Evolution of Air Interface towards 5G
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Lecture - 40
Hybrid Beam Forming mm Wave

Welcome to the lectures in Evolution of Air Interface Towards 5G. So, we have been discussing the issue of increasing the number of antennas to very large numbers. So, we will just revisit that quickly and proceed on to the next few set of things.

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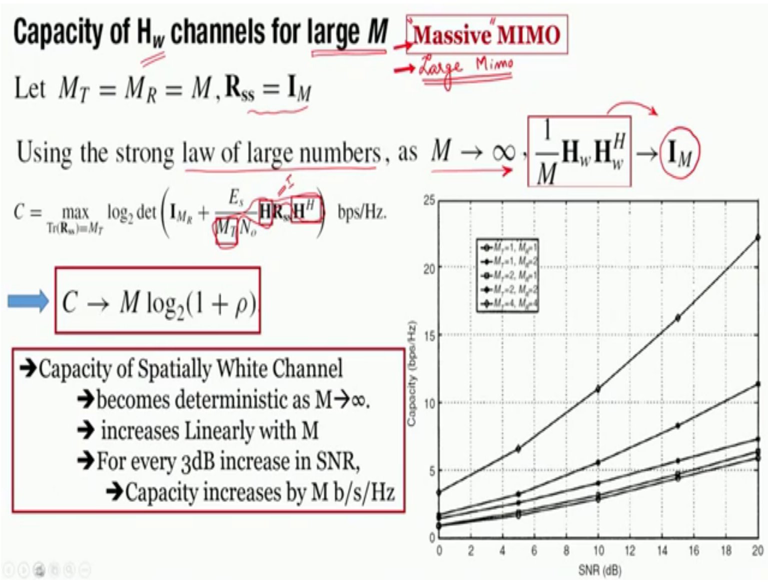

So, what we have been talking about is the case of spatially white channel, where we are saying that if we increase the number of antenna elements to very large values, then what ends up. So, originally this was proposed as Large MIMO you can look up the internet for literature on Large MIMO and almost at the same time or later on the term massive MIMO became very very popular. And however, the earliest possible literatures you can find using this set of keywords and of course, a huge amount of literature. Following that on almost on the same time you will find with the keywords massive MIMO. Now of course, there are a huge amount of work that has developed based on the term massive MIMO and certain newer concepts.

So, what we have said is that if you set the number of antennas going to very large value, we have defined we have said in the last discussion that, take this as an assignment and you will find that 1 upon M H w H w Hermitian tends towards an identity matrix by law of large numbers. And then we had discussed that if you set R ss equals to I as given over here, these few terms as we are encircling would turn out to be an identity matrix.

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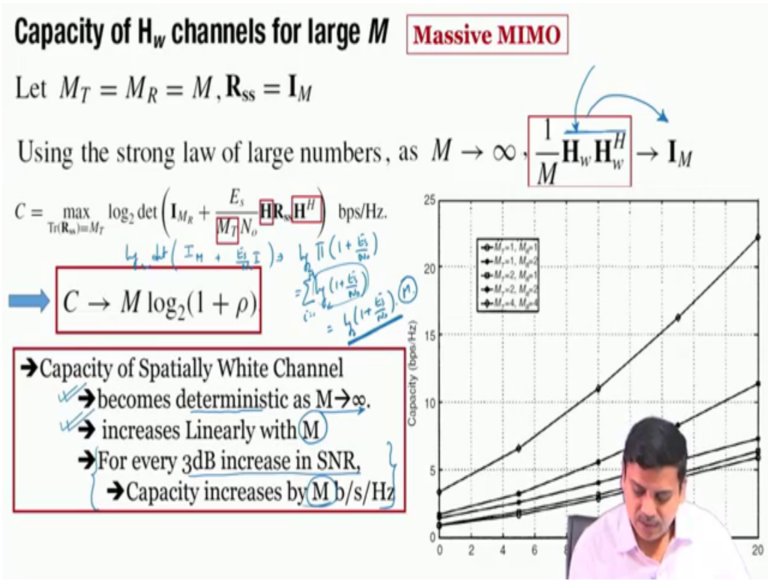

So, inside the expression what you will find is you are getting I M plus E s by N naught I determinant log base 2 so; that means, it is a log base 2 product of 1 plus E s by N naught which turns out to be log base 2 1 plus E s by N naught summation i equals 1 to M which is log base 2 1 by E s by N naught multiplied by M, because this is a constant term and hence what we see there is an M fold increase in capacity over a C solving and we said this is a major gain that one gets when using very very large number of antennas.

So, some of the assumptions play a vital role over here; so what we find is that as M becomes very large, the channel becomes more or less deterministic, which is understood from this expression. That means, as M becomes large this tends towards identity matrix; that means, the diagonal elements are all having the same power and the rest of the non diagonal elements are 0 and this is what you get at the receiver processing or in the capacity expression, this whole thing right.

This is one of the very important gains. So, one is not affected by the channel variability. The capacity increases linearly so one can simply get the desired spectral efficiency by increasing M and in turn which would boil down to this few set of conclusion; that means, every 3 dB increase in SNR capacity increases by M instead of a logarithmic growth. Now, along with this a few other considerations that we must make at this point is a few more things.

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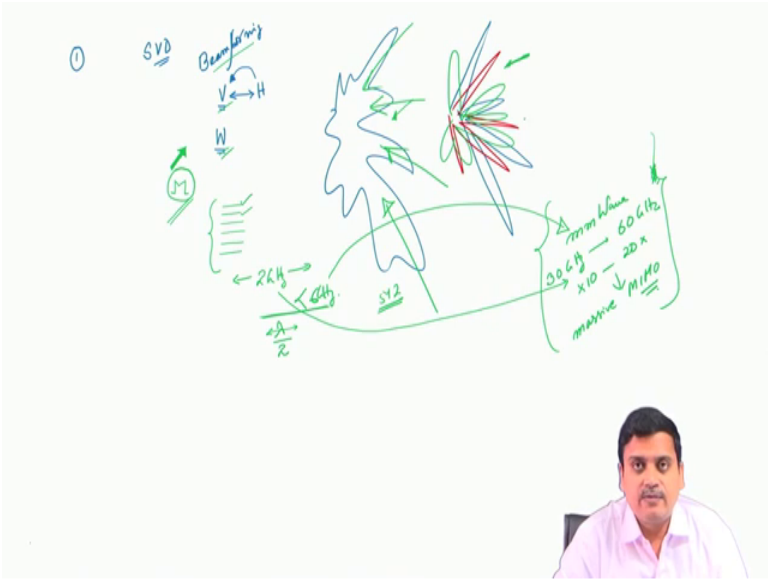

One, when we are using S V D we said it is also a kind of beam forming that is what we are doing; because the precoding matrix V is matched to the channel. So, one can think of an arbitrary shape beam that you are able to form based on the particular cluster realization of the channel which we will see shortly. So, when V is arrived at from the channel you get exact matching with the channel whereas, if you are choosing from codebooks you have certain predefined matrices, and you are choosing the one which is the best matrix for the particular realization.

You can imagine the whole situation like this. So, this entire set of things can be thought of as kind of beam forming as you increase the number of antenna elements, you have a much greater control on the kinds of beam that you can form; you can match it more and more closely to the channel. And if it is codebook then you are much wider option to choose from where by one can expect that one of the code books is going to match very closely with the channel.

So, now this code so as you increase the number of antennas, if you look at the channel estimation procedure the number of pilot training symbols that are required that is number of time stamps or time instants grows linearly with M. That means, your training period becomes bigger and bigger and bigger, but of course, if you use o f d M, then you have one advantage that if there are a large number of carriers within the coherence bandwidth you can assign one carrier to one antenna. And thereby reducing the training time interval required by spreading the training sequence in the time as well as in the frequency domain; however, the number of pilots required would grow with the size of the system, that is one aspect that we should keep in mind.

The other aspect we have already mentioned the channel variability reduces. So, thereby you get closer and closer to the best performance matching towards in AWGN link. The third thing is if we increase M we have to also accommodate it in the size. So, if we look at the 2 gigahertz range of frequencies, rather the sub six gigahertz then the antenna spacing as we have said earlier is required to be lambda by 2 in a general situation in order to make the links uncorrelated, because uncorrelated gives you the better advantage as we have just now seen.

So, even then with these set of frequencies the lambda spacing is in order of centimeters. So, if I have to place 512 antenna elements, it becomes a very very large dimension in space. And if it is a very large dimension in space then it becomes system which is not realizable and probably in some situations the narrowband antenna array assumption may also break. Whereas, there has been a lot of interest in going towards the millimeter wave band of frequencies, millimeter wave bands of frequencies are around 30 gigahertz and 60 gigahertz. These are some of the ranges of bands which are usually made available for the mobile communication system.

So, there if we compare the wavelength there is a factor of 10 to 20 fold reduction in the wavelength, thereby a reduction in the antenna spacing as well as the component size and antenna dimensions get significantly reduced in the millimeter wave band. Thereby naturally enabling massive MIMO, another important fact which we will see is that in these millimeter bands the number of such clusters which provide the angle of arrival for different ways are also significantly less compared to the sub 6 gigahertz band.

So, thereby you have a more sharper beam to be formed in case of millimeter waves; overall millimeter waves is kind of enabler for massive MIMO systems it makes things much more feasible compared to sub. So, what we will do is we will quickly take a look at some of the aspects of the millimeter wave band and then we will get back to the details of these things.

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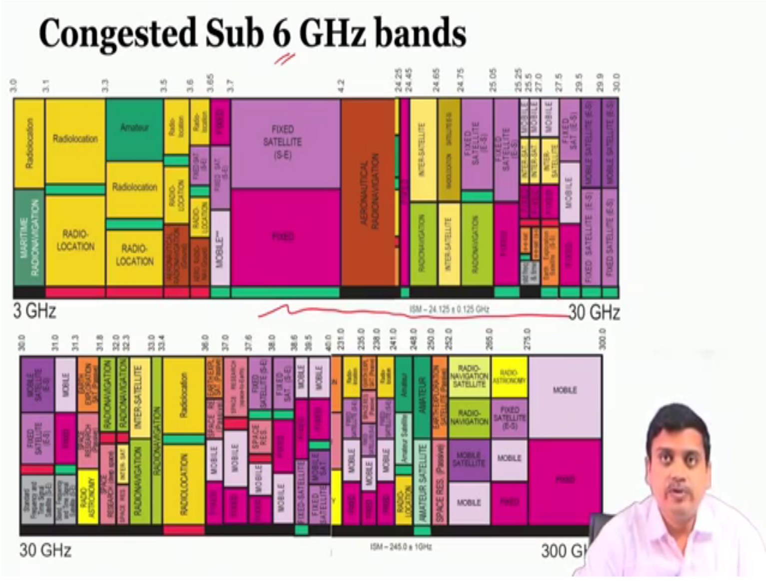

So, in the millimeter band when peals people have moved towards the or they are excited towards millimeter band; because the sub six gigahertz is highly occupied and the bandwidth available is also very very less. So, people are moving towards band which are between 30 gigahertz and 300 gigahertz.

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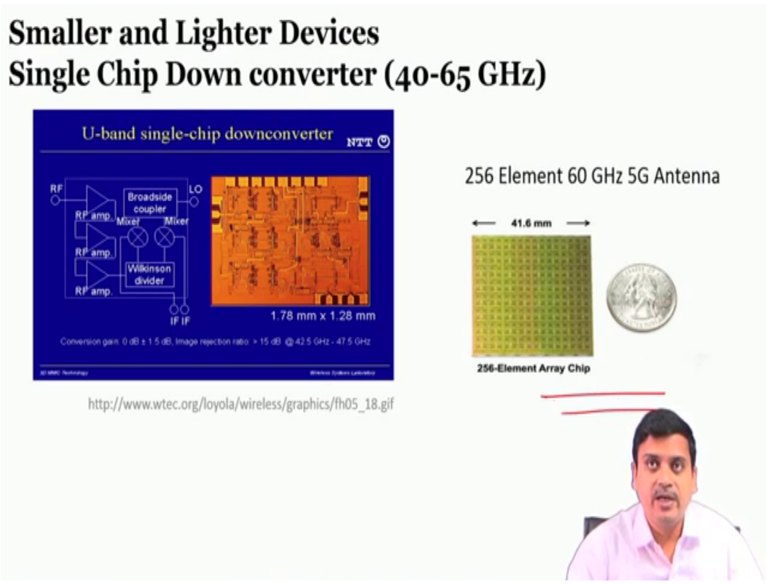

So, the size of elements would be much much smaller, within a very small dimension one would be able to encompass a very number of antenna elements, thereby enabling the use of massive MIMO.

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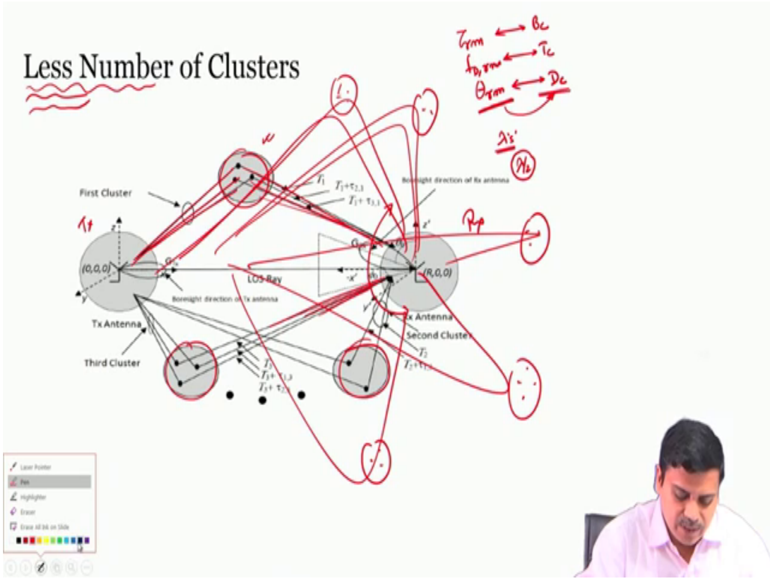

So, in a typical configuration of MIMO architecture, one has the transmitter and receiver locations and the rays emanating from the transmitter come to the receiver after reflection diffraction of scattering through different clusters. In millimeter wave the number of such clusters are much less compared to the sub 6 gigahertz band in the same propagation environment. For example, the room that you are sitting in if you use a sub 6 gigahertz band the number of multi paths, the number of angles that you are going to get signals from would be much more in subsequent than in the same room just when you shift the frequency to millimeter band.

Now, we would like to recall that we said in the time frequency relationship tau rms delay spread affects the coherence bandwidth. The Doppler spread affects the coherence time and the theta r m s that is the angular spread affects the coherence distance. Now, if we design antennas what we will find is that the theta rms when it is less coherence distance is large right.

So, if we space antennas in order of lambdas so we are not putting absolute separation we are talking about lambda separation then, if theta r m s; that means, if signals are not coming from all directions with equal probability then lambda by 2 spacing does not hold anymore right; we have shown this thing earlier. And now what we find is that if the number of clusters are less the direction spread or the angular spread of arrival of signals at the receiver would be much less compared to that of the other situation.

So, in sub 6 gigahertz we said there are much more number of clusters right. So, signals are going to come from all directions, this is the kind of thing that we had shown whereas, in the millimeter band of frequencies they are going to come only over a few set of such directions; and hence the theta rms is relatively lower in case of millimeter band of frequencies.

So, then this tells us that the covariance for the correlation would be higher; in case of millimeter wave for the similar antenna spacing when determined they are expressed in terms of lambda separation but in absolute terms this is different. But you have another advantage that if the separation requirement is larger since we are going to millimeter band we can afford to have a larger separation.

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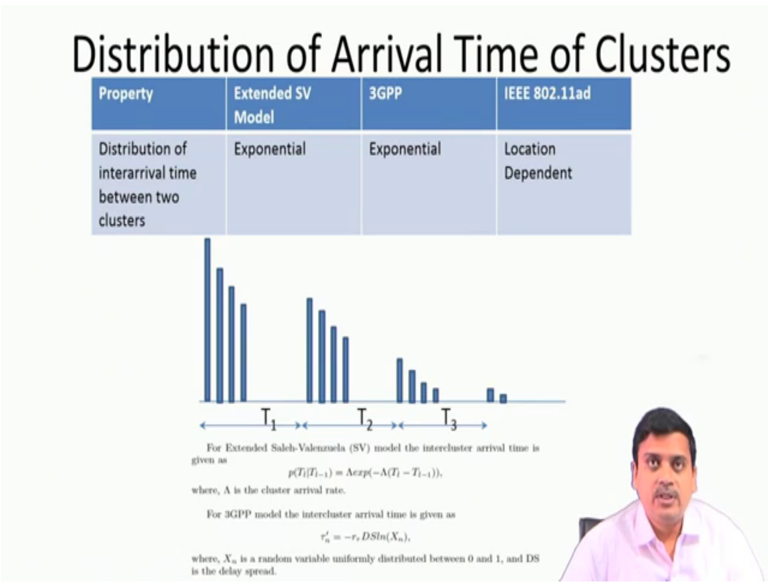

So, we move forward with this and there is a detailed description of the propagation of the channel profile in case of millimeter wave; because we are kind of towards the end of this we are not discussing the details.

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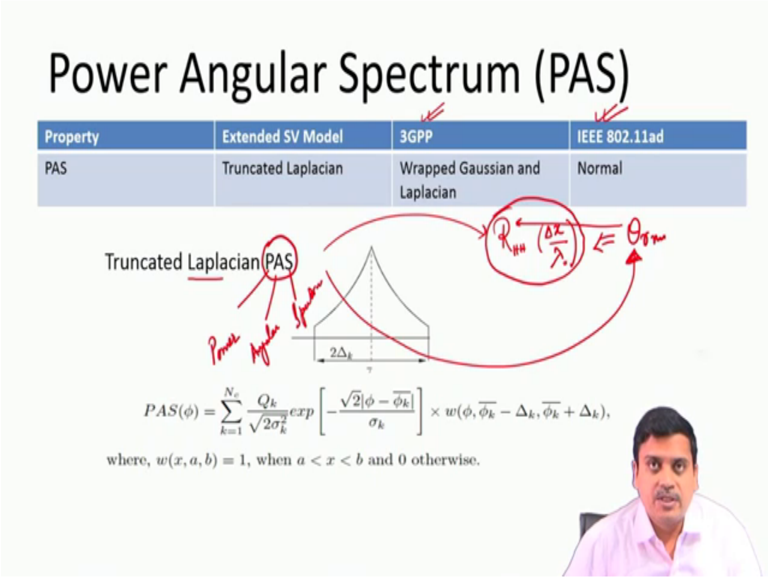

But all I am telling you at this point of time is there a detailed description of the power angular spectrum that is exactly what we were talking about; that means how the power is distributed how the power is distributed over the angle. Using these one can calculate the covariance matrix of the channel as a function of separation distance between or as a function of separation distance between the antenna elements with respect to the lambda spacing right. And this is of course, influenced by the theta rms which is in this path.

So that means, one can finally, calculate R H H covariance matrix given the power angular spectrum of the channel. The expressions that we show over here are arrived at from various descriptions of power angular spectrum, which is provided in the evaluation methodologies of the different communication standards especially we are talking about the millimeter band, but this analysis is general for any set of such MIMO communication links.

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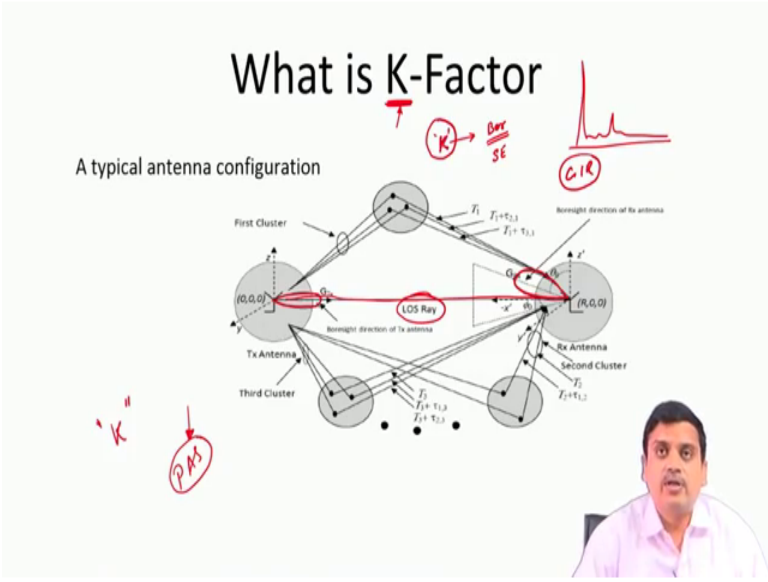

So, another important factor in millimeter wave is the line of sight factor, which is called the Rician K factor, this is also an interesting fact which are like to point out over here.

In case of millimeter wave a major amount of power is carried by the line of sight because there is huge attenuation upon hitting upon a particular surface. So, usually the first multipath, the first path which arrives in the channel impulse response is the line of sight component. You probably know that the Rician K factor is usually described in these propagation detail characteristics of 3GPP ITU and 802.11 AD which is particularly for its millimeter wave as well as for other substance gigahertz bands; what we have done an analysis is because you have a lot of directivity in these links and one is expected to use directional antennas.

We have been able to compute analytically the impact of such usage of directional antennas under specific channels which are governed by the parameters of the third generation partnership project or ITU or 802.11 series of documents. That means, we are talking about practical channel models there are many theoretical works which provide power angular spectrum description.

But they are primarily motivated with the analytical tractability of those equations whereas, the models which we have just mentioned from the practical measurement works which are like 3GPP and others. They mainly use the method of simulation, because those PAS are not mathematically generally mathematical or tractable.

So, we have analyzed these kind of channels in two aspects; one is the addition K factor; that means, generally you would be given a K factor, we use the K factor in calculating the bit error rate or the SIR and hence the spectral efficiency. What we show is that it is not sufficient to use only the K factor that is present in these documents; there is a lot more details that one has to consider which is described in the papers that have been sited in our work. So, one can feel free to get into those papers and find out all the details, we will simply summarize and show the different effects.

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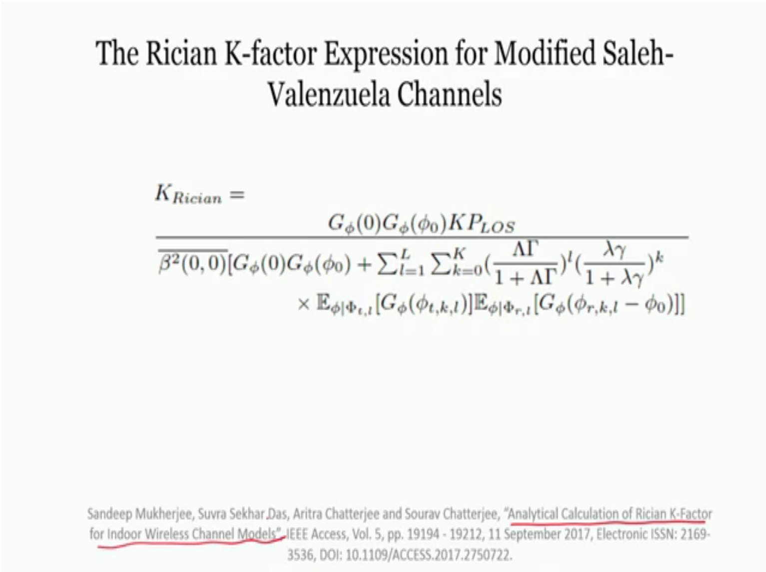

So, the paper we are talking about is the analytical calculation of Rician K factor for indoor wireless channel models right; what can easily access that paper and get into the details.

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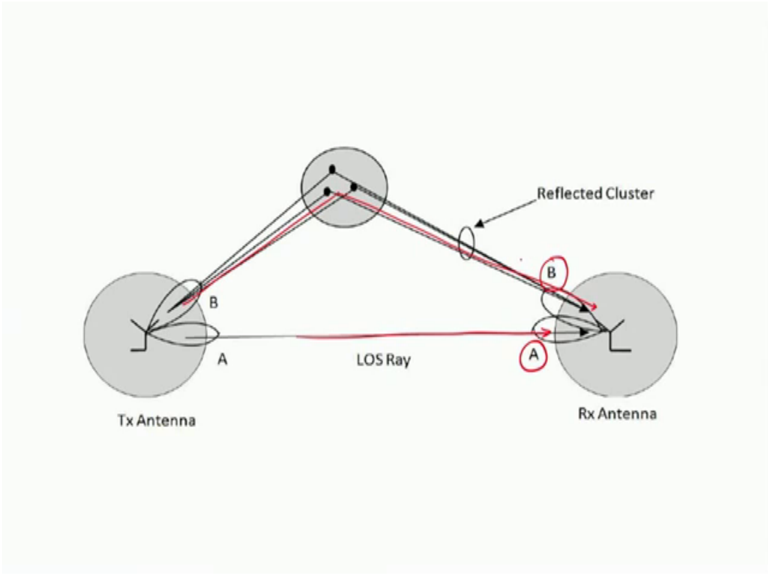

What we are going to show is that two situations; one is when there is line of sight which is determined by the case A and when the signal is coming from this direction and that is case B.

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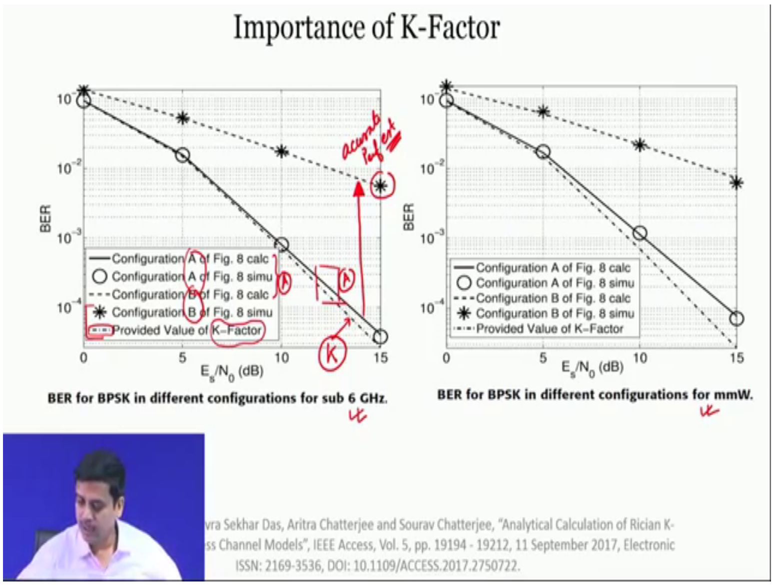

So, what we show here is results in the sub 6 gigahertz and 4 millimeter wave band; and these set of results as you can see are for configuration B and these set of results as you can see are for configuration A alright.

So, what do I find is that in configuration B the provided value of K factor makes a good sense whereas, if you are in configuration A then we clearly find that the Rician K factor sorry I mean we just made a wrong statement; these set of lines are the ones which provide the Rician K factor. So, this is the curve which is for the given Rician K factor which is matching closely with the case of A whereas, if you are in the case B I mean if you just go back to case B, case B is when you are tilted in some other directions; because the devices they do not know they can be configured in any orientation. In case the beam pattern is not oriented towards line of sight you are not going to get the K factor which is given in these documents.

So, in that situation you will be significantly away in the bit error rate performance estimation. So, we are talking about the expected value of performance if I use the K factor given in the channel models. So, all that we are saying is you need to do a detailed modeling which has been given in details in the paper; if you use the expressions and details that are available there you will find a more accurate performance estimation.

The importance of such works is that you can get a theoretical or analytical performance estimation without needing a huge amount of simulation, which are generally the practice in order to estimate the performance of such systems. So, because of not much available time we will cut short this discussion over here and we will move forward to some additional results on such effects.

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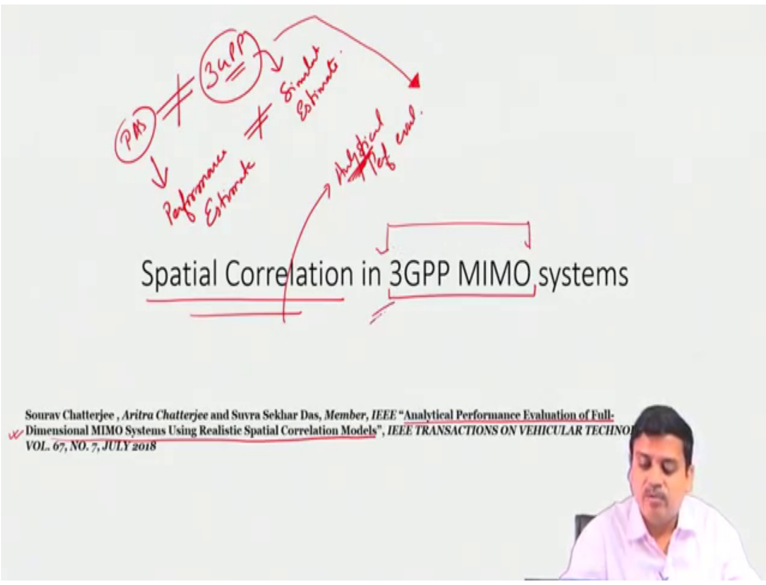

So, will also talk about another work over here, you can find the publication which I have underlined over here; now this work is again in a similar line that we have taken the propagation characteristics are described in the 3GPP MIMO system; because if one has to evaluate the performance of these 5G systems and others one has to take the propagation characteristics. As described in this 3GPP documents ITU documents or even wants the performance evaluation for 11 series one must take the standard specified simulation channel models.

So, if you take this channel models you have to go through a huge amount of simulations to get a realistic performance result. If you use theoretical works other papers again as mentioned they will provide you PAS which is not matching with the 3GPP PAS and hence, the performance estimate will not match that of the simulated performance estimates that from the 3GPP PAS.

So, this particular work finds out the spatial correlation for the 3GPP PAS thereby enabling analytical performance, evaluation of such channels which are generally done using simulation. Thereby reducing a huge amount of simulation time, we will show you only the fundamental result and the things which matter to our present discussion.

But I would highly encourage people to get into this document and find out how these results can be used in your performance evaluation, in reducing the simulation time by a significant margin; whereas, at the same time you are going to get the results for these practical channel models.

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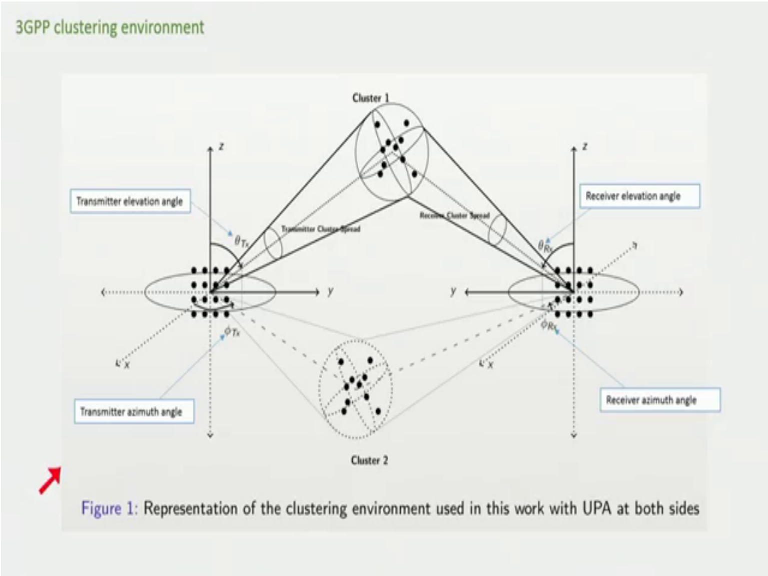

So, if we look into the description of the channels you will find a picture which looks like this, which provides the detail propagation modeling scenarios one has to implement in analyzing the performance of a particular MIMO scheme one come comes up with.

So, if you use the simulation models as described in this and evaluate your scheme then you would be assured how good or bad is your scheme with respect to 5th generation communication system. So, let us look at the correlation performance of such schemes we will not get into the details of the procedure and the details of the models which I leave to you to find out.

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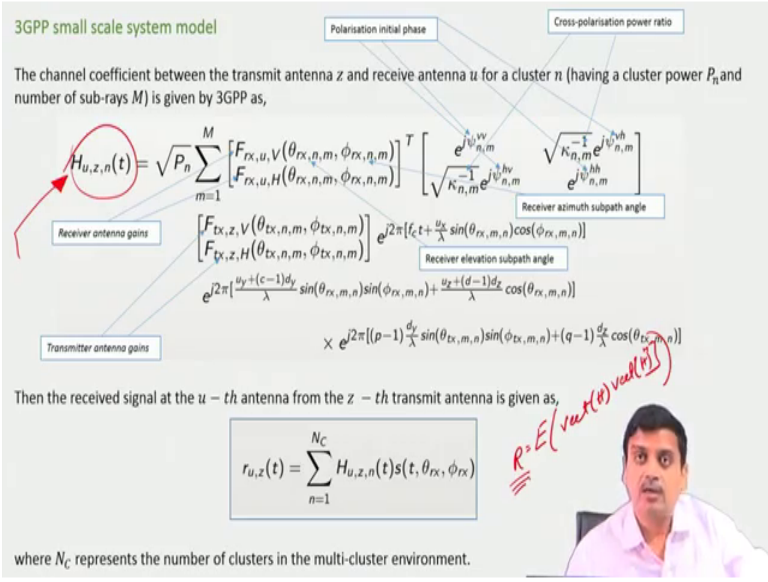

So, the expression of the core the channel as given in the document is this which is a cumbersome the expression as given in the channel model. So, one has to typically implement these channel models in order to get the channel coefficients. So, these are the channel coefficients which we have been talking about evolve in time they evolve in space and thereby give you the covariance.

So, R would be equal to expected value of vect H vect H Hermitian that still holds right. So, through all this process will tell you what kind of R evolves out of these channel models So, we will keep the detailed description and will go to some of the important results that we get out of this. So, what we show is that we look at one such result.

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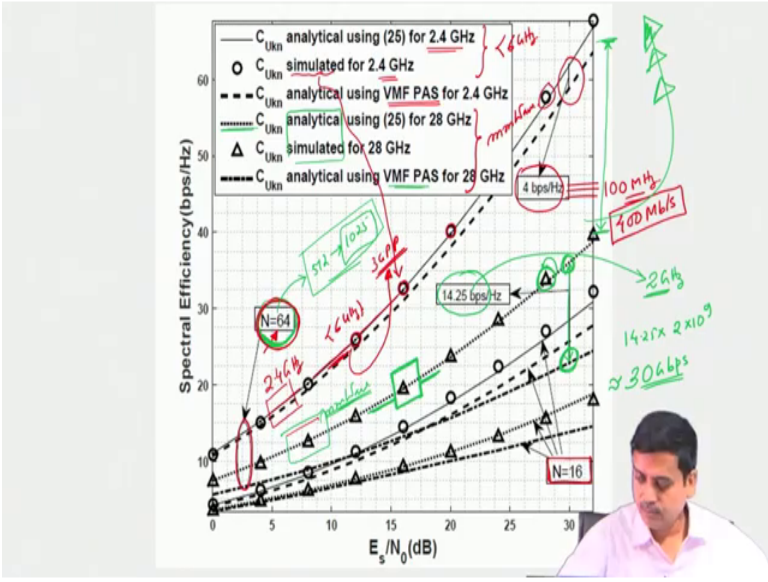

So, we have certain set of results for the 2.4 gigahertz band of frequencies which is effectively the sub 6 gigahertz band, and we have another set of results which is 14 millimeter wave band right.

So, what we find is that this group of curves which are being identified are when we have 64 number of antenna elements and we have also identified another set of curves which are with 16 antenna elements right. So, now let us look at one such curve if we look at this particular one this is for a sub 6 gigahertz using the expression that we have derived. And these circles are the ones for sub 6 gigahertz through simulation; that means, using the 3GPP models.

So, what we see is that the analytically provided performance matches that of the 3GPP result right what we see over here. Whereas, the theoretical pas which is the one miss us we us pas has a performance cap at higher SNR it gives us a 4 bits per second per hertz cap. Now, again if you multiply 100 megahertz you are going to get 400 mega bits per second gap with respect to a real situation. Whereas, if you use the analytical method that we have developed and the paper is available, you would not get a significant notable gap between the performance estimation only advantage that you get is a very quick result, through analytical expressions of capacity that we have already described in the few earlier slides. Now if we look at the 28 gigahertz set of frequencies.

So, let us change the color and again what we find is that this one. So, that is these set of ones are the ones for the millimeter band of frequencies ok; what we see is that when N is equal to 64; again the simulated and the analytical they are in close match. That means, whether you do the cumbersome simulation using 3GPP channel or use the expression that we have developed which uses only parameters of the channel model you are going to get a performance estimate which is not going to be different.

You can easily predict the performance using analytical techniques within few seconds whether simulation is going to take a huge amount of time. When you compare this result with that of the theoretical pas again you will find a significant difference and this difference is huge; that means 14.2 bits per second per Hertz.

Now look at this we are talking of millimeter band, so, we are talking of a 2 gigahertz channel bandwidth. So, 14.25 multiplied by 2 into 10 to the power of 9 this clearly means roughly 30 gigabits per second gap between an analytically provided PAS and the simulated PAS whereas, based on the parameters provided by 3GPP using the result that we have derived; if you get the analytical result then you can see that there is no gap in performance. That means, you can easily predict the performance even in millimeter band when using large number of antennas, massive MIMO configurations very easily capturing the realistic effects of the correlation.

The other fact which is also pointed out from this particular figure is that is a very interesting fact we are talking about N equals to 64 antennas so kind of large number of antennas. And these set of curves are for the 2.4 gigahertz whereas, these set of curves are for the millimeter band ok.

So, what we find is that because the clusters are less, the angular spread is less the correlation is very high and hence there is a difference in the performance. But one should not take the result as it is one should remember that, when we are going for millimeter wave in the same space where in we are putting 64 antennas for the sub 6 gigahertz one may be able to put a very large number of antennas within that same space. And hence the capacity would jump significantly higher than that of the sub 6 gigahertz band.

When you have a very large number of antennas the beams that one is forming is again huge and hence one can get even large performance gains. So, this summarizes the different issues that are involved when you are actually evaluating a large MIMO system with realistic channel models, the difference between sub 6 gigahertz and millimeter band of frequencies which one needs to consider in details in predicting the performance of such systems. So, we will proceed with certain more discussions on this particular aspect.

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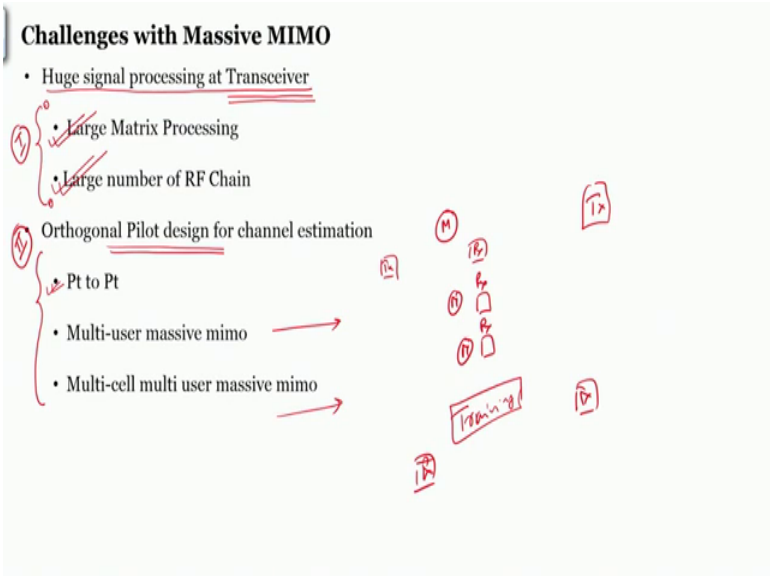

So, we go ahead with the massive MIMO systems. So, some of the challenges of massive MIMO are, huge amount of signal processing at transceivers which you can easily guess as the size of antenna increases, simply because the matrix that we have to operate become significantly large. These large number of RF chains that come into play not only that, beyond the signal processing and device design issues there is communication system design issues. So, if one has to design pilots which are orthogonal. So, for point to point communication there is one kind of effect.

So, you have one transmitter and one receiver you are only affected by the number of antenna elements that you have, if you have multi user it is not only one antenna, one user you have each user with connecting to a large number of antennas. Now, if you go to multi cellular you have even more transmitting antennas or base stations around the place. So, what we find is that training becomes a very very critical problem in this particular dimension and people have been working towards it finding better solutions. So, that things can be implemented it is a whole field by itself and unfortunately we cannot cover this in this short time limitation that we have this particular course. So, I would like to only highlight that in massive MIMO there are these few sets of problems that one needs to be looking at while designing or implementing the solutions.

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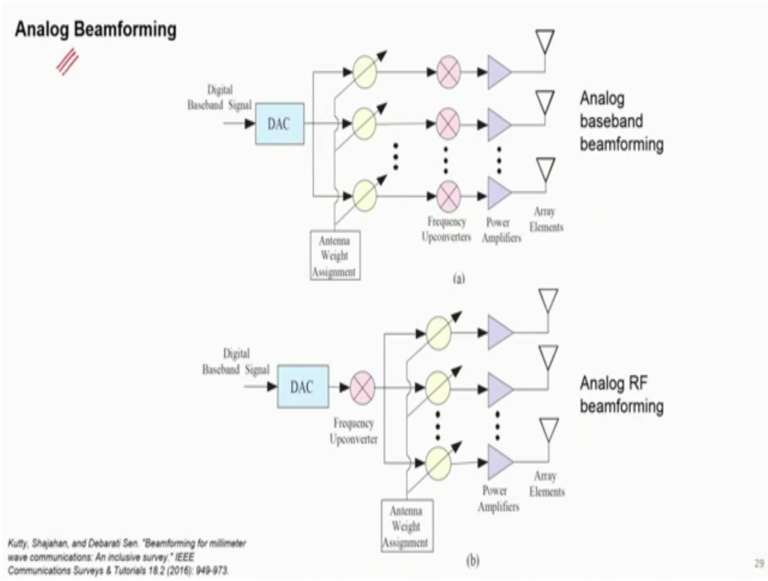

People have thought of analog beam forming to reduce the problem over here as well as people have gone towards other problems also.

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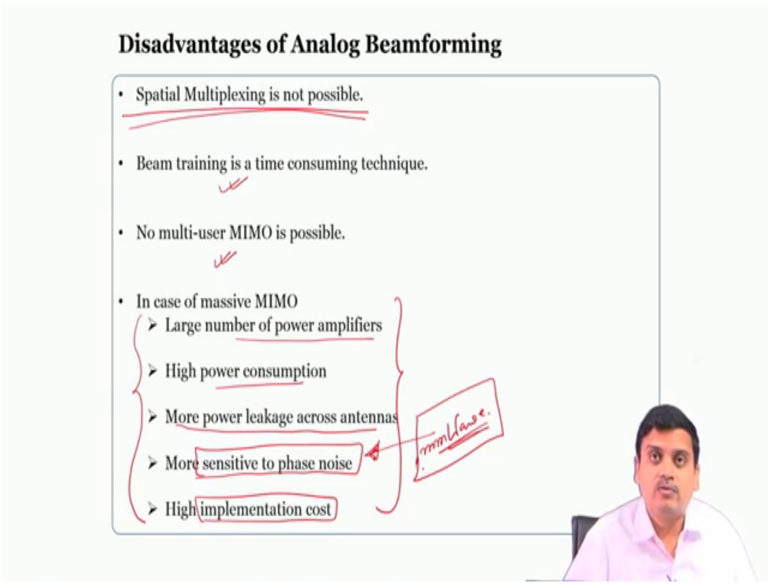

So first when you look at analog beam forming spatial multiplexing is not this possible under such conditions. Beam training of course, we have said is time consuming multi user MIMO is not possible under such cases ok. And the typical other problems of massive MIMO which we have highlighted in a short discussion in the previous slide is highlighted with larger number of points over here which is for your consumption; amongst which some of the important aspects other ones which I am highlighting. This factor is also critical as one goes towards millimeter wave system right. So, there are a whole bunch of issues which needs to be addressed when implementing such systems.

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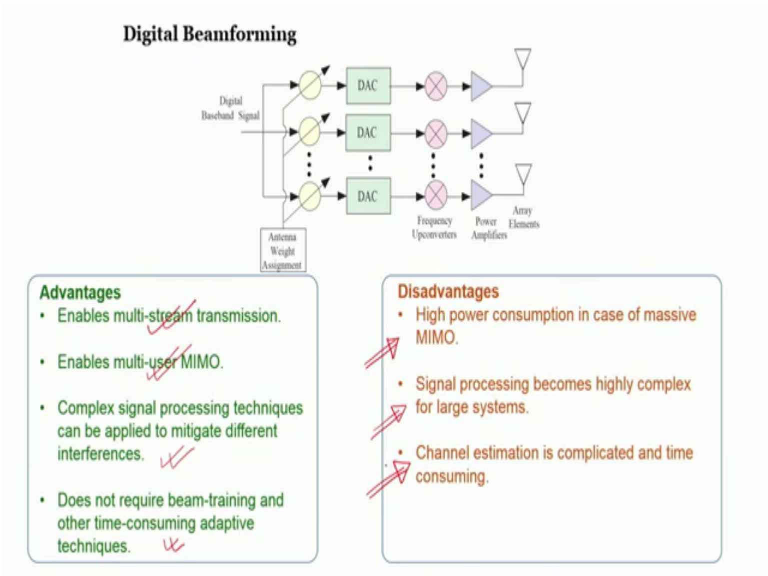

Digital beam forming is a solution, but digital beam forming has a lot of problems, digital beam forming allows multi stream we have seen how does multi stream works multi user MIMO we have not discussed in details, but one can get into it and find out and there is lot of feasibility potentials in this, but it is constrained by the typical list we have already highlighted. That means, large power signal processing, complexity, channel estimation complexity and so on and so forth.

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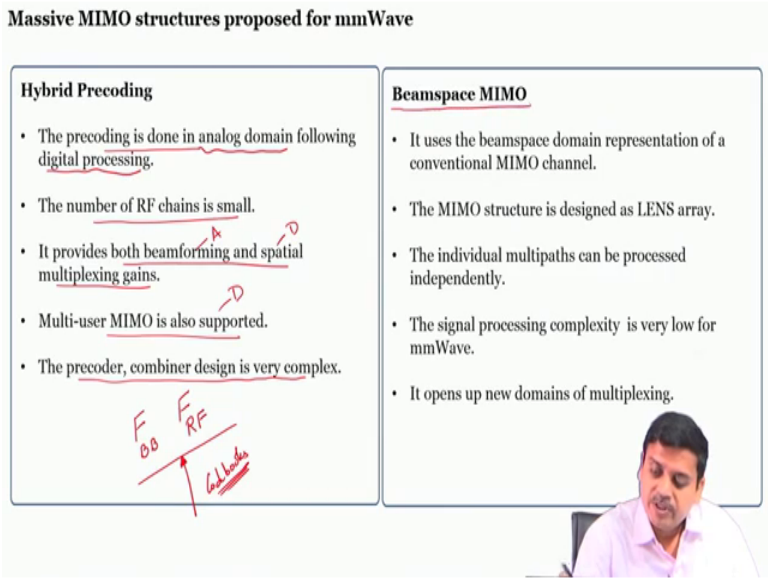

So, one goes towards implementing hybrid beam forming; that means, you have a mix of digital and analog will again give only a brief overview of such things over here. So, in hybrid beam forming precoding is done in analog domain as well as in digital domain taking advantage of both the things. That means, from digital domain you can form more signal processing in analog domain you can reduce the number of RF chains thereby taking advantage of both.

So, the number of RF chain is relatively small it provides both beam forming gain as well as multiplexing in multiplexing gains, comes from the digital beam forming gain comes from analog. Multi user MIMO is supported because of the digital part and precoder combiner design is very complex because now you have a precoder for the basement digital design part as well as you have a precoder for the RF part.

Because RF weights have to be taken and again, these are preferably done using code books, because of the amount of overhead that needs to be sent a cross. In comparison there has been also proposal for beam space MIMO, which we will look at shortly as well. So, in a typical hybrid beam forming architecture, you have a base band beam forming.

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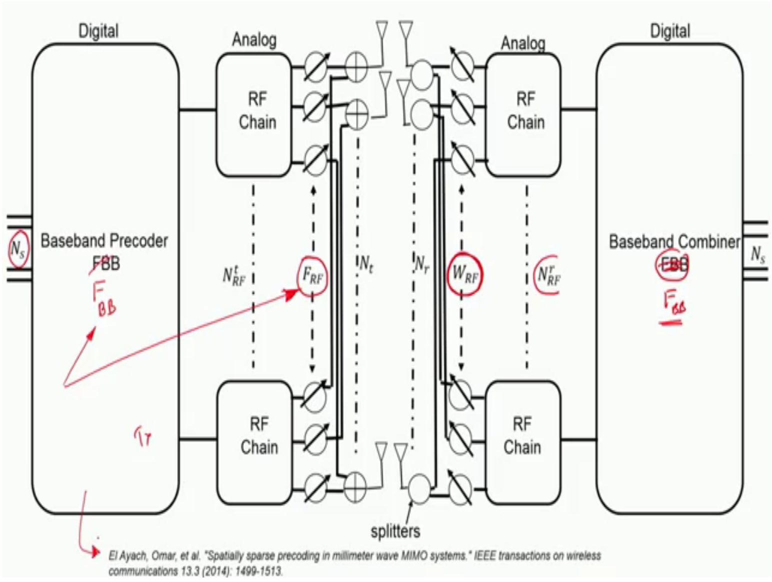

So, you have precoding matrix and you have an RF codebook matrix. So, this is the transmitter site and you can choose a certain number of special streams; at the receiver side. Again you have the weight matrix in the RF domain as well as you have a weight matrix in the baseband domain right.

So now, one is not restricted to choosing only from one set, but one has to choose from two sets which enhances the complexity of decision making problems. But anyway it helps in alleviating some of the problems of large MIMO while giving some of the huge benefits that massive MIMO promises. Details can be found in this particular paper and many other references.

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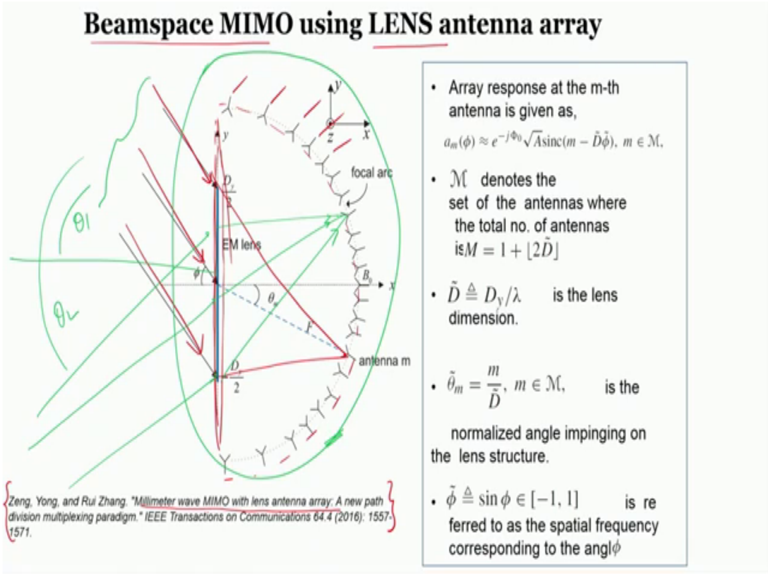

So, will go beyond these things and will now briefly talk about the beam space MIMO using lens antenna this is primarily from the paper which is given below millimeter wave MIMO with lens antenna array its a very interesting work. So where some kind of an electromagnetic lens is thought of in front of the antenna; and there is kind of a hemispherical space behind the lens where antenna elements are connected.

So what it does effectively is that, the multi paths that arrive so, let us go here. So, when signal comes from large distance from the antenna after going through the lens it converges to a particular antenna element; if the rays are coming from different direction, the length those particular rays would converge to another and an element and so on and so forth. So, what we see is that these elements are coming at an angle of theta 1 whereas; these ones are coming at an angle of theta 2.

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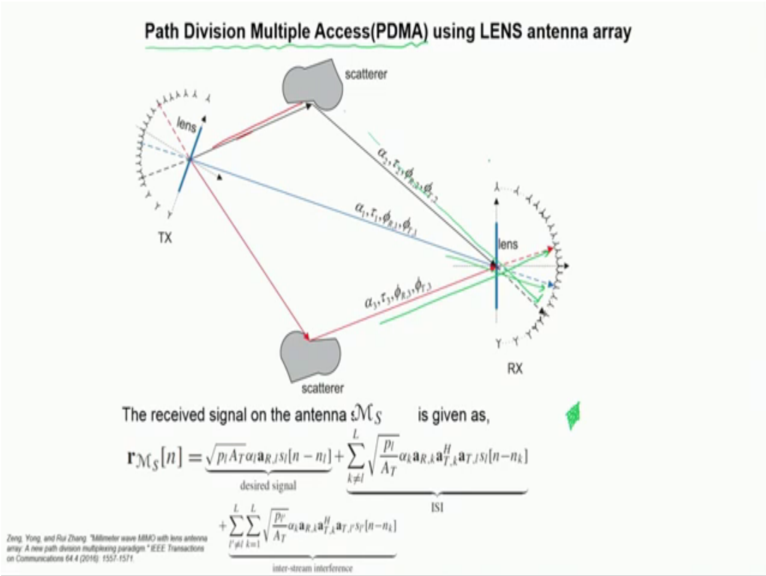

Effectively meaning that if there are clusters at different angles the paths along those angles would go to different antenna elements. That means, each of the multi paths from the cluster can be resolved and that can be used for path division multiple access compared to the space division multiple access and many other techniques. This is also a very very promising technique and it is highly recommended that one can explore these techniques, in providing much simpler solutions. The biggest advantage of this scheme is that one need not do the separation of the paths in the digital domain because the architecture that has been proposed in this particular work, enables an analogue domain separation of the path.

So, that reduces the signal processing complexity in a significant and a huge manner. So, when this becomes practically feasible a massive MIMO would again get a new dimension and the benefits would obviously, come to the users. So, now we would not discuss more details about these things, I would leave it as an open issue and we will go on to see certain more things alright. I think we can summarize our discussion over here when we have been talking about the millimeter wave and massive MIMO structures.

So, what we will rather discuss is that so far, the MIMO gives us a huge amount of benefit in terms of reliability through diversity spatial multiplexing gains are possible, but you need precoders to achieve the different objectives, we have talked about code books. And then we have said that, if you increase the number of antenna elements you can actually achieve the scalar or the linear increase in capacity over a seasoning.

So, that is why MIMO was very very popular, you can do beam forming using precoding which can be matched to the channel or based on code books. We have also said that when you increase the number of antennas there are a lot of problems and millimeter wave seems to be a matching solution for implementing massive MIMO.

But again millimeter comes with a lot of problems of its own and towards enabling massive MIMO through millimeter wave people have thought of hybrid architectures, which include analog beam forming as well as baseband beam forming. There as huge amount of literature, it is a detailed almost a detail subject by itself now, but it uses all the basic fundamentals that has been discussed earlier. But there are of course, different mechanisms and algorithms which are used in finding the different solutions. Beyond the hybrid beam forming there is also proposal for lens MIMO which is able to resolve the different paths or the cluster directions based on the physical mechanism of the antenna design itself.

So, this particular area is evolving, there are many solutions and 5th generation communication system is expected to use the massive MIMO solutions. But these are of course, deployment specific there are of course, still challenges to be solved, but a huge amount of potential gains that can be arrived at from these techniques. So, we would conclude our discussion on the MIMO processing techniques with this in this particular series of lectures. And will continue with the discussion of one very important access mechanism called the non orthogonal multiple access in the next lecture.

Thank you.