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 - 18
Hybrid Network LiFi and WiFi Coexistence

Hello everyone. So, today we are going to discuss one of the applications of visible light communication, which is LiFi WiFi coexistence, which means both LiFi and WiFi will coexist and you will see during the course of the lecture that there is a improvement in the performance.

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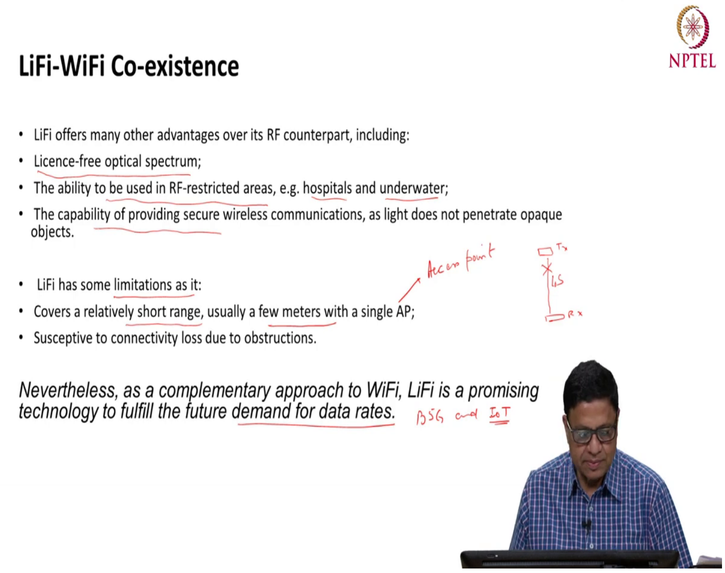

So, let us discuss some of the advantages of LiFi over RF. It is licence free optical spectrum unlike RF where one has to pay for the spectrum and since this is being visible light communication there is no licence required for optical spectrum. The ability to be used in RF restricted areas, we cannot use RF in for example, in hospitals or underwater in hospitals it might interfere with some of the machines which are sensitive to electromagnetic radiations, underwater the RF losses are very very high.

So, we cannot use you know RF technology in hospitals and underwater. So, whereas, the VLC or optical communication or the light communication can be used in hospitals and underwater. The LiFi or light communication is secured in the sense that the light does not penetrate opaque objects. So, the light is confined inside the room it does not go outside.

So. LiFi or VLC communication is more secured as compared to RF or WiFi communication. LiFi has some limitations. It covers a relatively short range usually few meters with single AP. AP is access point. It is susceptive to connectivity loss due to obstruction. So, whenever there is a obstruction between the source and the receiver there may be there may be loss, there may be you know there may not be any signal between transmit and receiver.

So, there will be obstruction for example, this is your T X and this is R X. Essentially this is a line of sight technology. So, if there is a obstruction here it will be blocked the light will be blocked and you will not get anything in the receiver. But if you combine both WiFi and LiFi it is a promising technology to fulfill the future demands of data rates. It can offer you performance which is required for beyond 5G and IoT applications.

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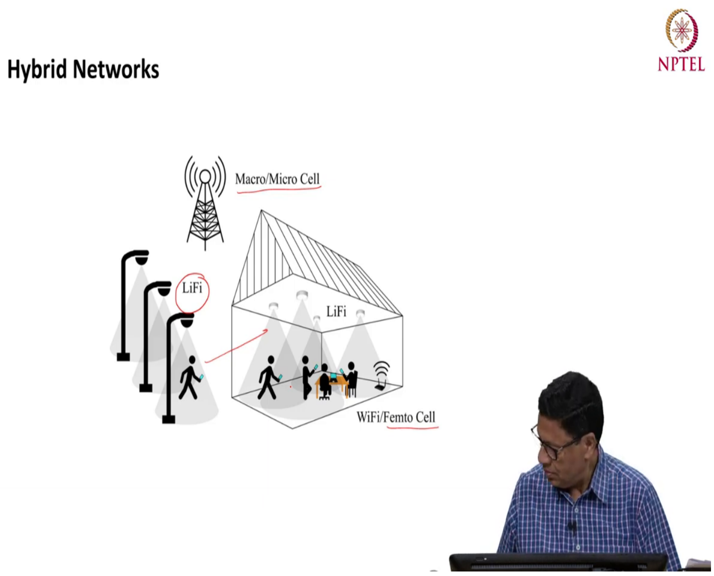

So, there are various types of hybrid networks. Suppose a user is in outside environment is connected to either a macro cell or a microcell cellular part of cellular communication. As he moves and he if he happens to be below a lamp then he may be connected with LiFi. And as soon as he enters a building you have both LiFi access point and WiFi access point or there could be a femtocell inside then this combination of LiFi and WiFi or femtocell will give enhanced performance.

So, these are some of the examples of hybrid networks where the light communication RF communication they coexist.

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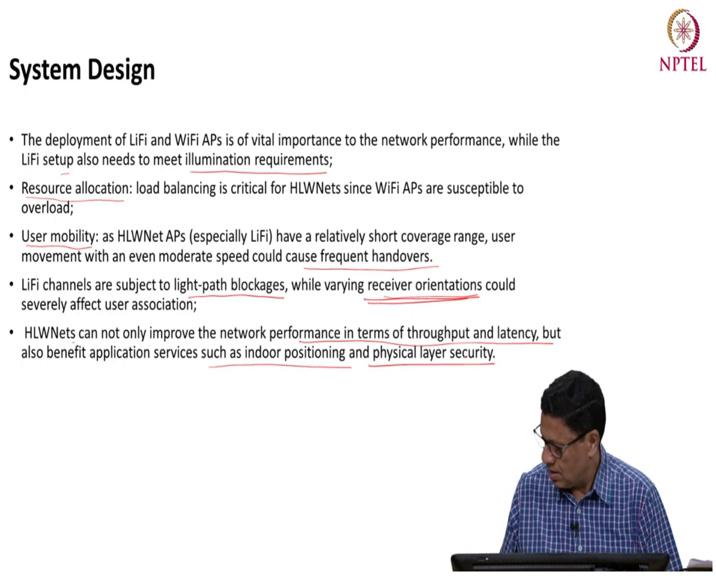

Now, system design is very important in such coexistence scenario. So, the deployment of LiFi and WiFi access point is of vital importance to the network performance and we need to ensure that LiFi also meets the elimination requirements. So, the light has to be, light intensity has to be such that it meets both elimination requirement as well as communication requirement.

Then resource allocation load balancing is critical for hybrid LiFi WiFi networks. Since WiFi if there are many users accessing WiFi access point it may result into some overload. So, one has to do a intelligent resource allocation between the LiFi access point and the WiFi access point.

User mobility is a matter of concern and coexistence because in LiFi you know it is relative relatively a short coverage range and if the user moves even with a moderate speed there will be frequent handovers from one LiFi to another LiFi.

So, one has to be careful while designing a system. So, that these frequent handovers are avoided because each handover will result into some overhead which may decrease the throughput of the system. LiFi channels are subject to light path blockages and also the receiver orientation. Suppose it is a mobile you know the mobile is not is not always facing the luminaire or the light or the transmitter.

So, it may be at some angle. So, one has to handle take care of this receiver orientation. It may affect you know the performance. So, LiFi channels are subject to light path blockages this is because any obstruction coming between the line of sight will obstruct and also the receiver orientation is continuously changing.

So, one has to take care of this receiver orientation by having you know some sometimes angle diversity receivers where you have receivers at different angles mounted there and then whenever the device is you know changing orientation one of the receivers is getting light. So, this is how this can be handled receiver orientation can be handled.

So, hybrid LiFi WiFi networks can only not only improves the network performance in terms of throughput and latency, but also benefit it gives you indoor positioning you are able to find out the accuracy the position accuracy I mean you are able to find out the positioning of the object using VLC or using different optical transmitters which are there in the room and also it increases physical layers security. So, there is improvement in the performance in terms of throughput and latency.

But also, you are able to find the accurate position of the objects and also enhance enhanced physical layer security.

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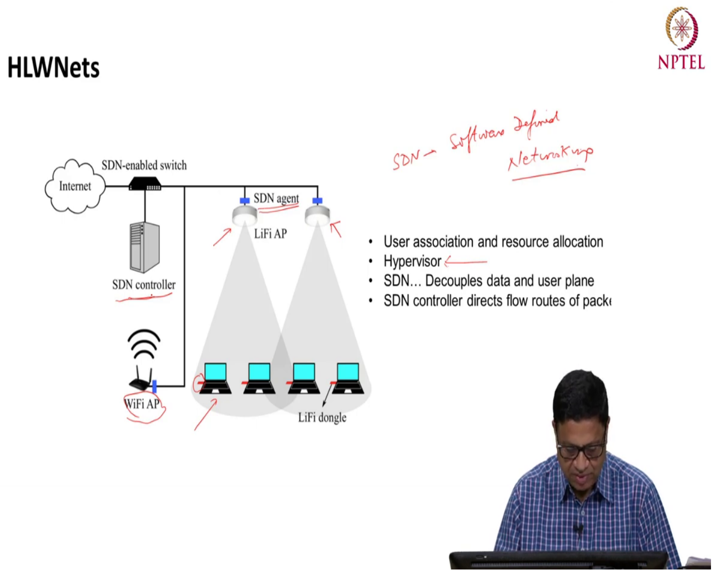

So, this is a typical diagram of a hybrid LiFi WiFi network. So, you have these are the you know for example, laptop devices and there is a dongle here, LiFi dongle and anyway WiFi is part of the laptop. So, this is the dongle the red strip you see is the dongle here and then you have these are the LiFi APs access points and also you have WiFi access points inside the room.

So, the important thing here is how do you associate user to different access points, how do you allocate the resources which are from LiFi access points and WiFi access points. So, there is a hypervisor required to elevate you know resources and association appropriate association with the access point and this is done using software defined networking SDN Software Defined Networking.

So, basically SDN decouples data and user plane and SDN agent will extract the information and you know convey the information to the SDN controller which will direct flow routes of the packets. So, this is how a typical hybrid LiFi WiFi network works.

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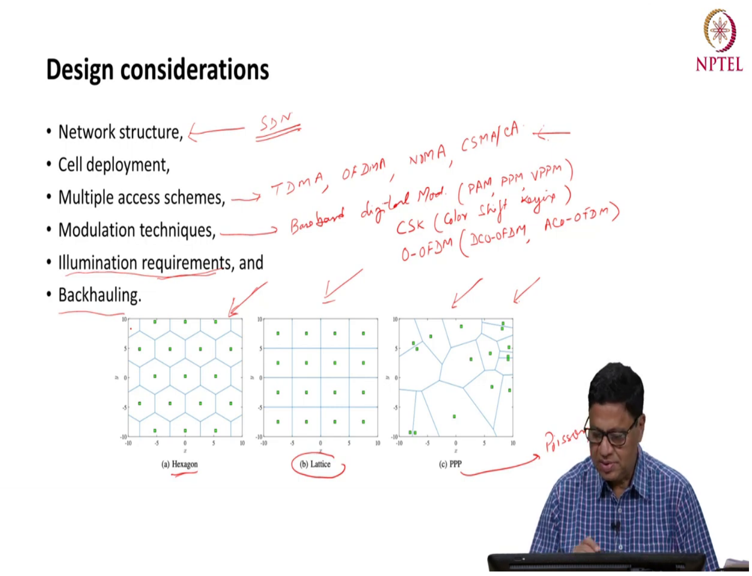

There are various design considerations while designing the LiFi WiFi architecture. The one is network architecture which I has just discussed using SDN Software Defined Networking. And then how your cells are deployed in for example, in cellular you have you know different options one is this hexagon which is very popular in cellular deployment and then you have lattice kind of deployment and then you have Poisson point process which is some random deployment of a base stations Poisson point.

In LiFi hexagon may not be a suitable option because you also have to worry about the elimination part whereas, the lattice may be a good solution for VLC transmitters you know deployment on the ceiling because it can give you uniform elimination throughout the room and Poisson point process may not be a good option for LiFi deployment.

And then there are various kind of multiple access scheme the simplest being TDMA time division multiple access or if you are using OFDM OFDMA, Orthogonal Frequency Division Multiple Access or NOMA Non-orthogonal multiple access or standard says CSMA CA carriers has multiple access collision avoidance.

So, these are some of the options of multiple access schemes we used in LiFi and there are lot of modulation techniques which can be used starting from baseband digital modulation this we had covered in the course also baseband digital modulation.

For example, PAM, Pulse Amplitude Modulation, pulse position modulation or variable pulse position modulation these are some part of the standards or you can have color based on CSK which is Color Shift Keying we had a detailed analysis of color shift keying shift keying and we also discussed about optical OFDM under this said we had discussed about DC OFDM and ACO-OFDM these are different variants of optical OFDM.

So, there are various techniques available and all these techniques have been studied in the literature and then you have to maintain some elimination requirement because each place requires different kind of elimination of factory where some you handle very very small objects may require good elimination, office may require certain other type of or certain other value of elimination.

So, one has to keep in mind for which application the system is being designed and one has to ensure the elimination part and then one has to worry about the backhauling how the information is back-haul to the network. So, these are some of the design considerations for LiFi, WiFi, hybrid networks.

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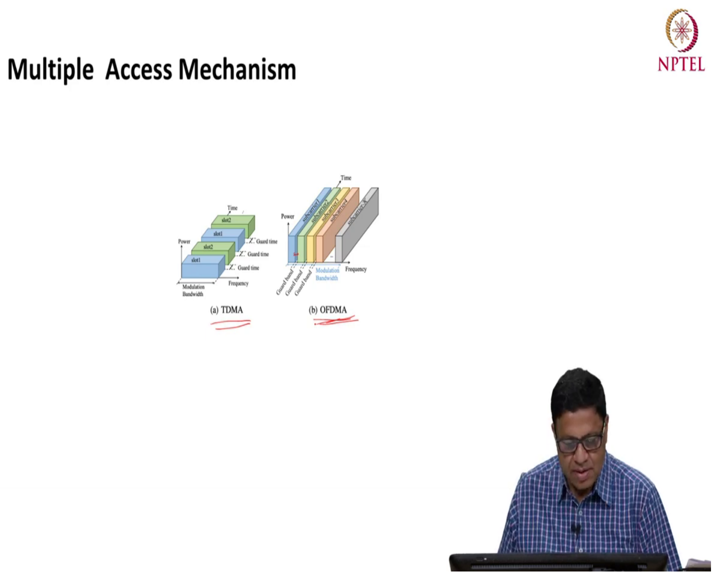

So, this is an example of a multi access mechanism where I have shown TDMA and OFDM which are quite popular. So, in TDMA the whole bandwidth is allocated to the user and it is given in some time slot for example, slot number 1 and then it is given in the slot 2 in a different slot the whole bandwidth is given to user 2 and so on and so forth.

And there is some guard band between the two slots and in OFDMA you divide the whole bandwidth into sub-channels or they have the sub-carriers and the sub-carriers are allocated to the user. So, it is depending upon the requirement of the user you allocate the resources or number of sub-carriers to the user and there is some sort of guard band. So, that there is no interference between sub-carrier 1 and sub-carrier 2.

So, these are the two examples of multiple access mechanism, time division, multiple access and orthogonal frequency division, multiple access.

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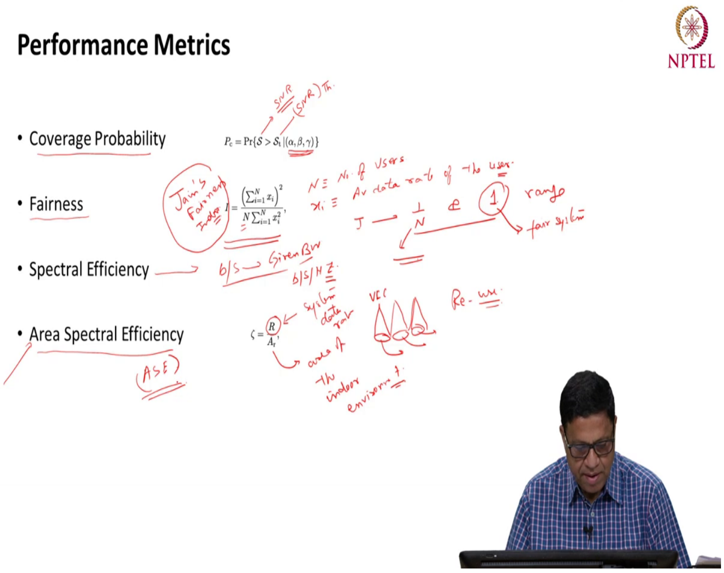

The performance metrics which are used in such networks in such hybrid networks is coverage probability. This basically is defined as probability this S stands for say SNR, a probability that S the signal to noise ratio is greater than some threshold and this alpha beta gamma are the angles of the device because it also depends on the orientation of the device.

So, this is the orientation is defined by these three angles alpha beta and gamma. So, the coverage probability is defined as SNR greater than SNR threshold given the orientation of the device. The second is fairness and this fairness is defined as I is equal to summation i is equal to N x i whole square divided by N summation i is equal to 1 to N x i whole square where N is number of users and x i is average data rate of the user. So, it basically tells this with number i tells how the data rate is divided among the users.

If everybody gets same data rate the fairness of the system is 1. So, the limits of fairness or the limits of I is actually between 1 by N and 1. This is a range. If this value is 1; that means, every user is getting similar amount of data rate and the system is called fair. This is a fair system most fair system.

If somehow all the resources are given to one users and others they do not get anything then the value of the fairness is 1 by N which is the least value. So, system is not fair at all. So, one has to ensure that this I value of I should be as close to 1 as possible. So, that all the users get fair amount of data.

Third, this is also called as Jain Jain's Fairness Index; Jain's fairness index. If there are other definitions also for example, max-min fairness or quality of experience fairness, but in literature Jain's fairness index is used quite often. The third performance metric is spectral efficiency. Spectral efficiency is actually what is the bit rate per unit hertz. So, it is defined as how many bits per second you are able to transmit in a given bandwidth.

The units are bits per second per hertz. So, this is spectral efficiency rather performance metric which is evaluated in such networks. Then another important unit is area spectral efficiency. Now, area spectral efficiency actually if you see VLC, it has a footprint which is called as atto cell and there are many atto cells inside the room because there are many you know transmitters.

So, you can reuse the resources, bandwidth resources in each cell. Reuse. So, if you are because atto cell is very small and you are able to reuse the resources then the spectral efficiency if you defined per unit area is also an important parameter. So, for visible light communication, area spectral efficiency which is defined as R which is the data rate of the system, system data rate and AR is the area of the indoor environment.

So, area spectral efficiency when you have both LiFi and WiFi makes better sense as compared to spectral efficiency. So, that is why in hybrid networks Area Spectral Efficiency or also called as ASE is important.

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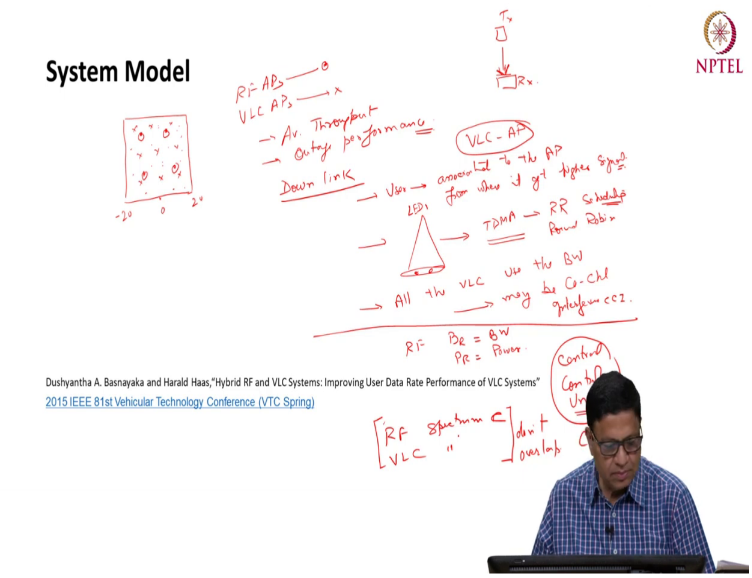

So, now let us try to understand this LiFi coexistence and let us draw the system model which we are going to study. So, system model suppose you have a room this dimension can be say minus 20 to 20 this is 0. So, about 40 meters or can be you know 10 meters or some other dimension and it has RF APs and VLC APs, VLC access points. So, VLC I am denoting by for example, this crosses these are the optical transmitters or the elimination source inside the room.

So, these are VLC APs and RF APs for example, inside this room I have 4 RF APs. So, this is RF APs and then users are let me make bigger circle here and the users are uniformly distributed inside the room. These are the users which are uniformly distributed inside the room. So, we need we will need to calculate the average throughput and the outage performance.

So, we will try to evaluate this average throughput and outage performance and see that as can compare to standard on LiFi or standard on WiFi this coexistence of LiFi and WiFi gives a improved performance. So, in the analysis we will consider the downlink only downlink that is from transmitter to receiver.

We will evaluate this performance and we will assume that user is associated with the AP from where it gets a higher signal associated to the AP from where it gets higher signal and if there are many users which are coming in the atto cell for example, this is atto cell and there are many users coming here which is associated with this LED or this transmitter 1 then to avoid interference it will use a TDMA scheme which is based on round robin round robin scheduling.

So, each user will get access to LED 1 for sometime slot and then it will go to the user another user which is in the same (Refer Time: 24:37) So, we will assume that it follows within the atto cell TDMA protocol which is round robin scheduling and all the VLC use the same bandwidth. All the VLC use the same bandwidth. So, there may be CCI Co-Channel Interference. So, these are the assumptions we are making while evaluating this model maybe may be co there will be Co-Channel Interference CCI.

So, regarding RFAPs this was about VLC AP regarding RF AP we will assume that BR is the total bandwidth and PR is the total power and we are assuming that there are four RF APs and PR is the power and BR is the bandwidth of the RF AP and also there is a Central Control Unit CCU central control unit which controls VLC in RF system. So, this particular device CCU controls both VLC and RF devices and it is known that RF spectrum and VLC spectrum they do not overlap; do not overlap.

So, there is no question of interference from RF source to VLC access point or VLC access point to RF because their spectrum is entirely different.

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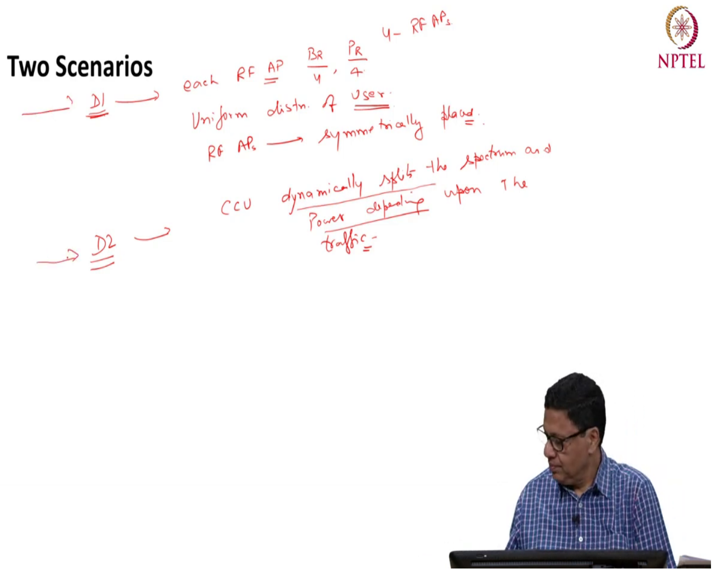

So, let us discuss two scenario while evaluating the performance of hybrid network. One let us called as the D1 scenario. In D1 each RF AP access point gets one-fourth assuming there are four RF APs inside the room. Each RF AP gets one fourth of the bandwidth and one fourth of the power.

The total bandwidth is BR for all the APs and total power is PR, but in a in one scenario which we are considering each RF AP will get one fourth of the bandwidth and one fourth of the power and there is a uniform distribution of users, uniform distribution of users on the inside the room.

And also let us assume that RF APs are symmetrically placed. The other scenario D2 could be where the central unit or Central Control Unit CCU central control unit it dynamically splits the spectrum and the power depending on the traffic spectrum and power depending upon the traffic, instantaneous traffic. So, for example, if all the users are near RF1, RF access point 1 then the total bandwidth and total power is given to that particular AP.

If there are less number of users then it is given to some other AP where you have more number of users. So, it basically dynamically splits the spectrum and the power depending upon the instantaneous traffic depending upon how users are located inside the room. So, these are the two scenarios which we will try to evaluate.

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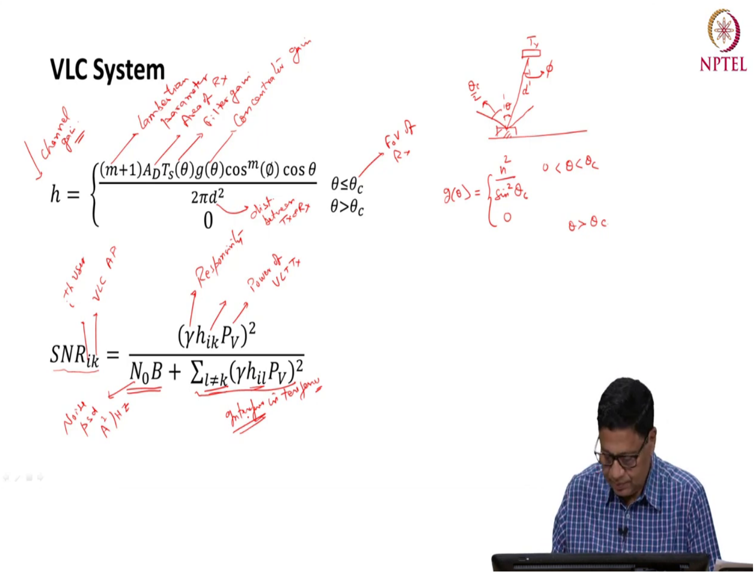

So, now let us start modeling the VLC system. So, the channel gain, this h is channel gain, this we have done many times channel gain is given by this expression where m is the

Lambertian parameter. A D is the area of the P D, area of the receiver. This is T x, T s theta is filter gain. This is concentration gain, concentrator which are using as the receiver.

And this D is the distance between the T x distance between T x and R x and this theta C is the FoV of the receiver. So, just to tell you what is what are these phi and theta. So, you have a T x here, our receiver is say somewhere here. This is the line of sight which the distance is d and this is for example, the FoV. So, let us draw the normal here. So, this is half of the FoV.

So, this is theta c by 2 and draw a normal here. This angle is phi and this angle which it makes is theta. So, this channel gain is given by this expression. This we have done many times when we were discussing indoor channel modeling. And of course, g theta which is a concentration concentrator gain depends on the refractive index of the concentrated sin square theta c and this theta has to be between theta c and 0. It is this value is 0 if it is. If theta c theta is greater than theta c.

So, if I calculate the SNR ik where i is the ith user. This is ith user and k is the VLC access point. So, SNR, SNR between the VLC access point and ith user is given by gamma h ik P v whole square where gamma is the responsivity.

This is a channel gain between the kth access point, VLC access point and ith user and P is the power of the VLC transmitter. This is the noise part where N 0 is noise psd power spectral density units are ampere hertz and this is the interference term. It is coming from all other sources. This is l is equal to k.

So, other than k for the other sources in the room other VLC access point this is interference term where h il is the between the user i and the lth VLC AP. So, this is the interference term. This is the interference term.

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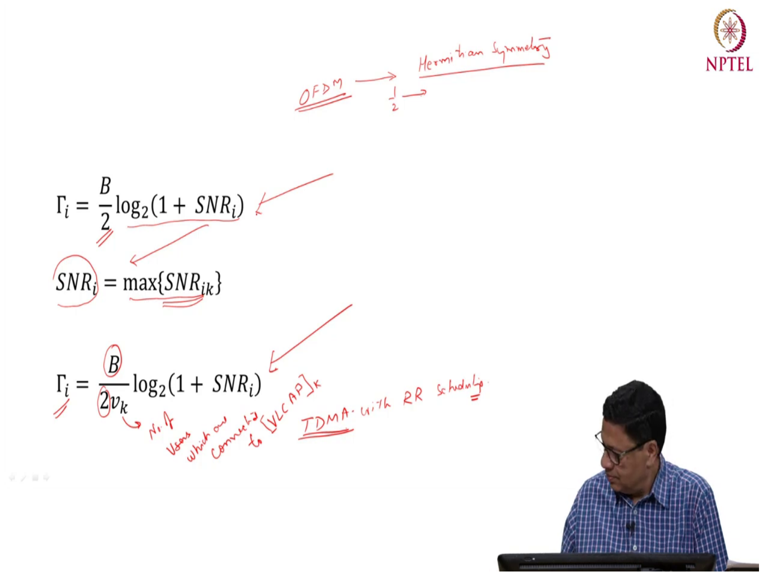

So, if I calculate capacity of the ith user is given by B by 2 log 2 1 plus SNR i. Now, this B by 2 is coming because I am using OFDM modulation technique and in OFDM modulation technique we have studied that the half of the subscribers are conjugate of the other half because we need to maintain the Hermitian symmetry. We want to make the signal real and unipolar.

So, only half of the subcarriers are carrying data. So, that is why you get a factor of half here. So, the rate becomes B by 2 log 2 1 plus SNR i and this SNR i is actually maximum of SNR ik. So, there are k VLC access point. So, the user will be associated with the VLC which gives the maximum SNR. So, this SNR i is actually maximum of SNR ik.

And if there are many users which are a part of the single atto cell and connected to a single VLC AP in that case the rate is given by B divided by 2. This is coming because of the

OFDM and this is the number of users. So, this is number of users which are connected which are connected to VLC access point k.

And there may be many users and we have discussed earlier that if there are many users to avoid interference, we follow a TDMA protocol for these users with R with round robin scheduling. So, this is the expression for rate when there are more than one user inside the atto cell and this is a rate when there is only a single user inside that atto cell.

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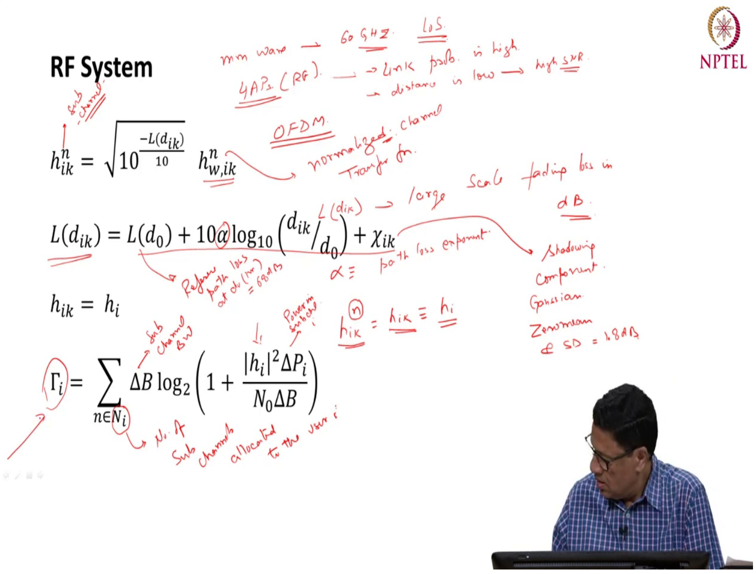

Now, let us discuss about the RF system. So, we are let us assume that RF system is millimeter wave where the frequency is 60 gigahertz and majorly line of sight. And as I mentioned the system model, we have used 4 APs, RF APs. The idea is that you know the user should be connected to a AP which has the shortest distance. So, that he gets maximum

SNR. And the other could be if there is some blockages or some obstruction between one of the RF AP the signal the user gets signal from other RF APs.

So, there is some sort of diversity built into the system. So, that is a whole idea of using multiple RF APs. So, the link probability. So, let me write this link probability is high and the distance is low because you know the user will be connected to the nearest RF AP. So, that you get you know high SNR. So, that is the idea for using multiple APs. And also, we are assuming that same as VLC we are using OFDM modulation in the RF also.

So, as for the modulation is concerned for both RF and VLC, we are using orthogonal frequency division multiplexing. So, if I calculate the channel gain between kth RF AP and ith user for the nth sub channel. So, this denotes the sub channel because there are sub carriers. This is given by which is written here as h n ik.

Once again this is a channel gain between the kth RF AP and the ith user for the nth sub channel is given by root 10 raised to the minus L d ik divided by 10 h w n ik where this is normalized channel gain. This is normalized channel transfer function and L d ik let me write here this is important L d ik is large scale fading loss in dB.

And this L d ik is given by this expression where L d 0 is reference path loss at distance 1 meter path loss at d 0 distance which is actually 1 meter and this is roughly 68 dB. And this alpha which you see here is path loss coefficient path loss exponent and this ik is used as shadowing component. So, shadowing component this is the distribution is Gaussian here for this Gaussian with zero mean and standard deviation is of the order of 1.8 dB.

So, this is how L d ik the loss at distance d ik is defined that is it consist of a reference path loss plus because of the path loss component and then there is a shadowing component which is Gaussian distributed with zero mean and standard deviation 1.8 dB. I can take h ik as i. So, first of all let us see h ik n is h ik because I am assuming the loss of the channel will be same for all sub channels.

The figure I mean the optical wireless channel gives is a flat channel for different sub channels of the OFDM signal. So, I can equate this h ik n it is independent of frequency is h ik and this h ik is can be approximated as h i because you are taking the larger signal from the RF AP. So, it is nearly equal to h i in all the cases. So, the rate tau i is given by delta B and delta B is the sub channel bandwidth.

This is sub channel bandwidth and this is a power in the sub channel i power in sub channel i and h i is the channel gain and this N i is the number of users number of other sub channels allocated to the user N user i. So, this is the rate it will be sum of N going from N i up to N i. So, basically N i is number of sub channels allocated to the user i and delta B is a sub channel bandwidth and delta P is the power in the sub channel and then 0 is the noise psd. So, this is for the case of RF this is the rate.

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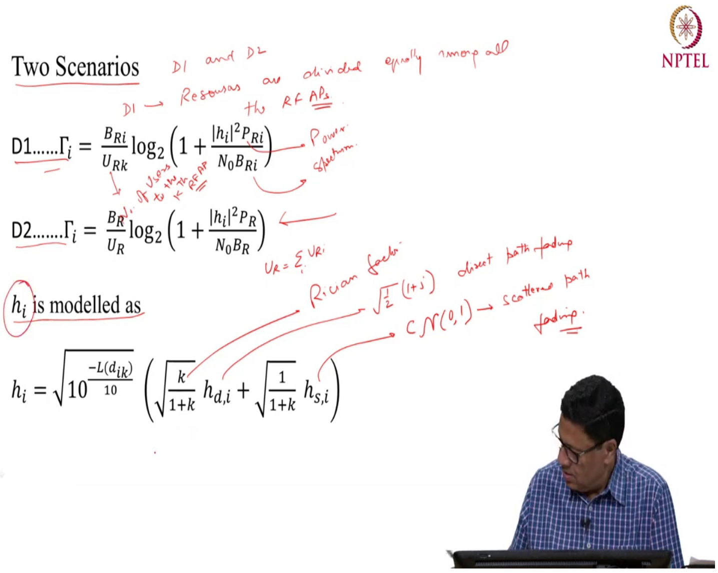

Now, let us discuss the two scenarios which we have discussed earlier which we had called as D1 and D2. So, in D1 the resources are divided equally among all the RF APs. And so for this case D1 the rate will be B Ri divided by U Rk log 2 1 plus h i mod square P Ri divided by N 0 B Ri where this is the power and RF power and this is the bandwidth or the spectrum. And this is the number of users to the kth RF AP.

So, this is the rate and another case which is D2 where the central unit of CCU dynamically allocates resources depending upon the instantaneous traffic requirement. So, let us assume that all the users are linked to one particular RF AP and it gets the full power and full spectrum. And you know if they are distributed among say for example, R 2 APs then half of the power is given to RF 1 the other half is given to RF 2 so on and so forth.

So, I am assuming a case here where the total power all the users are connected to RF AP single RF AP and the total bandwidth is given to that particular RF AP and total power is given to that RF AP. So, for that case the rate is given by B R divided by U R where U R is summation of all the users. Log 2 1 plus h i mod square P R divided by N 0 B R N 0 is the noise psd. So, h i is modelled as for the millimeter wave propagation is given by h i is equal to 10 raise to minus L d ik by 10 where L d ik we had defined earlier.

Which has the reference component and the path exponent component and the third one was shadowing component into root k 1 plus k h d i plus root 1 plus 1 plus k h s i where this k is the Rician factor. And h d i is actually is 1 by 2 1 plus j is a complex number and it is a direct path direct path fading and this h s i is given as complex is a normal Gaussian function with zero mean and variance 1 and this is scatter the component which is scatter scattered path fading. So, this for millimeter wave this is the expression for h i.

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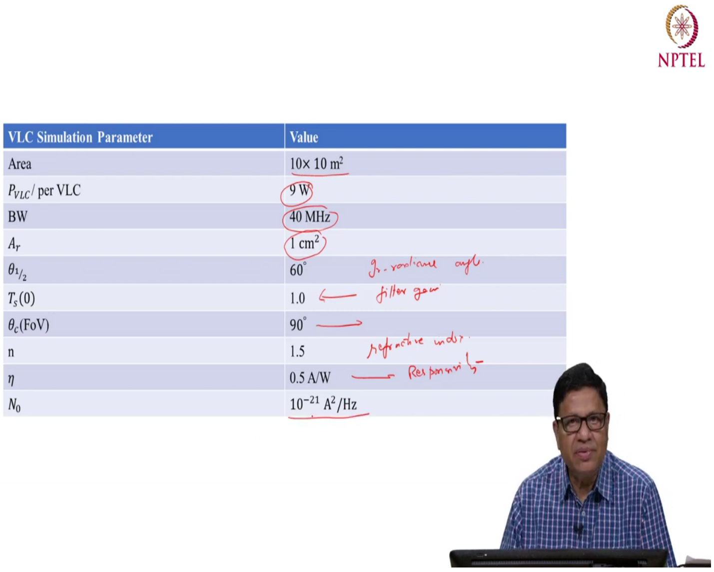

And the VLC parameters which have been used in the system is area we have taken 10 into 10 meter square and the P VLC per VLC power is 9 watts the bandwidth of the source is 40 megahertz the area of the detector is 1 centimeter square. The irradiance angle, irradiance angle is 60 degree this is the transmission or emergence angle from the transmitter irradiance angle.

And this is the filter gain which we have assumed as 1 and FoV as 90 degree field of view for the receiver this is a refractive index this is used in when we when we calculate the gain because of the concentrator it is equal to n square divided by sin square theta c.

So, n is the refractive index of the material of the concentrator and this is the responsivity 0.5 responsivity 0.5 amperes per watt and the noise spectral density is defined as 10 raise to power minus 21 ampere square per hertz. So, these are the VLC simulation parameters.

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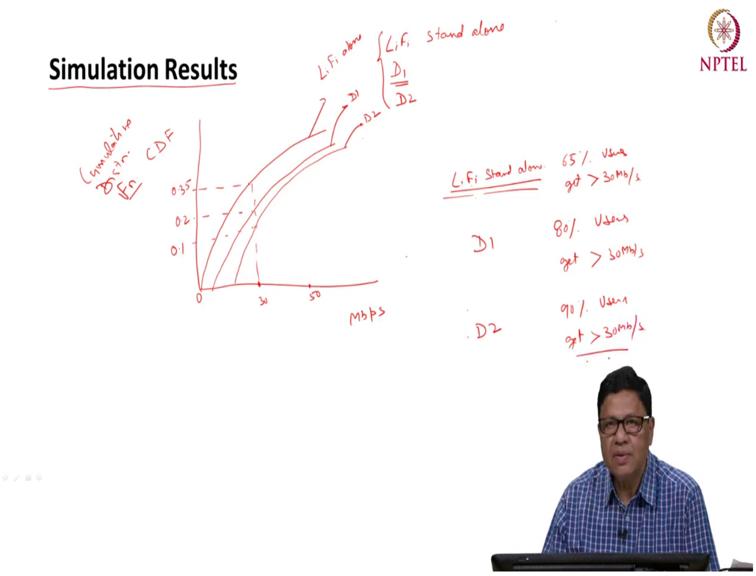

So, now let us discuss the simulation results based on the parameters which we have discussed in the last slides. So, I will plot this simulation results for three scenarios one is where you have only LiFi stand alone in the room there is no WiFi stand alone. The second scenario is D1 where the resources are allocated equally to all the APs RF AP's this is D1's scenario which we have discussed earlier.

So, the second third one is D2 scenario where you dynamically allocate power and spectrum resources to RF AP's depending upon the instantaneous user requirements. So, we will try to compare these three scenarios. So, let us draw a plot between say this is average data rate megabits per second. So, this is 0, this is 30 this is 50 and this is on this y axis is CDF that is Cumulative Distribution Function.

So, for LiFi is stand alone this is something like this. For D1 scenario it will be something like this and for D2 scenario this will be something like this. So, this is LiFi alone, this is D1 scenario and this is D2 scenario. So, let us see at some points a 30 megabits for example, 30 megabits per second. So, basically you can draw and find out the CDF value for each one of them. So, suppose this is 0.1, this is 0.2, this is 0.35.

So, basically this curve tells me that for LiFi stand alone 65 percent of the users which is 1 minus 0.35 actually 65 percent of users get more than 30 megabits per second. If you consider the D1 scenario 80 percent of the users get more than 30 megabits per second. And if you take the D2 scenario where you dynamically allocate resources, power and spectrum 90 percent of the users get more than 30 megabits per second.

So, one thing is very clear if you compare with the standalone LiFi this coexistence of LiFi and WiFi that is hybrid network they perform better. We have seen one parameter of throughput here and within coexistence there can be different algorithms. We have discussed you know two algorithms here D1 were equal resource sharing and D2 were dynamically resource sharing depending upon the traffic requirement or traffic demands.

We have seen the performance of LiFi, WiFi, Coexistence is much better as compared to standalone LiFi and WiFi for that matter. So, under this you know in this topic there is a tutorial also as one of the lectures where the T has explained how this scenario can be simulated, what are the tools used, how we can you know do the simulation and find out standalone LiFi, standalone WiFi and coexistence LiFi, WiFi the different parameters.

So, this is also included in this course which will be taken by one of the Ta; PhD student who works in this particular area.

Thank you.