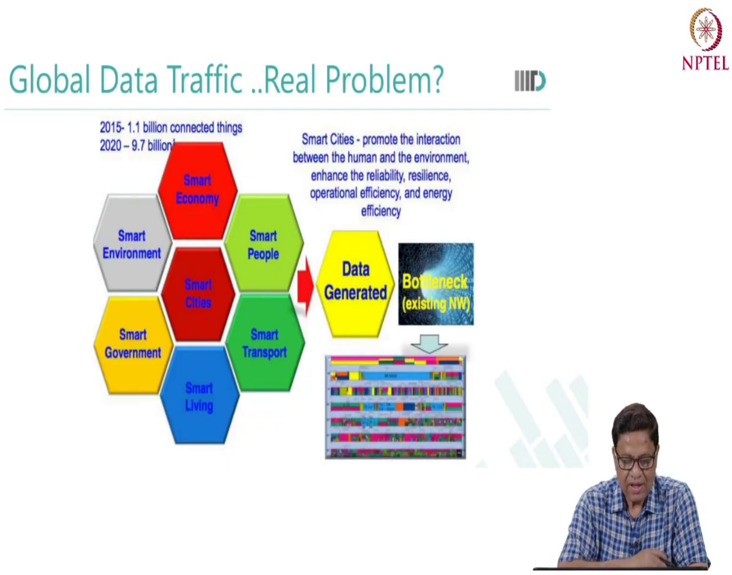
Optical Wireless Communications for Beyond 5G Networks and IoT

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

Lecture - 01
Introduction to Optical Wireless Communications (OWC)

Hello everyone, so today we are going to start the course on Optical Wireless Communication for Beyond 5G Networks and IoT. So, this is the 1st lecture in this course module. So, today under this lecture we will study about the Optical Wireless communication technologies, what are the different technologies, how what are the research challenges here?

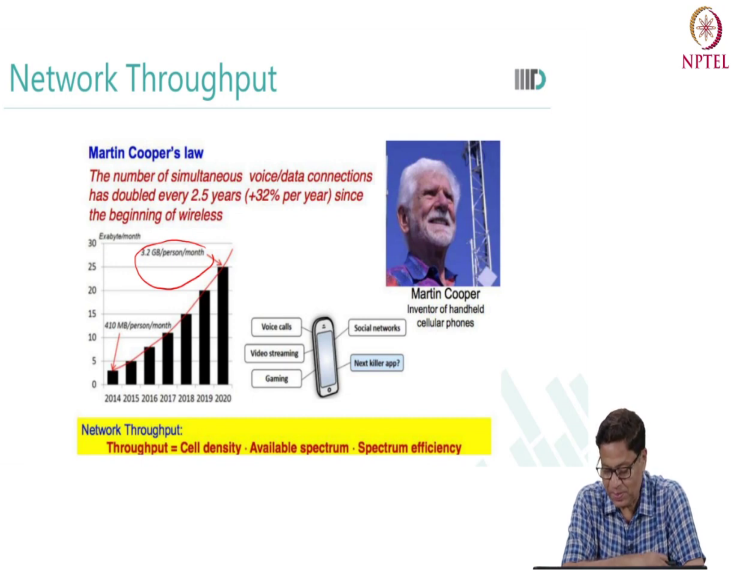
(Refer Slide Time: 00:54)



So, let us start. So, as all of you know the global data traffic is a real problem, everything is becoming smart whether it is economy or environment or government or cities or people or transport smart living. So, smart cities basically consist of all these things and it promotes the interaction between the human and the environment to enhance the reliability, resilience, operational efficiency and energy efficiency.

So, all these things they generate lot of data. So, lot of data is generated and the bottleneck actually comes from the existing network, because if you see the spectrum available for communication is limited and the data is huge. So, it is very difficult to transport this amount of data over the existing network.

(Refer Slide Time: 01:48)

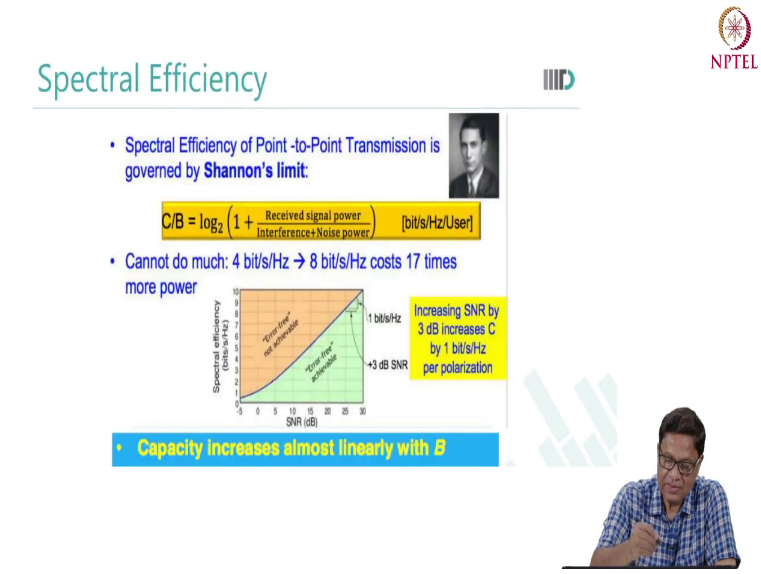


So, let us understand what is Network Throughput, in the past the number of simultaneous voice and data connections they are doubling every 2.5 years which is a growth of 32 percent per year. As you see in this graph on an average a person consumes about 3.2 gigabit per person per month and if you try to calculate the network throughput, this throughput depends on cell density on available spectrum and the spectrum efficiency.

Now, cell density is you can make it smaller and smaller, but there are issues you will have to have more number of transmitter and receivers, spectrum is limited spectrum efficiency we will understand this is also sort of not improving with time. So, and the spectrum efficiency is defined as bits per second per hertz, how many how much data you are able to transport over you know 1 hertz of bandwidth that is how spectrum efficiency is defined and there is a limitation to this spectrum efficiency.

So, the network throughput if you want to increase the network throughput you have to increase either the cell density or the available spectrum or the spectrum efficiency.

(Refer Slide Time: 03:14)

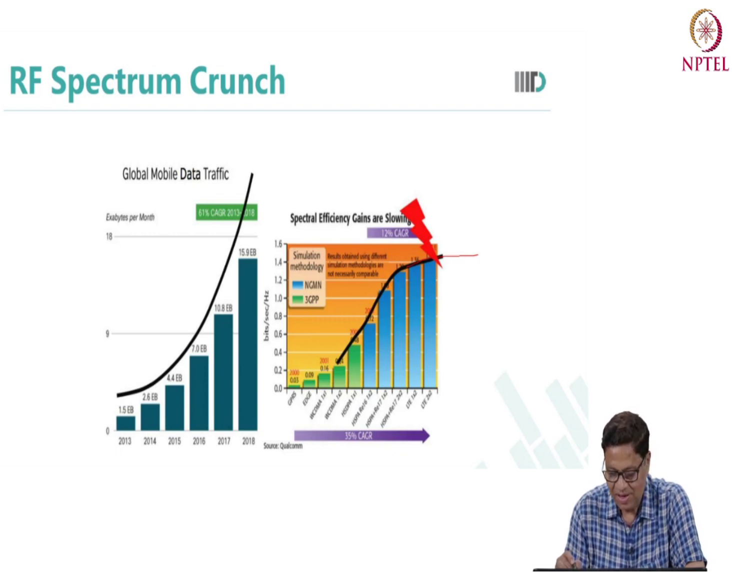


So, let us understand about the Spectral Efficiency part, now spectral efficiency of a point to point transmission is given by channel limit which is given in this formula C by B log 2 1 plus SNR the units are bits per second per hertz per user.

Now, if you want to increase the spectral efficiency, then you have to increase the signal power there are there are 2 ways of doing it either you increase the signal power or you increase the bandwidth and with bandwidth there is a linear relationship and with signal power it is logarithmic relationship. So, if you want to increase the spectral efficiency from 4 bits per second per hertz to 8 bits per second per hertz you will have to increase the signal power by 17 times which is huge.

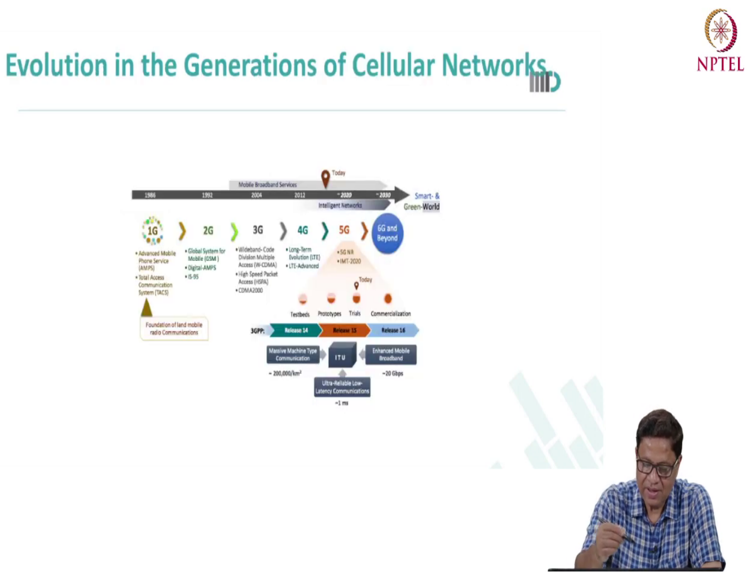
So, and in this example you know this graph is plotted between SNR and spectral efficiency. So, if you see here if you increase the SNR by 3 Db, then you get a increase of 1 bits 1 bit per second per hertz per polarization. So, signal power increasing that is not a solution and bandwidth is limited. So, the spectral efficiency gains are actually there is not much scope for increasing the spectral efficiency.

(Refer Slide Time: 04:38)



And also if you see the different technologies in the past the initially the spect the engineers were able to increase the spectral efficiency of the system starting from you know 1st generation of communication system to 2nd which is GPRS and edge and then 3rd generation which is WEDMA and then next generation LTE. But as you see the graph is sort of you know getting saturated, so there is not enough scope for increasing the spectral frequency a spectral efficiency.

(Refer Slide Time: 05:13)



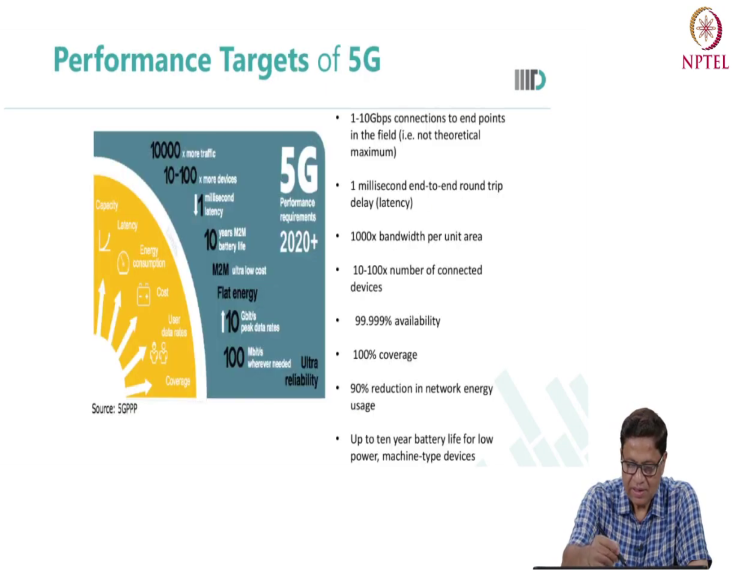
So, let me also explain you the different generations of cellular networks, 1st generation was actually analog which is amps advanced mobile phone services, then the 2nd generation was digital 2G which was called as GSM and the 3rd generation was Wideband Code Division Multiple Access which is known as WEDMA and also High Speed Packet Access HSPA CDMA 2000 they were some of the standards of 3G systems.

And 4th generation system is long term evaluation and long term evolution advanced. Now currently we have 5th generation of systems. So, 5th generation of systems basically the standards are being done under the 3 GPP, 3 GPP stands for 3rd Generation Partnership Project. So, they are responsible for making the standards.

And so, they have different releases so currently we have about release 16 and then release 17 is also about to come and if you see the 5th generation communication system. There are 3 basic parameters on which 5 gen 5th generation system is realized one is you should have enhanced mobile broadband, the speed should be as high as 20 gigabits per second and it should support ultra reliable low latency communication of the order of 1 millisecond and it should also support massive machine type communication about 2 lakh devices per kilometer square.

So, these are the three things which 5G system is able to support and then there is also a discussion on 6G systems and beyond.

(Refer Slide Time: 07:19)

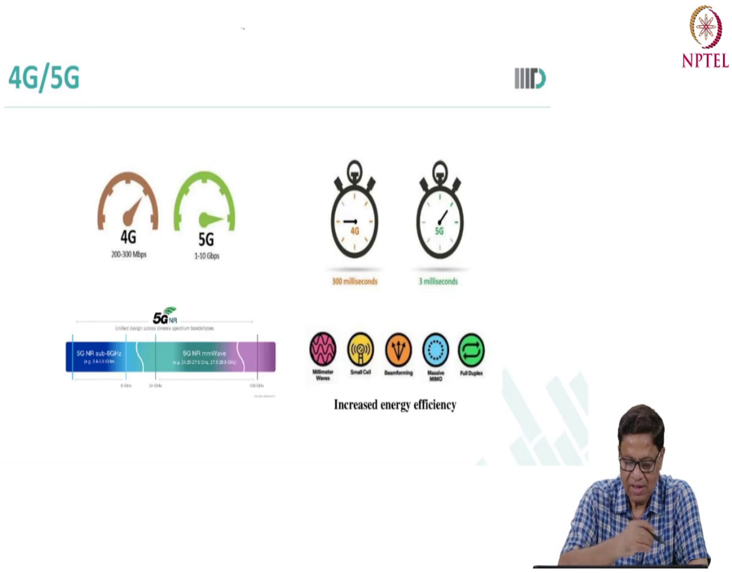


So, these are some of the performance targets of 5th generation system, basically it gives some targets about the capacity, about the latency, about the energy consumption, about the cost, about user data rates and coverage.

And 5th G targets for the speed is that you should be able to get 1 to 10 gigabits connection to end points in the feed and not theoretical maximum. And also as far as the latency is concerned of the order of 1 millisecond end to end round trip latency and 1000 x bandwidth per unit area as compared to existing 4G systems and you should be able to handle 10 to 100 times number of connected devices using 5G generation 5G systems.

And availability is 5999.999 percent and it should give 100 percent coverage and as far as reduction in the network energy usage is concerned there should be a significant reduction in the network energy usage of the order of 90 percent and the battery life should be 10 year battery life for low power machine type devices. So, these are some of the aspirational goals of 5G and we will see how optical wireless communication technology will fit in to meet some of these goals.

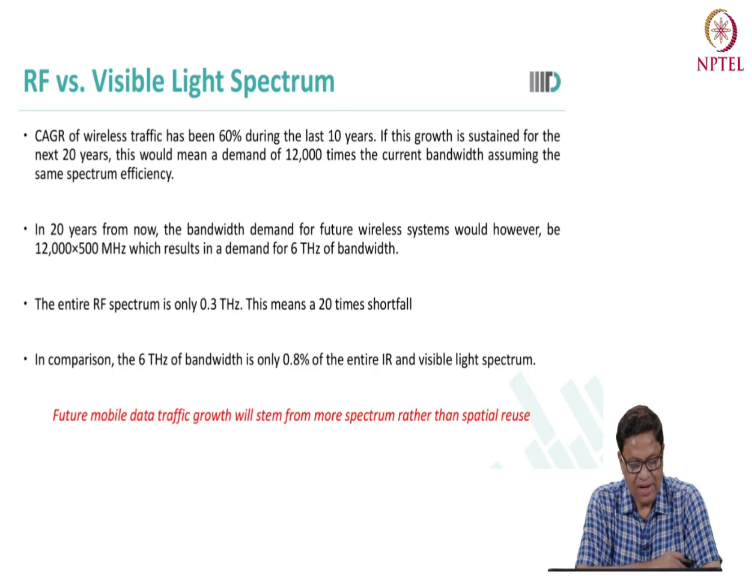
(Refer Slide Time: 08:47)



So, this is very basic definition difference between 4G and 5G technology, 4G the data rate is about 200 to 300 megabits per second whereas, for 5G it should be in excess of gigabits per second should go up to 10 gigabits per second and as far as latency end to end delay is concerned for 4G is 300 millisecond, whereas 5G guarantees a few milliseconds or typically 3 milliseconds. And the spectrum which is which will be used for 5G new radio is sub gigahertz which is 3.4 to 3.6 gigahertz and also millimeter wave which is in excess of 20 gigahertz.

And also by using millimeter waves and small cells and beam forming and massive mimo full duplex will be able to increase the energy efficiency of the system.

(Refer Slide Time: 09:46)

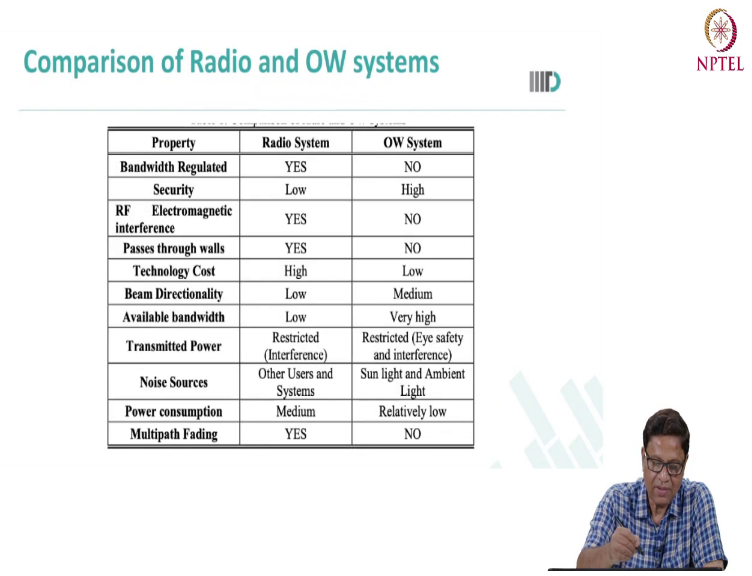


So, now, let us see why we need optical wireless or why we need to go to different spectrum? So, this slide basically gives you the difference between RF spectrum and visible light spectrum.

So, CAGR that is the growth of wireless traffic is about has been 60 percent during the last 10 years. So, if this growth continues then you would you would need 12000 times the current bandwidth, assuming you know there is not significant growth in the spectrum efficiency. So, in 20 years from now the bandwidth demand for future wireless system will be of the order of 1200 into 500 megahertz assuming 500 megahertz is needed by the operator.

So, which results in a demand of total 6 terahertz of bandwidth and if you see the entire RF spectrum that is just 0.3 terahertz, this means a total of shortfall of 20 times. Whereas, in comparison 6 terahertz of bandwidth is just 0.8 percent of the entire infrared and visible light spectrum. So, the future mobile data traffic growth will actually stem from spectrum rather than special reuse, because we need enormous spectrum which is not available in RF domain. So, we need to switch to you know IR or visible light spectrum or ultraviolet spectrum to make to me to meet in order to meet this feature requirements.

(Refer Slide Time: 11:36)



Property	Radio System	OW System
Bandwidth Regulated	YES	NO
Security	Low	High
RF Electromagnetic interference	YES	NO
Passes through walls	YES	NO
Technology Cost	High	Low
Beam Directionality	Low	Medium
Available bandwidth	Low	Very high
Transmitted Power	Restricted (Interference)	Restricted (Eye safety and interference)
Noise Sources	Other Users and Systems	Sun light and Ambient Light
Power consumption	Medium	Relatively low
Multipath Fading	YES	NO

So, this is the comparison of radio and optical wireless system. So, if you see the bandwidth it is regulated in radio systems. there is agency there are agencies which regulate this allocation of spectrum for RF and order optical wireless system there is no such regulation, because it uses the visible light spectrum which is coming from for example, illumination or a typical light emitting diode or some optical source.

So, there is no such regulation in optical wireless system, security in radio system is low in optical wireless it is high because the light is contained within the room and it is mostly line of sight. So, there is a there is better security as compared to radio system. RF electromagnetic interference it is significant in radio systems, whereas optical wireless is immune to RF electromagnetic interference.

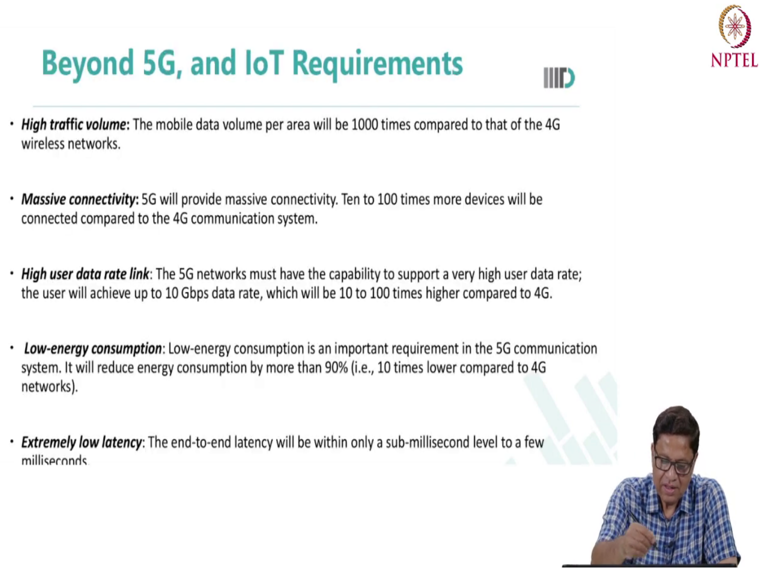
Radio system can pass through the walls whereas, optical wireless is contained inside the room cannot pass through, the walls the technology cost is for radio system is quite high and optical wireless system it is low. And you have very low beam directionality for radio systems because I mean one can do beam forming, but up to a certain limit whereas, there is a good amount of directionality which can be achieved using optical wireless system.

The available bandwidth as I mentioned earlier is very low and the available bandwidth in optical wireless system is quite high. The transmitted power there is upper limit it is restricted because of interference because you might interfere other communication systems. There is restriction on optical wireless also, but that is from eye safety perspective and interference perspective as well.

The noise sources for radio systems are other users and systems which are currently operating and the noise sources for optical wireless system is comes from sunlight or ambient light. The power consumption for radio system is medium too high whereas, for optical wireless system because it uses devices which consume very less power is relatively low.

The multipath fading is significant in radio system, whereas there is no such thing in optical wireless system.

(Refer Slide Time: 14:17)

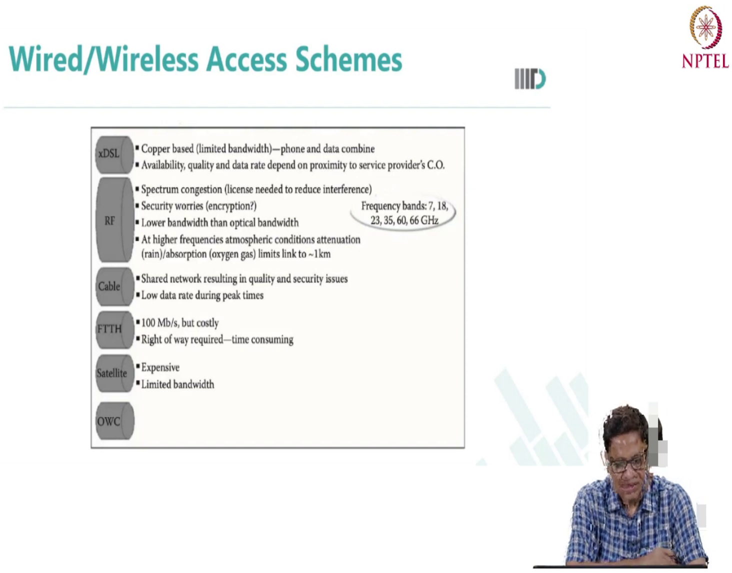


So, in short what are the different requirements of you know beyond 5G and IoT systems. We need high traffic volume the mobile data volume per area will be 1000 times compared to the 4G we need massive connectivity. So, 5G because 5G provides massive connectivity and the requirement is 10 to 100 times more devices as compared to 4G systems, you require very high user data rate link.

So, the order of the data which is requirement in 5G is about 10 gigabits per second which is actually 10 to 100 times higher than 4G, low energy consumption is very important. So, you require low energy consumption that is 10 times lower at as compared to 4G networks and extremely low latency. So, there are certain applications which require very low latency.

So, the requirement for beyond 5G is of the order of you know few millisecond or even some millisecond for some of the applications.

(Refer Slide Time: 15:31)



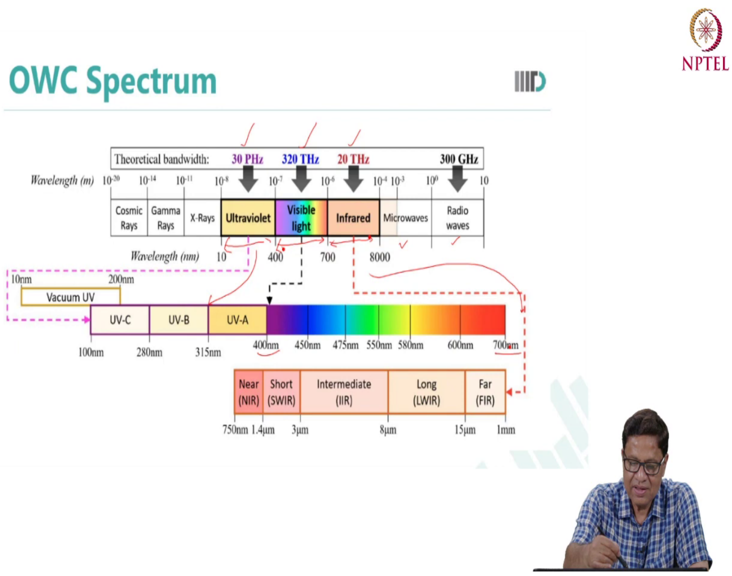
So, let us now understand what are the existing wired or wireless access schemes? Now we have so far understood the requirements of beyond 5G and IoT and let us see what are the existing wired or wireless access schemes? So, one of the wired scheme is xDSL DSL stands for Digital Subscriber Line is a copper based technology, it has very limited bandwidth you know where you combine the phone and the data onto the copper network.

And the quality of the signal actually depends how close you are to the central office. The 2nd wireless access scheme is RF. So, spectrum congestion is one of the issue security concerns it has lower bandwidth as compared to optical bandwidth and at higher frequencies where you want to have more bandwidth atmospheric conditions attenuation because of rain or absorption of electromagnetic waves, it can limit the distance up to 1 kilometer.

Another option is Cable shared network resulting in quality and security issues and it actually gives only low data rate during peak times. Other option for access network is fiber to the home 100 megabits per second or even more one can achieve, but it is very expensive because you have to lay the fibers all the way to the home and because of right of way requirement it becomes time consuming and sometimes may not be practical.

The other option is satellite it is very expensive and it has very limited bandwidth. So, considering the issues with all these existing technologies, let us see how optical wireless communication can meet some of the requirements of you know 5G or beyond 5G and IoT systems.

(Refer Slide Time: 17:45)



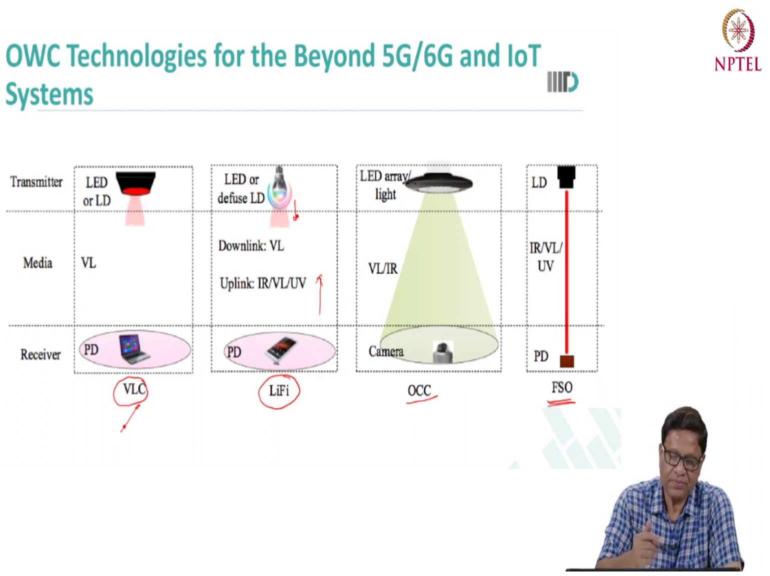
So, just to explain you about the spectrum of optical wireless this if you see on the top you have the visible range here and then you have the IR here infrared here and then you have the ultraviolet here and here on this side you have the microwaves and the radio waves and on the left side you have x rays gamma rays and cosmic rays.

So, this visible light spectrum is further you know you can see the details which goes from 400 nanometers of wavelength to 700 nanometers and if you see the ultraviolet there are different categories here ultraviolet A ultraviolet B and ultraviolet C and similarly for IR infrared you have different categories here.

So, optical wireless communication actually exploits visible light spectrum the IR spectrum and for certain applications ultraviolet and as you see here the theoretical bandwidth is huge here, visible light offers you about 320 terahertz infrared theoretically can offer 20 terahertz and ultraviolet 30 petahertz.

So, the spectrum is not an issue you have enormous spectrum, the limitation actually comes from other factors. For example, your devices may not be working at that speed. So, one has to do lot of research in getting devices which can respond to this high frequency. But whereas, the spectrum is available and it is definitely much more than what is available for RF.

(Refer Slide Time: 19:32)



So, basically there are three types of optical wireless communication technologies which will be used or likely to be used in beyond 5G systems and IoT systems. The 1st one is visible light communication VLC. So, in VLC it is a physical layer connection between a transmitter and receiver the transmitter could be a source it could be a LED light in your room or one can have laser diode we will see under what under certain conditions only laser diode can be used, that we will you know understand in subsequent lectures.

But the transmitter basically consists of either a light emitting diode or a laser diode. And then you have optical wireless channel where the light is propagated from the transmitter which could be on the ceiling. For example, ceiling of the room and then on the ground or on the table you have a device where a photo detector is connected and photo detector basically converts that light energy into electrical energy and you get back your data.

So, the basic VLC consists of a transmitter could be a LED or LED and receiver consist of a photo detector again photo detector can be of different types that we will discuss in subsequent lectures. The 2nd option is the 2nd technology for OWC is light fidelity which is equivalent or a higher version of Wi-Fi wireless fidelity.

Because when you want to have a communication you want to have a bi directional communication, you want to have high speed communication, you should be able to support you know handover from one device to another device or from one access point to another access point and you should be able to support mobility of the users.

So, a technology which fulfills all these requirements of high speed bi-directional mobility handle mobility and handover is actually called as li-fi and it uses LED or the illumination luminaire which is there in the room for communication or one can use diffuse laser diode I mean these are different options.

And then on the downlink because it has to support both Uplink as well as Downlink, downlink is actually visible light which is coming from the source and then you have a device here which will have a photodiode or some sort of dongle, where the light is received and converted into electrical signals and processed.

And similarly for uplink you can have different options you can have either IR, IR you know you are you one is not able to see physically because its infrared you cannot see with your eye or you can have ultraviolet. And in some cases where you know eye disturbance is not does not matter that much, then one can use visible light otherwise most of the times visible light is downlink and uplink is IR or in some cases one can use Wi-Fi as a uplink.

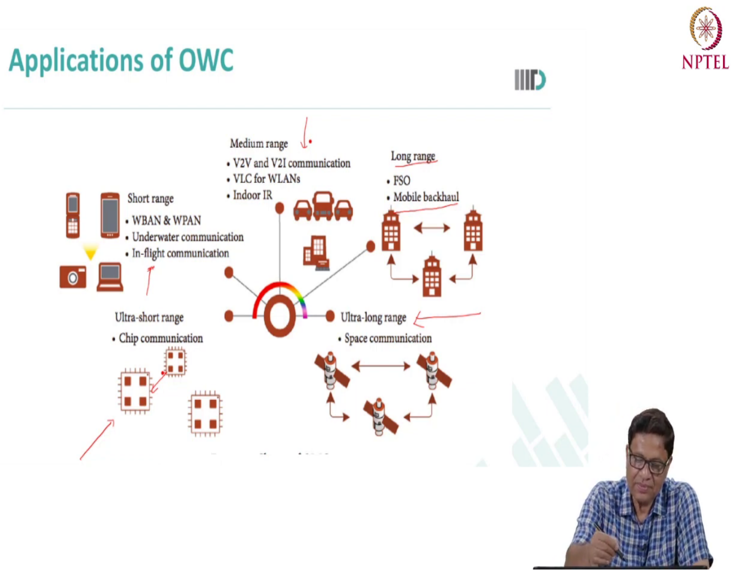
So, the different options are available in li-fi that we will again discuss when we go to you know detailed discussions on li fi. The 3rd technology is OCC which is called as Optical Camera Communication it uses LED array or light as the transmitter and then the camera of the device is used as the receiver.

So, it basically say short range low data rate applications which will be you know termed under which will be discussed under optical camera communications. The other 4th technology is free space optics, this is not indoor I mean all previous technology which I have mentioned is mainly indoor this is a outdoor technology free space optics.

Suppose you want to connect you know two points which is which are 2 kilometers away for example and you are not able to lay you know cables because of certain issues. Then one can use a free space optics for transmitting or covering that distance of 2 kilometer by installing a laser transmitter or optical transmitter and then there is a line of sight with the optical receiver and then one can establish a you know a connection or link between the transmitter receiver, so this is outdoor.

So, these are the basic 4 technologies which will be used in 5G and IoT systems. So, once again I will repeat visible light communication this is limited to physical layer point to point and li-fi which is bi-directional and supports high data rate supports mobility supports handover. And then optical camera communication for positioning and low data rate short distance communication and outdoor for outdoor communication free space optics using laser diode and receiver on the other side.

(Refer Slide Time: 25:10)



So, let us now see what are the different applications of optical wireless communications? So, let us start from here. So, you can have communication between 2 chips for example, where the distance is of the order of millimeter. So, this is under the category of ultra-short range. So, if you want to connect you know very high speed signal from one chip to another chip I mean I you can use other techniques also, but there may be some interference. So, using optical wireless you can connect 2 chips with high speed.

So, this is the application actually and the typical distance is millimeter which is there you know in the PCB, for example if you want to connect 2 chips with high speed or in data centers. For example, the 2nd is short range this is of the order of few meters. So, the examples are broad area network or personal area network or underwater communication if you want to connect you know there are divers in the inside the sea and they want to communicate with the ship.

So, they can communicate using optical wireless communication in flight communication when you are sitting in a flight you know the light overhead you can always have you know communication using that light. So, that those kind of applications are under the category of short range which is few meters.

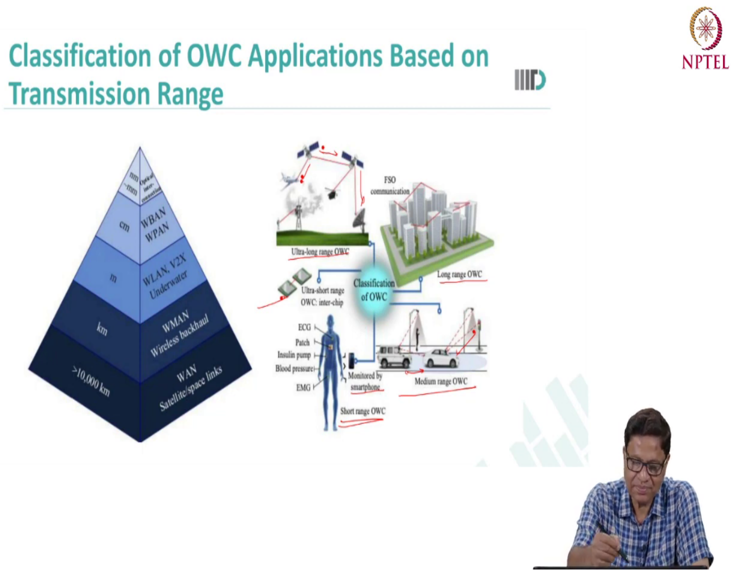
The next is medium range some of the examples are mentioned here which is one of them is vehicle to vehicle communication, you can exploit the headlight of the headlight of the car and you know communicate with the vehicle which is ahead of you or vehicle to infrastructure communication from the vehicle to for example traffic lights or from the roadside lamp or from infrastructure which is situated you know near the road.

So, vehicle to infrastructure so this is typically of the dist of the order of few hundreds of meter typically 150 or 200 meters or one can use for wireless local area networks or indoor infrared. So, these are the some of the examples of medium range. Now in the long range one can use free space optics if you want to cover a distance of, for example 3 or 4 kilometers you using 1 gigabit per second link and you do not want to install any cable, then one can use this free space optics.

So, this comes under the category of long range or mobile backhaul these are some of the applications of wrong long range, the typical distance is the of the order of few kilometers. The another application is ultra-long range that is communication in the space. So, satellite to satellite communication or satellite to aircraft communication or from satellite to ground communication they all come in this category and the typical distances are the order of 1000 of kilometer.

So, as you see here the use of optical wireless technology ranges from millimeter you know distance communication to 1000 of kilometers of communication. So, it has a wide spectrum of applications.

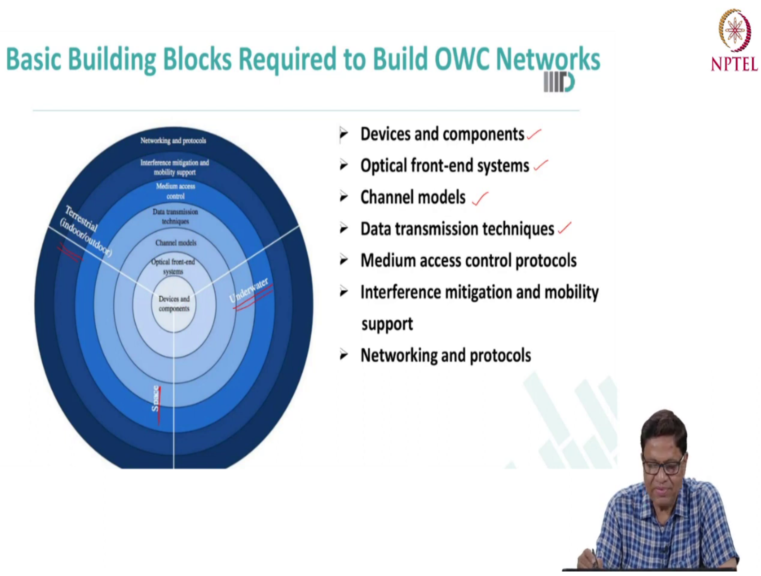
(Refer Slide Time: 28:50)



This is a pictorial view of the applications here as you see here this is medium range which is car to car communication or car to you know traffic light communication. This is short range optical wireless communication wherein you know all these parameters body parameters there is there are body sensors it can be monitored by a Smartphone this is an example of short range optical wireless communication.

This is an example of inter chip communication ultra-short range and this is an example of long range connecting 2 buildings which could be 1 or 2 kilometers away where laying of fibers is an issue. And this is an example of ultra-long range that is satellite to satellite communication, satellite to aircraft communication and you can have satellite to ground communication. So, basically it covers all facets of communication.

(Refer Slide Time: 29:55)



So, for making any optical wireless system these are the basic building blocks. So, 1st let us understand the use of optical wireless communication is in underwater, it is in space and it is in terrestrial which includes both indoor and outdoor. And all these technologies they require different type of strategies different types of design and for each of these technology each of these communication or each of these domain you require you know devices and components, you require optical front-end systems they are all different for you know different domain. For example, underwater things are different space things are different.

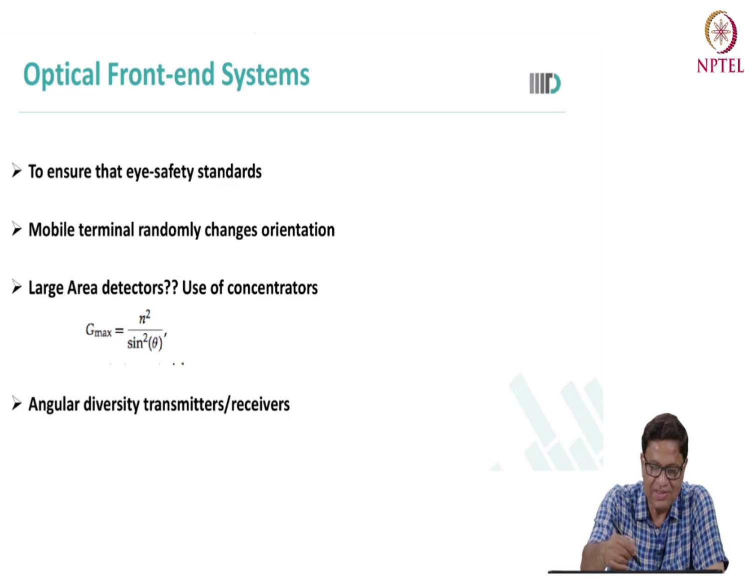
There is still again you know the design is different the channel model, in each case is different the data transmission modulation techniques which you require is again different for different domains medium access control protocols, interference mitigation mobility support and networking and protocols. Let me just explain you one by one some of these things

Devices and components, I mean we have seen that the bandwidth is enormous there is a huge bandwidth available, but can I use that bandwidth the answer is no.

Because the devices and the components are not available which can respond to that high speed, still you know research is going on where in we have components and devices which can respond to very high speed.

So, this becomes a limitation device and components and the next is Optical front end systems.

(Refer Slide Time: 31:48)



So, optical front end systems is basically you have because you are dealing with optical signals and it could be in the IR region. So, one has to ensure that the eye safety standards are met, because you should not use high power you know the kind of wavelength which may damage the eye.

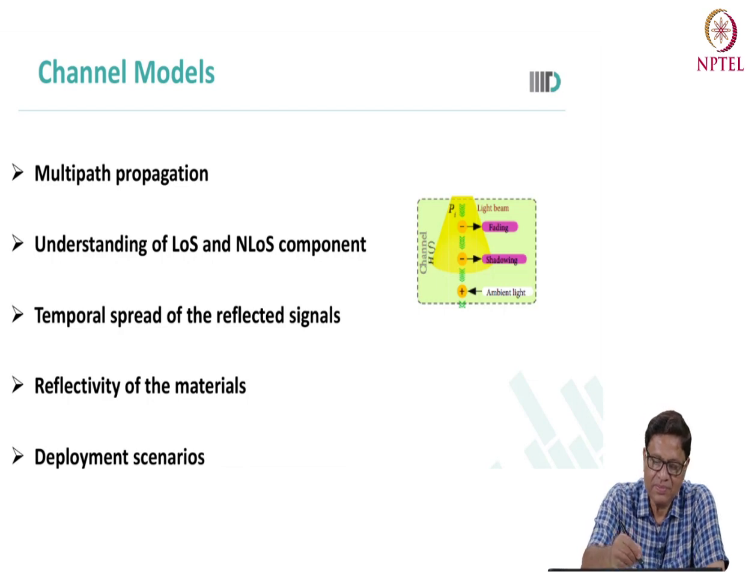
So, you have to ensure that the eye safety standards which are all available should be met when you are discussing. You know communication using optical wireless you have to also ensure that your mobile terminal. For example, your phone which is in your hand is changing the orientation every time. So, there is a random orientation of the mobile terminal. So, you have to ensure that your system is able to handle that orientation I mean it should not be blocked.

Suppose your mobile terminal is upside down even then you should be able to communicate there should not be any you know blockage in the communication. Also we want to use very large area detectors, because I want to capture the light available coming from line of side non line of sight. So, that I get good signal onto the detector, but then the moment I make a large area detector the capacitance of the device increases which will limit your speed of communication.

So, there is a trade off and then one can use you know concentrators again the you know physical size of the concentrator those are some of the constraints one has to worry about. So, this is you know different in different domains as I mentioned these designs you know require different for terrestrial, different for underwater, different for space.

And also one has to use angular diversity transmitters, because optical wireless is primarily a line of sight technology and if something comes in between it will be stopped. So, one has to ensure that in order to have continuous deception of signals one has to use you know multiple transmitters or multiple receivers.

(Refer Slide Time: 34:11)



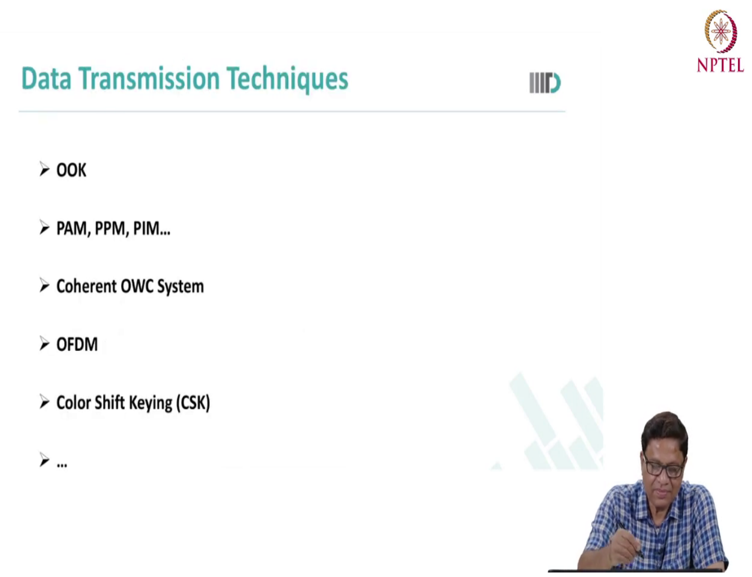
So, that the blockages are taken care of and communication is not disturbed. Channel model is another area which we will study during the course of our course and it is different for indoor and outdoor. Indoor channel model is deterministic can be modeled easily, whereas, the outdoor channel model is you know is time dependent and its very complex.

So, we need to model channel models both for indoor and outdoor where we have to consider the multipath propagation the light can come from line of sight or it can come after reflection. So, there should be a good understanding of line of sight components, non line of sight components and when you get many components line of sight and non line of sight there may be some temporal spread of the reflected signal.

So, you need to control that temporal spread, otherwise your data rate will get reduced it also depends on what kind of reflectivity of the material you have reflectivity of the material in the walls. For example, so that basically it will tell you how much power you receive after reflection and also you need to consider different deployment scenarios, it could be a office setup or it could be a factory or it can be a roadside where you are communicating from vehicle to infrastructure. So, depending upon the deployment scenarios you have to model your channel.

So, this is another challenging area for optical wireless communication community to understand to have good understanding or proper understanding of channel models.

(Refer Slide Time: 35:57)

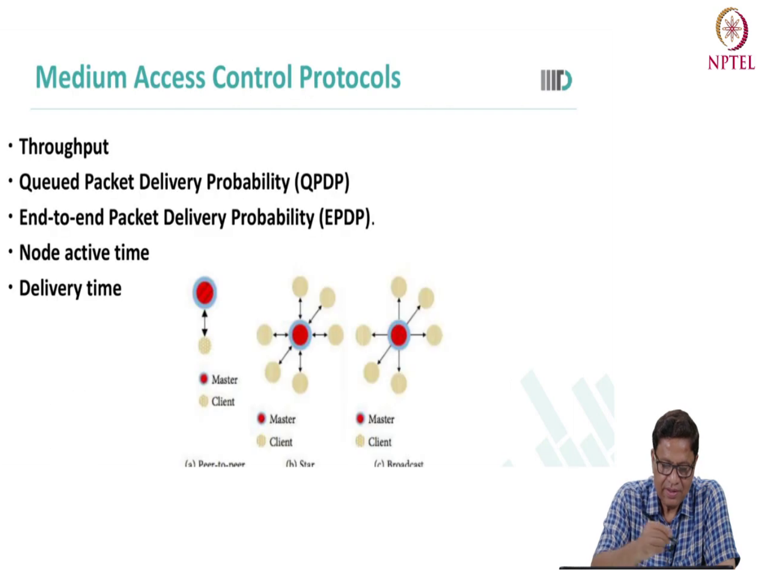


Now you want to have good power efficiency and bandwidth efficiency and for different domains there may be a requirement of different data transmission techniques.

So, some of these techniques we will study, for example on off keying or pulse amplitude modulation or pulse position modulation or pulse interval modulation and also if you want to increase the overall length or distance of communication, then we might have to use coherent optical wireless communication system which will give you some advantage over the conventional system. And if you want to further increase the data rate then use of OFDM that is Orthogonal Frequency Division Multiplexing.

And also to exploit different colors in the light white light one can use a new type of communication a modulation technique which is called as color shift keying csk. So, all these schemes we will discuss in detail. There are other schemes also which gives you benefit of you know low energy efficiency or low spectrum efficiency high spectrum efficiency.

(Refer Slide Time: 37:17)

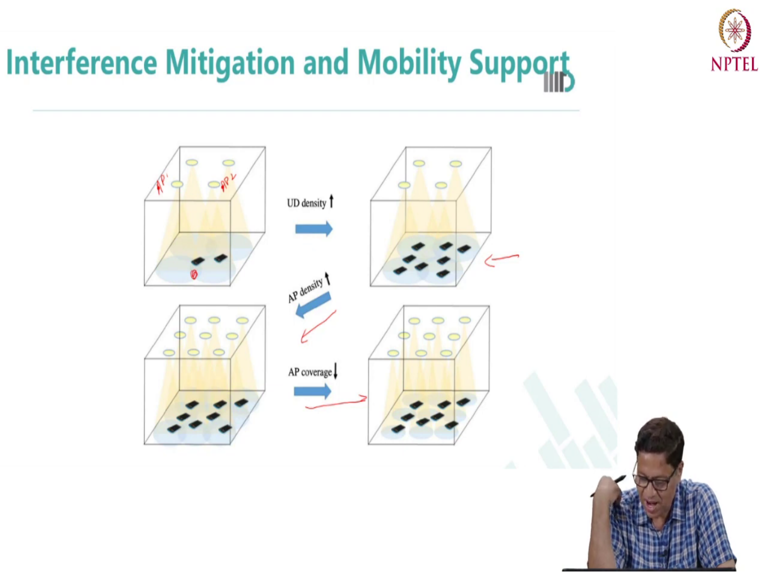


And when you are considering bi directional communication or communication inside the room, for example in the case of li fi one has to choose a medium access protocol this could be a TDMA, could be OFDMA, could be CDMA. There are different medium access control protocols and depending upon the application the requirement whether you want low latency or you require high speed.

So, you use a particular access control and using these MAC protocols you should be able to find out throughput, I mean these parameters are concerned the throughput. What is the throughput? You are getting what is the queued packet delivery probability or what is the end to end packet delivery probability and how much time the node is active and what is your typical delivery time that is when the packet 1st is transmitted by the time it is received what is that delivery time?

So, all these metrics have to be measured for different medium access control protocols.

(Refer Slide Time: 38:30)



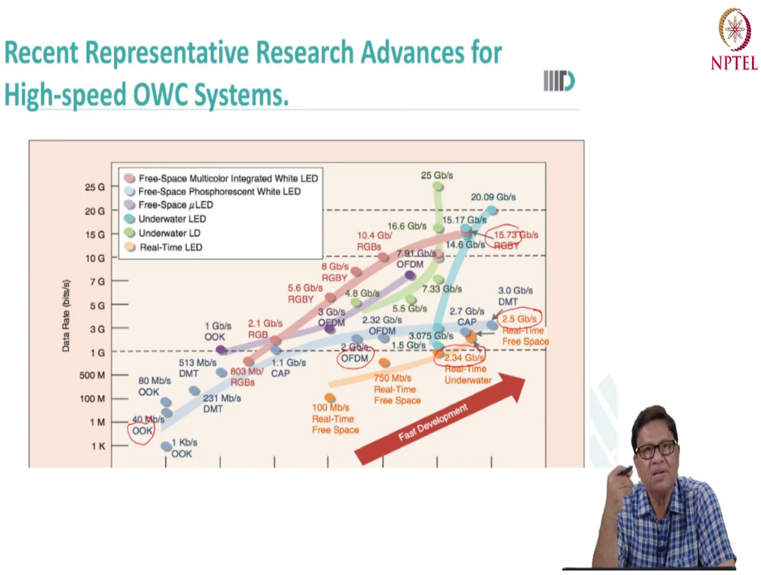
The other issue which one has to consider while designing optical wireless communication design is interference, mitigation and mobility support. The interference can come from you know access point other access point; for example, if you see here in this diagram there are 4 access point and there are 2 users.

So, there may be interference because if you see the light which is falling from one for this is excess point 1 and say this is excess point 2. So, there is some area where the light is you know both the lights are falling at the same place. So, there is some interference coming from other access point. So, one has to consider while designing such interference and should have techniques for mitigating such interference and there can be a possibility that the user density increases as is shown in this diagram right.

So, there are again challenges if the user density increases also when the excess point density is increasing. So, you will see here about 9 access points. So, you so there may be some challenge because of increased access point density and number of users and also depends what is the coverage of each access point. So, AP coverage that is access point coverage. So, that also is going to affect your design.

So, while designing your system you have to take care of interference mitigation and you should be able to handle the mobility of the users.

(Refer Slide Time: 40:12)



So, these are this is in brief about the different topics I am likely to cover during this course and before I close just to give you some information about what kind of systems have been experimentally built. So, this view graph actually tells you different type of systems which have been designed and actually there has been a significant progress in the last 4 5 years.

And if you see whether using free space or communication in underwater you know OWC community has increased very high data rate of the order of for example 15.73 gigabits per second using integrated white LED. And this is somewhere here for free space 2.5 gigabits per second and underwater you know it 2.34 has been achieved and lot of different modulation techniques started from on off keying to OFDM they all have been used.

So, there has been a good progress in this field and in years to come, I am sure this technology will further grow and will meet will meet the requirements of 5G and beyond. We will start the next lecture with basic optical sources and optical detectors which will which are likely to be used in optical wireless communication.

Thank you very much.