Optical Wireless Communications for Beyond 5G Networks and IoT
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Lecture - 16
Part - 2
NOMA VLC

Hello, so, in the last class we had discussed about NOMA where we discussed the basic principle of NOMA and also, we discussed about the comparison between NOMA and OMA.

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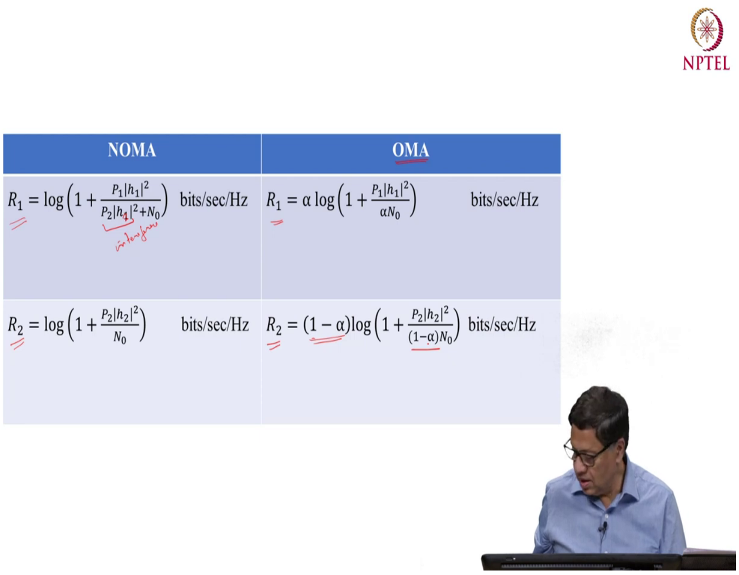

So, just to recap the earlier discussion in NOMA the R 1 achievable rate by user 1 is given by log 1 plus P 1 h 1 mod square divided by P 2 this is h 2 mod square plus N naught. And this being the interference term the interference is coming from the other user and then you do the SIC which is successive interference cancellation. And you remove the P 1 part and then you are left with only P 2 part and the R 2 in this case is given by log 1 plus P 2 mod of h 2 square divided by N naught.

So, there is no interference term here which you have already detected, subtracted the user 1 power level. And as far as OMA is concerned it is given by R 1 alpha log 1 plus P 1 h mod h1 square divided by alpha N naught, where here alpha is the power coefficient and the resource block allocated in the OMA scheme.

And similarly for the other user it will be 1 minus alpha and the resource block will be the power coefficient will be 1 minus alpha. So, this is the value for OMA and we have also seen the sum rate in case of NOMA is higher as compared to OMA. If you choose the power allocation scheme appropriately; so, now we will try to use this NOMA in VLC environment.

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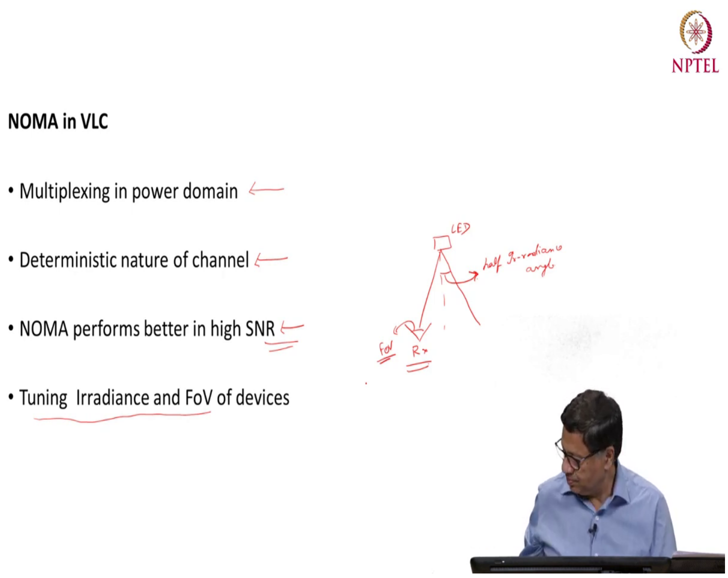

So, what is the motivation for using NOMA and VLC? So, first of all multiplexing in power domain; for example, inside a user in a inside in the indoor they are only limited number of users. We can have you know multiplexing of user signals they will have different you know power gains and we can multiplex them; so, this is the requirement for a power domain NOMA.

So, this is easy in case of visible light communication; for example in a indoor VLC environment. The second thing is that for SIC you have to estimate the channel you have to accurately estimate the channel. In RF there are challenges of as far as estimation of channel is concerned, but VLC is actually a deterministic channel it does not change with time it only changes with distance. So, user 1 and user 2 depending on the distance you can all easily estimate the channel in VLC.

NOMA performs better in high SNR, this we have seen where in the earlier class we had assumed that gamma which is a SNR tending to infinity. And under those conditions under this particular condition we saw that the sum rate for NOMA is higher as compared to sum rate of OMA. And in indoor communication; for example, we are using NOMA you are using the same lamp which is actually there for elimination.

So, you have enough power at the receiver; so, basically you get high SNR at the receiver; so, NOMA is likely to perform better when you have high SNR. And also you can change the performance or improve the performance of NOMA by tuning the irradiance angle and the FoV of the device. For example this is your LED it has some irradiance angle; so, this is called as half irradiance angle. And you have the receiver here and the receiver may have some FoV, this is RX and it will have some FoV.

So, in order to have you know high SNR, if LED and the receiver they are aligned they can be aligned if the LED; for example, has a narrow irradiance angle and receiver also has a narrow FoV. So, there is a almost a direct line of sight in the communication and you have you know high amount of power falling out of the receiver which is basically a high SNR condition.

And we have seen that in high SNR condition the performance NOMA is much better. So, you can actually tune the irradiance angle this angle irradiance angle of the device of the transmitter and the FoV of the device in order to get a better performance in NOMA or you can optimize the performance by tuning these angles.

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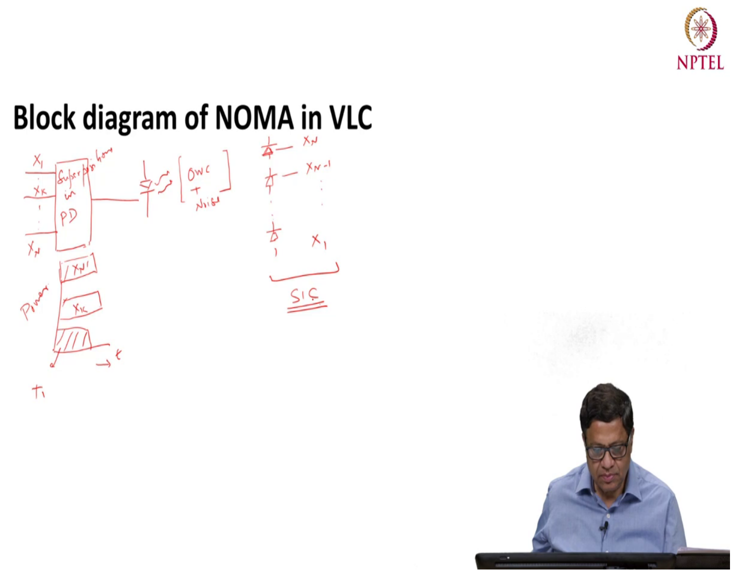

So, now let us understand the block diagram of NOMA in VLC. So, suppose you have user X 1 here and then you have user say X K and then you may have user the last you say X N. So, these signals they are superposed in power domain this is superposition in power domain and this superposed signal is transmitted is given to LED and this LED transmits and it goes through the optical wireless channel here.

So, this is optical wireless channel and of course, some noise will get added here and then there will be noise because of the detector also then on the receiver side you have detectors.

So, there are many the X N detectors and you perform you first detect the highest power level signal. So, if I assume here the power levels assigns to this X 1, X 2; so, this is your t this is the power level this is power level, assigns to say X 1 this is say to X K and this is to X N.

So, these are the power levels defined, this is X 1; so, there are different power levels you want to different user data. And in the first; in the first SIC you detect the highest power level. And once you have detected; for example, in this case you have detected X N here then you subtract X N from the remaining superposed signals and then detect you know X N minus 1 and so on till you get X 1.

So, this is basically you do the SIC operation here Successive Interference Cancellation. So, this is the block diagram of NOMA in VLC and we also saw why NOMA is preferred in VLC.

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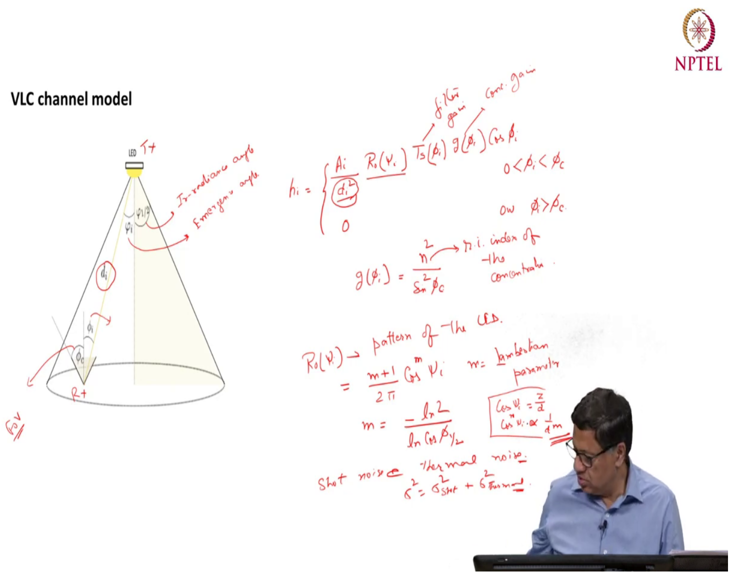

Now, let us try to understand the VLC channel model which actually we had done when we were discussing indoor channel modeling. So, in this model this is the LED this is a transmitter here and then you have the receiver here and this is the half-irradiance angle of the transmitter. And psi i is the angle which the normal of the transmitter makes with the line of sight; so, this is the emergence angle one can call it emergence.

And similarly phi c is the FoV any light falling out of this phi c will not be captured by the receiver and phi i is the angle which the normal of the receiver makes with the line of sight. And the distance between the transmitter and receiver is shown here as d i. Now, the channel coefficient for such a VLC channel is given by h i A i which is the power of the receiver divided by d i square there is distance square that is the distance from the source to the user and R 0 psi. So, I will just discuss about this R 0 psi in a bit in a little after some time.

So, this is psi i and then you have a filter gain which is function of; so, this will be phi i function of this. And then you have the concentrated gain which is represented as g and this will be phi i and you have cos phi i. So, this is valid when the phi i angle is between phi c and 0 otherwise this value is 0 otherwise or when phi i is greater than the phi c which is the FoV.

So, it is given by A i divided by distance square into R 0 psi i into T s phi i this is a filter gain which is used as the receiver. This is the concentrated gain which is again used as the receiver and g psi that is the concentrated gain g phi i rather is given by refractive index of the concentrator divided by sin square phi c; so, this is the refractive index of the concentrator. Now, let us see what is this R 0 psi and this we have discussed also earlier R 0 psi i is pattern of the LED.

And it is given by m plus 1 over 2 pi cos m psi i where m is the Lambertian parameter. So, it basically tells about the beam whether it is a narrow beam or a wide beam depending on the value of m. So, this is pattern of the radiation pattern of the device. And this can be this m which is defined as minus log natural 2 divided by log natural cos that is irradiance angle which is half-irradiance angle of the transmitter.

In addition to this the receiver will have noise which is a short noise and thermal noise. So, the total noise will be sigma square is equal to sigma square short plus sigma square thermal; so, this is a VLC channel model which we will use in our analysis.

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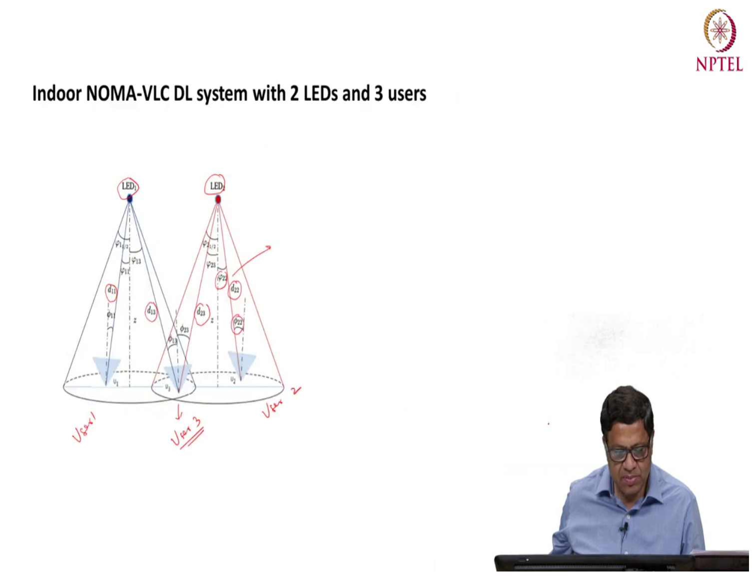

Now, let us try to understand for a case where there are two LED’s, LED 1 and LED 2 and there are three users. One user is in the autocell of LED 1, this is a user one, the second user is also is in the autocell of LED 2. So, this is user 2 and user 3 actually gets intensity or light both from LED 1 and LED 2. So, this user is actually in the edge of the autocell for each LED; so, this gets light from this user 3, this gets light u 3 gets light from both the LED’s.

And in the same way we have defined different angles; so, for example, this is a psi 11 which is a normal mix with the line of side. And then you have 5-11 the normal mix or normal mix of the receiver mix with the line of side. D 11 is the distance with the LED1 and user 1. And similarly you have for user 2 here this psi 22, 522 and the distance is d22 d22.

And this user 3 actually gets light from both from LED 1 and LED 2 and these are the angles which are defined and the distances are actually d 13 from LED 1 to user 3 and d 23 from LED 2 to user 3. So, this is the system model which we want to evaluate; so, now having understood this system model.

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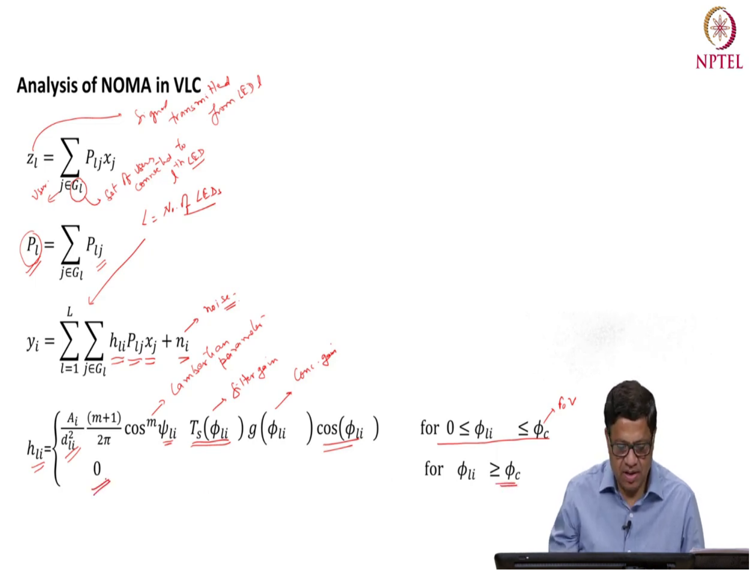

Let us try to analyze this NOMA in VLC; so, Z l is equal to P lj x j where j belongs to G l. So, this Z l is actually signal transmitted from LED l and this G l is set of users, set of users connected to lth LED. So, in our case we have LED 1 and LED 2 and this the users which are connected to LED 1 are u 1 and u 3 and users which are connected to LED 2 are u 2 and u 3.

So, this G l is the set of users connected to the lth LED and j is the user; so, this is the user. And P lj is the power, the P l is the total power and this is the power from the LED to the jth user, P lj and the total power from the LED is P l which is summation of all the users which are connected to lth LED. So, if I, capital L is the number of LED's; so, if you see the power at y i, signal receives in y, it will be summation from l is equal to 1 to l where l is the number of LEDs.

Summation j belonging to G l, h li coefficient into P lj into x j is the data plus the noise, that is the received signal of the i-th user. The h li, the channel coefficient between l-th LED and the i-th user is given by this, A i A i is the area of the receiver, this is the distance d square l i m plus 1 divided by 2 pi where m is the Lambertian parameter, Lambertian.

So, this is psi li and then you have the filter gain, this I have used the indoor channel model as I had discussed earlier. This is the concentrator gain and the cos psi li and this is only valid when the phi li is between 0 and FoV, this is FoV and for phi li greater than phi c it is 0.

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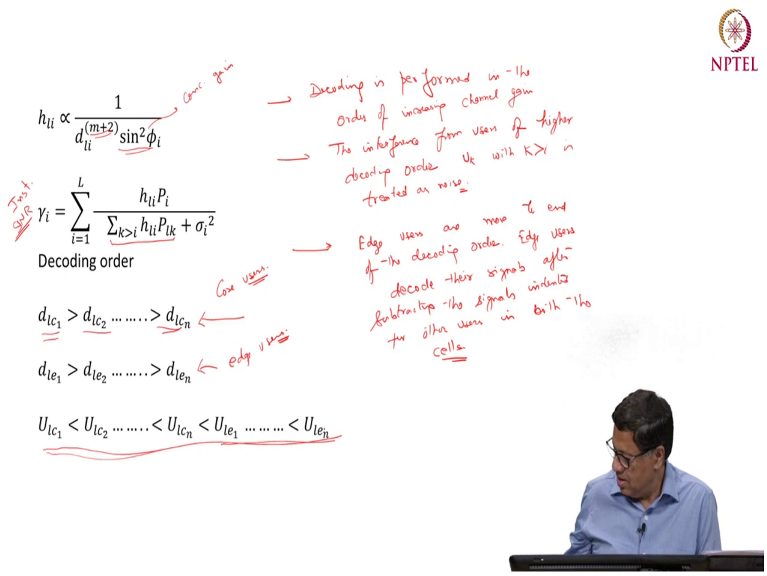

So, having modelled h li; now, we see that this h li is actually among other parameter it is proportional to 1 by distance raised to the power m plus 2 and sin square phi i. So, this is actually coming from that concentrated gain. And if you see here, this cos psi if you see here for example, cos psi i is the distance, the height of the between the transmitter and receiver divided by distance.

So, cos m psi i will be some you know proportional to 1 by d m and the other there is square term is coming from here. So, this becomes actually d raised to power m plus 2; so, m is becoming because of the Lambertian pattern of the LED and then square term. So, this whole thing becomes 1 by d m by 2 and the same thing I have written here; so, this is distance raised to power m plus 2 into concentrator gain.

And the SNR gamma i that is a instantaneous SNR, gamma i is sum of i is equal to 1 to l h li pi and this is the interference term. This is plus sigma i square and this is for k is equal to i we will understand why this k k greater than i; so, this is the instantaneous SNR. Now, we are doing the decoding in the following fashion.

So, the decoding is performed in the order of increasing channel gain in the order of increasing channel gain, this is what we had studied in NOMA. The decoding is performed in the order of increasing channel gain. The interference from users of higher decoding order U k with k greater than i is treated as noise.

So, this is what if you see in the instantaneous NR, SNR expression siSNR rather treated as noise. So, anything greater than k plus i is treated as noise, because at every stage we are subtracting the detected signal and rest of the signals are actually noise. And when we subtract the detected signal, then you the remaining signal again one uses successive information cancellation successive interference cancellation scheme and detect the next higher power level and then so on and so forth the process goes.

So, the interference from users of higher decoding order with k greater than i is treated as noise. So, we follow here pattern for decoding; so, this is for the users which are inside the autocell. So, this d lc l is the l is the LED; so, these are the users which are actually in the directly in below the LED or they are only covered by lth LED there is no light coming from any other LED.

So, depending on the distance these users are decoded in this fashion; so, this is let us these are the core users which are covered by the LED. And these are the edge users which are there on the edge of the word autocell and they may be getting light from other sources; so, this is edge users. So, first only core users are decoded and then the subsequently the edge users are decoded.

So, edge users let me write here edge users are moved to end of the decoding order. Edge users decode their signals after subtracting the signals intended for other users in both the cells. So, this becomes the decoding order final, you have the core users here and then the edge users here; so, this is the decoding order which is followed here.

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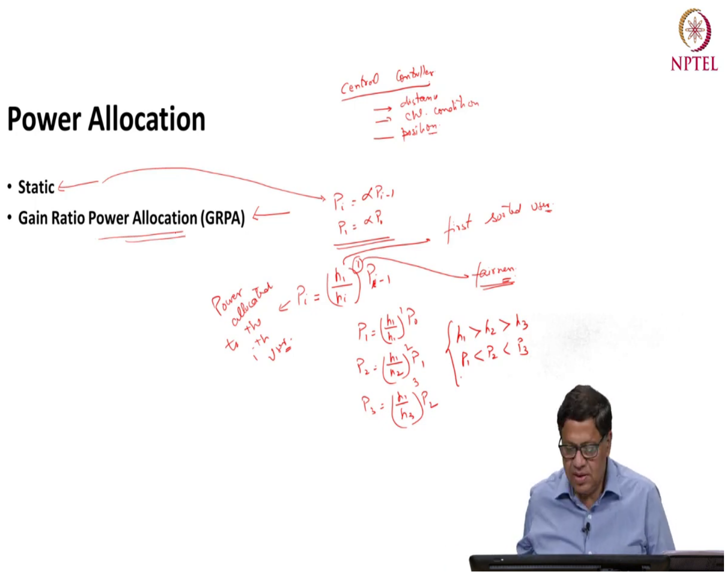

So, now let us discuss about the power allocation scheme, how power is allocated to different signals? So, assume that there is a central controller which has the information of the position of the users, what is the distance from the transmitter and also channel condition. So, the central controller you know has information and accordingly it gives power to different users.

So, it knows the distance of the user for example, distance it knows the channel condition, of course position is also known normally then you can find out the distance. So, all these things are known by the central controller based on these inputs the power is allocated to different users. So, there can be two possibilities, one is you know static power allocation other is gain ratio power allocation or also called as GRPA.

So, in static power allocation you have for example, P i is given as P i minus 1. So, alpha is the coefficient; so, suppose power to P 1 will be alpha P 0, P 0 is the power to the user number 0 then the user 1 will get alpha P naught. So, this is one way of allocating the this is a static way of allocating power, the other one is a gain ratio power allocation or GRPA.

So, this basically depends on the power given to the ith user power allocated to the ith user is given by h 1 divided by h i raised to power i P i minus 1. So, h 1 is the first sorted user; so, this is with respect to the first sorted user, first sorted user. So, suppose there are three users then P 1 will be h 1 over h 1 raise to power 1, P 0, P 2 will be h 1 over h 2 raise to power 2, P 1 and P 3 will be h 1 over h 3 raise to power 3, P 2; so, this is how the power will be allocated.

And then this i which you see here is actually for fairness, the signals which are being detected first they have you know noise coming from rest of the users. So, they have to be given more power and this is how you know the power distribution is done and which actually ensures that there is a fairness among different user signals.

So, this raise to power i is the fairness and we assume that h 1 greater than h 2 greater than h 3 depending upon where the users are located. So, the power allocation will be P 1 less than P 2 less than P 3; so, this is how the power is allocated in GRPA, Gain Ratio Power Allocation.

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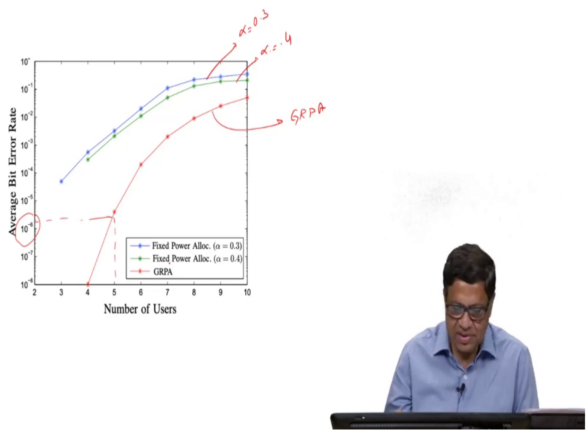

And if you see the results for both static and GRPA this is assuming fixed allocation static is allocation where alpha is kept as 0.3. And for alpha is equal to 0.4 there is little improvement here and, but if you use GRPA then the gain is much more as compared to static allocation; so, this is for GRPA. So, suppose I want to see minus 6 you know I can support 5 number of users with this quality of service having BER of 10 to the power minus 6.

Whereas, if I do the static allocation probably I cannot use achieve minus 6 and only less number of users can be supported in case of static power allocation, if I keep my criteria of bit error rate as 10 to the power minus 6. So, there are other techniques also power allocation technique which can give further improvement. So, this is just to show a difference between a static power allocation scheme and a little modified power allocation scheme.

And we have seen that modified power allocation schemes gives a better performance as compared to static.

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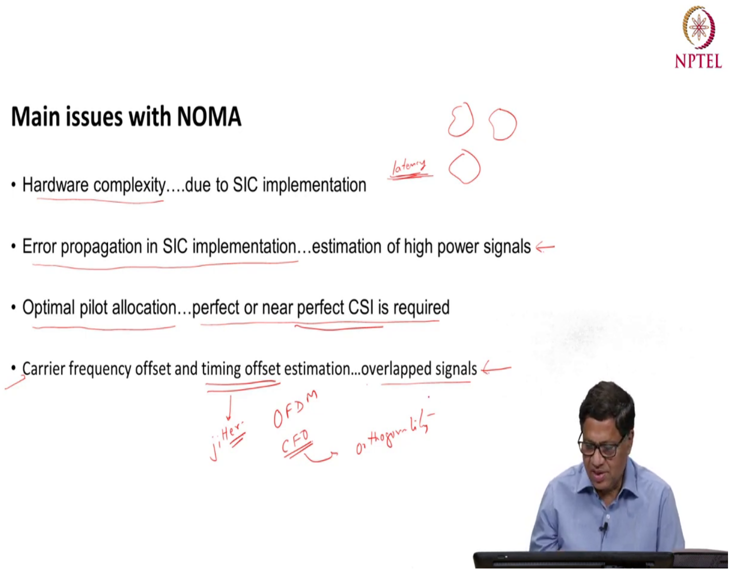

So, the issues there are few issues with NOMA which are being people are working on to solve some of these issues. One of the main issue is hardware complexity, because you are doing successive information at each stage and this actually consumes power also. And if you know if user has a for example, a mobile it has limited battery; so, the power may be consumed by for decoding NOMA.

So, this is one issue the other issue is successive interference cancellation requires a lot of hardware processes. So, it is hardware complex and also there may be a latency issues, because the last user is detected last after subtracting you know all previous users who have higher power levels; so, this might introduce some sort of latency. So, these are some of the issues which are which have to be addressed in NOMA and they are being this addressed as well.

The other issue is that error propagation and sick implementation. So, actually the whole process of SIC depends on how accurate is your channel estimation. So, if channel estimation is not accurate, you may detect or decode the signal wrongly. And then when you subtract you know this way when you subtract it might affect decoding of subsequent signals. So, the error may propagate if you are using SIC and your estimation of higher power signals is not accurate.

So, this is another issue which has to be addressed; so, for example, to address for example, hardware complexity sometimes you know you make clusters of users. So, that there are only less number of users in that area and then SIC process is little easier as compared to if there are more number of users. And the third issue is optimal pilot allocation that is perfect or near perfect CSI is required.

So, how many pilot symbols you require, because adding pilot is basically adding to the overhead; so, there has to be some optimum size of pilot allocation. So, that you have near perfect channel state information which can which is actually the core principle of SIC the estimation of the channel; so, this is another area where lot of work is being done.

And the second and the last thing is the carrier frequency offset; now, in OFDM we had studied that the CFO actually carrier frequency offset degrades the performance of the system. Basically it will spoil the orthogonality in OFDM and this happens because the local oscillator frequency may be changing.

And it also introducing timing offset; so, basically with this timing offset there will be jitter. So, in RF this estimation of CFO carrier frequency offset and timing offset there are lot of techniques available and it can be done easily. But whereas, in case of NOMA you know CFO and timing offset, becomes little challenging because NOMA has overlapped signals.

In OFDM you can always distinguish between the signals because they are they are orthogonal. So, it becomes little easier you know estimating and correcting CFO and timing offset and its little TDS when it comes to NOMA. So, these are some of the issues with NOMA which are being addressed by research community.

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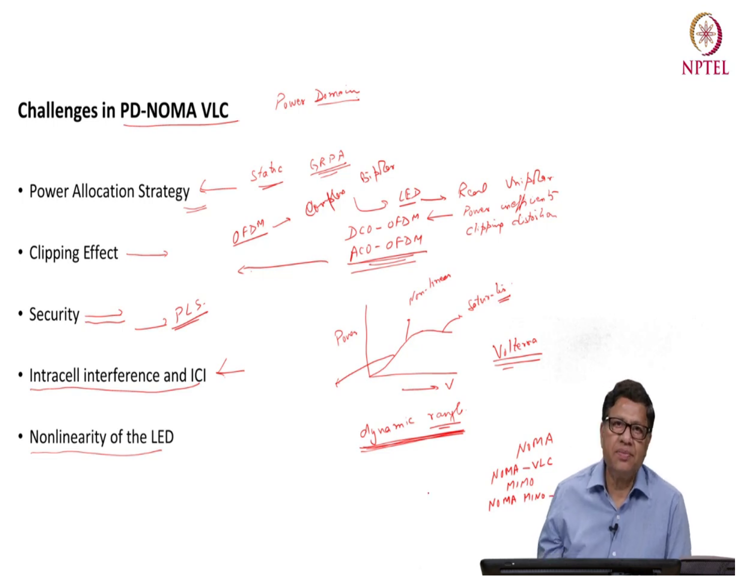

So, the challenges in power domain NOMA this is power domain whatever we have studied is actually power domain only, because we are sending signals at different power levels; so, power allocation strategy. Now, we studied as simple example of static and a and a GRPA that is a modified which depends on the gain ratio power allocation; so, we saw improvement in GRPA.

So, there can be other technique also there can be still another better technique which can give you know better advantage as compared to this existing scheme. So, power allocation strategy is one has to look for efficient power allocation strategy which gives the you know best performance in NOMA. The second challenge is actually clipping effect, this effect may not be there in Base band transmission.

But in OFDM as we know in OFDM the signals are complex and bipolar, and to the LED I cannot give this complex in bipolar signals, because the two LED the signals have to be real and unipolar. So, there has to be some conversion process which will make the complex bipolar signal into real unipolar signal. So, we did this when we were discussing OFDM and we discussed two schemes DCO, OFDM where you give a DC shift to the signal and the other was ACO OFDM.

In DCO OFDM actually give a DC shift; so, there is a constant DC current force; so, it makes this signal as power inefficient. And the spikes in the signals are large; I mean you cannot make everything positive. So, normally you give some minimum amount of DC shift and you clip rest of the part; so, basically you introduce some sort of clipping distortion.

So, with this and ACO also you clip the signal the lower half is clipped. So, there is a clicking clipping distortion happening both in DCO OFDM and this ACO OFDM and this may degrade the performance of NOMA because of this clipping. The third is security; now, we are actually sending the super-pose signals where signals from all the users are getting combined; so, it is a security threat.

So, what normally is done that you have the security at higher levels, you do the encryption at higher levels whereas, you transmit the data over the physical layer. But then when you are sending high amount of data, then you know having security at higher level will introduce some sort of delay; so, you want to have security in the physical layer itself.

So, some PLS or Physical Layer Security is to be ensured when you are dealing with power domain NOMA. There are issues of intracellular interference and inter-ah inter channel interference; so, this also have to be studied and the last challenge is nonlinearity of the LED.

So, non if you see the characteristic of LED this is a voltage or current this is power; so, this is not linear actually here and then it saturates.

So, this is not fully linear; so, this is non-linear and it saturates after a certain. So, basically it will limit the dynamic range, because after that after that it starts saturating. So, you can have only power levels which are dictated by the dynamic range of the LED. So, this is one limitation here and this nonlinearity may also because of different constellations will suffer this will suffer due to this nonlinearity and this will degrade the overall performance.

So, while doing this one has to take care of this nonlinearity and there are different models available. Volterra is one example which takes care of the nonlinearity of the device and hence improves the performance. So, one has to handle this nonlinearity and also one has to keep in mind the dynamic range of the device. So, and these two limitations actually have some there are some challenges posed in power domain NOMA.

VLC because of these two limitations. So, these are some of the issues which are being currently addressed by the research community. So, this was regarding use of NOMA in VLC; so, we have studied about NOMA initially and we also now seen in this lecture how NOMA can be used in VLC environment.

The next we will study how NOMA and MIMO can be used in VLC environment, because in RF if you see the NOMA and MIMO they generally go together that was in that is in RF; so, before we go to NOMA, MIMO in VLC environment. In the next lecture I will give some basics of MIMO and then we will move to how to use NOMA, MIMO in VLC environment.

So, that will complete the discussion of use of NOMA in a visible light communication.

Thank you.