cases; so, we stop the discussion at this point for underwater channel modelling.

Thank you.