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

Lecture - 46
Underwater Wireless

A Good morning, my name is Rehana Salam and I am pursuing my PhD from Triple IT, Delhi. My research area is Underwater Wireless optical communication.

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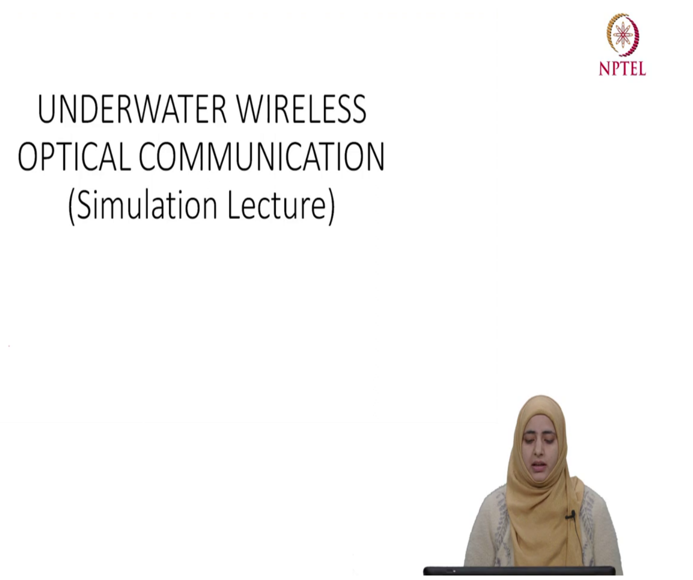

And in today's lecture we are going to have underwater wireless optical communication and this lecture is about the simulation of underwater wireless optical communication.

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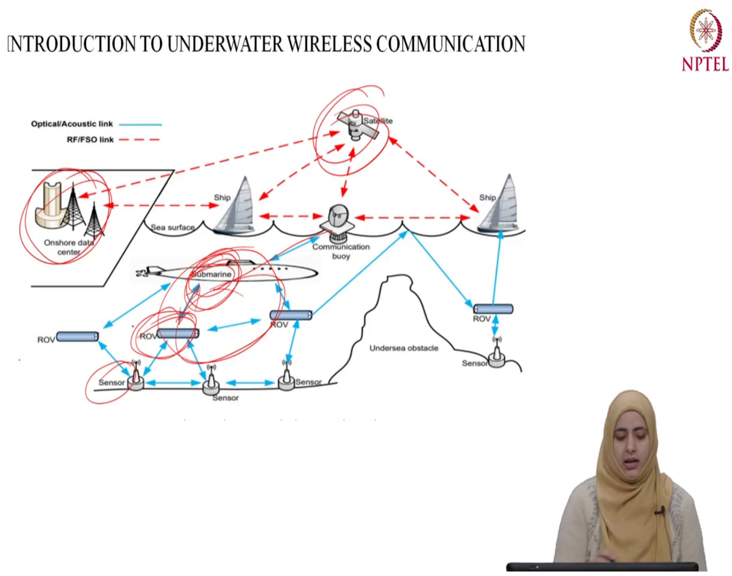

So, starting with this slide it is the about the introduction to the underwater wireless communication. So, here this figure is actually an underwater wireless sensor network with aerospace and terrestrial communication and it is actually combining the terrestrial part with the aerospace to that of the underwater communication part.

Here if we look deep into the underwater communication part, here you can see that in this underwater part the ships are communicating with the submarines or we can say the communication voice which convert the signal from the free space to the underwater communication underwater signal they are communicating with the submarines and these submarines are in turn communicating with the ROVs which are actually the remotely operated vehicles.

And finally, these ROVs are communicating with the sensors. Also, we can see that the communications are possible in both the ways these double arrows these doubled arrowed lines are showing that the communication is possible from inside the water to the outside as well as from the outsider outer space to the inside. And this is also one of the goal of the 6G is to have the combination of this terrestrial communication with the aerospace and the underwater communication.

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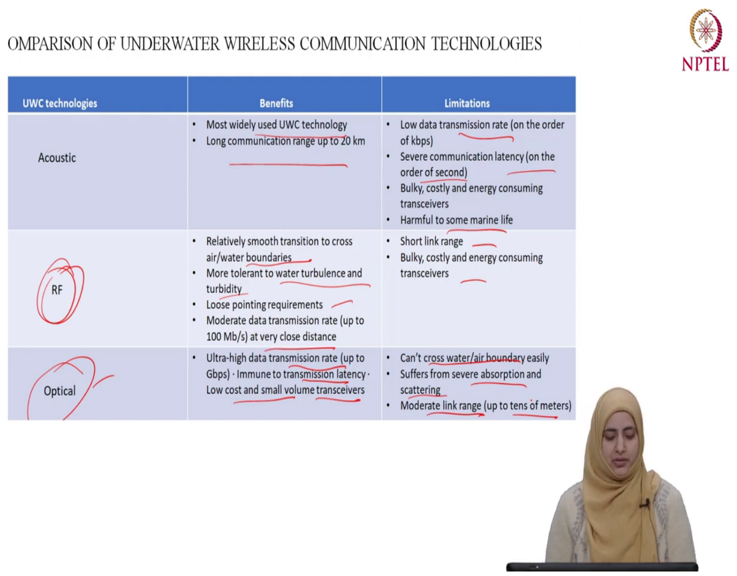

So, next is the comparison of underwater wireless communication technology and for the underwater wireless communication we have right now presently we are having 3 different communication technologies one is the acoustic communication, another one is the RF communication and the last one is the optical communication and all of them have their own benefits and the limitations.

So, starting with the acoustic communication, this acoustic communication it is most widely used underwater communication technology and it is used because of its long range which is up to 20 kilometres. But it is having the limitation of low data rate of the order of KBPS, severe communication latency of the order of seconds, bulky costly and energy consuming trans receivers and the most important limitation of this acoustic communication is that it is harmful to some of the marine life.

And next is the RF communication. In this RF communication, the benefits include the relatively smooth transition to cross the air water boundaries, more tolerant to water turbulence and turbidity, loose pointing requirements and moderate data rate transmissions at very close distances. So, using this RF communication we cannot go up to our distances of kilometers and the limitations of this RF include short link ranges and the bulky costly and energy consuming transceivers.

And the last one is the optical communication. You might have studied about these underwater communication technologies in your theoretical lectures and I am just giving the brief again revising these things. So, that you will you can understand the simulation things easily. So, talking about these optical underwater communication technology. It is an ultra high data transmission rate having the benefit of immune to transmission latency, low cost and small volume trans receivers.

And the limitations of this optical communication include the include that it cannot cross the water air boundary easily and it suffers from severe absorption and scattering. And the most important limitation of this underwater communication, optical underwater communication technology is that it is moderate, it has a moderate link range up to tens of meters.

That means if we are using the optical communication with that optical communication, we cannot go beyond a distance of 100 meters. That means we cannot go a distance; we cannot have the distances up to kilometres as we are able to get in case of the plastic communication. So, this is the main benefit, main limitation of the underwater optical communication.

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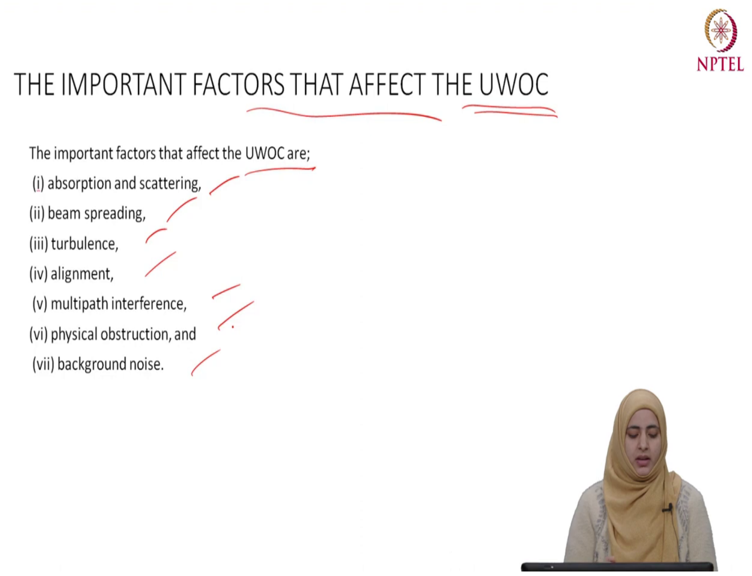

Next, next is the important factors that affect the underwater optical communication. So, here in the previous slide I discussed about the different underwater communication technologies and since the underwater optical communication technology have the benefit that it can, it has the benefit that the overall data rate is large compared to, it is in GBPS compared to the RF and the acoustic communication that is the reason that we are focusing on this optical communication.

So, that we can have the real time data transmission for which we need in many of many applications like the military applications and many such other applications as well. So, that is the reason that we are focusing on the underwater optical communications and the most important factors that affect this underwater optical communication.

Now, we will be talking about the underwater optical communications only. The important factors that affect the underwater optical communications are first is the absorption and the scattering, the beams spreading, the turbulence, alignment, multipath interference, physical obstructions and the background noise. So, these are some of the factors that affect the underwater optical communication.

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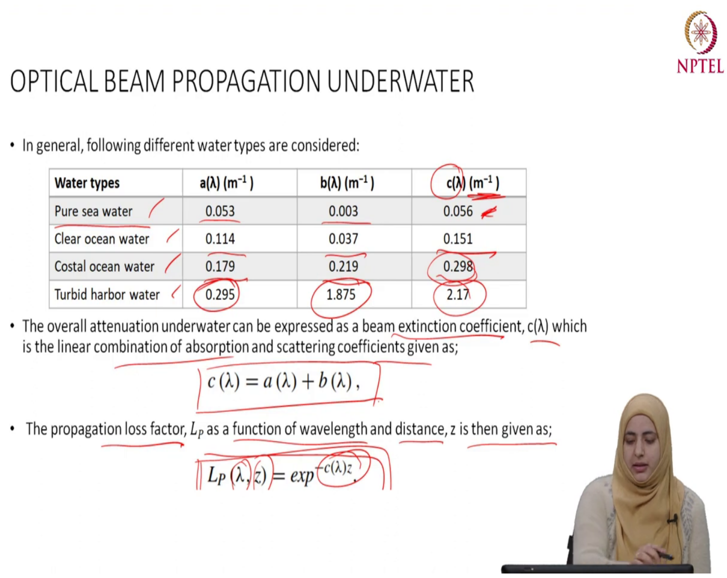

So, next is the optical beam propagation underwater. So, if we talk about the underwater propagation, optical underwater propagation, in general we say that we have different type of waters and these water types include the pure sea water, the clear ocean water, the coastal ocean water and the turbid harbor water. And these different waters has been divided on the basis of their absorption and the scattering coefficients.

So, talking about the pure sea water. So, here you can see that the absorption coefficient is 0.053 whereas, its scattering coefficient b lambda is only 0.003 and the c lambda which is actually the summation of a lambda and b lambda is the in the pure sea water it is only 0.056 meter inverse which is its unit.

Now, talking about the clear ocean waters in clear ocean waters the absorption coefficient is 0.114 and the scattering coefficient is 0.037 and hence the total attenuation coefficient of this clear ocean water is 0.151. Next is the coastal ocean waters. In coastal ocean waters the absorption coefficient is 0.179 and the scattering coefficient is 0.219 and the total absorption total attenuation coefficient is 0.298.

Next is the turbid harbor water. This turbid harbor water it has most of the dissolved particles in it because of which its absorption coefficient is large compared to all the other type of waters. And in addition to that the scattering coefficient is also the highest among all the water types and hence the total attenuation coefficient is 2.17 meter inverse.

But the overall attenuation coefficient can be expressed as the beam extension coefficient c lambda which is the linear combination of absorption coefficient and the scattering coefficient; that means, the c lambda is equals to a lambda plus b lambda. So, but let me tell you one thing that these pure sea water clear ocean water these a lambda and b lambda c values these are not like these are not fixed you will they will vary on the basis of papers.

For example, I have taken these from one paper in some other paper the values may vary a bit, ok. So, it is not like it is always it will be 0.056 it is 0.056, but in some other papers the values may vary a bit. So, that you should take into that you should keep in your mind that it is 0.056 according to the paper I am considering I am referring which I have given at the end of one of the slides at the end of the presentation and, but in some other papers this these values may vary.

And now we are familiar with this attenuation coefficient which is actually the summation of the scattering coefficient and the observation coefficient that is b lambda and a lambda respectively. Now, we can calculate the total path loss of the total path loss from the transmitter to the receiver. So, the total propagation loss or the attenuation loss or the path loss L P as a function of wavelength and distance z is then given as e raise power minus c lambda into z.

So, this L P lambda and z it is a function of lambda and z and it is equivalent to e xp of e minus c lambda into z. So, it is a function of lambda and z and this law is also called as the Beer Lambert's law. So, this is the how we actually account for the how we calculate the attenuation in case of the underwater optical communications considering the scattering and the absorption coefficients.

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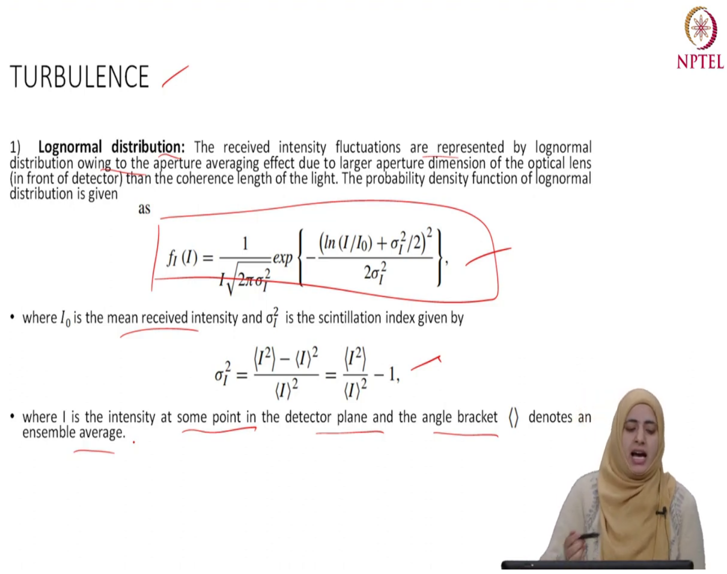

So, next is the turbulence. Next is the turbulence till now we consider the absorption and the scattering which will be happening because of the particles present inside the water. And the other factors which results in the loss of signal from the transmitter to the receiver while travelling is the turbulence.

Turbulence is actually we can describe it as an event where the refractive index of the water or the medium will change because of because of certain events like the change in the pressure, change in the temperature or change in the salinity of the water or water medium. So, that is called as the turbulence and it is one of the important factor which results in the loss of the overall, loss of the overall signal loss of the signal from the transmitter to the receiver.

So, it should be considered when we consider the underwater communication. So, it is necessary to consider the turbulence when we consider the underwater communication. So, a turbulence for the underwater communication for these generally the what the researchers are doing they are simply taking the free space optical communication turbulence models and using them for the underwater communication.

For example, here is the log normal distribution this is the received intensity fluctuations are represented by the log normal distribution owing to aperture averaging effect due to larger aperture dimensions of the optical lens in front of the detector than the coherent length of the light.

The PDF of this log normal distribution is given by this PDF and where I naught is the mean received intensity and sigma, I square is the scintillation index given by this formula where, I is the intensity at some point in the detector plane and the angle bracket denotes and ensemble every. So, this is the log normal distribution.

But there are many turbulence models. Here I am talking about the log normal distribution which is the first distribution we generally use for the underwater communications, but this log normal distribution only accounts for the weak turbulence of whenever we assume that the turbulence is weak in that case, we take this log normal distribution log normal distribution.

But, if we want to consider all the type of turbulence is sorry all the kind of turbulence for example, from strong to weaker turbulence in that case we cannot use the log normal distribution we have to use some other distribution in that case.

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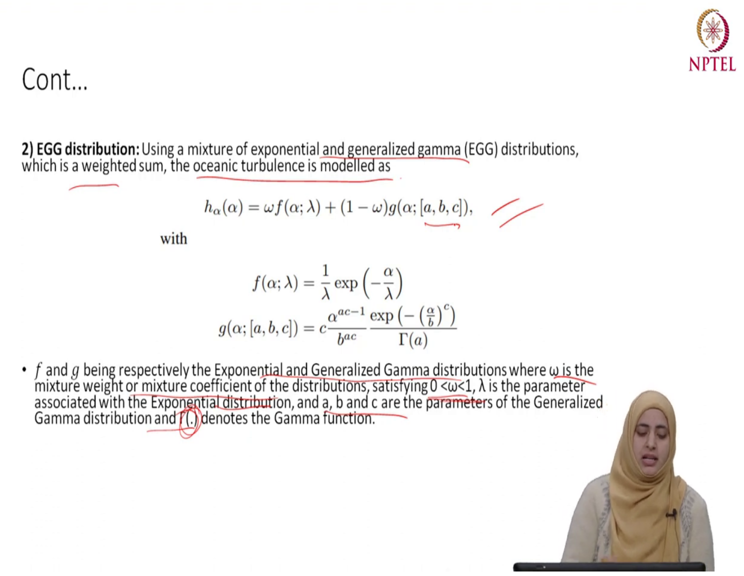

And here this is the distribution we can consider and this distribution can be considered when we assume that the turbulence can be from weaker to the stronger. So, even if we are having with a weak turbulence we can use the log normal distribution, but we can also use the egg distribution. But for the strong turbulence we cannot use the log normal distribution, but we can use this egg distribution.

And this what is this egg distribution it is simply using a mixture of exponential and generalized gamma distribution which is weighted some the oceanic turbulence is modelled as this is the PDF of this distribution where f and g being respectively the exponential and generalized gamma distributions where omega is the mixture weight or mixture coefficient of the distributions. We satisfy this omega from lies from 0 to 1 and lambda is the parameter associated with the exponential distribution.

And a, b, c are the parameters of the generalized gamma distribution and this is the gamma function this symbol denotes the gamma function. So, here you can see that we are having three variables a, b, c and these variables a, b and c respectively represents the variation in the pressure, pressure, salinity and the temperature of the medium.

So, depending upon the values of a, b, c we can say that the temperature the pressure and the salinity of the water is like for example, these a b c values can a b c can take any values, which we will see in the later slides how we can model then them and how we can get their values.

So, this is about the turbulence model and we can have many other turbulence models, but in today's lecture we have only used these two type of turbulence models for the underwater communication simulations that is. So, that is the reason that we will be talking about only these two turbulence models.

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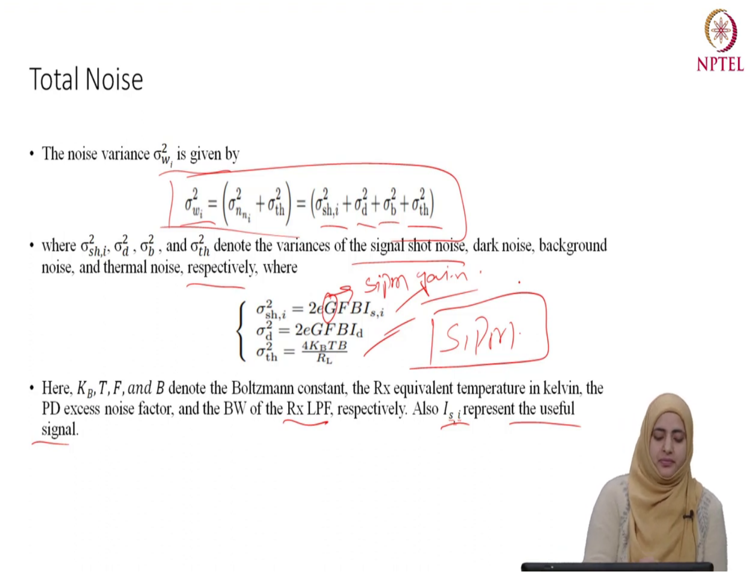

So, next coming to the total noise. Now, if we talk about the noises in underwater communication the noises can be given as there is a formula for the noises as it is for any other system as well not only for the underwater systems or the underwater communication systems only.

So, it is the combination of short noise, dark noise, background noise and the thermal noise where this is the equation and these sigma sh i sigma d square sigma b square and sigma th square denotes the variance of the signals short noise, dark noise, background noise and the thermal noise respectively. And the formulas for these short noise, dark noise and the thermal noise these are given by this equation and this is for the silicon photomultiplier.

This is for the silicon photomultiplier where K B T, F and B denotes the Boltzmann constant the receiver equivalent temperature in kelvin the photo detector excess noise vector and bandwidth of the receiver low pass filter respectively. Also, I s i represents the useful signal. This I s i means that the it represents the received signal. It is actually the multiplication of the transmitter signal with that of the channel gain and this G is actually the this is the silicon photomultiplier gain, ok. So, this is all about the noises.

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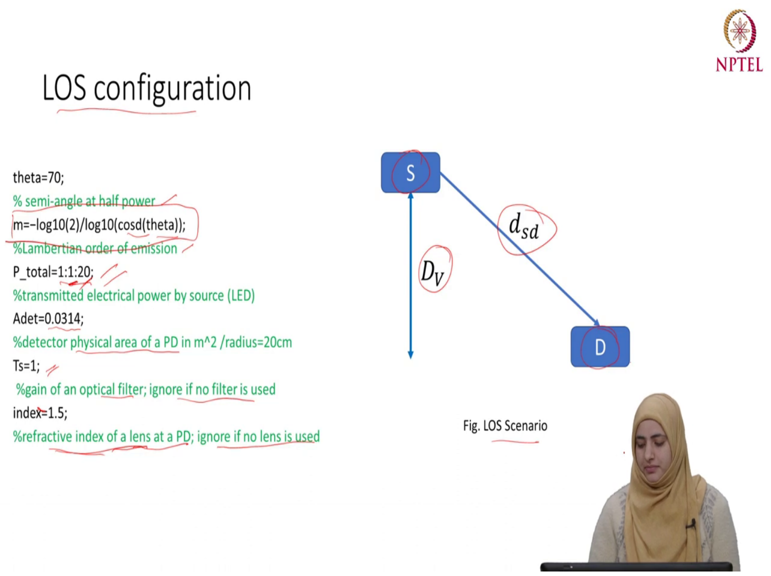

And next is coming to the configurations Anand sir might have taught you about the different underwater optical communication configurations, there are four different underwater optical communication configurations. One is the point to point line of sight configuration the other one is the point to multi point line of sight configuration and the third one is the retroreflective based line of sight communication and the last one is the non line of sight communication.

So, in today's lecture we will be talking about 2 configurations. One is the line of sight configuration and the other one is the non line of sight configuration. So, here I will be starting with the line of sight scenario and here you can see that we are having a source and we are having a detector or the receiver.

This is everything is inside the water. So, whole of this setup is inside the water and here you can see that this detector is at a vertical distance of D V from the source and it is at a distance of d sd from the source. And here how we can simulate this kind of a scenario for the underwater communication.

This is what I have given over here. Here you can see that starting with the semi angle at half power this is actually the LED parameter here in this setup we are considering an LED. Let me clear you that for the underwater communications we can use both type of sources like the LED as well as the laser.

But using LED it has its own benefits and the limitations and if we use the laser source that also have its own benefits and the limitation. So, for this scenario I have considered the source as LED and this is the detector and this is the semi angle at half power and this is we are considering the Lambertian channel model for this kind of scenario and that is the reason I have written over here that Lambertian order of ambition given by this m equals to minus log 10 log to the base 10 of 2.

So, now starting with the simulation part you might have sir might have taught you about different underwater optical communication configurations there are actually four different type of underwater optical communication configurations. One is the point to point line of sight configuration, the other one is a diffused line of sight configuration or point to multi point line of sight configuration.

The third one is the retro reflector base line of sight communication and the last one is the non line of sight non line of sight configuration. So, in today's lecture we will be discussing about two configurations which is the point to point line of sight configuration and the non line of sight configuration.

So, here in this case first of all we will be discussing about the line of sight configuration and here we have considered a scenario line of sight scenario where we are considering the source which is directly communicating with the detector and this whole setup has been placed inside the water.

So, this is an underwater setup where the detector is at a distance of at a vertical distance of D V from the source and it is at a distance of direct distance of d sd from the source. And in addition to that for the underwater optical communication simulations we can use different sources we can use the LED as the source as well as the laser as the source all of them have their own benefits and the limitations.

So, here in this case for this kind of a scenario we can we are using an LED as at the source and. So, the simulations can be done like this. The first I have started with the theta which is actually the semi angle at the half power and we are considering the Lambertian pattern of the LED.

And the it is given by this value m which is actually the minus 10 minus log to the base 10 of 2 upon log to the base 10 of cos d of theta and the total transmit a total electrical power by the source is given as 1 is to 1 is to 20 because my plot is going to be the received power with respect to the transmit power that is the reason that I need to vary the transmit power, which I have varied from one with the variation of 1 watt to 20 watts up to a distance up to a power of 20 watts.

And the total detector physical area is I have considered as 0.0314 it is actually it is actually the physical area of the photo detector in meter square and the gain of an optical filter or if we are using a filter only then we will consider this gain. And ignore if no filter is used this is represented by the variable Ts which is equals to 1 and the other this is the refractive index of the lens at the photo diode ignore if no lens is used.

So, let me clear one clear you one thing that the photo diode, which we are using inside the water it is actually the same photo diode we use in case of the terrestrial communication systems and that is the reason that it is made of the glass and its reflect it is refractive index will not change if we are placing it inside the water because it is placed in such a way that its refractive index will not change inside the water. So, the refractive index of the lens will again be 1.5 in the underwater cases as well.

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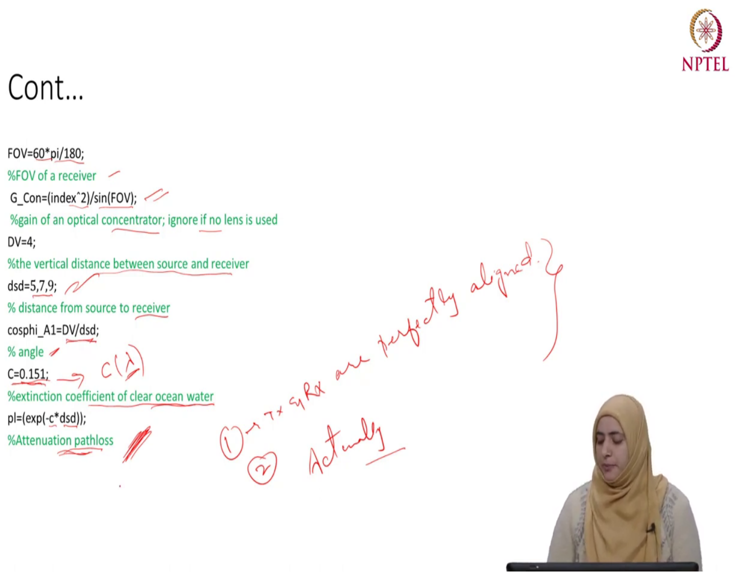

So, next is the next is the FOV of the receiver here the FOV has been taken in radiance that is the reason the FOV is taken as 60 into pi by 180 and the gain of optical concentrator is given by this formula. It is the index square divided by sin of FOV and the vertical distance between the source and the receiver is given as 4 meter.

And the distance from the source to the receiver is varied. I have here in the final result you will see that I have plotted the result for different distances as well that is the reason that I have written over here as 5, 7 and 9. And the angle cross of pi A1 is given by this and DV upon dsd and the extinction coefficient of clear ocean water is given as C equals to 0.151.

As I already told in the previous slide that we can have different type of waters and the type of water the value of C lambda depends upon the type of water. And here since we are considering the clear ocean water that is the reason that we have considered the value of C to be equals to 0.151 this is actually the value of C lambda it is actually dependent upon the lambda.

So, here I have represented this variable by C only and it is 0.151 and attenuation path loss we can simply calculate the path loss as e x e raised power minus C lambda into dsd as already discussed in the b lambda according to the Beer Lambert’s law. So, here we have considered the attenuation path loss by using the Beer Lambert’s law, but let me tell you one thing that here we have considered the Beer Lambert’s law, but we assume we take two assumptions while we consider the Beer Lambert’s law.

The first assumption is that the transmitter and the receiver and the Rx they are perfectly aligned perfectly aligned; that means, there is no alignment mismatch aligned. And the second one is that all the photons all the photons which scatters or we can say all the scattered photons we do not consider them although there might be some of the scattered photons may reach to the receiver of after certain scattering events, but we do not consider any of that any that any of that scattered photon.

And we assume that all the photons which are scattered are lost and they are not received at the receiver which is actually not true. There might be certain photons which after multiple scattering events which may reach to the receiver, but while we use this Beer Lambert’s law, we take these two assumptions. So, there are many other path loss or the attenuation path loss models for the underwater optical communication, but generally we take this Beer lamberts law because it is very simple, ok.

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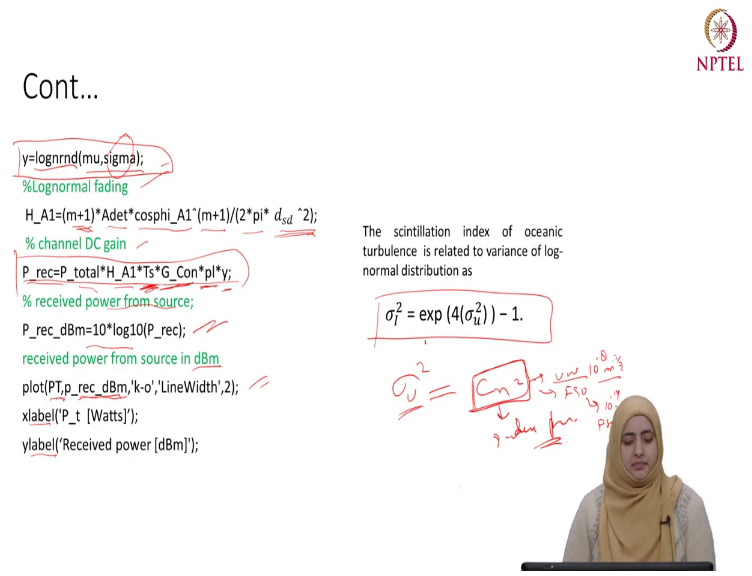

So, next is the log normal fading, we already discussed about the different fading models or different turbulence models. Here in this case for this kind of this line of sight scenario. I considered the log normal fading and it is there is a direct directly in MATLAB we can use this lognrnd mu comma sigma we can directly use this to generate the log normal fading variables randomly generated log normal fading variables and the total channel gain can be given as this using this formula.

It is a theoretical equation these equations you might have studied and it is given as m plus 1 area of the detector and cosphi A1 raised to the power m plus 1 divided by 2 pi d sd cos square d sd is the distance direct distance between the source and the detector.

And the total received power from the source can be given as total transmit power into the channel gain and multiplied with Ts which is actually the Ts is already in we discussed in the last slide concentrator gain multiplied with the gain of the concentrator. pl is the path loss and y is this log normal fading.

So, the total received power is given by this formula and if we want to present this in terms of dBm then we can convert this power into dBm using this formula and we can plot it like this. So, this is how we plot the total transmit power with respect to the received power the total transmit power in x axis the received power in dBm in y axis and this is the x label and the y label.

Here one thing I would like to mention that the this in scintillation index of oceanic turbulence is related to variance of log normal distribution this variance of log normal distribution using this formula. It is actually sigma I square is equals to exponential of 4 times sigma u square minus 1 or we can say we can also say that if you see the equation of this sigma u square with respect to each or we can say it is the right of variance for example, it is related to C n square which is actually the index parameter.

The although we take the same turbulence model which we use for the free space communications, but this turbulence this index parameter is different for the underwater and the free space case. It is around 10 raise to the power minus 8 meter minus 2 by 3 for the underwater cases whereas, it is around 10 raise to the power minus 14 for the free space optical communications. You can check it from any of the papers any of the underwater optical communication papers.

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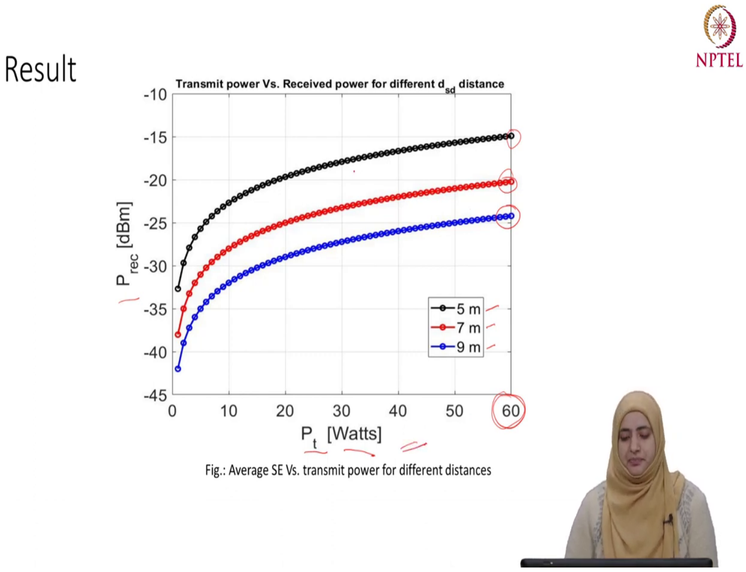

And next this here is the result which is plotted it is actually the receipt power with respect to the transmit power in watts. Here you can see that the I have plotted it for three different distances 5 meters 7 meter and 9 meter.

So, for the 5 meter of distance you can see that the received power in dBm I am getting at a transmit power of transmit power of 60 watts it is around minus 15 dBm and at a distance of sorry for a distance of 7 meters it is around it is around minus 20 dBm and for a distance of for a distance of 9 meter it is around minus 24 dBm.

So, here if we compare it for different distances you can see that as we increase the distance the received power is decreasing it is obvious that if we increase the distance the path loss will increase and hence the; obviously, the received power is will be decreasing which has been shown in this plot in this result.

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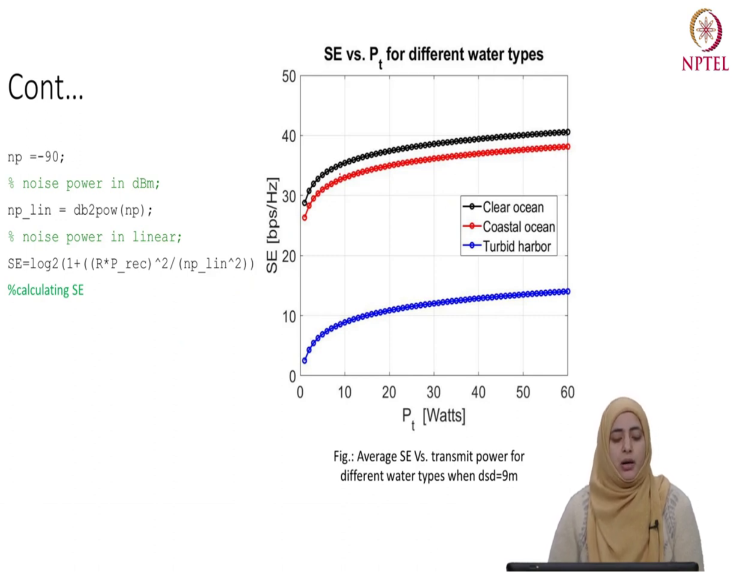

Next is the case here till now I plotted only the received powers, but for plotting the for plotting the spectral efficiency using the Shannon capacity formula which is given by log2 1 plus s n r for that I need to consider the noise powers as well and for this setup this line of site setup I have considered the fixed noise power of minus 90 dBm and converting it to the linear power. And finally, we can calculate the spectral efficiency using this formula log2 1 plus R into the received power of square divided by noise power linear cost square.

And I have shown over here that how the spectral efficiency varies with respect to the transmit power again you can see that the spectral efficiency for the it has been plotted not for different distances now I have plotted it for different type of waters wearing the value of c lambda I told you that by wearing the value of c lambda we can have we can the value of c lambda for different water types is different and by wearing this value of c lambda we can say that this water is clear ocean this is coastal ocean.

And this is turbulent harbor here you can see that the value of spectral efficiency it is around 40 bits per second per hertz at a transmit power of 60 watts for the case of clear oceans. And we already know why it is so? Because the value of c lambda for the clear ocean waters is small and in compared to that the coastal ocean waters have larger absorption and the scattering coefficient or we can say the overall attenuation coefficient and that is the reason that its spectral efficiency is lower than that of the clear oceans.

And compared to these two the turbulent harbor has the highest dissolved particles that is the reason that its absorption coefficient as well as its scattering coefficient is highest among all the type of waters that is the reason that its spectral efficiency is least compared to all the other type of waters.

So, it has been shown over here that this is the average spectral efficiency versus the transmit power for different water types when the distance from the source to detector is considered to be 9 meters. So, we can say that the spectral efficiency will the total spectral efficiency received at the receiver will vary according to the type of water and it will be least for the case of turbid harbor waters whereas, it will be highest in the case of clear ocean waters if we are considering these three kind of waters. So, this is all about the line of site scenario.

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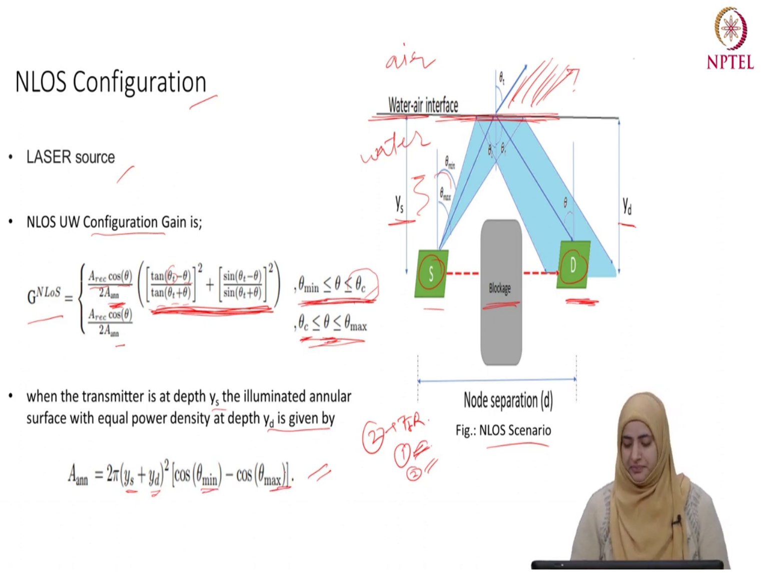

Now, next is the non-line of site communication scenario. Till now we consider the line of site scenario where we considered a single source and a single detector similarly, following the same kind of simulation simulations we can have the results for different kind of setups like the single transmitter with multiple receivers and or multiple receivers with the single transmitter which we called as SIMO single input multiple output, multiple input single output that kind of scenarios we can have.

And now I am going to talk about the non-line of site configurations. Till now we in the line of site configuration we were considering the transmitter is an LED and in addition to that we considered a simple photo diode at the receiver and we considered the Lambertian pattern. Lambertian channel model we considered for calculating the received power as well as the spectral efficiency and the Shannon formula was used to calculate the final spectral efficiency and the receiver.

And in addition to that the noise power wall was also considered to be fixed which was around minus 90 dBm. Now, coming to the non-line of site configuration here in non-line of site configuration we are actually assuming the laser source instead of a of an LED. So, I already told you that we can use an LED as well as the laser source for the underwater communications depending upon the distance, we want to cover depending upon the scenario we want to consider.

And here in this case I am considering a non-line of site communication scenario or configuration where I am considering a laser source. And in this laser source the non-line of site underwater communication configuration gain is given by this formula gain of NLOS is the area of the receiver multiplied with cos of theta where theta is actually the incidence angle it is actually theta i divided by 2 times a annular a annular is the annular surface given by this formula.

And this is actually the tan of theta t transmission angle minus theta i divided by tan of theta t plus theta i cos square plus tan sin of theta t minus theta upon sin of theta t plus theta cos square when the theta lies between theta min to theta c here this is theta min is this angle, which I have presented over in this figure and theta c is actually the critical angle.

And the gain of the non-line of site configuration will be area of the receiver into cos of theta divided by 2 times A annular where theta lies between theta c and theta max. So, first of all there is no line of site before having the simulations about the non-line of site configuration. First the concept about the non-line of site configurations must be clear then the non-line of site configuration will happen inside the water.

For example, here I have shown a scenario of non-line of site communication scenario. Here we can see that there is a source which is trying to communicate with the detector, but there is a blockage in between the two here I had represented the blockage because of which it is not possible to have this line of site communication possible.

So, I am I need to have some different I need to do something. So, that this communication is possible for that, but we are having is the non-line of site configuration for which is based on the total internal reflection actually. But now the what are the conditions for this total internal reflection, I will be talking about that first.

First of all, there are two conditions for the TIR to happen. First of all is that the light must be travelling from the denser medium to the rarer medium. And here you can see that this is this medium in which the whole setup has been placed it is actually the water medium and here it is the water air interface this is the surface of the water air interface and this is air actually.

So, in my setup the light is travelling from the denser medium to the rarer medium from water to the air. So, my first condition is fulfilled. The second condition is that for having the for transmitting the signal back into the same medium the angle of incidence must be greater than that of the critical angle that will be decided over here.

When this angle when we are transmitting this signal, what angle it is making at this what angle it is making at this point with respect to the water air interface if it is if this theta is greater than that of the critical angle. In that case my whole of the signal will be reflected back into the same medium and it will be received by this receiver which is not in direct line of site communication with that to that of the source.

So, here in this case I need to take care about these two these two conditions so, that we can have the total internal reflection. So, we are having two conditions first condition is already fulfilled that we are the signal is transmitting from the denser medium to the rarer medium and for the second case we can have that the theta lies between theta min and theta c that is theta critical or we can have that that theta lies between theta c and theta max.

So, if it is less than theta c in that case some of the light will be reflected back into the same medium, but some of it will be lost into the surface that is the reason that we are having this additional term in the case when the theta lies between theta min and theta c. But when the theta value is greater than theta c in that case there will be no loss of light into the medium, but whole of the light will be reflected back into the same medium.

So, we can see that this water air interface will act as a mirror and it will not it will not allow the light to come out of the surface, instead the light will be reflected back into the same medium as shown by this. So, there is no reflectivity component in this equation when theta is greater than theta c.

So, here we can see that we are having to theta min and theta max theta these theta min and theta max are the angles of the transmitter, laser, lasers, a minimum and maximum angle and here we can see that we are having the annular area this is the actually the illuminated area.

When the transmitter is at a depth of y s the illuminated annular surface with equal power density at depth y t is given by this formula. So, it depends this annular area is depending upon y s and y d, here we have taken y s and y d and it also depends upon the theta min and theta max of the laser we are considering with.

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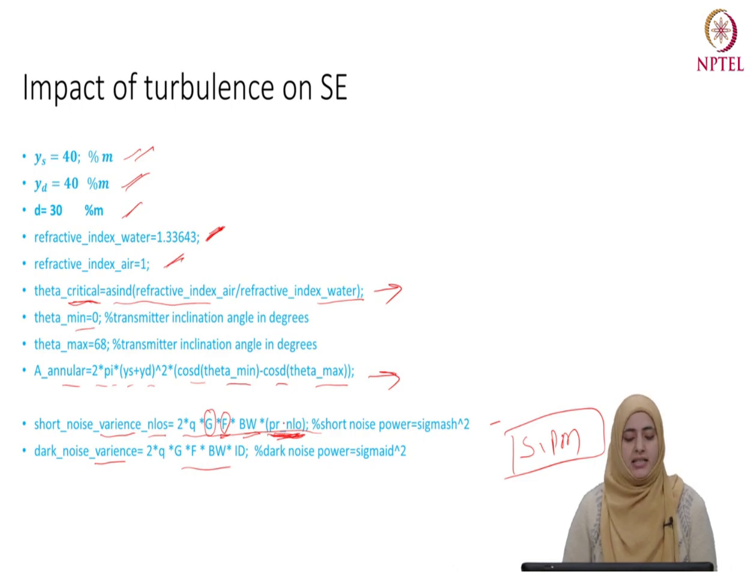

So, first of all we will see the impact of the turbulence on the spectral efficiency. In our dissimulation case we have considered the value of y s to be 40 meter y d the distance of the this is actually the depth of the transmitter from the water air interface and y d is the depth of the receiver or the detector from the water air interface and d is actually the distance between the direct line of side distance between the transmitter and the receiver.

Here we need to consider the refractive index of water and the refractive index of air we have considered. Why I need to calculate need to consider this refractive index of water as well as air because I need to calculate the value of critical angle that is theta critical which is given by this formula a sin d of refractive index of air divided by refractive index of water.

And in addition to that we are also considered the value of theta min to be equals to 0 and the theta max to be equals to 68. So, that we can calculate the annular area A annular by using this formula of 2 pi by s plus yd cos square into cos d of theta min minus cos d of theta max.

So, this is how we calculate the theta value of theta c and this is how we calculate the annular area for this non-line of side communication. In addition to that in the previous in the line of side configuration we did not consider the different type of noises. We just take the value of noise to be minus 90 dBm from I have taken that value from one of the papers.

Now, but for non-line of side communication we are considering different type of noises like the short noise variance for the for this nlos. It is given by this formula which we already discussed in one of the previous slides and the dark noise variance since we are considered the silicon photo multiplier as the photo as the receiver in this case. But we were considering the simple photo diode in the line of side case.

So, here because of this silicon photo multiplier we are having these parameters like G which is the gain of the photo multiplier F is the excess noise. This is the bandwidth and pr nlo is actually the received power of the non-line of side communication and we already discussed that the short noise variance depends upon the received power actually the useful signal.

So, that is the reason that we are multiplying this short noise with the pr nlo it is actually the received power, which is basically the product of the transmit signal with that of the channel gain non-line of side channel gain.

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Cont...

- thermal_noise_varience= (4*KZ*T*BW/RL);
- Total_noise_varience_nlos=((short_noise_varience_nlos+dark_noise_varience))+thermal_noise_varience;
- c2_nlos(1,j)=log2(1+((e/(2*pi))*snrr_nlos_avg*hp(i)^2));

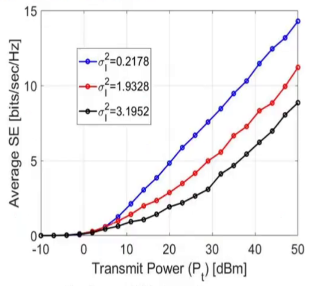

Fig.: Average SE Vs. transmit power

And next is the thermal noise we have calculated the thermal noise by using this formula and the total noise variance can be calculated by the addition of all these noises. Here we have not considered the background noise and we have taken the value of the background noise to be equivalent to 0. And here the finally, calculating the capacity here we have calculated the capacity using the same Shannon formula as log2 1 plus e by 2 pi snr nlos average into hp of i whole square.

But is this hp of i square these are actually the egg distributed random variables and we discussed about the PDF of this egg distributed random variables and different parameters of this egg distributed random variables and here we have to multiply this snr with that of the egg distributed random variables. So, that we are also considering this egg distribution in our simulations.

So, here you can see that the plot for the every spectral efficiency with respect to the transmit power for different scintillation indexes here we can see that we have considered the values of every spectral efficiency from the weak turbulence where we are taking the values from 0.2178 to moderate turbulence of 1.9328 to the strong turbulence of 3.11952.

And here from the results you can see that when the transmit power I have taken the transmit power in terms of dBm instead of watts over here and here you can see that at a transmit power of 50 dBm you can see that when the turbulence is weaker that is 0.2178 in that case the spectral efficiency every spectral efficiency is highest which is which actually should be the case because here the turbulence we are considering the weak turbulence.

That means, that the overall refractive index variation will be lower compared to the case when sigma i square equals to 1.9328 and for and the case when sigma i square equals to 3.1952 which is actually the strong turbulence.

So, here we can easily see the effect of varying turbulences varying turbulences for different sorry for a particular water type when we are varying its turbulence from very weak turbulence to moderate to a strong turbulence and we can see that the there is a variation in the overall every spectral efficiency which is given in bits per second per hertz.

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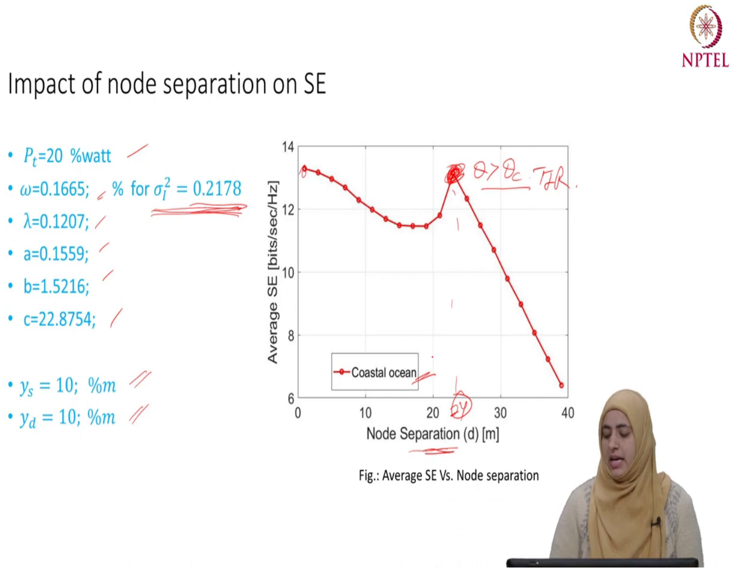

Next is the impact of the node separation on the spectral efficiency here the node separation means the distance line of side distance between the transmitter and the receiver or between the source and the detector. So, the line of side communication which was actually blocked is called as the node separation and here you can see that we have considered the transmit power of 20 watts and these are the parameters for omega lambda a b c these are the parameters for egg distribution.

Here I am considering the sigma i values sigma i square value of 0.2178 which are and these omega lambda a b c are corresponding to this scintillation value and we are considering the transmitter depth as 10 meter and the receiver depth as 10 meter. And here you can see the plot of again every spectral efficiency with respect to the node separation d in meters and here you can see that how this every spectral efficiency is varying with respect to the node separation.

The curve is different in the previous plot we were looking into the average spectral efficiency with respect to the transmit power, but here we are varying the direct line of side communication actually which is actually blocked. And we are varying this distance direct distance between the transmitter and the receiver.

And seeing the effect of this variation on the average spectral efficiency and here you can see that initially the transmitter initially when they are very close to each other when the transmitter and the receiver are very close to each other; that means, the node separation is only 1 meter. In that case this average spectral efficiency is very high.

But as the node separation is increasing as the distance at the as the if we fix the transmitter distance if the distance of the receiver is varied it is taken away from the transmitter in that case what is happening the average spectral efficiency is reducing. And there is a point at which it is showing a peak here at this point for example, it is around at 24 meter of distance. So, here you can see that it is showing a peak and after that the average spectral efficiency is reducing linearly.

Now, the what is the reason behind this kind of a curve we need to know the reason behind this kind of a curve. So, let me clear you that why it is this kind of a curve because initially when the transmitter is very close to the when the receiver is very close to the transmitter and it is moving away.

In that case if you see the if you remember the previous equations where the gain of the no line of sight communication no line of sight gain of the no line of sight link was given it was shown that when the value of theta incidence angle lies between theta min and theta c in that case the gain will depend upon two parameters.

One is the path loss parameter the and the other one is the reflectivity parameter. That means, in that case above the light is lost into the atmosphere because in that case theta c is less than theta is less than theta c that is the reason that as we increase the value of the node separation the value of theta c is less theta is less than theta c up to this point.

But at this point the value of theta is greater than incidence angle is greater than theta c that is the reason that at this point total internal reflection is happening and that is the reason that all of the signal is reflected back into the same medium.

And after this point only the path loss will be happening as shown in the in that equation that when theta is greater than theta c then the overall gain will depend up only upon the path loss of the signal only the path loss will be happening there will be no transmission there will be no signal loss from the water to the free space.

So, that is the reason that we are getting a peak overhead and after this we are getting this kind of a result. So, this is the result for when we are considering only the coastal waters.

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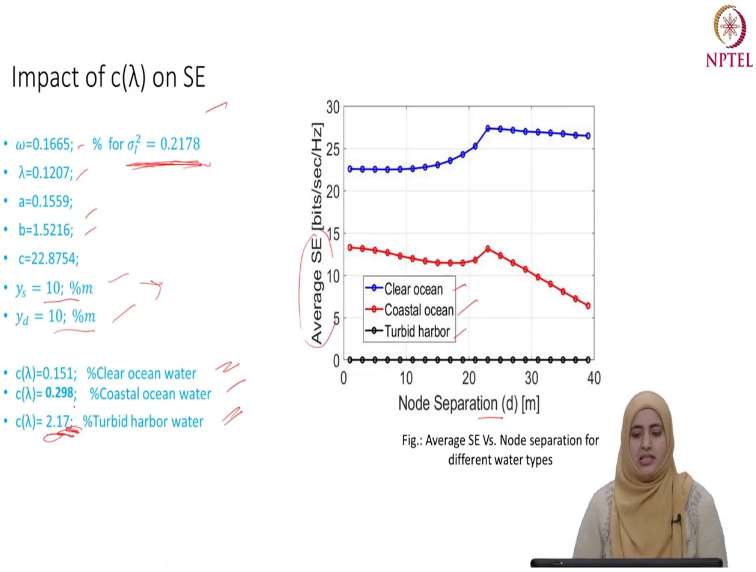

Next is the result when we have considered the impact of c lambda on the spectral efficiency and in this plot what we have done we have calculated the same spectral efficiency with respect to the node separation. But in this case, we are doing this for different type of waters which is which include the clear ocean water the coastal ocean water and the turbid harbor waters.

And here you can see that as always that the clear ocean water will give us the average higher average spectral efficiency compared to other two type of waters and this is also shown over here. And here you can see that how the node separation variation is happening for different type of waters and how the average spectral efficiency is calculated here I have given the values for different value of sigma sigma I square equals to 0.2178 is given over here for the for different I am considering here the weak turbulence that is the reason that we have taken this value only.

And here the value of omega lambda a, b, c is given by this and the value here y s and the y d that is the vertical distance of the transmitter and the receiver from the water here interface is taken as 10 meter and 10 meter respectively. And the value of sea lambda in this case is taken as 0.151 0.298 and sea lambda equals to 2.17 for the turbid harbor waters.

So, from this it is clear that the clear ocean is performing better, but if we are doing the same if we are considering the same communication setup in inside a turbid harbor water in that case, we are not able to get any average spectral efficiency because in that case the average spectral efficiency is equals to 0. This is because in case of turbid harbor waters the path loss is very high as you can see the value of lambda is 2.17 compared to other type of waters that is the reason that average spectral efficiency is 0 for this kind of water.

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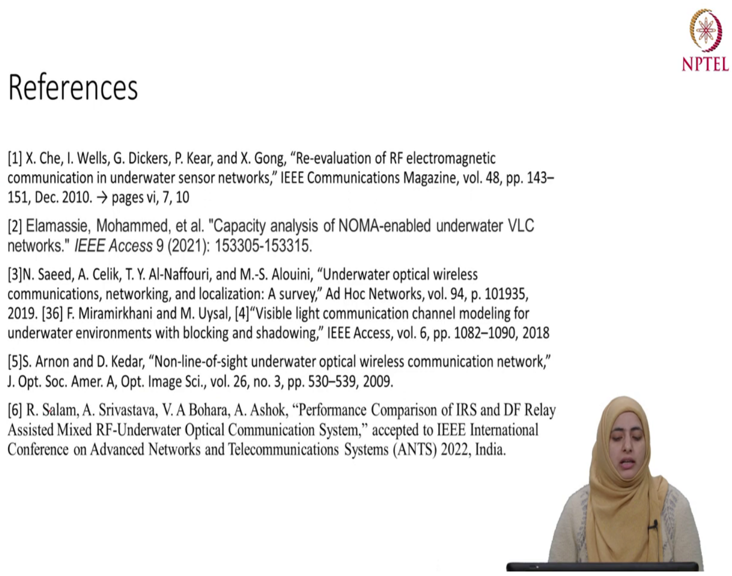

So, that was all about the simulation of the line of sight and the non-line of sight communications. And here in this I have given some of the references from which I have taken these equations and the values of sigma's which I have used in this simulation lecture.

And here you can see that for the in-depth knowledge about the line of sight configuration you can also refer to one of my paper which was recently accepted to IEEE International Conference on Advanced Networks and Telecommunication ANTS 202 in jobs. So, for any queries you can also contact on this number or on this mail or this mail and that is all.

Thank you.