Optical Wireless Communications for Beyond 5G Networks and IoT
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Lecture - 19
Vehicle to Vehicle communication using Visible light

Hello everyone. So, today we are going to discuss one more application of visible light communication in vehicular to vehicular communication or automotive applications. Last time we had discussed about Li-Fi, Wi-Fi coexistence. So, today we are going to discuss how VLC can be used in vehicle to vehicle transmission. And also, we will have one simulation study later by the TA of this course would be presenting a simulation study on vehicle to vehicle transmission.

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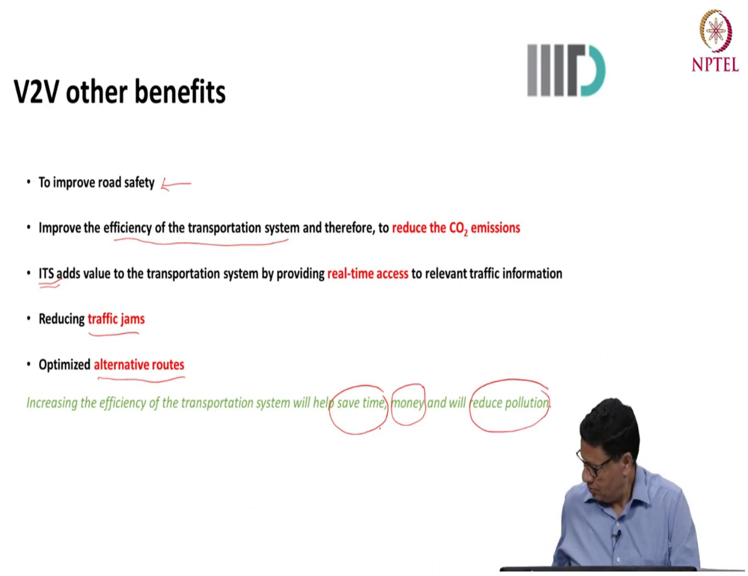

So, let us begin. So, what are the benefits of vehicular to vehicular communication? First of all it will improve road safety meaning there will be fewer number of accidents or injuries happening on the road if two vehicles are able to communicate with each other. It also helps in improving the efficiency of the transport system so which indirectly reduces a carbon dioxide emission because you are not stranded in traffic jam.

So, you are not emitting unnecessary carbon dioxide from the vehicle. So, it basically improves the overall efficiency of the transportation system. Intelligent Transport System ITS gives real time access to the relevant traffic information which actually helps in reducing traffic jams.

You can find out some alternative routes. So, these are some of the advantages of vehicle to vehicle communications. If all vehicles they communicate with each other or at least the vehicles which are in the vicinity of that particular vehicle. So, it will result in you know some of these benefits which I have just discussed.

So, basically increasing the efficiency of the transport transportation system will help save time. You are not stuck in a jam for example. It will save money; you do not unnecessarily burn fuel and it will reduce CO 2 emission or reduce pollution.

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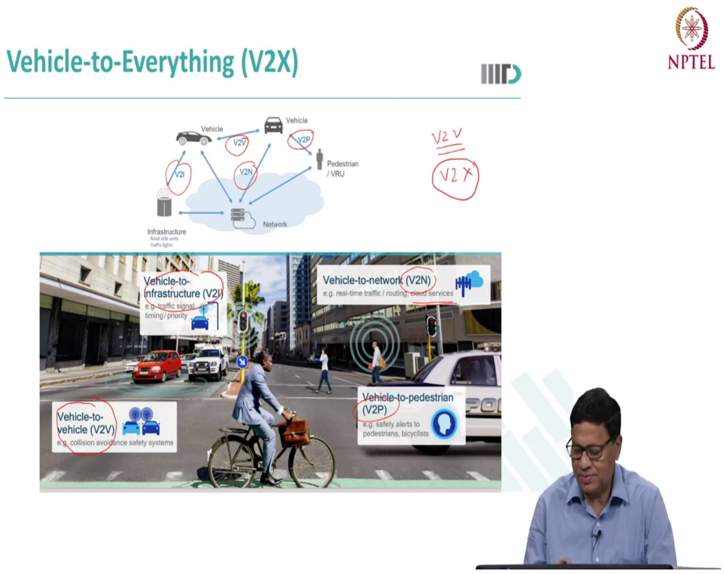

So, vehicle to vehicle communication is actually is not limited to V2V now. The recent standards define this as V2X where the X could be a vehicle, could be a pedestrian or could be the network or could be infrastructure. So, V2X basically is vehicle to vehicle, vehicle to pedestrian or vehicle to network or vehicle to infrastructure, which would be a traffic light or the road light or any kind of infrastructure.

So, this is a pictorial view of V2X where in you have V2V communication basically it is it is avoiding collision and it has safety systems built into it and then you have vehicle to pedestrian, safety alerts to the cyclist or the pedestrian and then you have vehicle to network. So, you get real time information of the traffic, routing and the information is processed in the cloud in the cloud.

And then accordingly you know appropriate decisions are taken and then vehicle to infrastructure, traffic signal for example, timing of traffic signal, priority which vehicle should be given priority. So, all those things are covered under these applications. So, it is no longer V2V, it is V2X.

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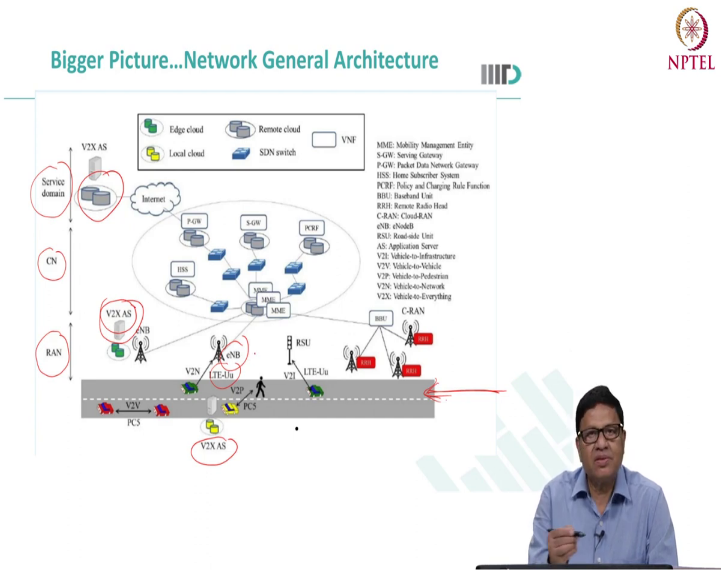

This is a bigger picture how this information is processed at different levels in the network. So, if I divide the whole network into three main areas, remote access network, core network and this is the service domain. So, the all the information which is collected here in vehicle to vehicle communication, some are processed in this layer itself by the V2X application server.

Some of the information through the RAN is given to the core network and some of the process, some of the information is processed in the RAN network through this V2X application server and then there is some processing, which is happening at the cloud level which is somewhere here.

So, the information which is generated here in the road, vehicle to vehicle or vehicle to infrastructure, to the traffic light, through the remote area network which consists of E node B's and LTE systems is transported to core network which has these entities and then it goes to a cloud application server.

So, depending upon the urgency or depending upon the latency requirement for different applications which are there in V2X communication, they are processed either at core level or at the in the layer where it is you know on the road itself or at the edge which is application server located in the remote access network or in the cloud.

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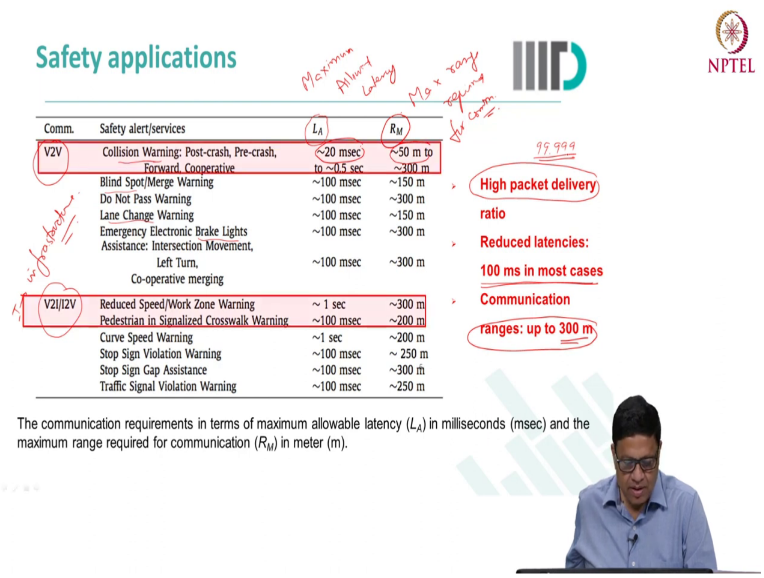

So, let us try to understand what are the different requirements for safety alert to safety services. So, basically it can be, we can basically classify, we are not dealing with currently with V2N or V2 other types of V2X services, but we let us focus on mainly V2V and V2I because we want to explore how visible light communication can be used for V2V communication and V2I or I2V communication.

So, I here stands for infrastructure. So, these are the some of the services, collision warning for example, or blind spot or lane change or brake emergency electronic brake lights, left turn and then there are V2I reduce speed, curve speed warning or stop sign violation, stop sign gap assistance, a traffic signal violation warning.

So, these are some of the applications of V2I and this L A actually gives the what kind of latency is needed. That is what is the maximum allowed latency. So, this is maximum allowed latency. You need to process this information within this time and this R M actually tells you what is the range maximum range you required for communication, maximum range required for communication.

So, for example, take an example, collision warning for example, you require a loud latency of the order of 20 millisecond and within 50 meters of distance you should be able to communicate to avoid this collision what collision. So, if you see this table for different safety alert or services you require on an average latency 100 millisecond in most cases, but there are exceptions where you require even low latency 20 millisecond and the range is of the order of 300 meters.

So, you should be able to communicate at a distance of 300 meter from one vehicle to another vehicle and you require high reliability that is high packet delivery of the order of you know five 9s that kind of reliability is expected in vehicle to vehicle communication system. So, these are some of the broad requirements for safety applications in terms of maximum allowed latency and maximum range required for communication and the reliability figures.

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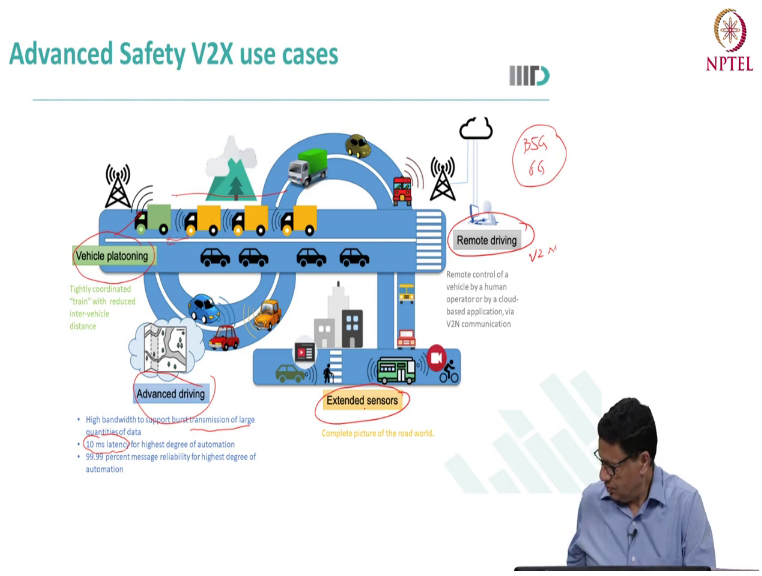

There are no advanced services which are actually part of 5G, beyond 5G and 6G applications where you know these some more applications are covered under intelligent transport system. One of them is vehicle platooning where you have tightly coordinated train with reduced inter vehicle distance and this green vehicle for example, is able to communicate with the second one, this communicates with the third one and so on and so forth.

So, the distance between them is reduced and they all the movement is coordinated. So, this is one example which is part of you know beyond 5G or 6G requirements in 5 beyond 5G and 6G requirements or you have remote driving, remote controller vehicle 5 by a human operator or by a cloud based applications which is a example of V2N application. The other application or use cases is advanced driving where you require high bandwidth to support bus transmission of large quantity of data.

So, you are talking in terms of 100s of megabits of 100 megabits per second of transport of data and the latency requirement is further reduced for some certain applications which is of the order of 10 millisecond. And then the reliability is four 9s or five 9s that is a requirement. The other area your use case is use of extended sensors.

So, you have more than one sensor. So, that you get a complete picture of the road around you about the pedestrians, about the vehicles in front of you, about the vehicles which are behind you or some of the vehicles which you cannot see with your eye you are able to get a picture of that vehicle onto your dashboard by use of you know extended sensors.

So, there are some advanced applications, platooning or remote driving or advanced driving or extended sensors which are becoming part of beyond 5G, 6G applications.

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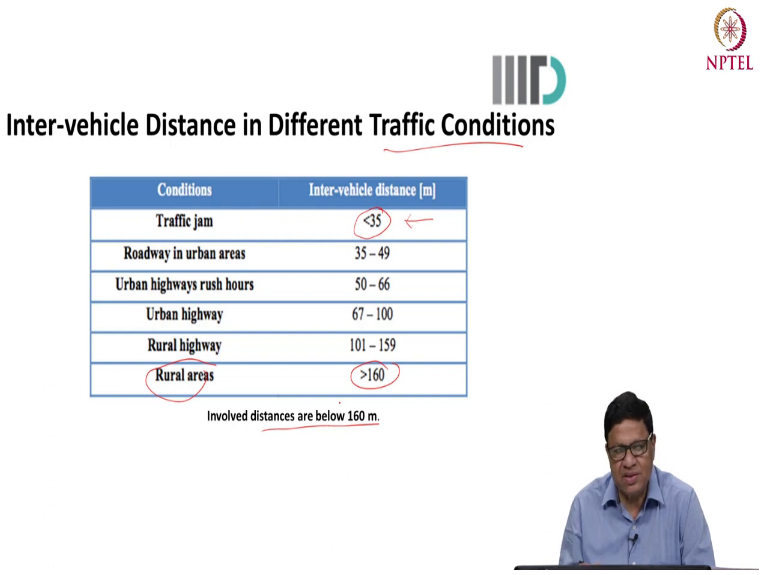

So, inter vehicle distance for different conditions in a jam the average distance is less than 30 meters because see you have to design a system based on certain requirements. We have studied what is the latency requirement, what is the communication distance, what kind of safety services are required and what are different latency and communication requirement for those safety applications.

And also, we need to understand what is the average inter vehicle distance in different traffic conditions. So, traffic jam it is 35 metre less than 35 meter for example, rural areas greater than 160 meters. So, the distances are of the order of 160 or 200 meters of that order. So, why should design a system you know based on all these requirements.

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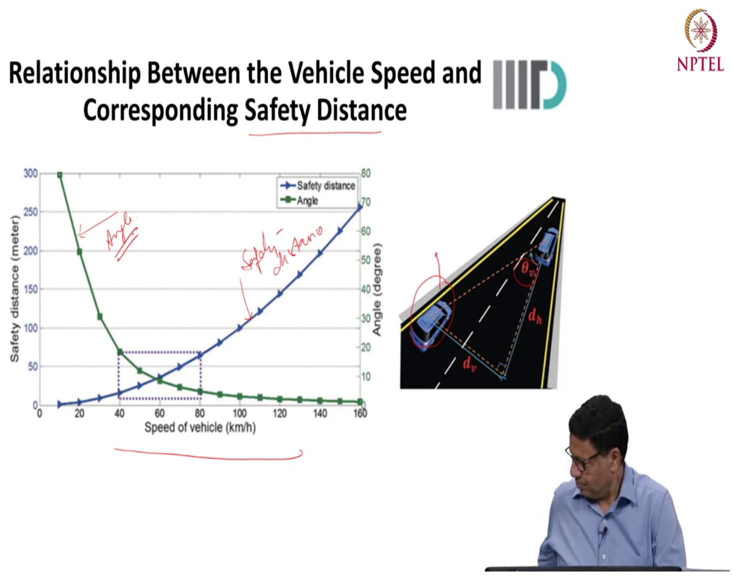

And also, how the vehicle speed and the corresponding safety distance is related. So, suppose this is you know speed of the vehicle, the speed of the vehicle is very large then you require you know more safety distance. So, this particular curve this blue curve is actually a safety distance curve, safety distance.

So, higher the speed you require higher safety distance and then the another curve is you know the angle versus the speed of the vehicle. So, if this vehicle for example, this vehicle is you know in line with the other vehicle; that means, theta V is tending to 0 then you require some safety distance and if this vehicle is little away where theta V has some finite value it require a different safety distance.

So, this particular green curve basically tells you about the angle part. So, one has to see the combination of velocity, safety distance and the angle in order to decide what is the safe distance for communication.

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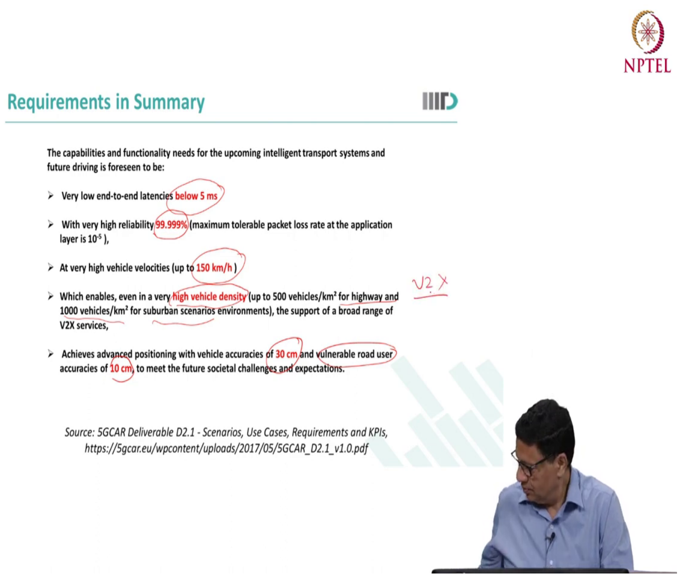

So, the requirements in summary for vehicle to vehicle transmission which is part of 5G and 6G that I require very low end to end latency based all the order of below 5 millisecond, very high reliability of the order of five 9s 99.999. And the vehicle may be moving at a speed of 155, 150 kilometres per hour and your solution should work for high vehicle density which is 500 vehicles per kilometre square on highway or 1000 vehicles per kilometre for suburban applications to support wide range of V2X services.

And also, you require positioning you should be able to position the vehicles around you to accuracy of about 30 centimetres and when it comes to a vulnerable road user it should be of the order of 10 centimetre. So, the positioning accuracy requirement is of the order of few 10s of centimetre. So, these are the broad summaries, which is required for V2X communication.

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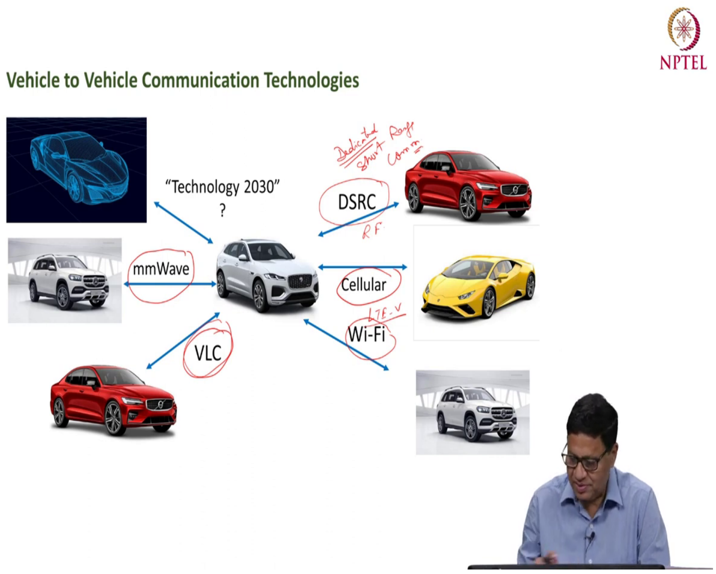

So, vehicle to vehicle communication there are different possibilities you can have DSRC which is a current technology being used which is actually dedicated short range communication. We have a standard for this DSRC. The other option could be your cellular for example, LTE V that is a standard for vehicular communication. You use LTE framework or LTE network for communication between two vehicles.

Wi-Fi was considered one of the solutions for vehicle to vehicle, but there are issues related to Wi-Fi. The one which we are going to explore is visible light communication system using headlamp of the traffic or headlamp of the automobile or the vehicle which will communicate with the other vehicle where you have the receiver or the tail light could be a transmitter visual communicate with the other vehicle.

The other option is millimetre wave which is not currently explored much and in future there can be some other technology where you have you know lot of sensors around the vehicle. So, we do not know about this technology.

So, there can be more options later. So, let us see you know we will in this lecture we are going to discuss about visible light communication and also, I will explain what are the issues with the existing technology which is RF based which has a standard da which has which is part of the standard which is DSRC Dedicated Short Range Communication.

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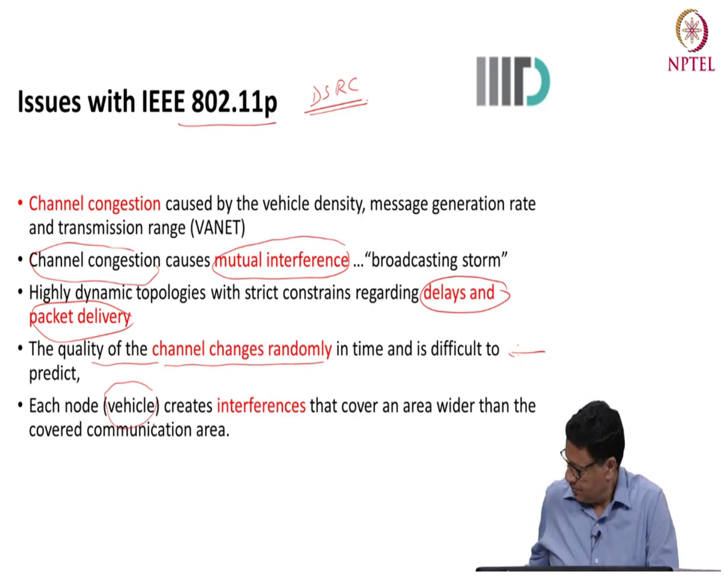

So, and this is the standard IEEE 802.11p DSRC standards. So, the problem in DSRC is that when the number of vehicles increase then there is a channel congestion and the message generation rate and the transmission range is reduced. So, this congestion channel congestion whenever you have more number of vehicles it will cause you know broadcasting storm every vehicle you know start broadcasting and this will result into a mutual interference.

And also, you know because if there are more number of vehicles the topology is dynamic it is changing with time. So, the packets may not be the delivery of the packets may not be successful. So, it will come back and which will relate which will result into delays and improper packet delivery and this quality of the channel changes randomly because the channel is a function of time and what is the topology around you. So, it is very very difficult to predict the quality of which quality of the channel.

It is unlike you know in indoor communication where the channel is deterministic here the channel changes randomly. So, prediction is very difficult and each node vehicle because each vehicle is a node here. So, they create interference that cover an area wider than the covered communication range. So, that is a node which is a source of interference for the two vehicles which are communicating.

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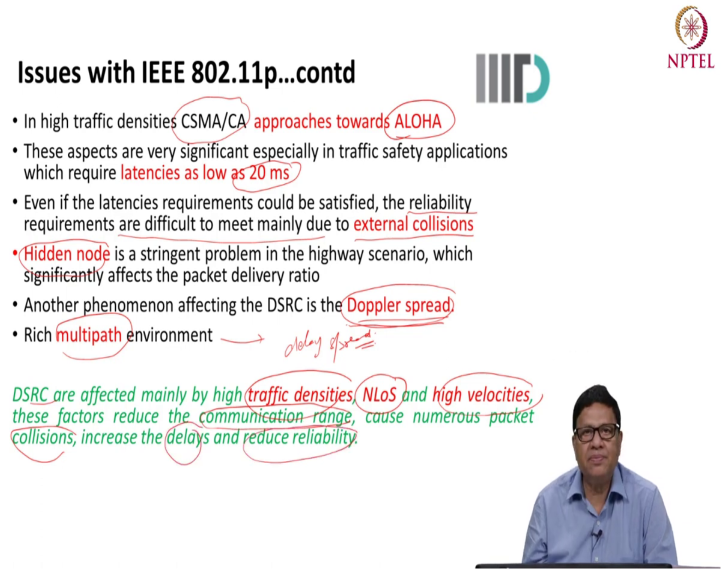

And it uses CSMA CA protocol, but when you have high traffic density the efficiency of CSMA CA actually gets reduced and it reaches almost efficiency of aloha which is not a efficient protocol. And these are the there will be issues because there are some services which require 20 millisecond of latency which cannot be met by DSRC.

Even if the latency requirements are met or satisfied the reliability requirements are difficult to meet because there are some external collisions are happening. There could be a issue of hidden node, there may be some vehicle which is not accessible to any other vehicle. So, you do not get picture of that particular vehicle.

So, a problem of hidden node is a problem which needs to be tackled. Another issue is Doppler spread when the suppose you are using you know OFDM kind of transmission then if the that the vehicles are moving at high speed it will result into Doppler spread and those subscribers, they will gets I mean they will the orthogonality between the subcarriers will not be maintained because it will void it will a Doppler spread will void in the spectrum.

So, this is another problem with DSRC. The if for example, in OFDM transmission because if you are interested in hybrid rate transmission then one has to use some advanced modulation techniques. The subcarrier are orthogonal in OFDM, but because of this Doppler spread they may not be orthogonal which will degrade the performance of the system and then reach multipath environment which will result into a delay spread.

So, these are the issues with the current DSRC technology I triple E 802.11p. So, D is DSRC is affected by traffic densities, non-line of sight and high velocities. So, these factors will reduce the total communication range, cause numerous collisions and increase the delays and reduce the overall reliability.

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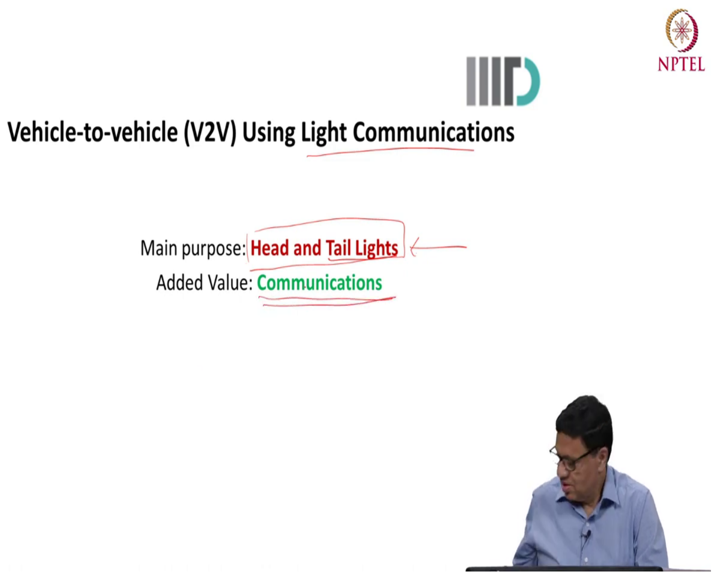

So, now let us see another mode of communication between vehicle to vehicle. So, here we will discuss using light, how the system performs if you use the headlight and the tail lights of the vehicle.

So, the main purpose of the headlight is you know eliminating the road or the tail light just to tell your other vehicle about your position. So, they have different purpose, but we want to exploit this head and tail light. The infrastructure which is already there in the car for communications. So, this is what we want to explore here.

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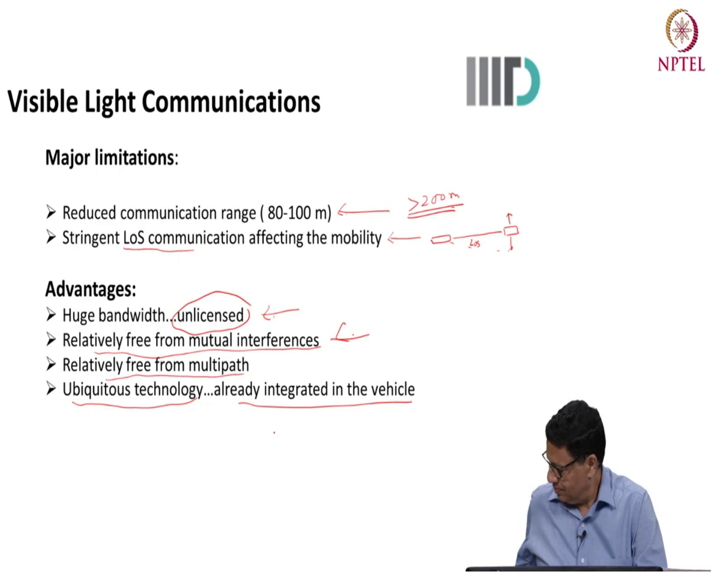

So, visible light communication as we have seen in previous lectures it has limitations. The distance is of the order of 100 meter although some experiments have been done greater than 200 meters and we also require line of sight if you are communicating with the other vehicles. So, there has to be line of sight, but anyway the researchers also have you know given solutions where some sort of mobility can be met.

So, suppose this is a vehicle here another vehicle here. So, normally you require a LOS, but using some techniques if a vehicle moves here or vehicle moves here even then the communication can take place. But these are still some of the limitations the communication range and the stringent LOS communication affecting the mobility.

The advantages are that huge bandwidth in the sense is light you have huge bandwidth and this is unlicensed unlike RF solution or LTE solution or any other millimetre way for example, in future they require licensed spectrum. So, it is that part of the spectrum is regulated one has to pay for that spectrum whereas, in light it is unlicensed.

Since it is a line of sight technology so, relatively free from mutual interference although there will be some light coming from some other vehicle which are surrounding that particular vehicle, but that amplitude is quite low. So, relatively free from mutual interferences and relatively free from multipath because it is essentially a line of sight technology.

So, the multipath is rather the amplitude of the multipath is rather less here and this is a ubiquitous technology; that means, all the lamps the LED lamps and the taillights they are already part of the vehicle. So, already integrated in the vehicle so, these are some of the advantages of visible light communication.

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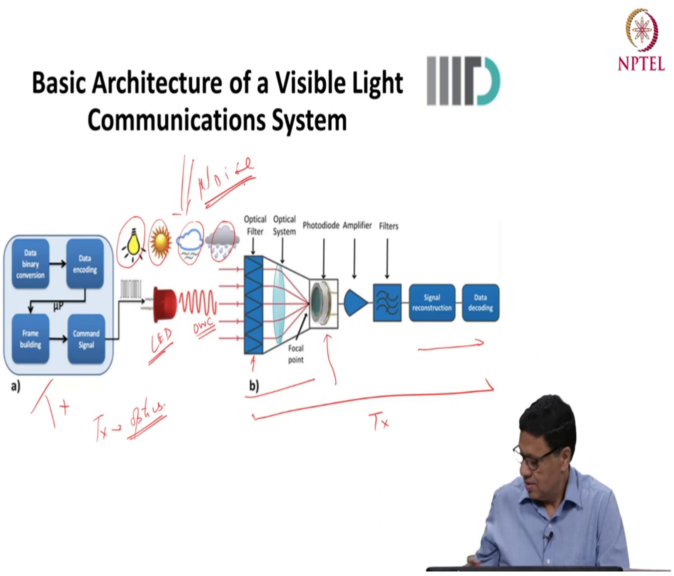

So, the basic structure of a visible light communication system is same as we have studied in the earlier lectures. So, you have a transmitter here which uses a LED and this is optical wireless transmission optical wireless communication and you have interference coming from light sources from sun, from rain or from cloud, from fog.

So, so environment there are environmental conditions which will actually affect the communication distance and then you have some sort of filters, some optics mechanism and then you have the photo diode, you amplifier do some signal reconstruction and signal processing you get your data back.

So, this is the receiver part which includes the optics as well and this is the transmitter part it may also have some optics so, that it meets both your requirement of eliminating the road as well as the communication and it is impaired by these noise, noise these are the noise in the system.

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So, these are the examples of LED which will be used in vehicle to vehicle communication and vehicle to infrastructure communication. So, you see some signs here, road signs, traffic lights, headlights, the taillights, the direction signs, turn signs, things like that they are all LEDs. So, these are the LED objects which are actually the transmitter which are which will be used for communication for both vehicle to vehicle communication and vehicle to infrastructure communication.

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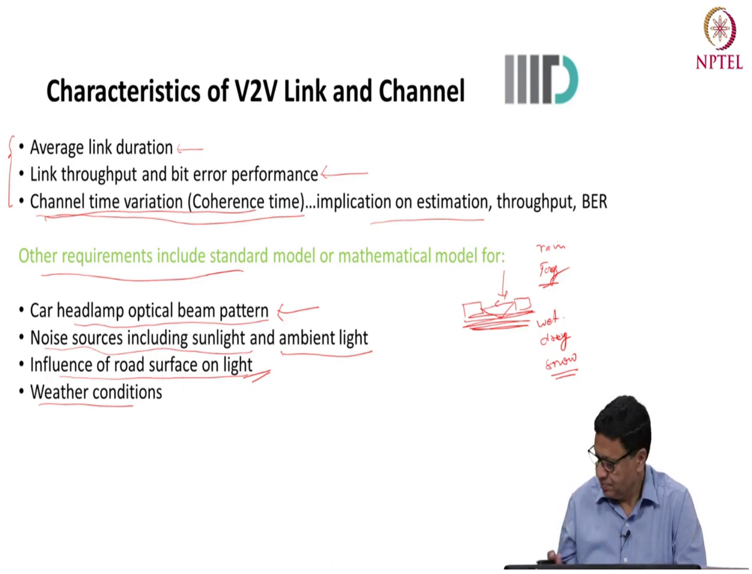

So, when you discuss, when you characterize vehicle to vehicle communication system. So, there are three important quantities which need to be calculated or which need needs to be investigated. One is average link duration. What is the average time the two vehicles are communicating with each other? Is it in millisecond? Is it in second? So, that we will see.

So, that is the average link duration, the time during which the two vehicles are communicating and what is the link throughput and bit error rate performance? What is the throughput you can get and what is the error performance? The third is channel time variation or coherence time.

When you are considering vehicle light as the communication medium between two vehicles. So, your channel is almost constant for how much time which is actually called as a coherence time. This has implications on estimation because you have to estimate the channel and accordingly you have to retune your equalizers.

So, this takes time. If you are doing it frequently estimation, it will basically involve some overhead and it will increase your throughput. So, we want estimation to be to happen in a longer time or we want the coherence time to be large, right? So, which actually will reduce the handover and effectively improve your throughput and BER performance.

So, these are the three quantities which are important if you are studying vehicular to vehicular communication link. The average link duration and the link throughput, bit error rate performance and what is the channel time variation coherence time of the channel.

Other requirements they include standard models or their mathematical model for car headlamp optical beam which actually originally is defined for eliminating the road not for communication and it is not symmetrical. It has a asymmetrical you know emission, radiation emission. So, that you know it does not affect the driver which is coming from the other direction and it lights up the road in the near field and the you know far field.

So, you have two types of headlamps which basically eliminates the road. So, this is we need to understand this optical beam pattern. We need to model this optical beam pattern which can be taken from you know standard cars. So, there are some standards for meeting this optical beam pattern and then we need to model the noise sources which is coming from sunlight or ambient light and we also need to model the road surface of the light because if the road is wet. You know and these are the two cars for example, and this is the road for example.

So, if the road is wet you know how much light gets reflected from hair reaches hair I mean there is line of sight anyway, but there is a component which is coming from the road also if the road is dry or if there is snow there is snow. So, behaves the light behaves differently in different road conditions. So, one needs to see the influence of road surface on the light and weather conditions.

So, for example, if it is raining then the light will get attenuated if there is a fog or rain light will get attenuated. So, one has to model this as well. So, these are the other requirements which have to be modelled in order to find out what is the average link duration and what is the link throughput and what is the you know typical coherence time.

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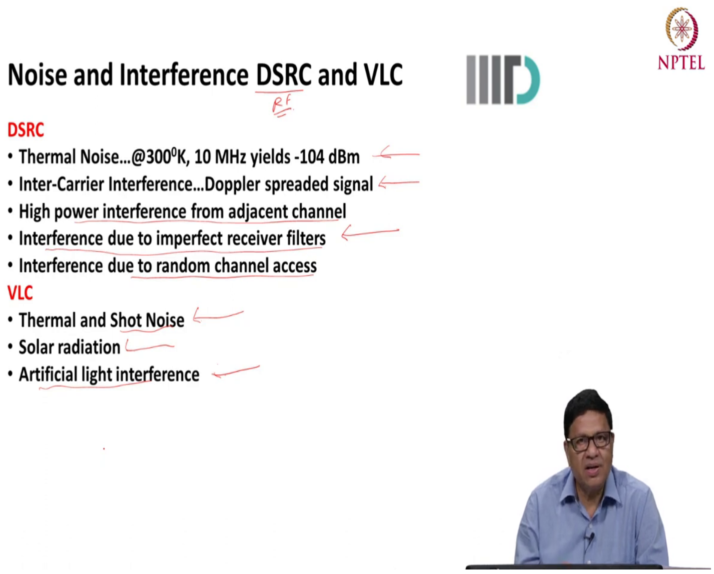

So, the noise and interference in DSRC which is dedicated short range communication which is RF based and VLC is listed here. So, you have thermal noise of the order of minus 104 dBm at 300 degree kelvin and the bandwidth is 10 megahertz. Then there is a noise which is coming because of inter-carrier interference.

As I mentioned earlier if the transmission is using OFDM then different subcarriers they may interfere because of Doppler effect and the orthogonality will be lost and this will result into some sort of inter-carrier interference, inter subcarrier interference and which it will degrade the performance of the communication.

High power interference from adjacent channels so, this may also be an issue in vehicle to vehicle communication. That is the interference coming from the adjacent channel. And interference due to imperfect received filters when you are sensing your OFDM signals there may be some drift because of Doppler spread or this local oscillator getting shifted.

So, your filter may not work optimally. So, there may be interference due to imperfect received filters and then also interference arising from the random channel access which is a protocol between vehicle to vehicle communication. In VLC there is a thermal noise and short noise because this is coming because of the detection process and also the short noise is generated if you have sunlight rather sources of light it adds to the short noise.

The solar radiation they happen to fall in the visible range. So, this is also going to contribute to the noise in the system. Then artificial light which is not from the headlight any light other than the headlight and the receiver you know that will contribute to noise. So, which is artificial light interference so, one has to handle with care these different types of noise which are getting generated DSRC and visible light communication.

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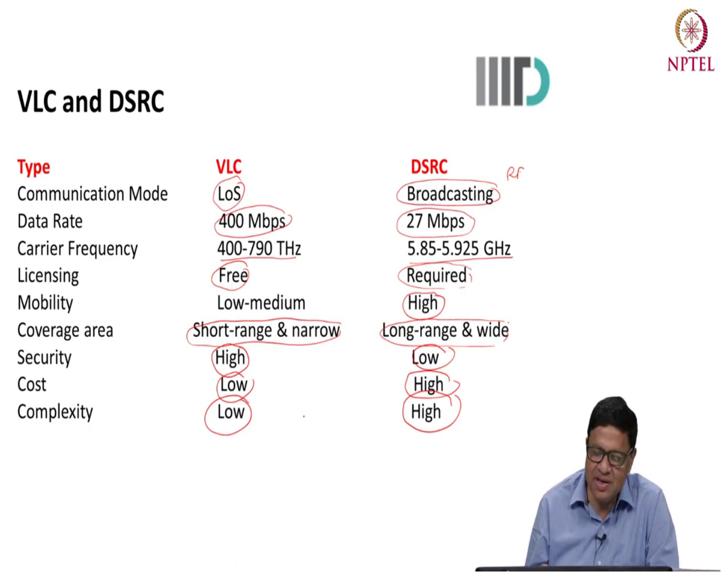

So, in short, the difference between a visible light communication DSRC is it is line of sight it is your broadcasting which is the RF technology. People have demonstrated about greater than 400 megabits per second whereas, in DSRC there is as for the specifications 27 megabits per second. This is the frequency of the visible range and this is the frequency of the DSRC 5.85 to 5.925 gigahertz. There is no license required here you require a license for this RF.

The mobility is very low to medium because essentially it is a line of sight technology, but it can support little mobility and here is the mobility is high in this case coverage area is short range and narrow or the order of few 100s of meter. This could be a kilometre for example, 1 kilometre.

Security this being a line of sight security comparatively higher as compared to RF because if the LOS is you know blocked you do not get any signal and you can get some alarm. So, security is high in VLC it is low here the cost is low in the sense the LEDs are already inbuilt into the car. So, there is no new infrastructure which is to be stalled.

So, the cost relatively is low whereas, DSRC is very very high because you have to put DSRC transmitters and receivers at regular intervals along the road. Complexity is low because you know designing a transmitter or a receiver for a visible light communication is not very complex whereas, the complexity of DSRC designing transmitter receiver is quite high.

So, at no point I want to say that DSRC VLC will replace DSRC VLC also has some limitations DSRC has some limitations. So, it is finally, a combination of these two technologies which will be a good solution which will actually improve the performance of the communication. So, places where DSRC is not giving good results one can use VLC where VLC is not giving good results one can use DSRC. So, these are two complementary technologies. So, the VLC is not going to replace DSRC.

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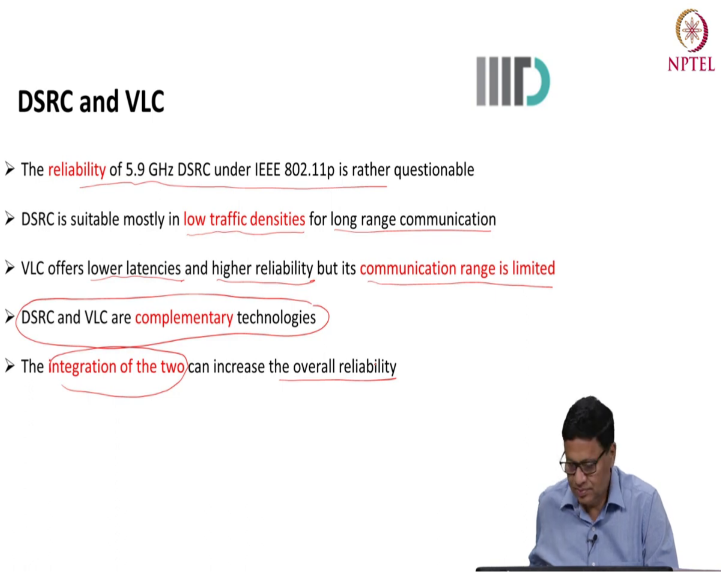

So, the reliability of DSRC is questionable because the reasons, which I have mentioned is actually suitable for low traffic densities and for long range communication. VLC is for lower latencies gives you higher reliability although the communication range is limited. So, this is what I want to impress upon the DSRC and VLC are complementary technologies and the integration of the two can increase the overall reliability for that matter any other RF technology not necessarily DSRC.

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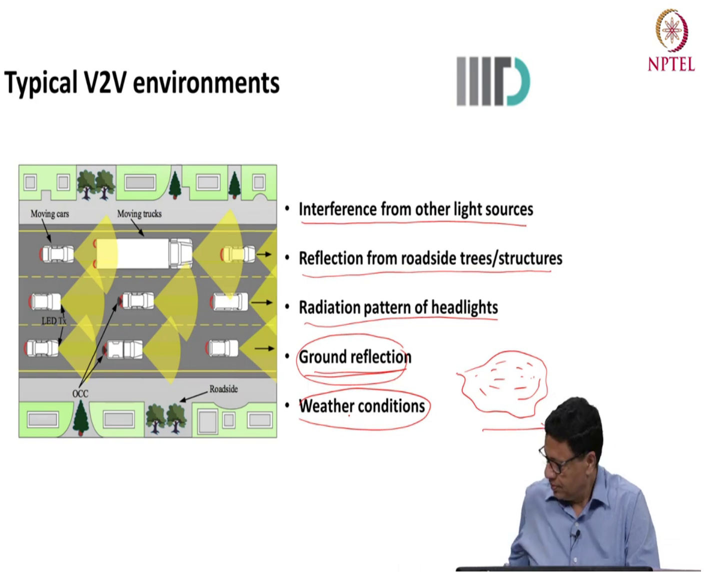

So, if we consider a typical V2V environment you will see that while analyzing this vehicle to vehicle communication you need to consider interference coming from other sources. The other sources could be the cars which are different from the cars which are communicating.

There could be reflection coming from roadside trees and buildings or some structures. The radiation pattern of the headlight actually again it is shown here as symmetric, but it is not symmetric. It has you know asymmetric pattern with different power levels depending upon where you monitor the power. So, it has a asymmetrical pattern which is designed actually for road safety and for eliminating the road during night conditions.

And then ground conditions what is the surface of the ground or the road what is a reflection coefficient of the road; whether it is diffuse or it is scattered or you know that depends on the quality of the road and then weather conditions because light communication will be impacted by the weather conditions.

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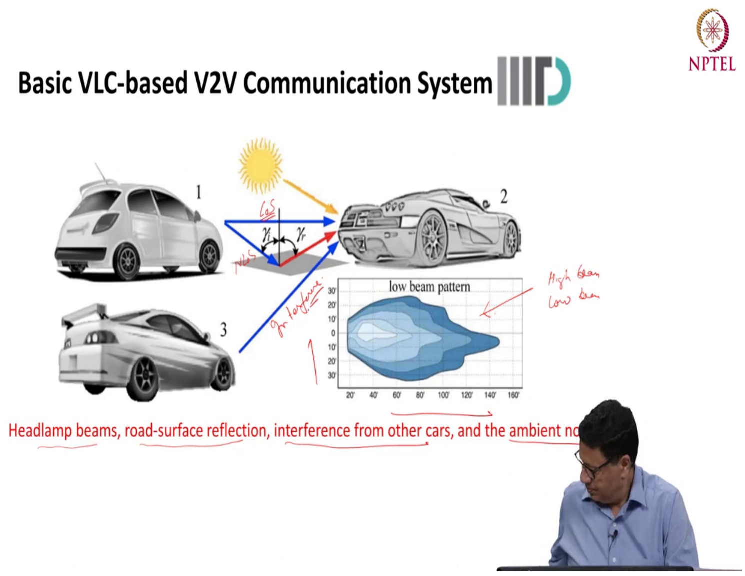

So, basic VLC to VLC communication is design if you see here there is a LOS you see here and this is the part which is non non-line of sight which is reflected from the source and then this is the interference part coming from a different vehicle. And this is the you know low beam pattern this is the angle this side. So, this is a low beam pattern. So, the car actually has high beam and low beam.

So, this is a typical low beam pattern the high beam is also similar to this only thing it eliminates a longer distance of the road. So, headlamp beams road surface reflection interference from other cars and the ambient noise one needs to consider while analyzing a vehicular to vehicular communication system.

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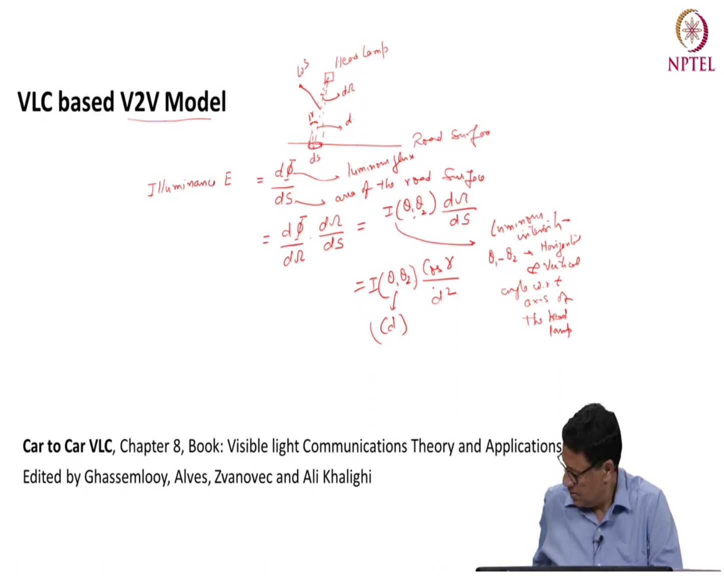

Now, let us try to understand VLC based V2V model. So, suppose you have a LED here sorry the headlamp here is the car headlamp for example. And this is a road surface. And let us consider a small area dS on the road. So, this is this solid angle which is getting lighted up here because of the headlamp of the vehicle. And let us denote this as d omega this solid angle is d omega. And this distance from headlamp to the surface is say d and let us draw a normal here.

And this angle which the ray makes the LOS this is LOS which makes with the normal is say gamma and this is area dS. So, if I calculate illuminance E, illuminance this will be equal to d capital phi over dS where, phi is the luminous flux this these things we have discussed during the initial part of the course where this illuminance, lumen flux, headlamp everything was defined, luminous flux and dS is the area of the road surface; area of the road surface. And so, the illuminance E is d phi by dS.

So, this can be written as d phi over d omega into d omega over dS. And this d phi over d omega is nothing but I theta 1 theta 2 d omega over dS where this I theta 1 theta 2 is a luminous intensity this is a definition luminous intensity d capital phi over dS luminous intensity. And theta 1 theta 2 are the horizontal and vertical angles with respect to axis of the headlamp.

So, d omega by dS so, E; so, this will become I theta 1 theta 2 into cos gamma over d square. So, this is the luminous intensity the units is in candela this is in candela this units are in candela Cd is given by cos omega by d square. So, this is the illuminance E happening in area dS. So, this is how you will find illuminance on the road surface area dS.

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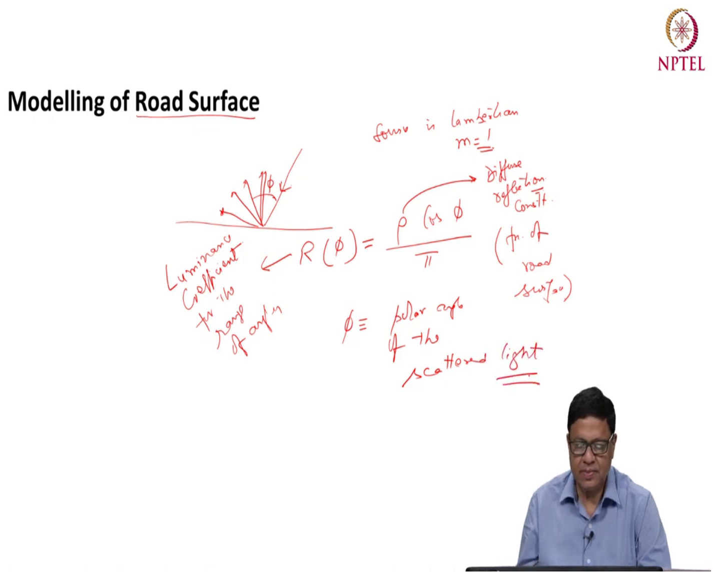

How do you model a load road surface? Now, there can be a different types of road surface. So, what happens actually if the light is falling from the headlamp onto the road surface it suffers a specular diffract it suffers a diffraction light goes in different angles. And this typical angle is actually phi which is not constant it is changing.

So, this is the input light. So, let us assume the source is Lambertian which is not a good approximation, but for simplicity let us assume the source is Lambertian with Lambertian parameter as 1. So, the R phi which is luminous luminance coefficient for the range of angles for the range of angles is given by rho cos phi divided by pi. This is the diffuse reflection constant, which is actually function of road surface. So, this is how broadly you know road surface can be modelled.

So, R phi which is luminous coefficient which is a function of phi. The scattering angle here is given by rho. Rho is diffuse reflection coefficient into cos phi this angle phi which these rays are making with the incident light divided by pi. So, this is a very simplistic modelling of road surface and phi we can call this as polar angle of the scattered light.

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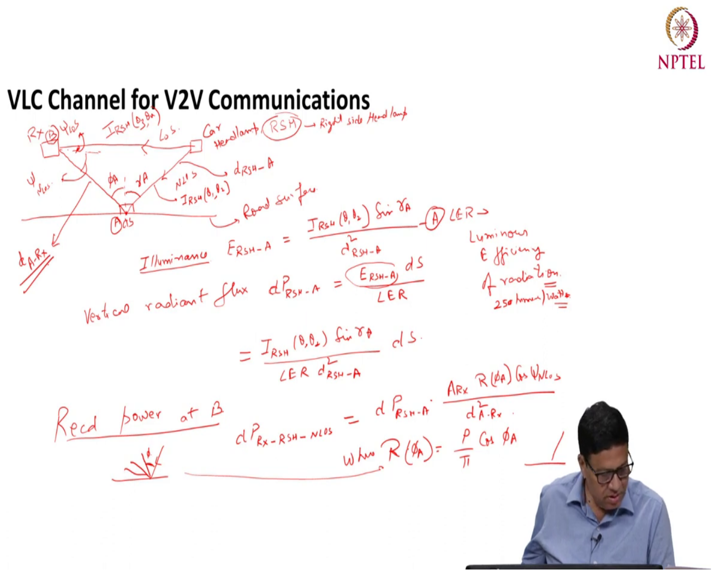

Now, let us see a VLC channel for V2V communication. How does the channel behave? So, let us draw a diagram where you have the car headlamp here. This is a car headlamp and this is the road surface and say suppose this is your receiver here. This is my receiver I call this as point B and this is say area dS I have taken on the road and I call this point as A for example.

So, there will be a line of sight this is line of sight and this is R. So, I am considering for example, this is Right Side Headlamp RSH right side headlamp right. I am just considering right now only right side headlamp. So, this will be I RSH and this is a function of two angles which are horizontal and vertical angle with respect to the axis of the car lamp. I call them let us see R rather theta 3 and theta 4.

The other one is the reflection non-line of sight this is non-line of sight and also. So, this will reach to the receiver here. So, let us draw a normal here. So, this angle which the line of sight makes with the normal here represent as psi LOS and the other angle which the non-line of sight makes let us call this as psi N LOS and let us make a normal here and this angle which the non-line of sight makes with the normal let us call this as gamma A.

And the other angle which the on this side let us call this as phi A and this is the point A this is the point B and this distance is from the right side headlamp 2 point A and this distance is from A to the receiver and this is I RSH and now let us write and yeah. So, there is this illuminance I RSH it will be function of theta 1 and theta 2.

This was function of theta 3 and theta 4. So, as I mentioned theta 1 these thetas are the horizontal and vertical angle with respect to the axis of the lamp. So, the illuminance which is E or right side headlamp at A is given by I RSH which is function of theta 1 and theta 2 sin gamma A divided by d square the distance that is RSH minus A this is illuminance at point A.

Now, the vertical radiant flux let us call as a dP RSH A there is a vertical radiant flux which is coming from the surface of the road let us called as dP because we are considering only small area dS from right side headlamp and from position A is given by E RSH A into dS divided by LER, where LER is important here LER is luminous efficiency of radiation.

So, normally the LEDs which are used in the cars they are phosphorus coated LED and actually the LED is emitting blue light, but it phosphorus coated it has yellow light. So, when they mixed up it gives you white light. So, that is a normal LED which is used with the car. So, and they have certain LER values. So, they have typically of the order of 250 lumens per watt I mean these are values of a good per watt good LED. So, this is how you measure LER lumens per watt so, luminous efficiency of radiation.

So, this is vertical radiant flux. So, this will be equal to we have to put this E RSH A from the earlier equations A this equation number A we put this value. So, what we get is R right side lamp theta 1 theta 2 sin gamma A divided by LER d square RSH minus A into dS. So, this is the vertical radiant flux. Now received power at B; received power at B that is at the receiver will be and this is we are considering currently the non-line of sight component.

So, let us designate this as dP coming from the surface dS at the receiver from the right side head LAMP and we are considering non-line of sight is equal to dP that is a vertical radiant flux dP RSH A into area of the receiver R X into R phi A this is the reflection or the scattering part phi A cos psi N LOS and divided by the distance and that distance is d square RSH A.

For this will be a d square d square this distance will be in A to R X. So, we are talking about this distance. So, this is the received power because of the vertical radiant flux from area dS on the road surface. So, where this R phi A as we have discussed earlier is rho over pi cos phi A because of the scattering.

So, this is how we had modelled you know the light is falling here light is falling like this and it is getting scattered and this angle is actually phi. So, this is given by this coefficient R phi A is equal to rho which is a diffuse constant or reflectivity constant divided by pi into cos phi A and this is a function of phi A.

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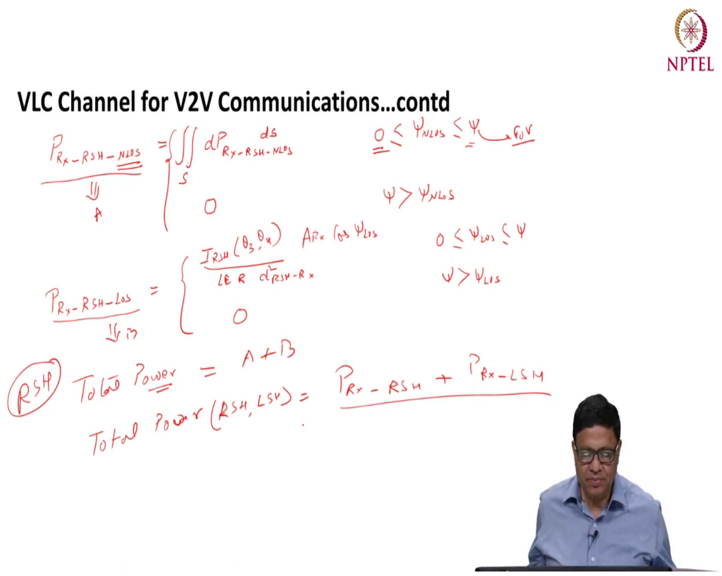

So, the total power received P R X from the right side lamp right side head lamp because of NLOS this is a total power now will be integrated over the total area which is getting eliminated from the head lamp. So, this will be integrated over the surface S and this is dP R X RSH NLOS into dS and this will be when psi NLOS is less than psi.

So, and this is only valid when the angle of psi NLOS is between 0 and psi because that is the FoV of the receiver. Anything away will not be going to the receiver as will not be counted and this is 0 if your angle psi is greater than psi non liner sight. So, this is the component from the non liner sight. Similarly, we can calculate the component which is coming from the line of sight that is P R X from the right side lamp LOS.

So, this will be given as I RSH now this is a function of theta 3 and theta 4 because these are the horizontal and vertical angles with respect to the axis of the headlamp into divided by

LER and this distance is d square RSH R X this is this distance into the receiver area ARX into cos psi LOS and when psi LOS is between this angle only this is very otherwise this 0 otherwise; if psi is greater than psi LOS.

So, what we get is the total power; total power both from line of sight component this is this component and this component suppose this is say A this is say B the total power is actually A plus B and this we have done only for the right side headlamp, but you need to include the power which is coming from the left hand left headlamp. So, the total power this is actually from the right side headlamp. So, the total power total power which. So, this is only from RSH.

So, the total power which is both from RSH and LSH. So, this is la RSH right side and left side headlamp will give a P RX minus RSH plus P RX minus LSH. So, this is the total power you get on to the receiver from left hand and right side lamps. So, this is how one has to calculate the power which is getting received at the receiver.

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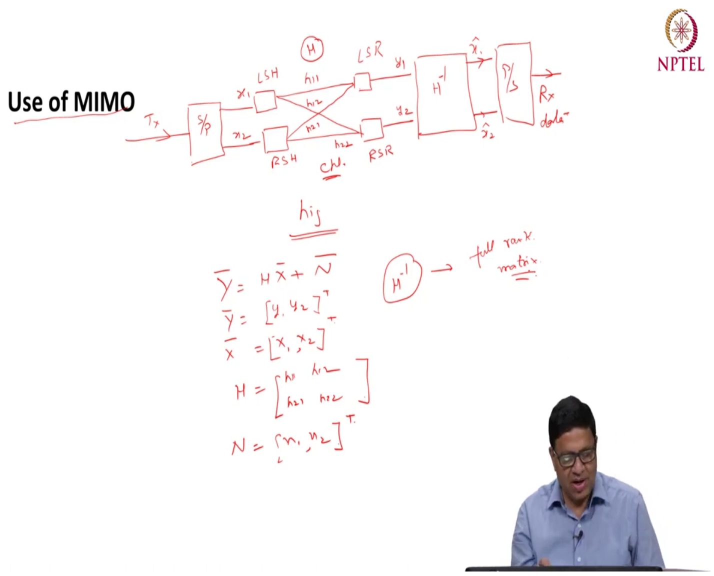

Sometimes one can use MIMO to increase the effective throughput. So, this also we have studied MIMO in earlier classes. So, normally you have two types of sources the right side and the head side and similarly you can have two receiver you know on to the two set of PDs on to the receiver.

So, the model will something become like this. So, this is for example, your transmitter. So, you will convert say for example, serial to parallel you get some x 1 here x 2 here and this can go from say left side headlamp this can go from you know right side headlamp and then you have two receivers.

This is a LSR that is right side receiver this is a this is right this is left side receiver this is a right side receiver and this is the channel actually. So, the MIMO channel will be light will go here as well as here it will go here as well as here and these they have the you know channel coefficient as hij.

So, this is for example, h 11 this will be h 12 this will be h 21 this will be h 22 and then you have y 1 here this is y 2 here and then you use some sort of equalizer. So, if this is H here and it is a 2 cross 2 matrix. So, you can always take a inverse. So, if you have equalizer which has this characteristic H minus 1 then what you get is and this is some period to serial and this is your received data.

So, this is your estimate here x 1 estimate this is x 2 estimate which is converted into serial and you get the received data and hij is the. So, if you see the whole model this is Y is equal to HX plus N we have these NR vectors and H is a matrix. So, and Y is Y vector is given y y 1 or y 2 transpose and X vector is given by x 1, x 2 transpose and H is given by there will be is a 2 cross 2 matrix.

So, it will be h 11, h 12, h 21, h 22 and the noise vector is given by n 1 and n 2 transpose. So, this is how you can model and one in order to take the inverse H inverse the it has to be a full rank matrix. So, one has to ensure that we get a full rank matrix only then you know inverse is possible. So, using this one can get you know better throughput or better performance in the system. So, this is how a MIMO principles can be used in vehicle to vehicle communication or car to car communication.

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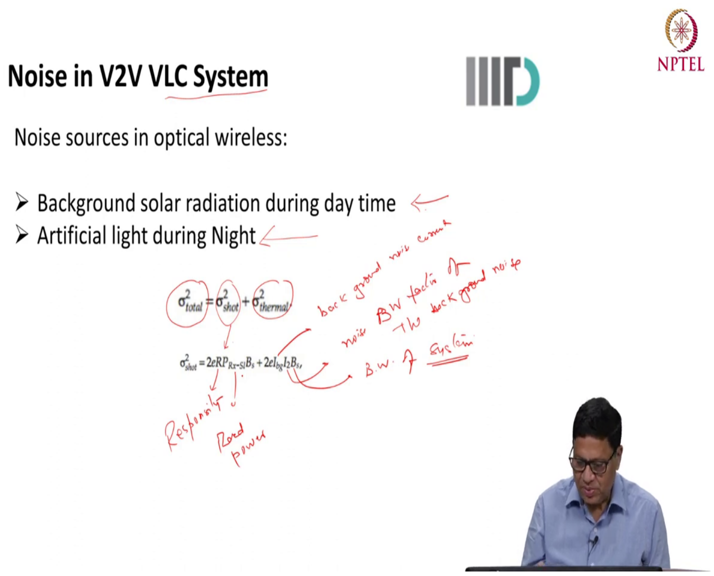

So, as we discussed the noise in the VLC system because ultimately you have to calculate signal to noise ratio. So, noise sources are background solar radiation or artificial light during night and you have this total noise is short and thermal noise. The short noise is given here where this is the responsibility is the electronic charge.

This is the received power onto the receiver received power. This is the background noise current background. This is part of the because of the short noise because of the background noise current. And this is some noise bandwidth factor noise bandwidth factor of the background noise.

And Bs is the bandwidth of the system. So, this also we had discussed when we were discussing about the detector. It has short noise and thermal noise. So, the expressions are given here for the short noise and thermal noise which is actually dependent on the RL of the that is the load resistance of the receiver.

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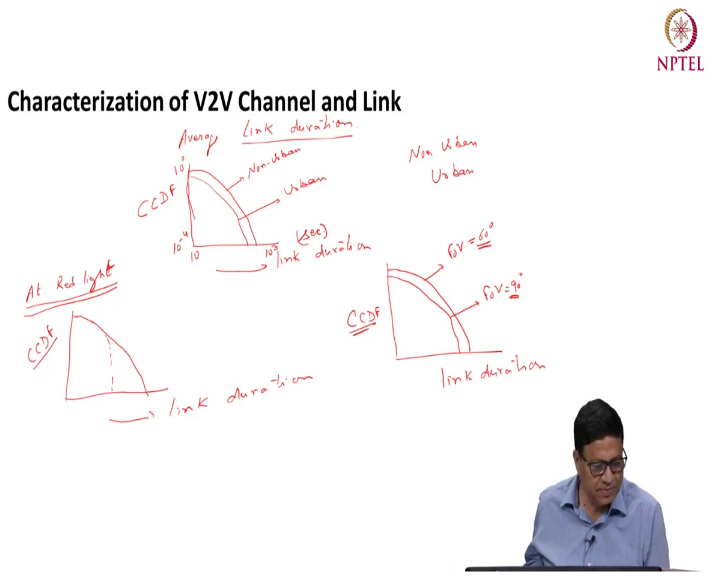

So, characterization of V2V channel link is done as we had discussed. We need to find out what is the average link duration. What is the time average time during which the two vehicles are communicating? So, in a typical experiment I am just sharing some results here. It is found. Suppose this is your link duration.

And this is could be in terms of seconds here starting from say 10 seconds to 10 raised to power 3 seconds. And suppose I plot CCDF here Cumulative Complementary Distribution Function. And you know this can be different for example, non-urban scenario where traffic density is not very high or urban scenario where traffic density is very high.

So, if you plot this curve the typical curve looks like something like this. CCDF value is say very low here minus 4 and it is say 10 raised to power 0 here. So, this is for example, for non-urban environment. And if you plot similar for urban this will be little less here. So, this is for urban.

Because in urban there are the traffic density is more. There will be more vehicles. They will have more interference. So, basically at the average link duration will come down in urban environment. But it is of the order of about goes up to 10 to the power 3 seconds.

And if you take a specific case at for example, at red light intersection. At say for example, red light intersection then if you if I plot the same curve. So, this is link duration here. And this is again CCDF Cumulative Complementary Distribution Function. So, normal case is something like this as we have drawn in the earlier curve.

But at the red light interference this will you know all of a sudden it will start dropping here at some point. Because during the red light all the vehicles are you know close by. And they are all they are all sources of interference to the communicating vehicles. So, it basically falls down sharply.

So, this is a case a specific case when the vehicle is at red light then the average link duration actually gets reduced. Similarly, one can study by changing the FoV field of view of the receiver. And plot the link duration versus CCDF for different field of use. So, so it will be for example, this FoV here is a 60 degree.

If I increase the FoV to 90 degree the performance will little go down. This is FoV is equal to 90 degree. Because if you have the wide FoV; that means, it is getting interference from in a larger area from different sources different vehicles which will actually increase the noise floor.

So, that is why you see the performance degrading when you increase the FoV of the system or FoV of the receiver as compared to smaller FoV. But if you have the smaller FoV which is good from this particular aspect of link duration, but smaller FOV will require strict line of sight you know communication. So, you lose on the mobility part. So, it is a trade off between the two. So, this is you know some typical results for a vehicle to vehicle channel and link for link duration average link duration.

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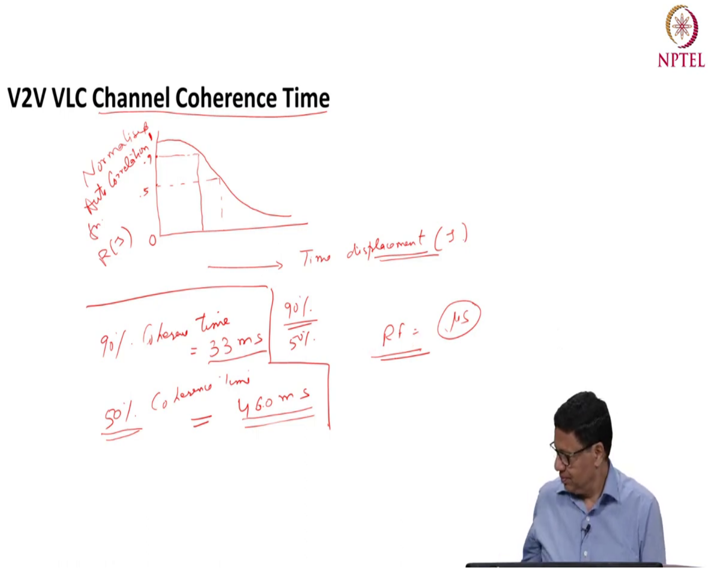

And if I see the coherence time V2V VLC channel coherence time and let me first plot a curve between say this is the coherence time or the time displacement. So, this basically tells you the channel is whether how long the channel is constant. What is the duration in which the channel characteristics are same because this is very important because you have to estimate the channel.

And if you are doing frequent estimation there is some overhead associated with the estimation which with which decreases the throughput of the system or the BER performance of the system. So, this is a tau. So, this is something like this. Here it is again let me call this as normalized auto correlation function R tau.

So, this will be 0 to 1 which is normalized here. So, there are two ways of defining coherence time either you use 90 percent correlation that is you know the channel has changed only by only 10 percent. The other is 50 percent a broader definition channel has changed by 50 percent. So, if you see the values at 90 percent, say this is a 0.9 and this is 0.5.

So, this will give me you know this value of coherence time whereas, this will give me this value of coherence time. So, the 90 percent coherence time is typically 33 millisecond whereas, if you take the definition of 50 percent coherence time correlation this is of the order of 460 millisecond.

So, the channel in the first case when you take the 90 percent definition is constant for 33 millisecond only after that you require estimation of the channel. And if you take a little loose definition which is 50 percent, it is about 460 millisecond but in the RF case these values are in microsecond.

So, clearly as far as coherence time is concerned VLC is significantly better as compared to its RF counterpart whereas, the coherence time of the order of few tens of millisecond as against microsecond in case of few tens of microsecond in case of RF. But this is a case in condition for a case when you are considering line of sight communication for these two for these two examples.

So, this is very important if you have a longer coherence time the estimation requirement is relaxed. You require estimation you know after a long interval which actually reduces the overhead and increases your throughput.

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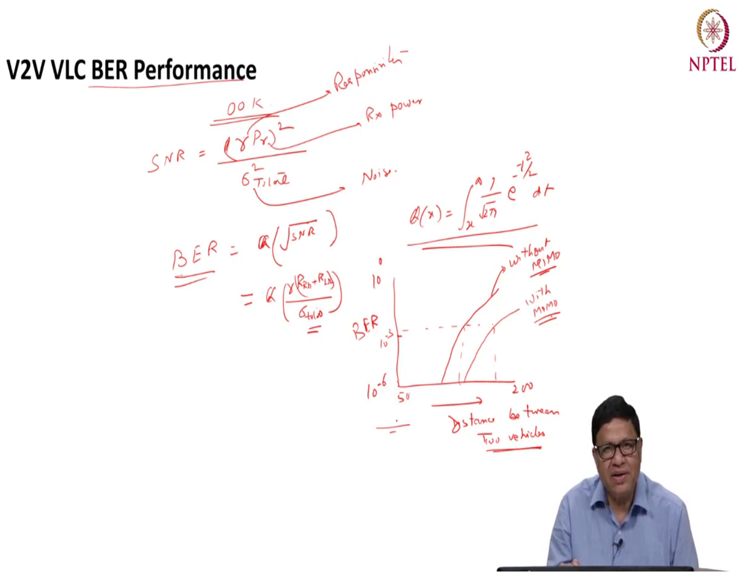

So, finally, let us see the V2V VLC BER performance. So, if I consider for example, a simple scheme of on of keying the signal to noise ratio is given by sigma r P square where this is the responsibility of the photo detector. Pr is the received power and this is the noise total noise in the system.

And we know for ok BER is given by Q function it is defined by the Q function which is nothing but root SNR because if you see the first term is signal power divided by the noise power and let me write here how you define the Q x the Q function it is x to infinity 1 over root 2 pi e raised to the power minus t square t divided by t.

So, this is the Q function. So, BER is given by Q of root SNR and if you see the Q is the gamma the power received by the left side right side let me write this as right side lamp plus R received by the left hand divided by sigma total. And if you plot for example, the distance between two vehicles and on this side if I plot BER Bit Error Rate and start minus 6 on this side and say this is 10 raised to power 0 and this distance let us start at 50 and this may be 200. So, what you get is something like this.

So, as your distance increases because your received power is less your BER performance goes down. So, this is actually case of without MIMO. If I if you use MIMO then there will be an improvement and you your performance will be something like this is with MIMO which I had discussed earlier.

So, this is a typical BER versus a distance between. So, one can suppose this is 10 raise to the power minus 3. So, you can find out the distance corresponding distance for these two cases. So, this is about the BER performance. So, we have seen you know different parameters the BER we have seen the link duration we have seen the coherence time.

So, these are the metrics which define vehicular to vehicle communication. So, we see that VLC can play an important role in vehicular to vehicular combination in communication. Specifically, if it is being done along with a RF counterpart could be a LTE V or DSRC. So, you get a increased performance if you use a hybrid system because they are complementary to each other.

So, in we also have one of the simulation exercise planned which we will discuss in detail about vehicle to vehicle communication and how you can you know simulate and you know and draw these different metrics or the results. So, this is another application of VLC, which we have discussed today.

Thank you very much.