Evolution of Air Interface towards 5G
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Lecture - 22
Waveform for 4G & 5G (OFDM) Numerology Part – 1

Welcome to the lectures on Evolution of Air Interface towards 5G. So, till now we have discussed the earlier waveforms as well of well as we have laid the foundation for discussing the waveform for 4th generation and 5th generation. And we have also discussed the basic framework on which the 4G and 5G stands that is the OFDM. And upon which we have DFT spread OFDM, which is also a modification of OFDM, and which is primarily there to reduce the peak to average power ratio.

So, this particular method we have said is used in the uplink direction, and it is valid for both 4G as well as in 5G. Whereas, when we go to the 5th generation standard, we said it primarily uses OFDM. So, today we in this particular lecture, we take a look into the specifications of the 5th generation system. Especially, the frame format and how OFDM fits in, and what are the different variations, what are the different documents that one needs to refer to. So, we will primarily look at the main contributions, the changes, and how does the whole thing work.

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So, today our discussion will be about the waveform in 5G, and this particular wave form is given a new name called the New Radio, so usually you will find NR as the terminology which is more popularly used. So, usually the industry goes by keywords and acronyms, so NR is the name which will often occur for next quite a few years at least in the next 10 years. And it is nothing but the air interface for the 5th generation, which is again need not be scared about the new name, it is just a modification of whatever existed before.

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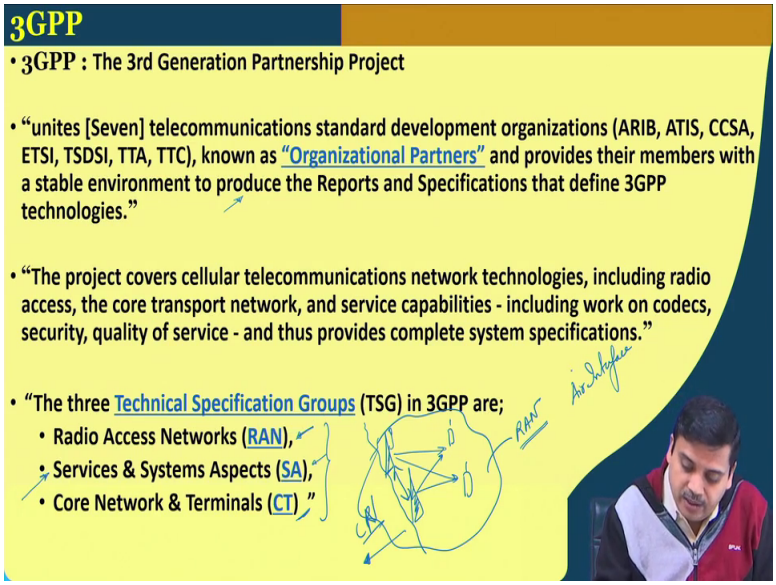

So, if we look at how things got developed, again we are looking at the 3GPP which is the 3rd generation project, which is come up with LTE the long term evolution, and which is again proposing the next generation system that is the NR as they call it and which will be the 5th generation system. So, as we can see that 3GPP from its standard, website what you will find is that it unites several telecommunication standards development organizations, and this is directly from the website that is what I have taken over here. And it is a group web many partners participate together towards creating specifications.

And primarily there are three broad categories or classifications. One of them is the Radio Access Network. So, what we are concerned is with the radio access network, which is the part between the base stations and the mobile units. So, the entire network where there will be multiple base stations, and multiple mobile units, they could be cross

connected, they would be interconnected. So, this last part of the network beyond which the core network starts is the radio access network part. So, this is the radio access network. We have described in on of the earlier lectures how does the radio access network work, what are the different procedures and protocols.

Then there are Services and System Aspects that is another group, and the core network and terminals is another group. So, primarily the radio access network is where we have been mainly concerned, because this is the one where air interface comes into play. Whereas, in the core network part, it is mostly wired network most of the time it is wired network, and of course along with it different kinds of services and system aspects are also present. But, as the name of the course suggests we will be in the air interface and hence primarily in the radio access network part.

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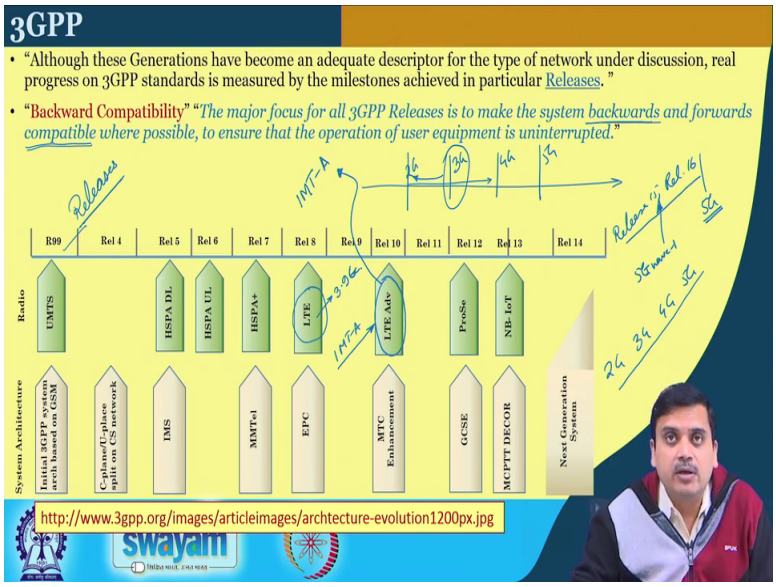

So, if you look at again the 3GPP, I mean whatever is stated in 3GPP is we are reading that particular out is that these generations that means, this 2G, 3G, 4G and 5G as we have been stating. They does not come just like that, I mean it is not a sudden release in as if there is a mile stone, and at suddenly at some point you reach 2G, and suddenly at certain point you reach 3G or 4G or at 5G it is not like that it is rather a continuous evolution from one stage to another that is what 3GPP primarily aims at, and describes it in that manner.

And amongst other major things, it also says that backward compatibility is very very important backward as well as forward compatibility. So, this is also primary thing, because it is a continuous evolving technology that means, suddenly if we find something some new technology over here, which does not coexists or does not work together with 2G, then it is a big problem overall huge amount of investment has to be done and so on.

So, here what 3GPP usually does is it presents new proposal in terms of releases, so you will find release 99, release 4, 5 and so on. And we are currently in the phase of release 15, release 16. So, these would primarily comprise what we are discussing about 5G. Release 15 specifications are available, so one can usually go to 3GPP websites and find the release 15 specifications usually this is called 5G wave-1 or the first part of 5G with release 16 one is expected to that the full specification of 5G.

So, what happened in this period LTE which is release 8, we have seen earlier that it met almost all of the requirements of IMT-advanced right. And LTE-advanced which is release 10 is basically the one which meets all of them without any problem, I mean all of them are exited significantly. And IMT-advanced is essentially LTE-advanced. And LTE is sometimes called 3.9G. So, what again we see is that there is the continuous development of things as things are moved on.

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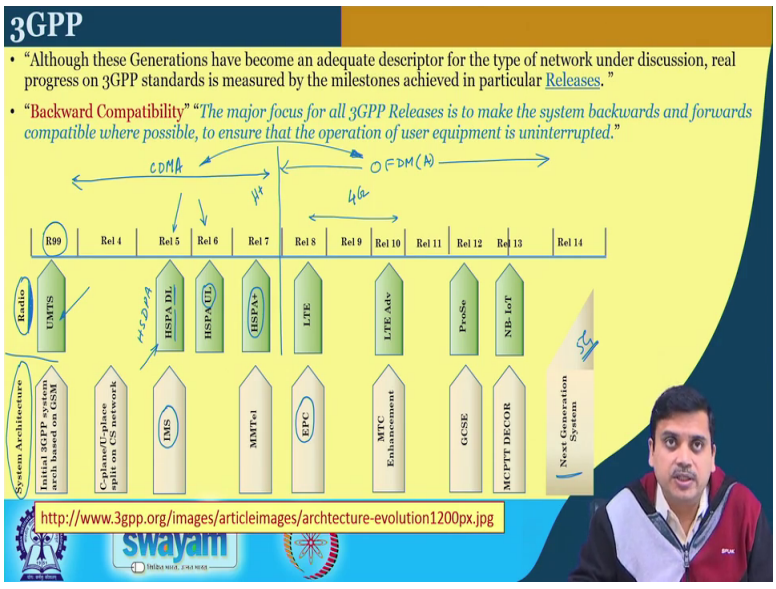

So, what we have here is basically two things. One is the radio side that means, the wireless signalling side. And the other is the system architecture ok, how the entire thing works. And this especially works with respect to the code network, the signalling, and the other aspects. And this one primarily talks about the wave forms, the air interface, and so on, radio access technology, radio access network.

So, what we see is that UMTS, which we have described earlier is usually coming under release 99. HSDP HSPA, which is the High Speed Packet Access downlink, and sometimes it is also called HSDPA High Speed Downlink Packet Access, it is part of release 5. High speed packet access for uplink, it is part of release 6.

So, one can see that continuous there is an evaluation evolution, and this is HSPA plus, so on our phones when we get H plus, we would think about getting HSPA plus. And these range of systems would be classified broadly as 4G, these systems they use a different air interface primarily they use CDMA, which we have discussed in some details. And these systems onwards, they use OFDM within brackets A framework. And we have discussed the basic layout for the OFDM system.

These two systems varies significantly from each other, in terms of the physical way of looking at the wave forms. But, when you write them mathematically, we can still find the lot of similarity between them if we look it at an abstract level, if we think it from the basis functions.

So, getting to the core network apps aspect there is IMS, which got introduced around release 5. EPC is the Evolved Packet Core, which got established around release 8. And then there were multiple developments, next generation systems or basically the 5G systems, which are coming into play. So, what we see effectively is that there is a gradual change of the different technologies, gradual improvement, and not a sudden change as we go from one generation to another. And this particular picture summarises, the change over from one generation to the next generation especially over the last three generations of things.

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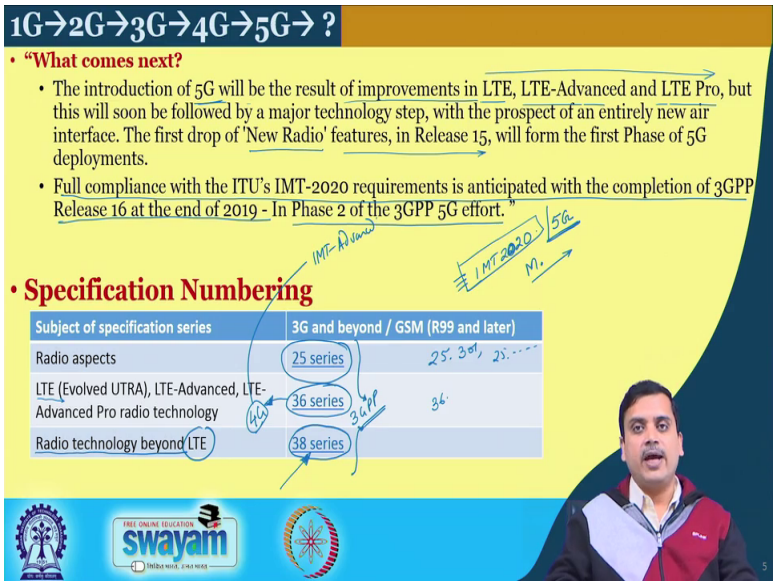

So, when we go into the sequence of events, the 5G has we have been discussing is primarily the main technology that are of our concern. And in order to look into the specifications one has to go into the series of documents that is listed over here. And what you find over here the introduction of 5G that what we are discussing is kind of improvement over LTE, over LTE-advanced, over LTE Pro see here you are again seeing that they are gradually changing over with slight change in the name as well as slight change in the technology that is why the name is changing. And the first drop of New Radio that is what we have been described, features in release 15, whereas in release 16 one is expected to get the entire range of 5G efforts.

But, it is be understood that 5G is not going to stop at release 16, there will be further developments beyond release 16, which would continue to enhance the so called 5G which we are waiting for eagerly. And we will slowly enhance and grow towards the next generation, which is 6G. So, when we go to 6G, we will again find there is dramatic change, slow change, gradual change, but overall between the 5th generation and 6th generation, there will be again a dramatic change as we have seen over here like the primarily the air interface got changed significantly in this particular case.

So, here what we have is the radio aspects for UMTS and all got enlisted in the 25 series documents that means, if you go to 3GPP website, you will get 25 dot 301, 25 dot x, y, z kind of documents, which describe the different specifications that are provided which

include the physical layer, which includes the user equipment, which includes the base station, which includes the services, the core network everything. So, whenever you are looking into the 25 series, it is primary with the UMTS set of documents.

If we go beyond that is the LTE and other document, it is the 36 series of documents. So, there again we have 36 dot 201, 36 dot 014, 36 dot 01, and several other documents. So, if you if you open, this 36 series documents in 3GPP, you will find a whole set of documents which describe the entire operation of the network. So, when we go beyond LTE, and especially we are talking about the radio technology beyond LTE, we will have to look at the 38 series of documents right. So, again this is from the 3GPP website, so all are from 3GPP. So, if you go to 3GPP, you are going to get the detailed specifications. So, the objective of this specifications is that they are going to meet IMT2020 requirements right, so as it is said.

Full compliance with ITU's IMT-2020 requirement is anticipated with the completion of 3GPP release 16 at the end of 2019 that is in phase 2 of 3GPP effort. So, we have described the IMT-2020 requirements in all our previous descriptions using the M series of specifications of ITU. And now 3GPP comes up with the set of specifications, which meets these IMT-2020 requirements. And as one will find generally it has been a case that these technical solutions meet all the requirements, and they will be branded as IMT-2020. And we have seen that IMT-2020 and 5G this terminology, they are interchangeably usable.

So, if we say which specifications would be meeting the IMT-2020 of five 5th generation standard will obviously, be going to the series of documents, which are numbered in 3GPP from 38 series.

Now, there could be other organisations than 3GPP, who could also come up with such technical specifications. And again if they meet the requirement criteria of ITU, then they will again be branded as the 5th generation technology. Same thing happened in the case of 4G, which was IMT-advanced we have discussed this in details earlier. So, 36 series of documents produced a set of technical specifications, which met the 4G or IMT-advanced set of requirements. Same sequence of events happens, when it is IMT-2020, and here again the thirty 38 series of documents would meet the particular requirements.

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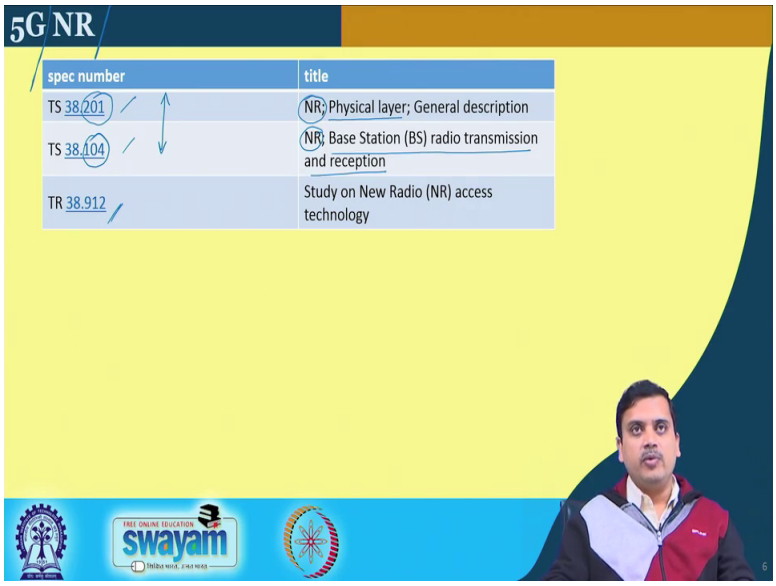

So, when we require the 38 series of documents, we are essentially talking about 5G from 3GPP perspective. And we are talking about NR or the New Radio from 3GPP perspectives. So, if one has to go into the details of these particular technology specifications, one would find 38 dot 201 which is the NR, again we are seeing that the name appearing often. It talks about the physical layer, so we have to go to 38 dot 201 document to get into the details as well as there are general descriptions.

And 38 dot 104 is the document, which is also pertaining to NR that is the New Radio, and it is the base station, radio transmission, and reception. Now, what you see is that there are two different set of documents, which together describe the NR. There are many other documents also, which are required in order to complete the description of description of NR.

Now, it is not possible to get into the details of all such documents in a course like this, and our main aim is to look at the fundamental technologies how things work, and what are the details which make things run. Whereas, this particular documents provides exact or rather bit exact specifications. So, if one has to design, rather one has to develop a particular equipment, which meets the ITU requirements or which is as per the 3GPP technology specifications. Then one has to follow these along with the entire range of other documents, which would describe the entire protocol structure.

There is the technical report of 912, which describes a new radio access technology. So, if you go to the website, you will find a whole set of documents, which can be used an in order to understand one particular methodology or the process which 3GPP would require you to follow, you have go into the details of this documents. So, in this particular course, we will take peak look into some of the documents as we found relevant with respect to the new technologies. So, primarily we will be looking at 211 as well as 104 in order to establish the physical NR.

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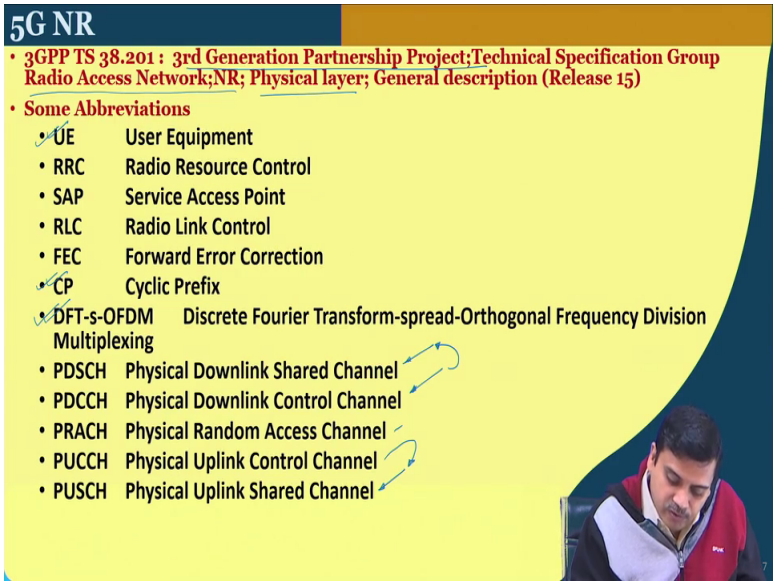

So, what we find is that the 201 document of 3GPP is the 3rd generation partnership project. It contains the technical specification of radio access network, NR, and the physical layer ok. And these are some of the abbreviations I do not need to go through all the abbreviations, you can easily understand them, and go through them as per necessary.

This User Equipment is something which we will refer to cyclic prefix CP, which will refer to DFT-spread-OFDM, we have already discussed in the previous lecture in the previous topics. And physical downlink shared channel is the one which carries data, control channel is the one which carries control information relating to the data carrying in the downlink direction, this is the random access channel, PUSCH is the shared channel, which carries data in the uplink direction, and this contains control information for the data which is being transmitted in the uplink direction ok.

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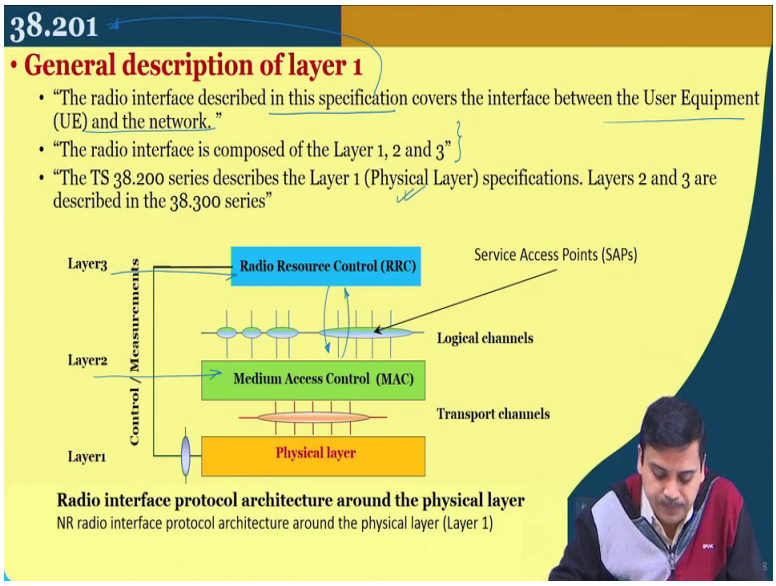

So, the general description of layer 1, what we find is that the radio interface described in this specification this is exactly taken from this particular document ok, these few statement are taken just to show you that how these things are mentioned, and what exactly is in the content. So, what we find is that 201 contains specifications, which covers the interface between the user equipment and the network.

So, user equipment is the handle device or the last unit of the entire thing that we are talking about it describes layer 1, layer 2, and layer 3. Layer 1 is primarily the physical layer, layer 2 and layer 3 would conclude or would include the medium access control as you could see depicted by the picture. And layer 3 would include the radio resource control. And between each layer there are service access points through which each layer gets access to the next layer. So, they communicate with the help of the service access points. And the physical layer or the air interface is primarily described in layer 1.

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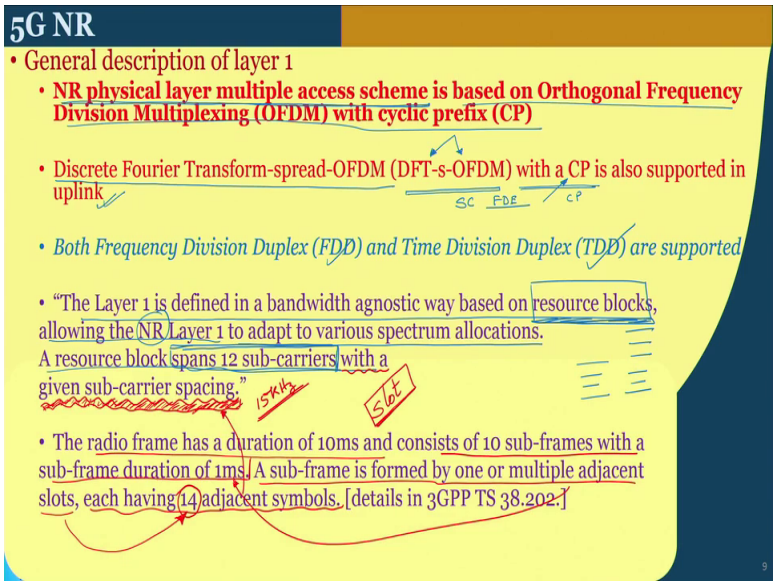

So, in layer 1, what we find is that this is very very important statement than what I have actually made bold with the reason, we take a note of it. The NR physical layer multiple access scheme ok, so this is the primary thing, when we talk about the air interface which is the multiple access scheme of the radio access technology is based on OFDM with CP.

So, this particular statement you will find exactly in the document and that is what is something, which we have to carefully note that there has been fundamentally node change from what was there in the previous description. But, there are certain changes which are important and critical, which we will take a look at.

We also see another statement that Discrete Fourier Transform Spreaded OFDM or DFT-spread-OFDM which we have described thoroughly in the previous lecture with CP that means, with cyclic prefix is also supported in the uplink direction. This we have also described, we have also given the reason why it is why it is so and we have also described that under one specific case that if the size of DFT matches that of the or the spreading in the DFT matches the size of the IFFT that is used for the OFDM, then you get a complete single carrier system with CP.

So, in that case you get SC-Single Carrier with CP, and the receiver processing can be frequency domain equalization, because you have a cyclic prefix ok. Both FDD and TDD are supported, so these are some important facts which we should keep in mind.

In another important fact which is also essential is that the layer 1 is defined in a bandwidth agnostic way based on resource block right, allowing the NR layer 1, NR is the new radio to adapt to various spectrum allocations. A resource block spans 12 sub-carriers. So, the entire definition is in terms of resource block. Resource block is an unit, which is addressable, which can be addressed by higher layers, and every description is with respect to resource block.

So, if you have a narrow band system, the number of resource blocks would be less. If you have a wide band system, the number of resource block is large. And in all cases what we find is that the resource block spans 12 sub-carriers. This description has also remained from the 4th generation to 5th generation. And if you ask the question probably why, one of the major reason is backward compatibility as well as forward compatibility.

Now, that would raise the question that would you do you think that the this kind of a framework is going to remain, when you go from 5G to 6G, we do not know the answer, but some potential overlap has to remain. And when we go from the 5G to 6G, what I think is that there would not be as much similarity to the 4G system as well as similarity to the 5th generation system. So, we there is there is no hope neither there is any speculation, but it all depends upon how the technology evolves from one stage to another alright.

So, now the modification that we see over here is the statement, now we are going by statement, because that is very vital with a given sub-carrier spacing now, this is vital, this is the modification that is happening over the previous system. In the previous system, there was no such no such statement like with a particular sub-carrier spacing, because the subcarrier spacing was fixed, and it was described for all possible implementations, which is constant and that was 15 kilohertz which we have seen in some of the specification charts that we have described earlier.

Another important thing what we see over here, which describes the earlier one that the radio frame has a duration of 10 millisecond ok, consists of 10 sub-frames with a sub-frame duration of 1 millisecond. Now, this the sub-frame duration of one millisecond has also been carried over from the previous generation. However, the description of slot which is not given in this particular slide, we will see that has changed from the previous generation to the next generation. So, we see a modification within some existing

structure. So, there is some kind of compatibility, and some new things which have come in. A sub-frame is formed by one or multiple adjacent slots. So, here we have the description of slot, each having 14 adjacent symbols.

So, now again summarily, we will off course see them in details. What we find is that each slot having 14 symbols, so a slot has 14 symbols. And this has carried over from the earlier generation right. Although there is some modification in terms of the cyclic prefix, and the number of symbols on very specific cases in the previous generation system. But, here the number of system the number of symbols is fixed to 14, but the number of slots that fit into one sub-frame is different, and that is dependent upon the sub-carrier spacing. And this is what our aim is to understand, and see how they fit in each other ok.

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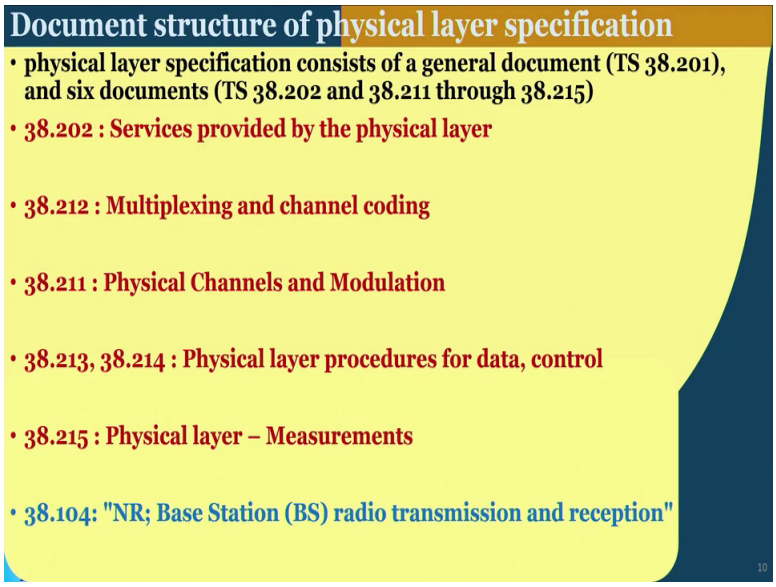

So, this is the list of some of the documents, which are necessary in order to completely understand the NR physical layer. We will not going to details of everything, but my main intention to provide you this list, so that all those who are interested in the exact specification details can follow this different documents ok.

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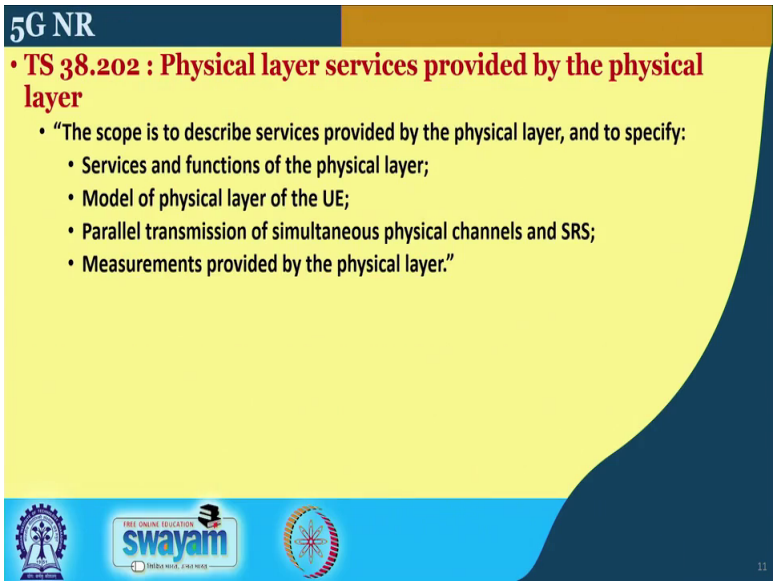

So, the 38 dot 202, which is one of the documents listed earlier. So, it provides the physical layer service provided by the physical layers. And the scope is to describe the services provided by the physical layer, and to specify services and functions, model of physical layer, parallel transmission of simultaneous physical layer and channels, measurements provided by physical layer that means, there could be multiple layers of transmission, and there could be a feedback provided by the user equipment to the base station and so on and so forth. So, all these things are described in 38 dot 202 sorry what we find.

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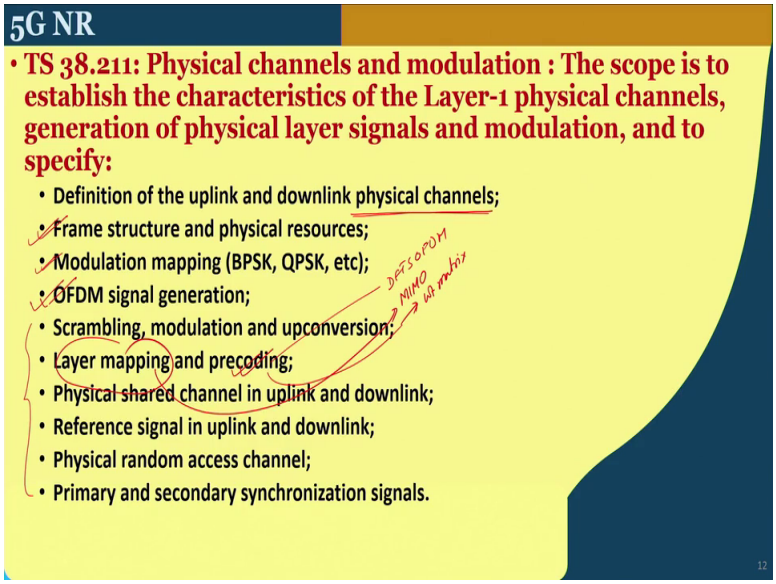

Next is the 38 dot two 211, which will be our primary description document which we intend to describe over here, it provides definition of uplink downlink physical channels. So, these are the actual channels over which the signals are carried. The frame structure, which we intend to discuss; we will talk about modulation at some point. The OFDM signal generation, and all other procedures that are necessary which are part of signalling as when the things go between the user equipment, and the base station.

So, we will see some part of the pre coding which is due to MIMO, and there is also something called transform pre coding which is nothing but again the DFT-spread-OFDM as well as there is also. So, when we talk about layer mapping, this primarily talks about the MIMO communications. And pre coding would talk about the pre coding weight matrixes right.

So, we will see some of them, all though not everything that is present over there, because our fundamental aim is to look at the way the technology works, and not into the way it is exactly implemented on a particular standard, because there could be other standards and other applications, where these technologies would work in a similar manner ok.

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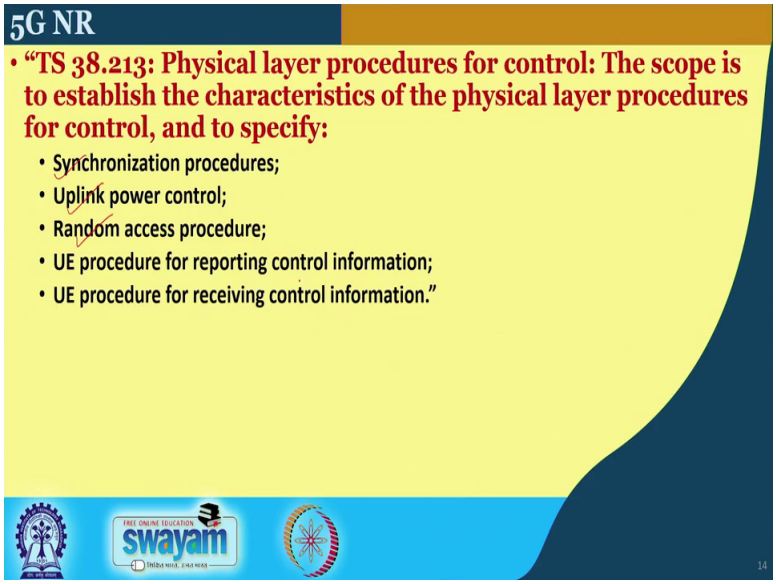

212 the next document, it talks about the channel coding. The moment you do channel coding, there has to be rate matching in order to fit into the frame structure, and then

transport channel descriptions, control information and so on and so forth. This includes description about multiplexing as well.

213 this talks about the physical layer procedures for control, and the scope is to establish the characteristics of the physical layer procedures such as the synchronization, uplink power control, random access procedure, for reporting control information, and so on and so forth. So, we will not go into this document, but please find your time to get into details, if you are really interested in the exact implementation.

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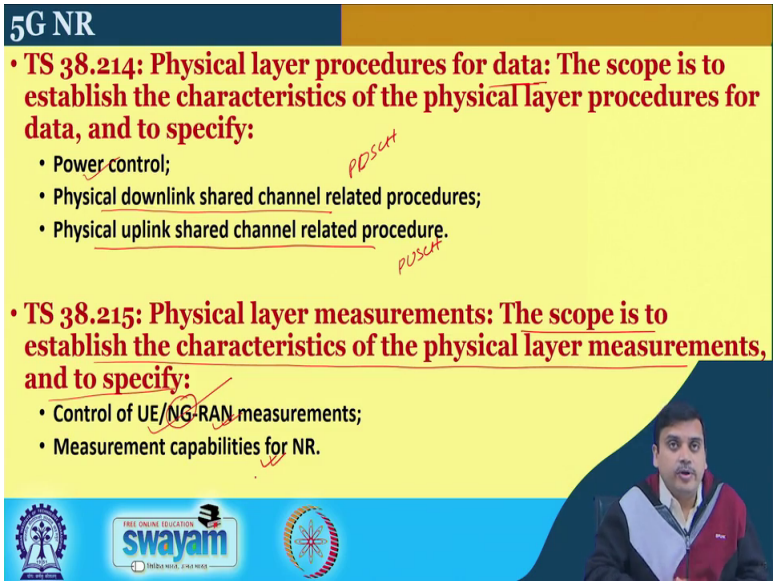

Then there is 214, which is with respect to the part of data. See the previous one is with respect to procedures for control, and physical layer control. Whereas, the next one is with respect to data right, and there also it is the power control, and physical downlink shared channel related procedures, so that is PDSCH and that one is PDCCH, PUCCH. So, here it is PUSCH, which we have described earlier ok.

And 38 dot 215 is with to the physical measurements. And the scope is to establish the characteristics of the physical layer measurements, and to specify control of UG and NG is the next generation radio access network measurements, and capabilities for the new radio. So, when you go into these documents, you will find all such detailed description provided ok.

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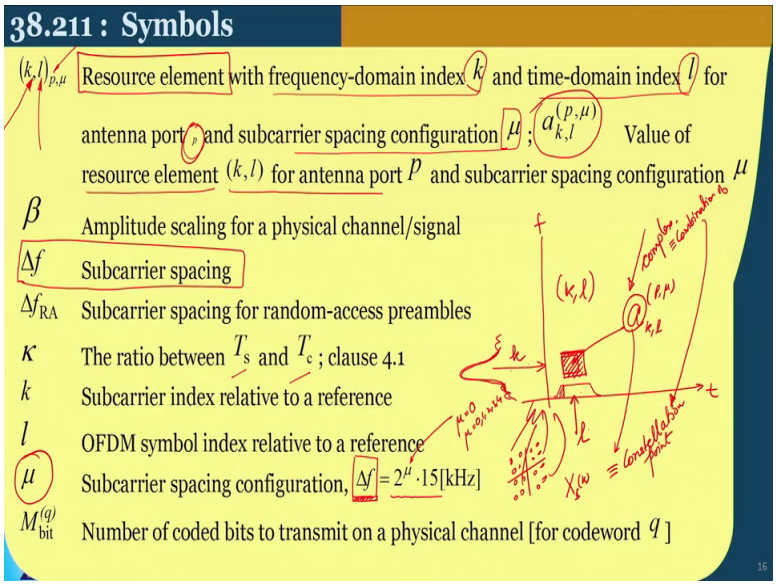

We will primarily talk about the 38 dot 211 document, we have carried over the same notation that is present in the document, so that when you refer to it there is no difference in the way we are describing them. So, k, l, p, mu these are some of the parameters which are important, because based on this everything will be defined.

So, k indicates in our notation, in our understanding a sub-carrier index. And l indicates the OFDM OFDM symbol index. So, what you can see over here. The frequency-domain index k, and time-domain index l for antenna port p. So, it is the pth antenna port through which signals are going out, and sub- arrier spacing configuration mu. So, we will see this details in due time.

Then we have a sub k, l to the power p mu indicating the value of resource element k, l for antenna port p and all kinds of things. So, k, l is some index in frequency axis which is k. So, this is time axis, this is frequency axis. Some index in time axis. So, this is the resource element for a particular antenna configuration. So, p is an antenna configuration, so that means antenna port. So, if it is a particular layer, it would corresponding to correspond to that particular antenna or layer. And mu describes the physical size of this resource element. So, one has to understand this is the smallest entity in the system right.

In other words, when we will describe this is one sub-carrier. So, we are drawing this part of the sync which is important for us, so that is one sub carrier. And it is one OFDM

symbol, we are not concerned with the CP, because CP is rejected. So, one subcarrier for one OFDM symbol forms the resource element, this is the fundamental entity ok.

And each of these are going to carry a complex symbol a k, l p mu. So, k is corresponding to this k, l is corresponding to this, a is the variable which carries the value. So, in other words this is corresponding to ours x s of k that is the constellation point ok. So, this we are writing constellation point. But, if you are doing DFT-spread-OFDM, in that case this will be some complex value which is a combination of several constellation points, so which is some combination of constellation points.

So, in in otherwise if you are not doing a DFT-spread, you can think of using an identity matrix inspread instead of the DFT-spreading matrix. Otherwise, if you are doing a DFT spread, then you can have a DFT spread. So, rather what we have is a combination of constellation points, the combination will vary according to the operation. So, if it is pure OFDM, this will be a constellation point. If it is DFT-spread we take several such constellation points on different carriers, and then we sum them up and that is this value. So, this has to be understood and connected to the notation that we have used before. Delta f sub carrier spacing, we have also described this in all our descriptions. So, this is also an important parameter right.

And here we have some more descriptions about T s and T c which we will see later on. So, what is what is critical here is what we see is mu is also described, so we have been talking about mu so long. So, let us see what is mu, what does mu mean. So, delta f is equal to 2 to the power of mu multiplied by 15 kilohertz right, so that means, mu can take different values. In case of 4G, mu was effectively 0. In case of 5G and others, mu can take values 0, 1, 2, 3, 4 right. So, what we see one of the major changes that have happened from 4G to 5G is that this delta f can take different values, which had otherwise been remaining constant for the previous generation system.

So, we conclude this lecture over here, where we have summarized the or we have projected a background to the description of physical layer for 5G. We have discussed the technical background earlier. Today, we have talked about the documents which are relevant, the documents one which should read and, also the parameters or the variables which are useful in describing the 5th generation frame or the particular physical layer which we are going to see in the next lecture.

Thank you.