Optical Wireless Communications for Beyond 5G Networks and IoT

Prof. Anand Srivastava
Department of Electronics and Communications Engineering
Indraprastha Institute of Information Technology, Delhi

Lecture - 11
Part - 1
Underwater OWC Channel Mode

Hello everyone. So, today we are going to start a new topic which is Underwater Wireless Optical Communication Channel Modelling. In the last few classes, we have done we have understood about indoor channel Modelling and outdoor channel modelling.

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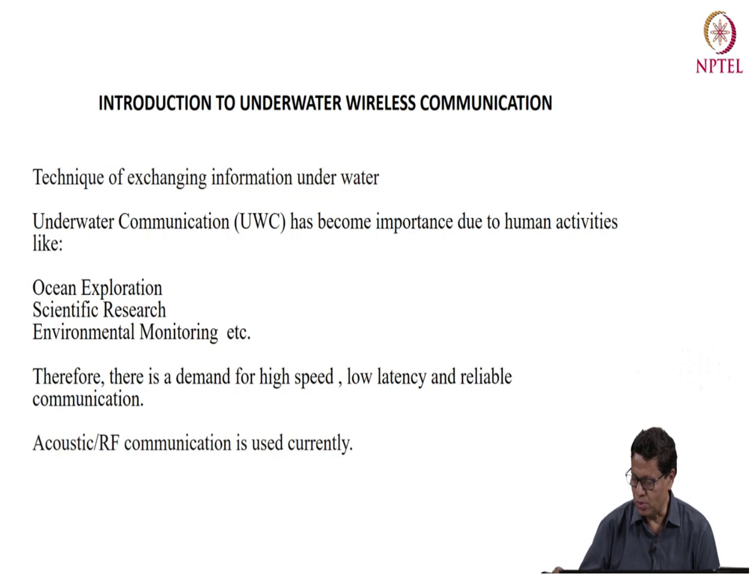

So, today we will be discussing about Underwater Wireless Optical Communication Channel Modelling. So, Underwater Communication is basically exchanging information between two devices which are submerged in the water.

Also, communication from underwater device to a to shore and from there it is connected to terrestrial network or satellite network. It has become very important at area because you know scientists, they want to explore the ocean, do some scientific research and some environmental monitoring etcetera.

And also, if you see 6G standards, it basically says that we should be able to integrate the satellite, the terrestrial network with underwater network. So, basically, we are looking towards our integrated network which will combine underwater terrestrial network and space network.

So, there is a growing interest in the area of underwater communication and also there is a requirement of high speed, low latency and reliable communication. So, far scientists have used acoustic waves and RF also as the communication medium for communicating between two devices which are submerged in water.

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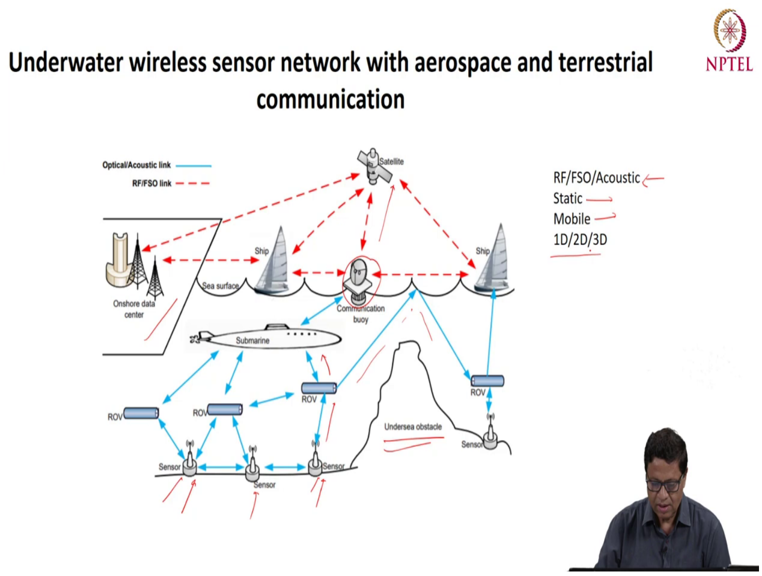

So, these are some of the applications of underwater communication as you see in this diagram. The red lines are either RF link or free space optics link or optical wireless link and the sky blue line is actually communication using either optical communication or acoustic link.

So, you see here there are lot of sensors on the seabed. They communicate with remote operating vehicles they are like robotic equipment which are submerged into water. And they interact among themselves as well they communicate with submarine and if there is some obstacle then the light or whether it is a acoustic or optical is reflected from the surface of the water and reaches another sensor node or another remote operating vehicle.

And these remote operating vehicles communicate with the ship which are on the surface or the communication boy which is again on the surface and from here it is connected to offshore terrestrial network or satellite network. So, this is overall picture of underwater communication network getting integrated with terrestrial and satellite network.

So, as I mentioned there can be you know three possibilities either you communicate using optical or acoustic or free space optics. So, there are three options available to us and these sensor nodes which are there in the at the bed of the sea or somewhere in the middle they can be static nodes.

They can also be a mobile node and they can have you know different configurations 1D, 2D, 3D. 1D is basically they are lying on the bed of the sea, 2D can be at different heights and you know 3D basically covers a volume kind of thing or in a small volume or within the sea. So, all configurations are possible in underwater.

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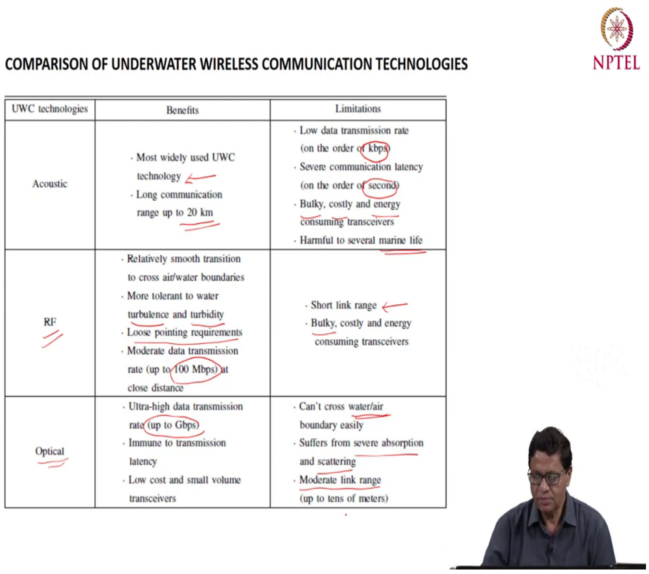

UWC technologies	Benefits	Limitations
Acoustic	· Most widely used UWC technology · Long communication range up to 20 km	· Low data transmission rate (on the order of kbps) · Severe communication latency (on the order of second) · Bulky, costly and energy consuming transceivers · Harmful to several marine life
RF	· Relatively smooth transition to cross air/water boundaries · More tolerant to water turbulence and turbidity · Loose pointing requirements · Moderate data transmission rate (up to 100 Mbps) at close distance	· Short link range · Bulky, costly and energy consuming transceivers
Optical	· Ultra-high data transmission rate (up to Gbps) · Immune to transmission latency · Low cost and small volume transceivers	· Can't cross water/air boundary easily · Suffers from severe absorption and scattering · Moderate link range (up to tens of meters)

So, this is a comparison slide between acoustic RF and optical communication. So, these are the three UWC technology Underwater Communication Technologies. So, if you see the acoustic the benefit is that this is so, far this is see you this is a main technology with you use or communication in underwater and it can give the plus point is that it can give a long distance range or long range of communication of the order of 20 kilometers.

The limitations are since it is acoustic the transmission rate is very very low which is of the order of kilobits per second. There may be a requirement of high data rate. So, this may not be an appropriate technology for high data rate transmission. And because it is acoustic there is a severe communication latency, the latency is of the order of seconds whereas, sometimes there are abdications which require latency of you know milliseconds or few tens of milliseconds.

So, this gives seconds and the equipment which are used in acoustic they are bulky costly and they consume lot of power and these acoustic waves it has been seen that they are harmful to some marine life. So, it is not a proper technology for use of communication inside the sea. On the other hand, the RF technology is relatively smooth transition to cross air water boundaries. So, if you are communicating from outside to the to a device which is submerged in water there is a smooth transition.

So, this is the benefit here and RF is also more tolerant to turbulence and turbidity. So, as you know ocean there is lot of turbulence sometimes. So, it is more tolerant to turbulence. And since it is or the waves are not very directional. So, we do not require a pointing arrangement or alignment of transmitter and receiver strict alignment of transmitter receiver is not required.

And one can achieve data rate of the order of 100 megabits and the distance is not very large. So, for a close distance we can achieve a data rate of 100 megabits per second. The range is the range is very small in RF because the attenuation of RF in water is very high and again the device is used for transceivers in RF communications are bulky costly and they consume lot of energy.

If you see the optical, you can have ultra-high data rate transmission of the order of gigabits per second using optical transmitters and optical receivers one can get a communication you know speed of gigabits per second.

And this is immune to transition transmission latency. The latency is very very less in this case and the these are very small you know transceivers. So, they are low cost and they require small volume or small area transceivers. The limitations are that they cannot cross the water air boundary.

So, the communication has to be with some you know structure on the surface could be a boy or some submarine and then from there you communicate to the outside network. So, they cannot cross the water air boundary. Optical waves suffer severe absorption and scattering loss inside the water that we will discuss in detail subsequently. And it gives a moderate link range of the order of few tens of meter or 100 or more about 100 meters or 150 meters. So, that is the kind of distance you achieve.

So, sometimes you know combination of these technologies can meet your application requirements. So, it is not that you know optical will replace acoustic and RF in some applications public acoustic could be a good solution in some applications you know RF could be a good solution or a mixture of acoustic and RF could be a good solution.

So, basically these are all possibilities we have for communicating with different devices which are inside the water.

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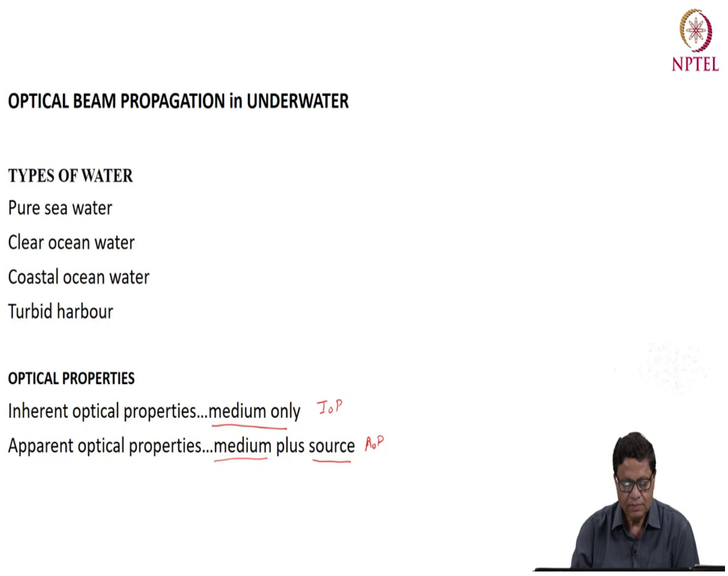

So, let us now understand how the optical beam propagates in underwater. So, as you know that water the properties of water changes from shallow to deep water. There are lot of physio chemical underwater environment inside the sea and there are different types of water could be is one of them is pure sea water where you have you know pure water and also some salt you know dissolved in it.

You have clear ocean water where you have high concentration of dissolved salts and then you have coastal ocean water where you have you know still higher concentration of dissolved salts and then you have turbid harbour where you have high concentration of dissolved salt salts and also suspended particles. So, this is if you want to communicate in turbid it is very very difficult because of you know suspended particles lot of scattering happening lot of absorption happening.

So, its a challenge for communicating in turbid harbour turbid harbour kind of water. Optical properties if I see there are two types one is inherent optical properties which basically deals with the property of the medium only that is how the optical beam is absorbed or scattered or how it is affected the propagation of the optical beam.

So, it deals only with the medium it does not deal anything with the source. So, that they are called as inherent optical properties deals with the medium only or in short this is called as IOP and the other one is apparent optical properties it deals with both medium and source.

So, as I mentioned medium basically tells how much light is absorbed, how much is scattered, what is the attenuation and source whether you are using a diffuse source or you are using a pointed source or it also deals with the geometry of the source. So, when you combine the medium and the source they are called as apparent optical properties and they are abbreviated as AOP.

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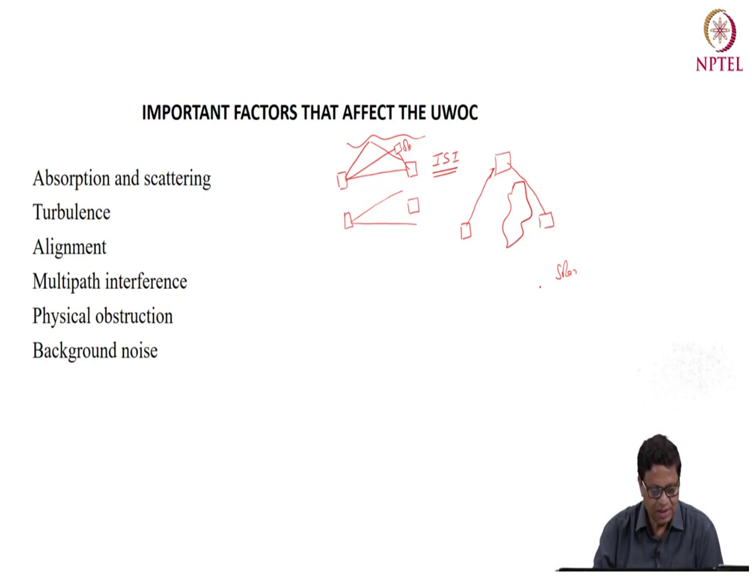

So, what are the important factors that affect underwater optical communication? One as I told you is a absorption scattering the light is absorbed and also scattered depending on the type of water.

If it has more suspended particles, then the light is likely to be scattered and depending upon the impurity in the water the light is absorbed. So, this is one major factor which basically decides how much power you will get at the receiver. Turbulence the water is not calm. So, depending upon the turbulence the received power intensity varies. So, this is also going to be an important parameter that will affect underwater optical communication.

Alignment whether the optical transmitter and sources they are aligned. If it is a point to point transmission then we need to ensure the strict aligned alignment between transmitter and receiver. We can also use some sort of you know or diffuse light suppose your receiver is there probably that requirement of alignment can be relaxed here because the beam width is quite high and the receiver will be able to send some amount of power.

But there are issues with that because you get you know less amount of power the power is actually spread over a large area. So, alignment is an issue and multipath interference in a point to point link it is not necessary that you get all the light from the transmitter in state path that is line of sight. There is a possibility of light also coming from different other paths getting reflected from the surface for example, this is the surface.

If there is some object somewhere air inside the water this is a object it may be reflected from here. So, this might result into some sort of multipath interference and you will have some sort of delay spread at the receiver and that might introduce you know ISI the multipath interference is high that is inter symbol interference. Physical obstruction.

So, if you have two transmitter receiver transmitter receiver communicating and suppose there is a interference here it could be a rock it could be a some animal or some animal inside the some sea. So, there may be a you know physical obstruction then you need to have some other node here.

So, the light will go like this and then some processing might happen here and then it is you know reflected back this is how you avoid the obstacle. The other issue which we need to worry about this is the background noise. So, the background noise basically may come from solar radiations which can go deep inside the water and also the radiations which are black body radiations coming as a result of bio-elements within the sea that also is some sort of background noise for the receiver.

So, these are the factors which are which will affect the underwater optical communication systems. So, we will study these factors in detail now.

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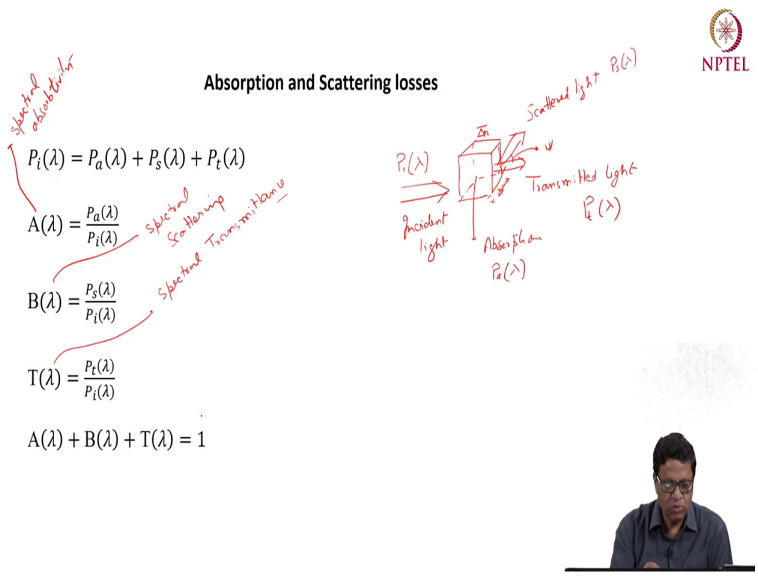

So, let us start with the absorption and scattering losses. So, if I assume a small volume inside the water which is something like this. So, this is my input that is P i lambda and suppose this is delta V which is you know perpendicular to the direction of propagation and this is say delta r which is in the same direction as the incident beam.

If I consider this small volume of this delta V-dimension delta r dimension and if I see across this some of the light will be transmitted this is transmitted part and some of the light will be scattered. And say this angle is say psi. So, this is scattered light and this is transmitted light and this is incident light.

Let me donate this scattered light as P s lambda and transmitted light as P t lambda. So, from the law of conservation P i lambda that is incident light is sum of light and some light will be absorbed inside this small volume of delta V and delta R. So, this is say absorbed light absorb absorption happens inside this.

So, this is absorption and the light which is absorbed is P A lambda. So, P i lambda incident light is sum of absorption scattered and transmitter the transmitted light. And if I define a spectral absorb sorbity this is say a spectral absorptivity. As the ratio of P A lambda that is the light which is absorbed divided by the total incident light and also let me define another factor B lambda which is spectral scattering.

So, let us write this here this is spectral scattering which is ratio of light which is scattered divided by light which is incident and the third one is spectral transmittance. So, this is spectral transmittance which is a ratio of light which is transmitted divided by the total incident light. And as you see here some of these parameters A lambda, B lambda and D lambda is equal to 1.

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$$a(\lambda) = \lim_{\Delta r \to 0} \frac{\Delta A(\lambda)}{\Delta r}$$

Spectral absorption coefficient ≡ spectral absorption rate per unit distance.

$$b(\lambda) = \lim_{\Delta r \to 0} \frac{\Delta B(\lambda)}{\Delta r}$$

Spectral scattering coefficient ≡ spectral scattering rate per unit distance

$$c(\lambda) = a(\lambda) + b(\lambda)$$

$$L_P(\lambda, z) = exp^{-c(\lambda)z}$$

Beer Lambert's law

Water Type	$a\,(m^{-1})$	$b\,(m^{-1})$	$c\,(m^{-1})$
Clear ocean	0.114	0.037	0.151
Coastal ocean	0.179	0.220	0.339
Turbid harbor	0.366	1.829	2.195

Also define a parameter which is a lambda and a lambda is actually spectral absorption coefficient. So, let us define this as spectral absorption. This is how we will characterize the loss inside the water absorption coefficient which is a spectral absorption rate per unit distance. So, this is as delta r tends to 0. I am considering a very small volume or area delta R. So, as delta r tends to 0 and limit delta a lambda by delta r where this is spectral absorption rate per unit distance.

So, this can be written as spectral absorption rate per unit distance. So, this I am defining as spectral absorption coefficient per unit distance. And similarly I am defining b lambda which is spectral scattering coefficient. So, this is spectral scattering coefficient. And this is equal to spectral scattering rate per unit distance. So, this is how it is defined limit delta r tending to 0 delta b lambda by delta r.

So, this is equivalent to spectral scattering rate per unit distance. Here we have combined these coefficients and a lambda b lambda. The sum of this a lambda plus b lambda is c lambda, this is a combined coefficient which takes care of both absorption as well as scattering.

And it has been shown, this is an approximate formula how the light is attenuated inside the water is given by L p which is a function of lambda and the distance is exponential minus c lambda by z where c lambda is sum of these two coefficients, the absorption coefficient and the spectral scattering coefficient there is a lambda plus b lambda.

So, this is exponential minus c lambda z. So, this is called as Beer- lamberts Law. And the values of ab for Clear Ocean is for example, 0.114 meter inverse, 0.037 meter inverse and c will be simply addition of these two. Similarly, these are the values for coastal ocean, turbid harbour, as you see the value of turbid harbour is very, very high because this is water which has lot of dissolved high concentration of dissolved salts and suspended particles.

The attenuation coefficient is much higher as compared to Clear Ocean and Coastal Ocean.

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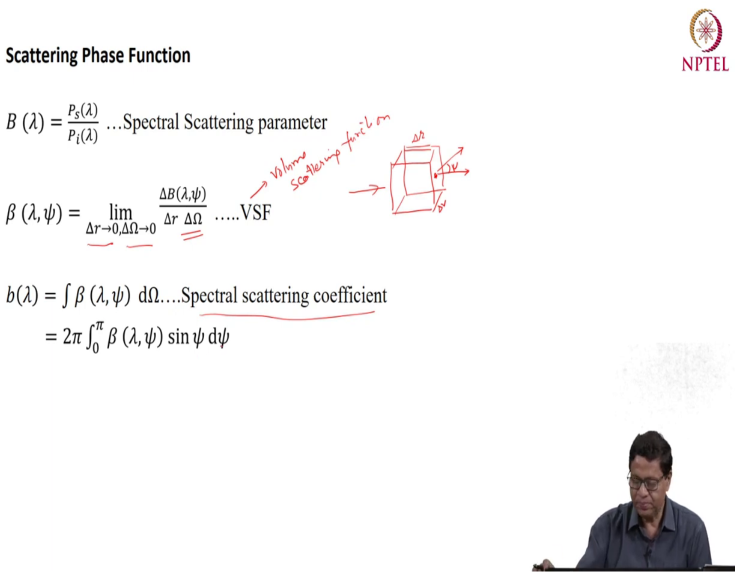

So, now let us define a another parameter which is called as scattering phase function. Scattering phase function, earlier we had defined one spectral scattering parameter which was actually a ratio of scattered power divided by the incident power which was b lambda.

And now I define a function which is beta lambda psi I will explain what is this psi. So, for example, you have a small area which is considered here as this. So, this as this is say delta v, this was delta r and this is incident light. So, some light will be scattered, some will be transmitted.

So, this makes an angle psi here. So, actually this is I have drawn in a two dimensional, but actually there is a cone around it which is defined by this d omega. So, I define a new parameter which I called as volume scattering function VSF. This is Volume Scattering

Function. And this is defined as delta r tending to 0, this is tending to 0 and the solid angle tending to 0 which is around this angle here.

So, delta omega tending to 0. So, delta B lambda psi divided by delta delta r into delta omega is called as a volume scattering function. And if I find out the spectral scattering coefficient, this will be basically I have to integrate over the total d omega, total solid angle this volume scattering function. So, this will give me a spectral scattering coefficient and if I convert this d omega in terms of psi angle, then I get 2 pi 0 to 2 pi beta that is a VSF for the volume scattering function to sin psi d psi.