Wireless Communications
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Lecture No. # 17
Mobile Radio Propagation - II (Contd.)

Welcome to the next lecture on mobile radio propagation. Today we will talk about channel measurements. A brief out line of today's talk is as follows.

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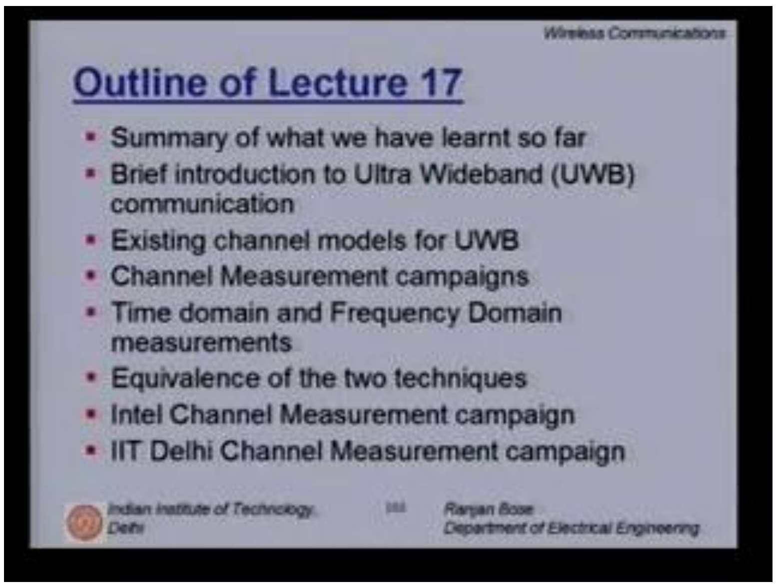

We will start off with the summary of what we have learnt in the previous lectures. We will then take the case study of ultra-wideband communication and try to understand how channel model measurements can be done for UWB scenario. We will first talk about the existing channel models for ultra-wideband communications. Then we will talk about some of the already-carried- out channel measurement campaigns. We will realize that these measurements could be done either in the time domain or in the frequency domain. We will also show the equivalents of these two techniques. Finally we will briefly talk about the channel measurement campaign carried out at Intel and some in-house IIT Delhi channel measurement data.

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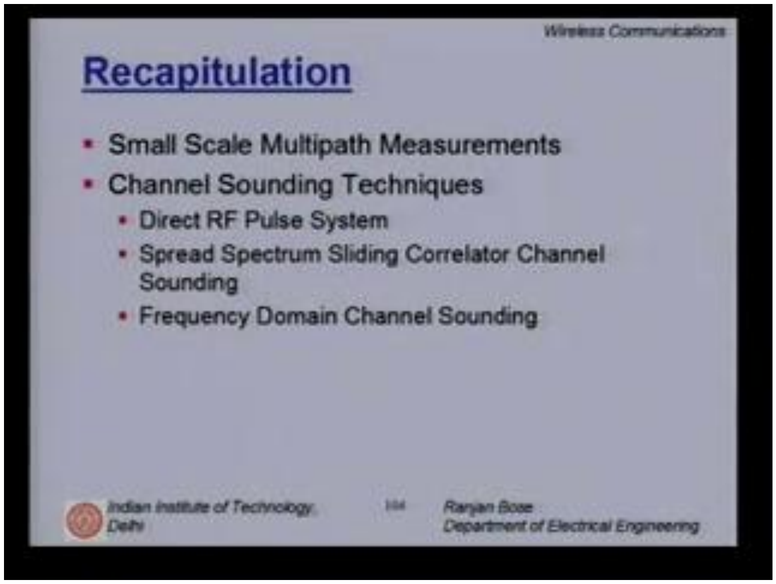

So let us first start with a brief recap of what we did last time. We talked about small scale multipath measurements. We then discussed channel sounding techniques. Specifically we talked about the direct RF pulsed systems. Then spread spectrums, sliding correlator, channel sounding technology and finally the frequency domain channel sounding technique. Today, first we will briefly mention these three and then go on to the ultra-wideband communication which we are taking as a test case.

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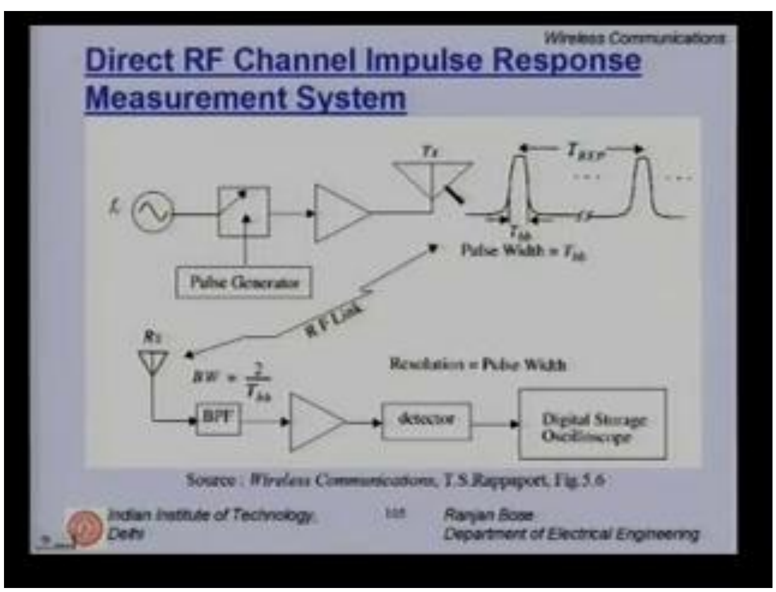

First, let's look at The Direct RF Channel Impulse Response Measurement System. We saw last time that you have to have a pulse generator followed by an amplifier and a transmitter. The pulse width is TBB and there is a pulse repetition time T_{rep}. the T_{rep} is normally kept more than the maximum excess delay possible for the measurement environment. We have an RF link followed by a receiver. Then a band pass filter whose band width is given by $2/T_{BB}$ low noise amplifier detector in most cases. This detector is an envelope detector which means we lose out on the phase information. This is one of the short comings of the direct RF channel impulse response measurement system. Then we take the data and store it in the digital storage oscilloscope. The good part is that we can directly get the channel impulse response without the need for any post processing. This is done entirely in the time domain.

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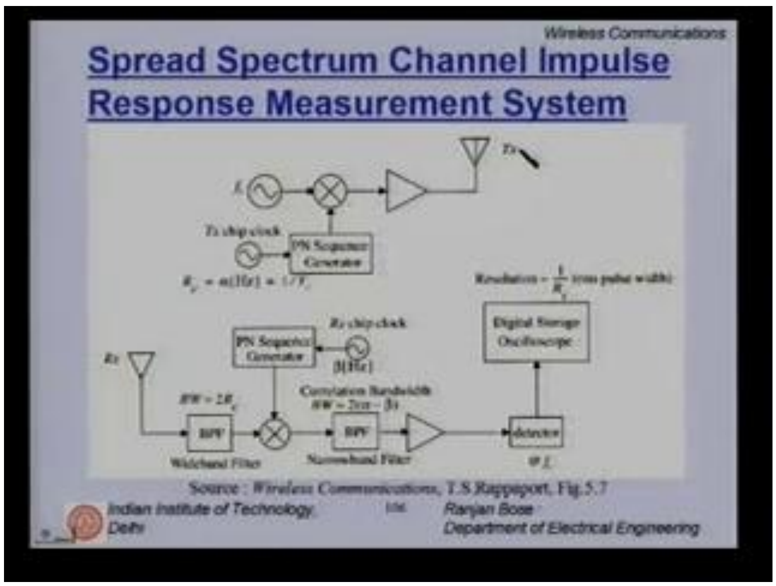

The other method is the use of spread spectrum channel impulse response measurement. Here we have a PN sequence generator which is multiplied with the carrier through an amplifier and transmitted out. The RC or the chip rate - 1 / TC is alpha Hz. now at the receiver; firstly we have a band pass filter which is actually a wide band filter because it must take into account the chip rate. So I need to have a wide band filter first. The band width of this filter is given by 2 times RC, RC being the chip rate. However at the receiver, we multiply with another PN sequence which should be identical to the first one except that the chip rate here is beta Hz. It's slightly smaller than alpha. This will lead us to the sliding correlator. If you fix one of the PN sequences in time, the other one appears to slowly move, catch up and then move beyond the second one. At a certain time, there will be maximum correlation and that is the time when we de-spread the signal at all other times. The signal gets expanded by the mere multiplication with the PN sequence. This is true also for a noise and interference but wisely, we have put another narrow band filter just after the multiplier and here it only takes in the frequency within the desired band. Only when the de-spreading occurs in all other cases the spread energy is rejected by this band pass filter.

This is the reason why the spread spectrum channel impulse response measurement system can do better in the presence of interference and noise. Then we have an amplifier followed by a detector. Again if this detector is an envelope detector, I lose the phase information. Whatever I detect, I store it using a digital storage oscilloscope.

Conversation between student and professor: The question being asked is: is it possible to recover the phase information simply because we are using a PN sequence generator and maybe we can extract that phase information knowing when the PN sequence starts?

The answer is: no, because whatever we do here we forcefully lose out the phase information because of the envelop detector and therefore we only get an amplitude plot. The phase information is lost. However if we have a coherent detector here, which means I must run another wire to the transmitter synchronizing the coherent detector or I have a method to recover the phase information here. Then I am in business. I can use the phase information as well. So those systems are also possible though a little bit more complicated. In most cases, we are interested in the power delay profile where we can do away with the phase part. The third method was a frequency domain channel impulse response measurement system.

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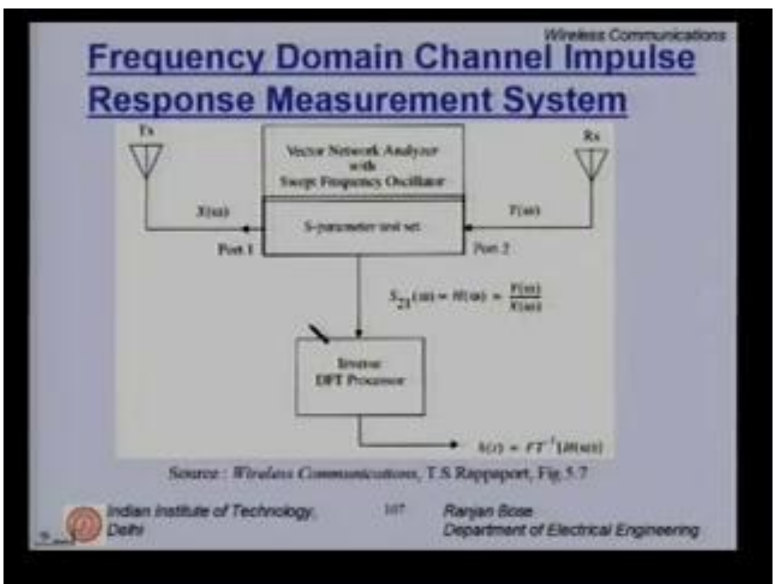

Here we learnt that we need to use a vector network analyzer which uses an S parameter test set to find out the S $_{21}$ which is nothing but the transfer function given by H omega = Y omega divided by X omega. Clearly, if we know this complex transfer function, taking an inverse Fourier transform would give me the exact channel impulse response. In fact this is one of the more popular methods for indoor channel measurements.

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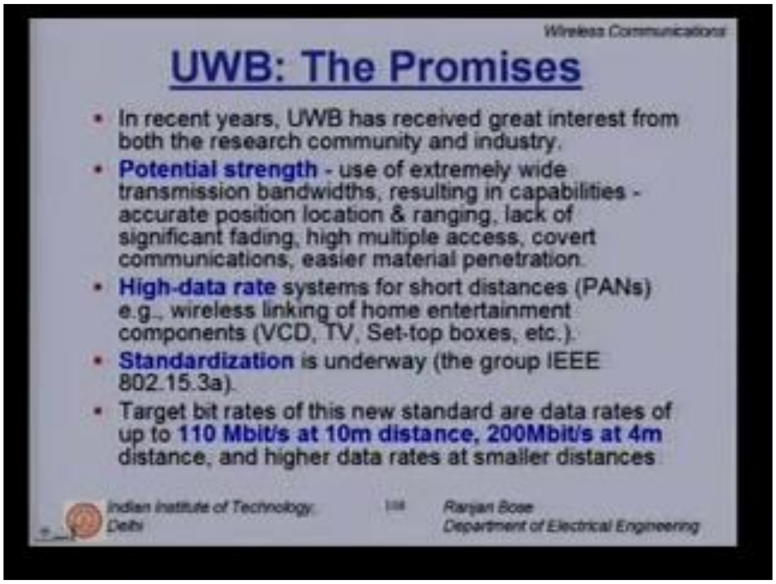

Since today we would like to take UWB as a test case and find out how channel measurements are being done for ultra-wideband applications, what are the efforts being carried out currently? Let us first have a very short introduction to UWB or ultra-wideband. What are the promises in the recent years? UWB has received great interest from both the research community as well as from the industry. What are the potential strengths?

It uses extremely wide transmission bandwidths which will translate to very high data rates. It can also give you accurate position, location and ranging. It can fight fading effects because it can resolve the multipath. It can handle large multiple access situations. It can be used for covert or secrete communications because it is very difficult to detect and hence very difficult to intercept and it can easily penetrate certain materials. So it can be used for imaging through the walls. The high data rate is of great importance over a very short distance. We will soon see that this UWB is usually limited to less than 20 m. so most of the channel measurements that we will study today are within 20 m. the applications would be home, entertainment, a wireless desktop, a personal area network. The standardization process is almost complete and the IEEE 802.15.3 a is the emerging UWB standard. Certain channel models have already been prescribed in this IEEE 802.15.3 a. the target bit rates of this new standard are in the range of 110 Mbps at 10 m and close to 200 Mbps at 4 m.

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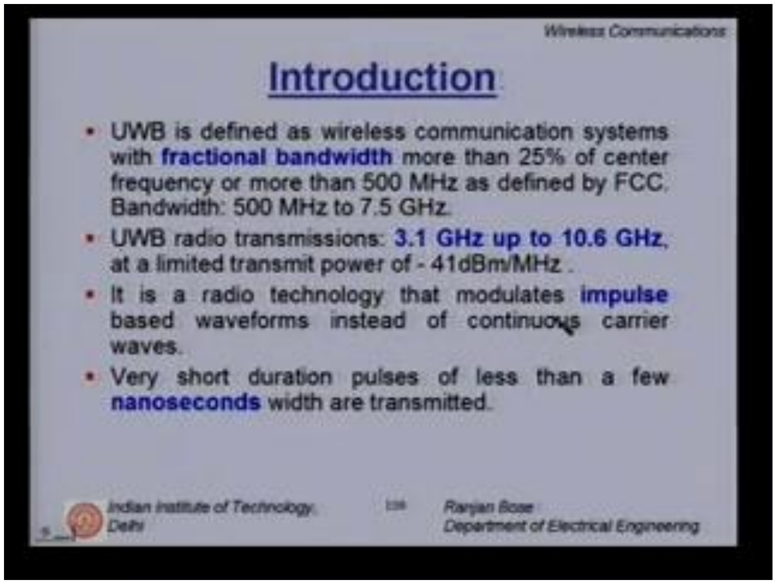

UWB or ultra-wideband is defined as a wireless communication system with fractional bandwidth which is more than 25 % of the central frequency more than 500 MHz. this has been defined by FCC. so the typical bandwidth that we have is 3.1 to 10.6 GHz. we are giving as a bandwidth of 7.5 GHz. the limited transmit power is of concern because this wide range 305 to 10.6 GHz spans existing wireless communication systems and we must not interfere the existing systems for that. There is an upper limit which is given by -41 dBm / MHz. this is an interesting regulation put in by FCC. It is also called the part fifteen limit. It is the limit imposed on all out of band emissions. So if I am making a device around 2.4 GHz, my out of band emission should not exceed -41 dBm / MHz. Please note it is “per MHz”. So for this, 3.1 GHz to 10.6 which is a bandwidth of 7.5 GHz. first we will multiply it and then find out what is the total power possible to be emitted.

At the same time, every MHz can have an upper bound. So I cannot say that for certain sub band within this large band I have an exceedingly high emission level and for the others I have negligible. They have put a constraint on that. It is a radio technology that modulates impulse based waveforms instead of continuous carrier waveforms. It’s also called impulse radio or carrier less transmissions. Of course, there is a second school of thought which divides this large band of 3.1 to 10.6 MHz into sub bands. But none of them below 500 M Hz which is a constraint and then uses these sub-bands and uses OFDM. But one of the more popular methods is to use the impulse radio kind. The pulse duration is very narrow. It’s a few nanoseconds to sub nanoseconds. It’s extremely good for ranging.

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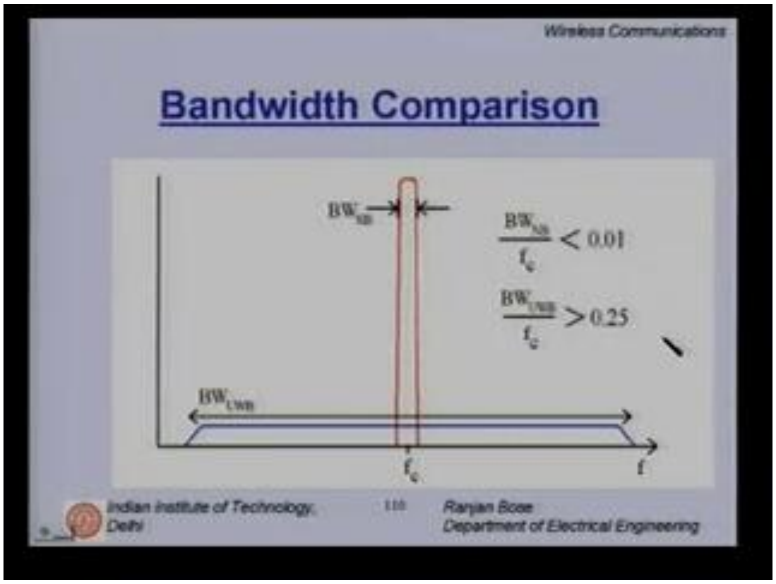

Just a bandwidth comparison. In the red is a typical narrow band system. Large power, very narrow band as opposed to R ultra-wideband system. It is extremely wide band but very low power and here the bandwidth divided by the centre frequency. It should exceed 0.25 - the 25% constraint.

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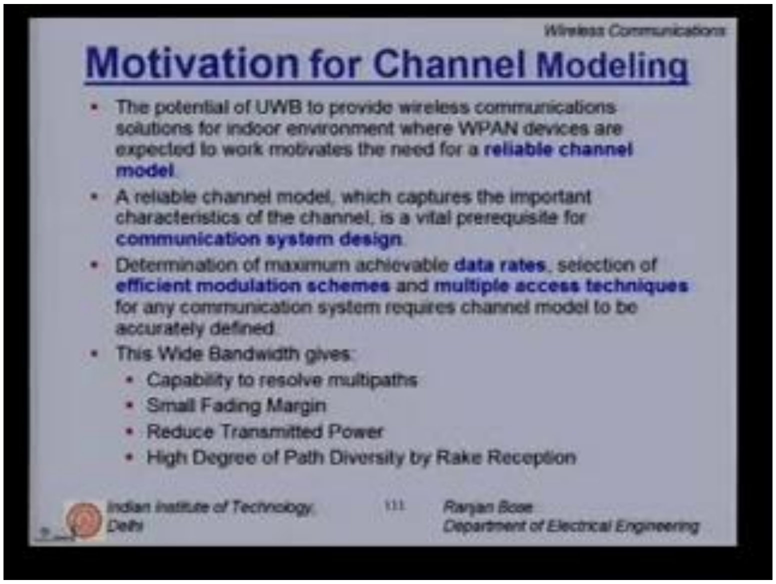

So let us now talk briefly about the motivation for channel modeling for UWB. The potential of UWB to provide wireless communication solutions for indoor environments exists where wireless personal area network devices are expected to work. This necessitates the need for reliable channel models. My predictions will be as good as the accuracy of my models. a reliable channel model which captures the important characteristics of the channel. We will talk about what characteristics are important in the subsequent slides. That is a vital prerequisite for communication system design. In fact, before we start a design, we should have a reasonably good channel model and after we design a system, we have to test it through simulations using the channel models as well. What kind of equalizers to put in the exact nature of the receiver design all depends on the channel model?

Determination of maximum achievable data rates. The selection of efficient modulation schemes? What kind of multiple access techniques to use etc. all require the knowledge of the channel model. Now this wideband for UWB gives us very interesting features. The capability to resolve the multipath. So maybe it will motivate us to use a rake receiver kind of equalization very small fading margins. So we have to account for that we also have to use very low transmit powers. Essentially your entire receiver design has to be not only low power in itself but it should be able to detect very low power and high degree of path diversity by rake reception.

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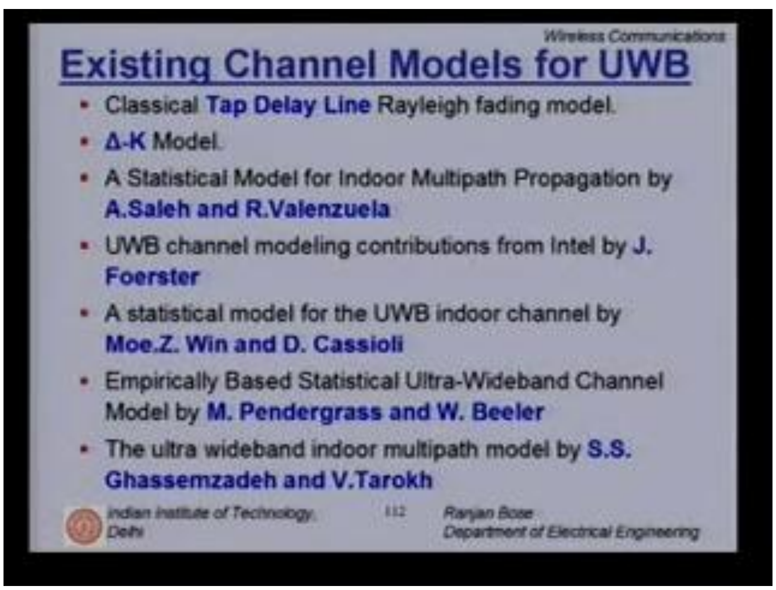

Let us now briefly look at what are the existing channel models for UWB. UWB for commercial applications is new but it has generally been around for the military applications for quire sometime. In fact, pulse compression, pulse compressed radar were the original UWB applications. Some of the existing channel models are as follows; we have the classical tap delay line Rayleigh fading model. Then a more evolved delta K model, a statistical model was proposed for indoor multipath propagation by Saleh and Valenzuela.

This is by far one of the most popular models being used for UWB, the original model that was reported did not cover 3.1 to 10.6 GHz. it was for much less but it has been since then modified and upgraded for the current UWB requirements. It is still one of the most popular models. inter proposers model by work done by Foerster another statistical model for indoor UWB channels was by Win and Cassioli, then empirically statistical ultra-wideband channel model was proposed by Pendergrass and Beeler. Then for a much narrower band, the ultra-wideband indoor multipath channel was also proposed by Ghassemzadeh and Tarokh. It works at a much lower bandwidth. As we will see some of them work from 2 GHz to 6 GHz. some of them work from 2 GHz to 8 GHz. so far none of the models have been actually proposed from 3.1 to 10.6 GHz although they can be extrapolated to that limit. In IIT Delhi, we are trying to carry out measurements which will cover the entire range from 3.1 to 10.6 GHz. it is still in process.

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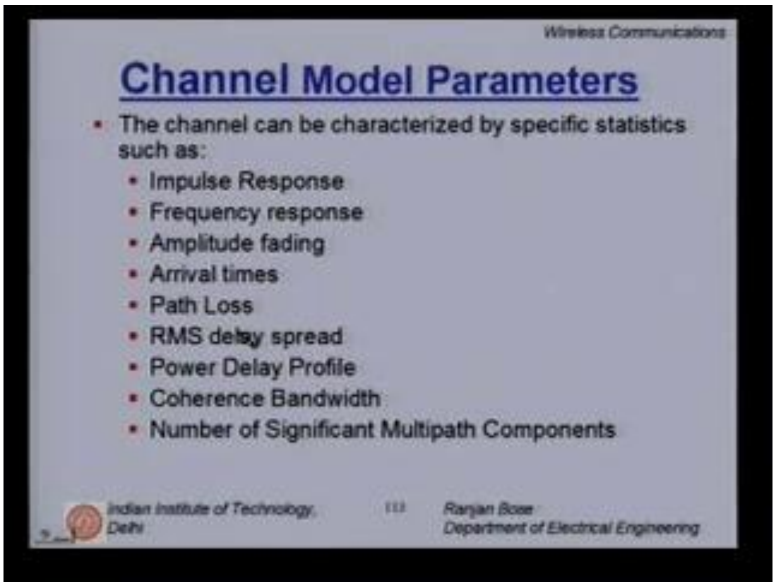

Now let us look at certain channel model parameters. The channel as we know can be characterized by specific statistics such as the impulse response, frequency response amplitude fading, etc. How good or bad is it? What kind of fading is it? Is there statistical model that can be applied for this fading arrival times. Again this is statistical. It can give us a lot of information as to how to design a receiver path loss that will tell me how far my receiver can work from the transmitter RMS delay spread. It will put a restriction on ISI and my maximum achievable data rates power delay profile. We have learnt about it. Coherence bandwidth which will help us overcome fading by using either a large bandwidth or two frequencies separated by the coherence bandwidth and of course the number of significant multipath components. This will help us design how many rake fingers to put-in in our receiver design. So all of these or at least some of these can be found out by measurements and having known these parameters, we can better design our receiver. That is, the motivation behind all of this.

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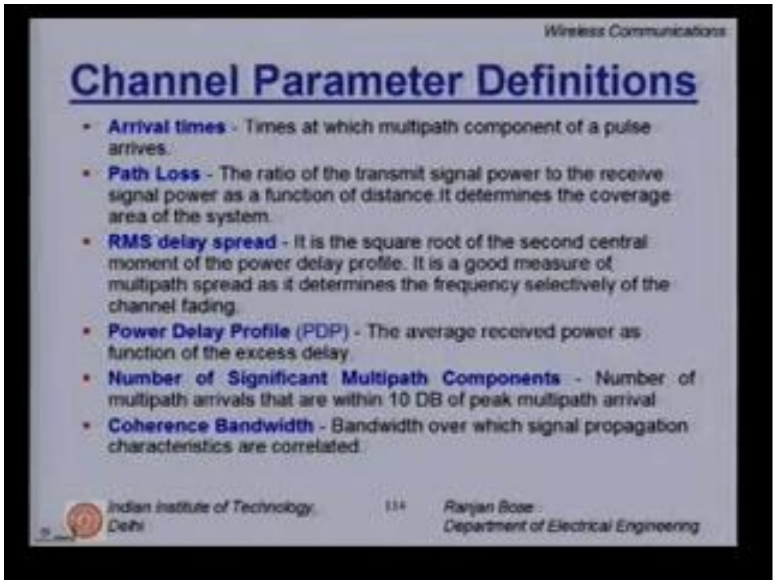

A quick look at channel parameter definitions. Arrival times: the time at which the multipath components of a pulse arrive. So think of it as a pulsed RF direct pulse system and a different reflected multipath comes at different times. Path loss is the ratio of the transmit signal power to the received signal power as a function of distance. it determines the coverage area of the system. This is the large scale effect as opposed to the small scale fading. RMS delay spread or the root mean square delay spread is the square root of the second central moment of the power delay profile. It is a good measure of the multipath spread as it determines the frequency and selectivity of the fading channel. If you are working in a larger room, RMS delay spread will tend to increase. Power delay profile, the average received power as a function of the excess delay. If you are carrying out channel measurements using a digital storage oscilloscope and the oscilloscope is in the average mode, we automatically get the power delay profile. The number of significant multipath components is clearly the number of multipaths that are arriving within 10 dB of the peak multipath arrival. Sometimes it is interesting to note that we have cleared 6 to 10 distinct multipaths and no more sometimes. It can be much larger also. Coherence bandwidth I is the bandwidth over which the signal propagation characteristics are correlated as far as fading is concerned. So if you are separating two transmissions in frequency which is more than the coherence bandwidth, they will tend to fade independently. Ultra wideband clearly has a bandwidth much larger than the coherent bandwidth of the channel and by definition is immune to multipath fading.

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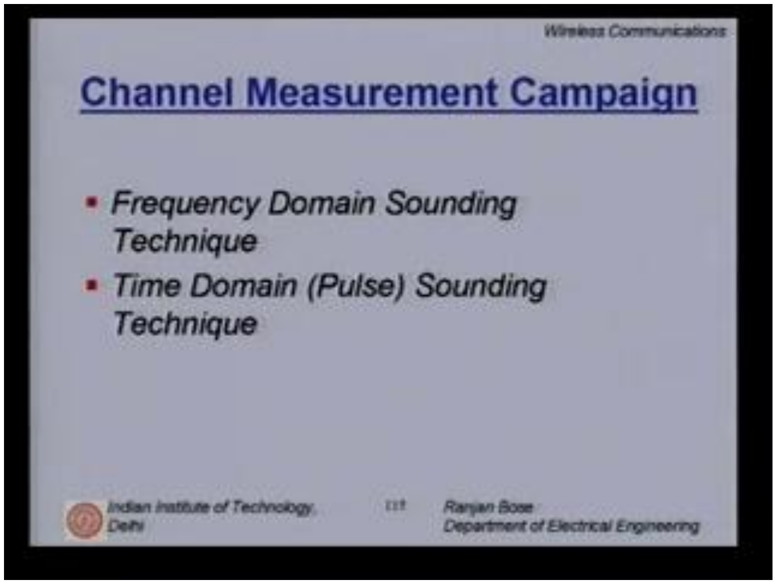

Let us now talk about channel measurement campaigns. People have carried out channel measurement campaigns either in the frequency domain or in the time domain. Today we will talk about certain channel measurement campaigns carried about by different people, organizations and universities and you will see that some of them have preferred to use a frequency domain whereas the others have done the time domain. Thus some organizations like Intel which has done both frequency domain and time domain and it is interesting to see the equivalence in the results that you get from frequency domain channel measurement. Do they correlate well with the time domain pulse sounding technique measurements and what we will see is interestingly they overlap quite a bit. Here at IIT, we have done frequency domain channel sounding for ultra-wideband communications.

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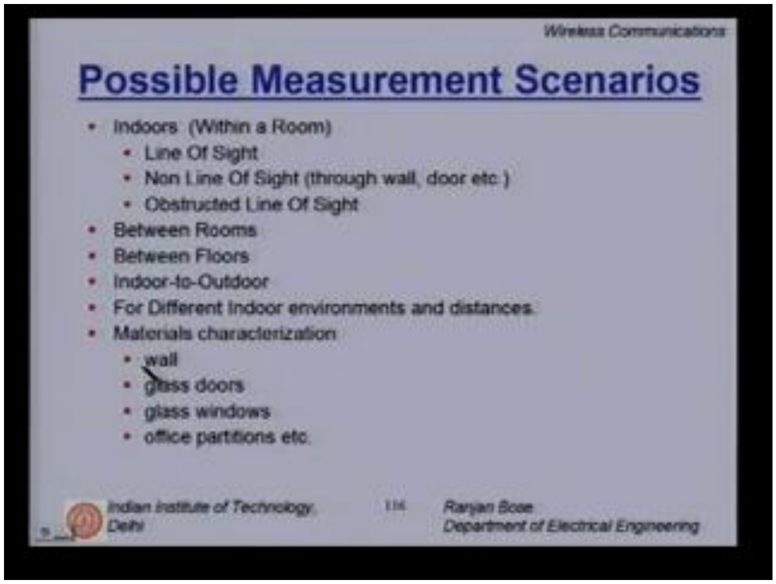

Now let us look at the possible measurement scenarios. This is detected by our applications. Since in today's lecture, we are talking about ultra-wideband as the example, we are going to talk about the home area network or the office area network or the personal area networks. So we have to consider the various measurement scenarios where the system will be deployed. Let us look at that. First is indoors. Within a room, you can have line of sight. This is clear if you are talking about a wireless desktop. My PC is connected to my printer and it's connected to the scanner. It's connected to my camcorder all wirelessly and high speed data download is feasible. There we most likely will have line of sight or non-line of sight. So it could be my home entertainment system where my speakers are in different rooms and they are connected to the TV or the music system placed in another room through the walls and the doors. We will need to know how much is the attenuation through the walls, glass, doors etc. this is useful for office scenarios also. Then you can have obstructed line of sight somewhere in the middle. So you almost have a line of sight.

One or two objects are obstructing the clear line of sight but you are clearly in the same room. This is opposed to the non-line of sight where you have to go through a partition or a wall or a door. Then you can have the measurement scenario between rooms. You can also have the scenario between floors. You are getting more and more ambitious or you can also have indoor to outdoor. Usually within the room and between the room is reasonable for our case of ultra-wideband but for general wireless local area network for example, IEEE 802.11.b where you would require to know between floors and indoor to outdoor scenarios as well. Now the measurements must be carried out for all these different indoor environments and distances. as we have seen some time back in previous lectures that the path loss exponent 'n' may be different for close up distances. It may change when you go to farther distances. Material characterization is important whether the wall is a concrete wall or a simple brick wall, the door is wooden or a glass door, etc. so we will talk about the wall, the glass doors, the glass windows and office partitions. This slide gives you a general picture about what we have to do when we take measurement. We have to take into consideration all these factors. in that we carry out the measurements under the following heads: line of sight, non line of sight, obstructed line of sight, etc. and then try to come up with a proper channel model.

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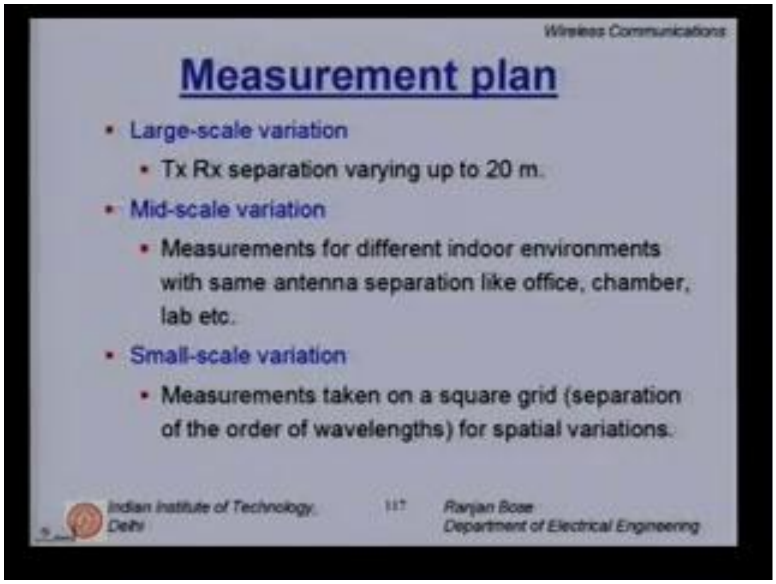

On top of that, we need a measurement plan. So we have to either talk about large scale variations where the transmitter- receiver separation is up to 20 m and it is varied. So you take distinct step as you move the transmitter-receiver distance. You move the receiver along a path or radially and go up to 20 m. clearly we are talking about indoor scenarios. 20 m is a large hall. Therefore we are talking about a large scale variation here. Then you could possibly have mid-scale variations. This effect will be different than the large scale variation. Here we are talking about measurements for different indoor environments with the same antenna separation like office, chamber, lab, etc. of course, you can have the small scale variations where the measurements are taken on square grid where the grid spacing is of the order of wavelengths for small scale variations. We know from our previous lectures that depending upon the signal used for excitation whether it is wideband or narrow band, the channel will behave differently. in most cases especially for ultra-wideband, we are using a very narrow pulse to sound the channel and thereby we are using a wide band signal. We have seen that in such cases the small scale variations do not fluctuate much. However they do fluctuate a little bit and that's what we measure. First let us talk about frequency domain measurement set up.

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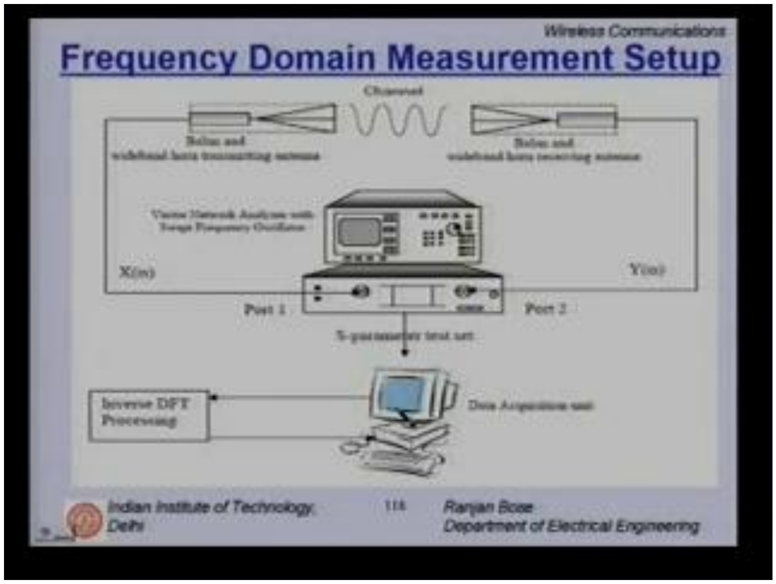

Some of this information has been taken from the people who have carried out measurements in their own office or home scenarios. The scenario is frequency domain measurement set up. You have a vector network analyzer: port 1 and port 2. It is supposed to measure the S parameters. You excite the channel through the transmitter. You receive, you get Y omega and then S $_{21}$ is nothing but Y omega by X omega. You take the inverse for your transform and you obtain the data.

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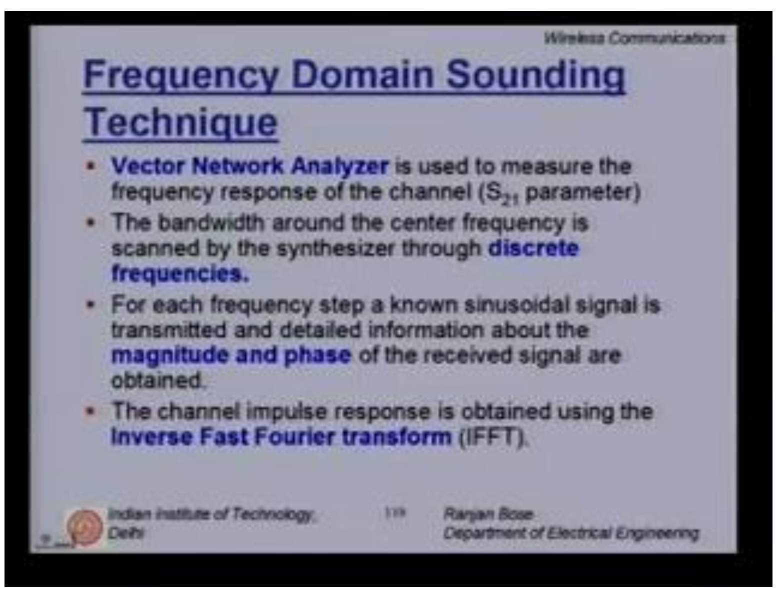

The vector network analyzer is used to measure the frequency response of the channel. the bandwidth around the centre frequency is scanned by the synthesizer through discrete frequencies. We have learnt that the spacing between the frequencies will have a direct bearing on how good your channel impulse response comes out to be. For each frequency step, a known sinusoidal signal is transmitted and detailed information about the magnitude and phase of the received signal are obtained and stored. Clearly by definition, we are obtaining the magnitude and phase. We are not losing the phase information as opposed to most time domain measurement techniques. In time domain, if we use coherent receiver, yes, we can get the phase information. Otherwise we cannot. The channel impulse response is obtained simply by using the inverse fast Fourier transform. So we have done a post measurement processing.

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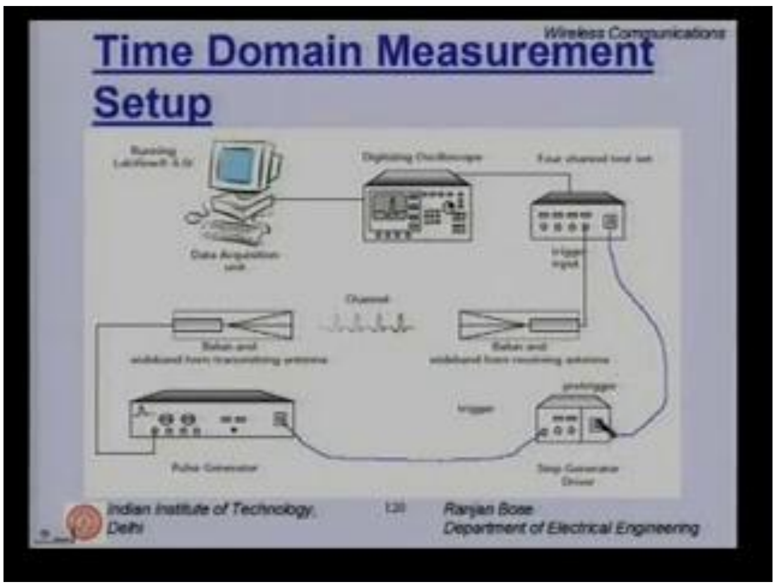

The time domain measurement set up is slightly different. As we have seen, we have a data acquisition system digitizing oscilloscope and this four channel test set connected to a receiver- the transmitter part simply has a pulse generator which uses the wideband. Here it is horn mentioned but many people used an omnidirectional antenna. We will see that the results will change when you have a horn antenna versus an omnidirectional antenna. Your delay spread will tend to increase if you use an omnidirectional antenna as opposed to horn antenna. We have used a horn antenna both at the transmitter and the receiver part and this is the step generated driver.

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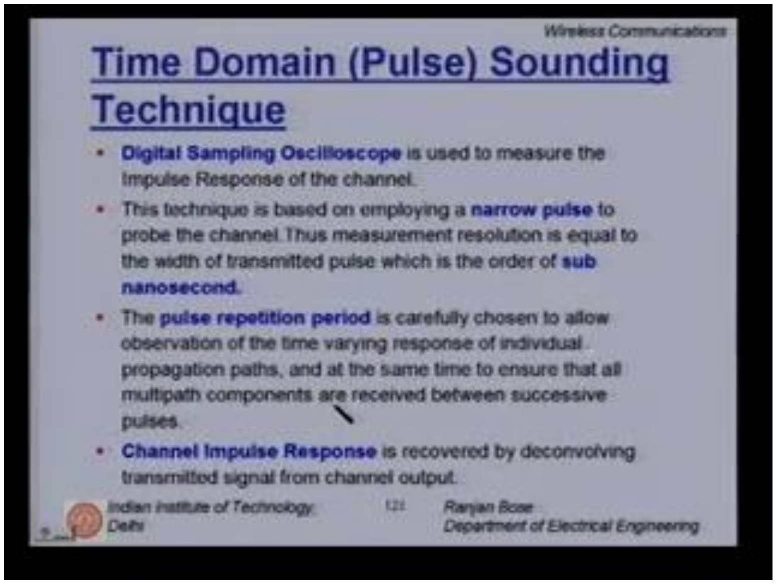

Here a digital sampling scope is used to measure the impulse response of the channel directly. No post processing is required. This technique is based on employing a narrow pulse to probe the channel. Thus the measurement resolution is equal to the width of the transmitted pulse. This is usually of the order of ns or sub ns. This term "sub nanosecond" is coming from the fact that we are carrying out indoor measurements. The pulse repetition period is carefully chosen to allow observation of the time varying response of the individual propagation paths at the time same time, to ensure that all the multipath components are received between successive pulses. So the larger the room, the larger the pulse repetition period required. The channel impulse response is recovered by deconvolving the transmitted signal from the channel output. So if you are using a very narrow pulse, then this deconvolution step is redundant. Otherwise if this is a certain pulse shape, we have to deconvolve it. To get the channel impulse response, any standard deconvolution technique is possible.

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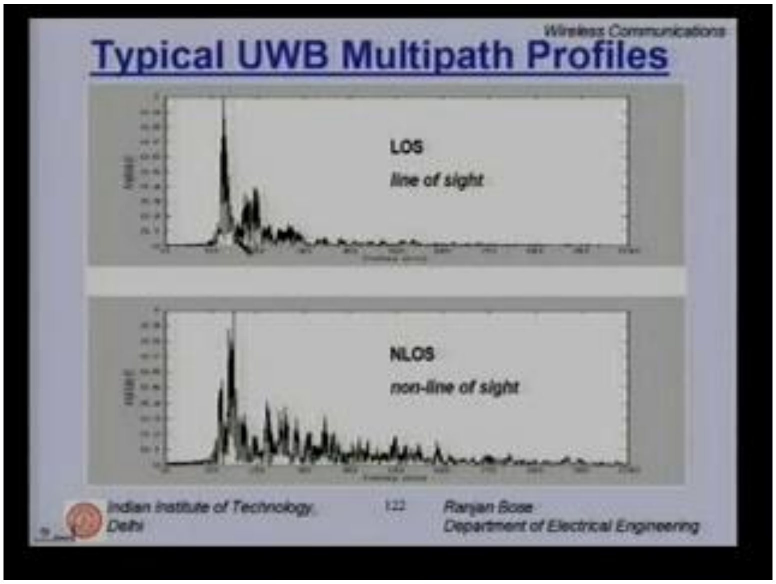

Now let's get back to the example at hand which is the ultra-wideband. Here are some typical measurement results of line of sight and non-line of sight in ultra-wideband communication. On the x axis is the delay in nanosecond. On the y axis is the amplitude received. The phase information is not being presented here. When you excite, the channel with a narrow pulse, what you receive is the series of pulses. Some of the pulses can be resolved. Others cannot be resolved. Clearly, there is a line of sight component and then some reflected components as well and here is a measure of the maximum excess delay spread going up to from 10 to 30. It's about 20 ns. Please note it doesn't start at zero. It triggers first at about 10 ns. This is the propagation delay. The same scenario changes when we have the non-line of sight or NLOS case. Here firstly you have a lot more reflections and the delay spread has increased going up to 50 ns. The more number of reflections being seen and clearly the signal that you get is through varied multi paths because we have done away with the line of sight component. So these are some typical examples for ultra-wideband scenario. Please note that the probing pulse is close to 1 ns here.

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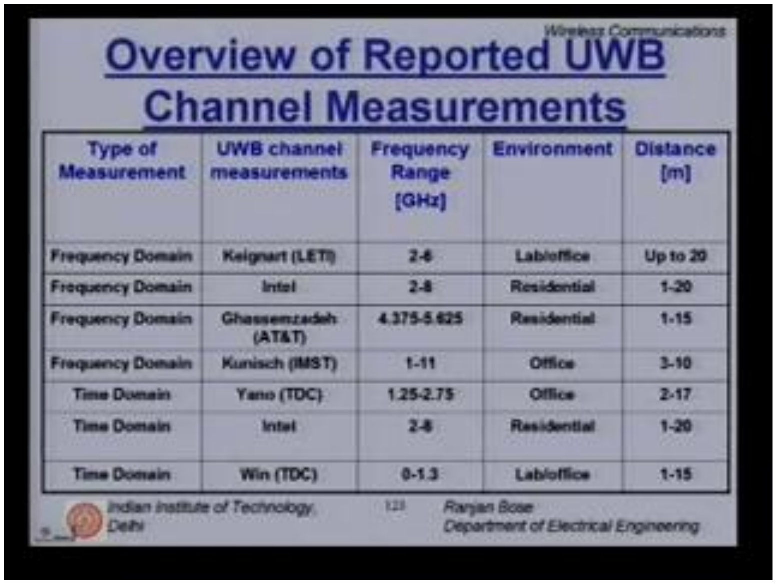

Type of Measurement	UWB channel measurements	Frequency Range [GHz]	Environment	Distance [m]
Frequency Domain	Keignart (LETI)	2-6	Lab/office	Up to 20
Frequency Domain	Intel	2-8	Residential	1-20
Frequency Domain	Ghassemzadeh (AT&T)	4.375-5.625	Residential	1-15
Frequency Domain	Kunisch (IMST)	1-11	Office	3-10
Time Domain	Yano (TDC)	1.25-2.75	Office	2-17
Time Domain	Intel	2-8	Residential	1-20
Time Domain	Win (TDC)	0-1.3	Lab/office	1-15

Here in this slide, we present an overview of some of the reported ultra-wideband channel measurements already done by people. In the first column, we have the classification whether it’s a frequency domain measurement or a time domain measurement. We have seen that people have done either in the frequency or time or both. The second column is the organization which is carrying out the measurement. Third column tells you the frequency range. What is interesting is people have gone from 2 to 6, 2 to 8. Some people have done from 1 to 11 GHz also. The typical UWB range from 3.6 to 10.1 to 10.6 GHz and then of course there are much smaller variations as well. The environment is of all types. The lab office environment where we most likely will deploy. This ultra-wideband base systems also residential for home entertainment. Distances are up to 20 m because the UWB application is expected to work within 20 m. these are the scenarios people have carried out channel measurements.

Conversation between student and professor: The question being asked is: in the last column here all the people have carried out measurements starting from 1 m up to certain level. Why not below that. So the answer is below this. This is coming into the near field region. So all the measurements are in the far field region and also the applications which have foreseen are from 1 to 20 in IIT. We have also carried out measurements below 1 m just for the sake of cataloging the measurement data because if I am working in a wireless desktop situation, these measurements do not hold good because clearly my wireless desktop is less than 1 m propagation distance. So we have carried out in house measurements for less than 1 m also.

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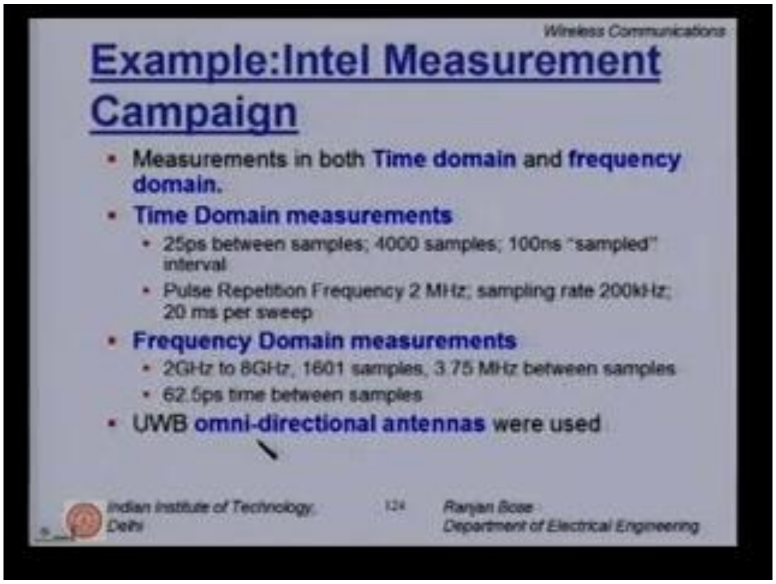

Let us now take for example the Intel measurement campaign. They have done it both in frequency domain and time domain and to satisfy the curiosity, they have tried to see whether there is any equivalence to the (check). Measurements have been carried out in both the domains time and frequency. The time domain measurements were taken 25 ps between samples in the separation. They took 4000 samples 100 ns sampled intervals. This is some typical point. We shall give you a feel for what kind of samples were collected and how many samples were collected. The pulse reputation frequency was 2 MHz. the sampling rate is 200 KHz 20 ms per sweep. So per sweep time 20 ms. the channel should not change the frequency domain measurements. They spanned from 2 GHz to 8 GHz. they took 1601 samples for every location and they had 3.7 MHz between samples. This is the spacing in frequency domain. You know this step through discrete frequency steps. This is the step size. There was 62.5 ps time between samples. The antennas that were used were omnidirectional UWB antennas antenna we have seen and will have a strong impact on the channel measurement.

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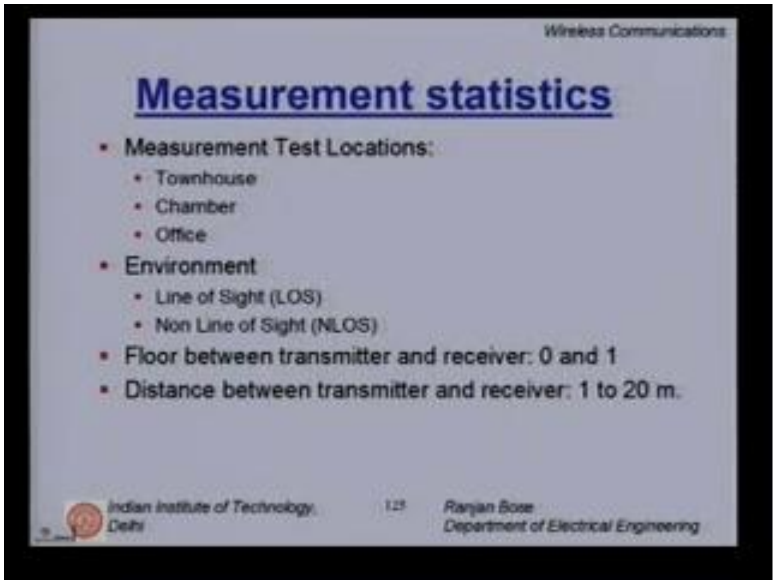

Let us look at certain measurement statistics. First the test locations. They carried out in three kinds of scenario: townhouse, chamber and office. What are the environments? They are the line of sight and non-line of sight. Then they talked about between floors, what is the received power. The distance between transmitter and receiver was from 1 to 20 m.

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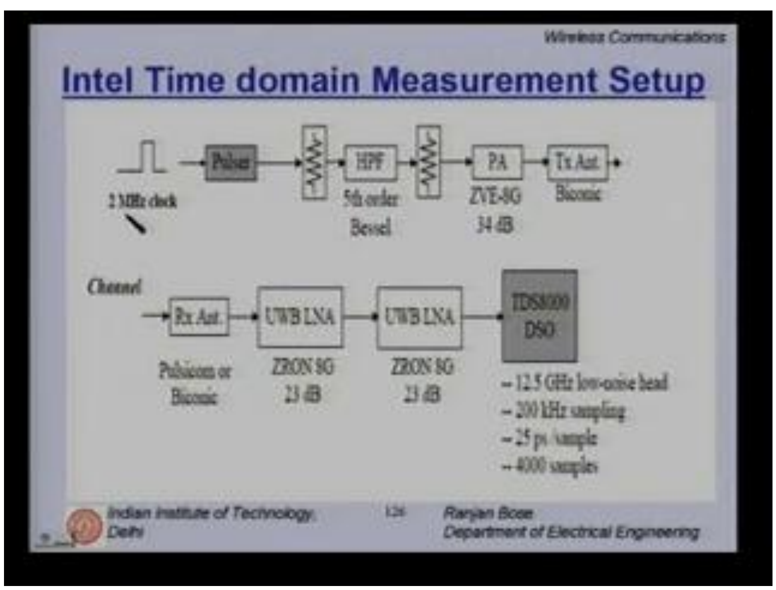

The measurement set up is as follows. As we mentioned, the 2 MHz clock is used to pulse it. Then they have a high pass 5^{th} order Bessel filter and then after amplification, they send it through a bi-conical transmitter antenna. At the received antenna, they have first a low noise amplifier and then finally their measurement setup. This is the Intel time domain measurement setup.

Conversation between student and professor: the question being asked is: why is bi-conical very close to an omnidirectional antenna and is it wideband? We have the two requirements and hence this has been used but this is large in size. So in typical applications, we will have hopefully close to an omnidirectional patch antenna for UWB applications but for measurements, these have not been used.

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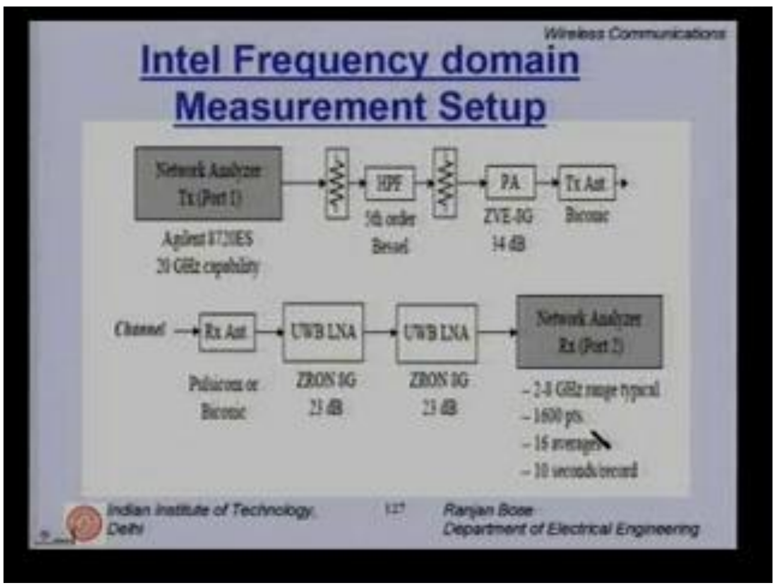

Now Intel also carried out frequency domain measurement. Their set up is as follows. They had an Agilent 8720 ES 20 GHz network analyzer. again the same 5th order Bessel filter transmitted through the bi-conical transmitter antenna receiver, the same bi-conical wideband antenna, low noise amplifier followed by the same network analyzer but ports 2. As mentioned, they took 1601 points. Actually the average is 16 times and then of course, off line took the channel impulse response.

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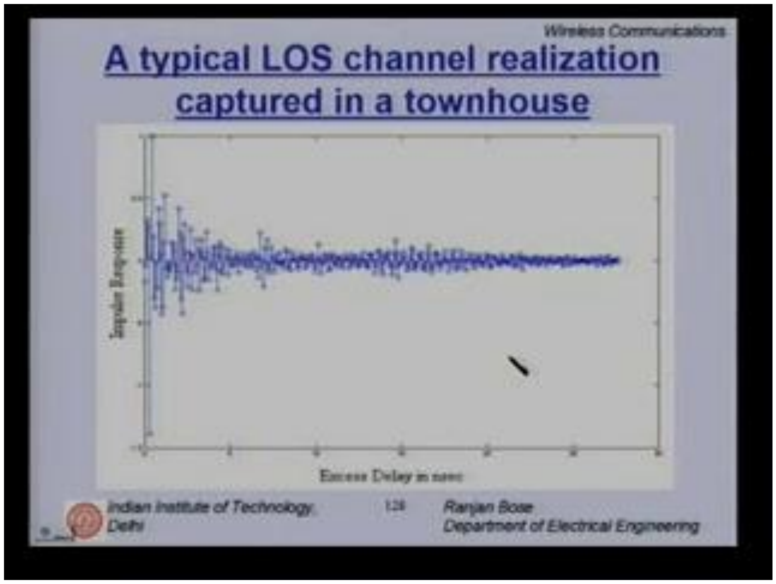

A typical line of sight channel realization captured in a townhouse scenario is as follows. Here is the excess delay in nanosecond in the x axis. It starts from 0, 5,10,15,20 and so and so forth. It practically dies down after 15 ns but you can still see some reflections here. But the reflections are more prominent. Here as you can see that there is a decay and the Saleh Valenzuela model can, to a great extent explain this behavior. This is the line of sight channel realization. it is coming from an actual channel measurement.

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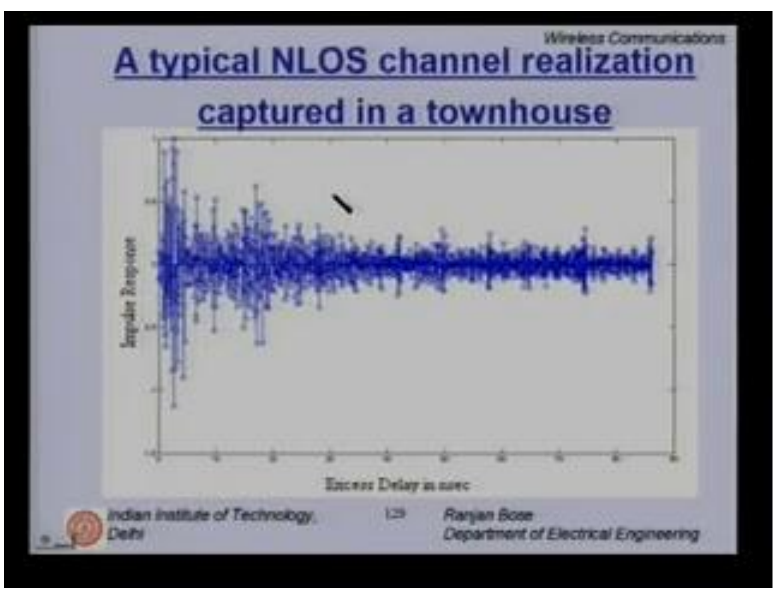

Now on the other hand, if you carry out a typical non line of sight channel realization again in the same townhouse, the situation gives a very different result on the x axis. Again we have the excess delay in nanosecond but this time if you see, the axis is much largely extended from 0, 10, 20, 30, etc. way up to 80. If you see yes, there are lot of reflections and then it dies down and then there are more reflections and so and so forth. The decay is also much slower. Clearly, if you have to design receivers for the two scenarios, we have to design them differently or at least account for the behavior for the non-line of sight channel measurements.

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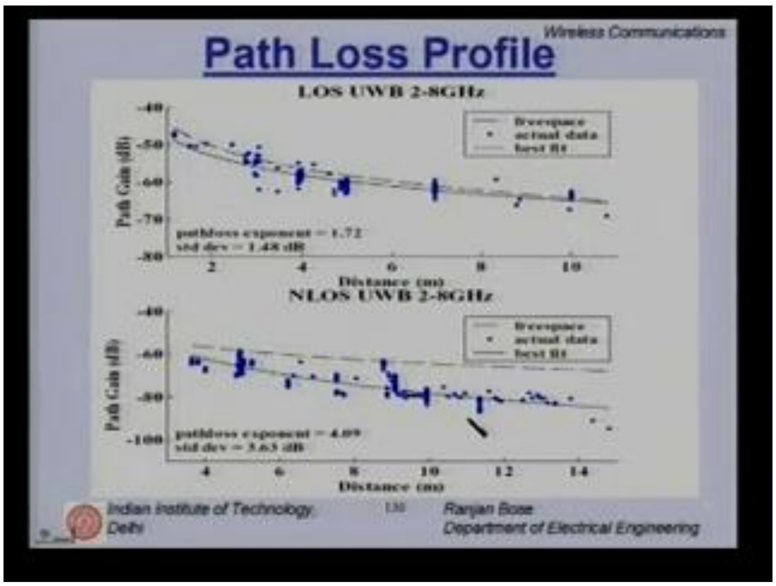

The path loss profile which is the path gain versus the distance in meters is given here. Again the top curve is for the line of sight. The bottom is for the non-line of sight. As you can see, the data points are highly scattered and some kind of a curve fitting has been done both for the line of sight and non-line of sight. Here the objective is to carry out the measurements and find out two things. The path loss exponent and what we have studied. For line of sight it comes as 1.72 much less than your 2 which is for the free space propagation. The standard deviation is 1.48 dB. On the other hand, for non-line of sight again, the measurements are from 2 to 8 GHz. we have a path loss as high as 4. Standard deviation is also much larger as expected as seen from the actual measurements.

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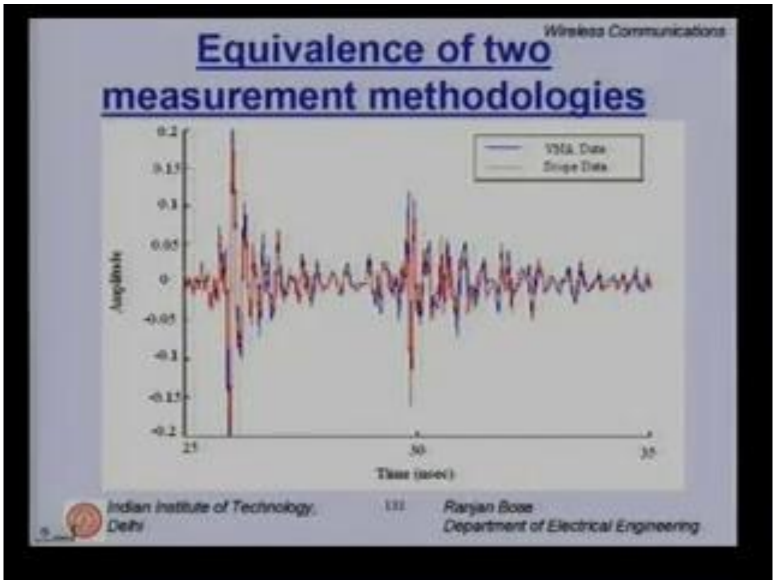

Now it is interesting to find out how similar the two methods: the time domain measurements and the frequency domain measurements are. Do they give entirely different results? Is there any correlation between the two results? So having done or carried out the experiments, both in the time domain and frequency domain. The measurement team at Intel tried to establish some equivalence of the two measurement methodologies and what they found was very interesting. The blue curve is the frequency domain measurement used with the vector network analyzer whereas the red measurement is clearly the scope data. As you can see, there is a very strong correlation between the two measurement techniques. The strong reflections and intermediary reflections are almost exactly captured by both the frequency domain measurement and the time domain measurement. So it gives us great comfort to know that yes, any of the techniques can be used. Whichever is simpler and more practical is preferred. In IIT, we are using a vector network analyzer to carry out frequency domain measurements.

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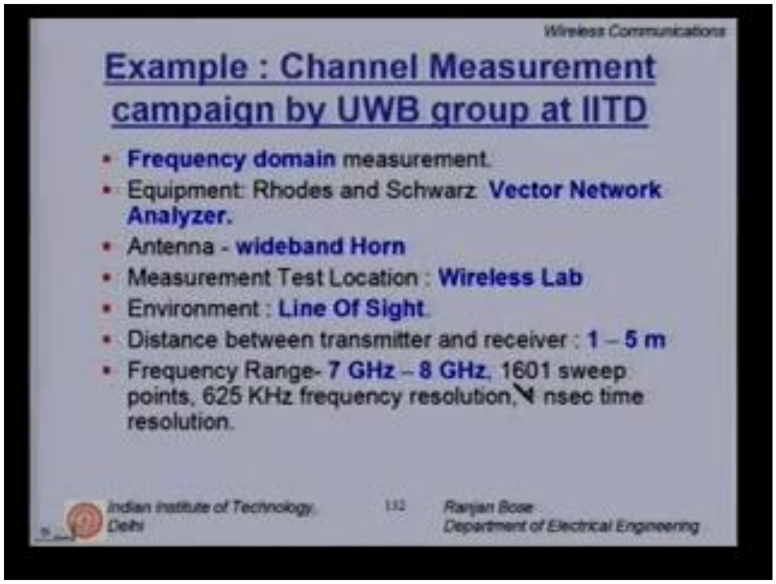

As a concluding example, let's briefly talk about the channel measurement campaign. By the ultra-wideband group at IIT Delhi, we have carried out frequency domain measurements. The equipment is a Rhodes and Schwarz vector network analyzer that goes up to 12 GHz. We are using a wideband horn. So it is not an omnidirectional antenna and it also doesn't cover a whole wide range as such. So the initial results that we are reporting is for a band which is within the ultra-wideband but doesn't capture the entire band. The measurement test location is a wireless lab scenario. The environment is line of sight. the distance between the transmitter and receiver is 1 to 5 m of reported results but measurements have also been carried out less than 1 m. the frequency range being shown in these slides is 7 to 8 GHz. but the efforts are on from 3.1 to 10.6 GHz. we are using 1601 sweep points, 625 KHz frequency resolution and 1 ns time resolution.

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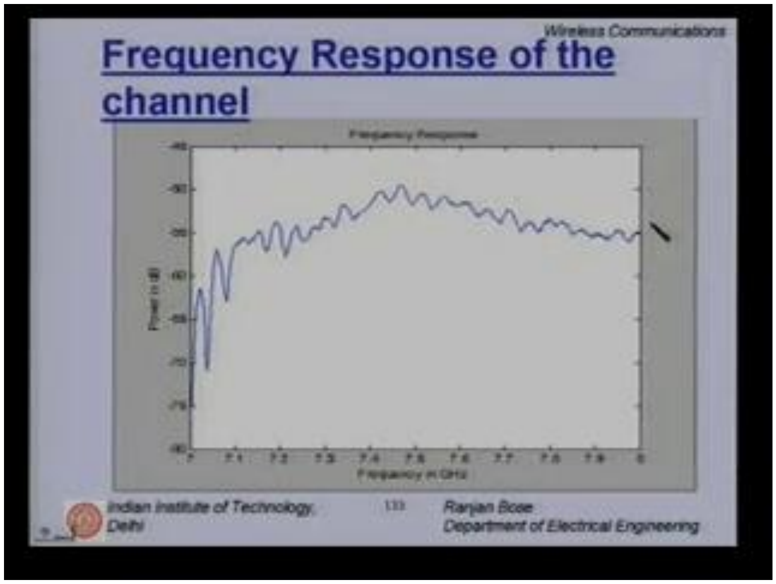

Just to give you a frequency domain response of the channel from 7 to 8 GHz. It is comes out like this. We are measuring the channel in the frequency domain. So this comes out directly.

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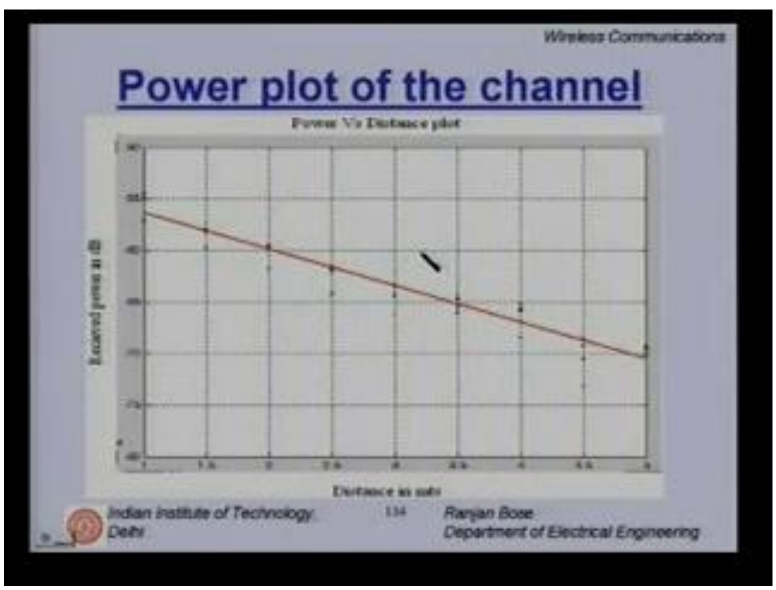

Now if you plot the power versus the distance and here we have shown only from 1 to 5 and as you can see, these are not very sharp but there is a wide range of data points available. These are the location of the receiver and a curve fit has been done. This is in the dB scale. So the slope of the curve will give us an idea about the path loss exponent.

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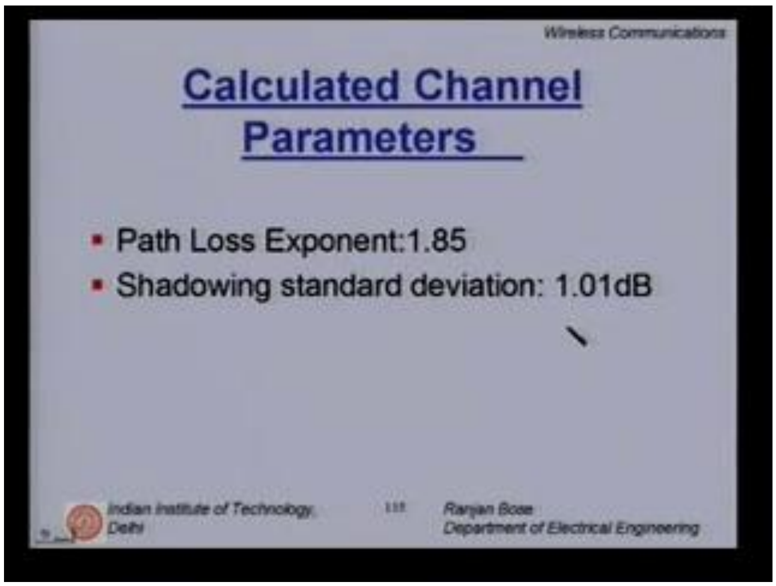

The calculated channel parameters are 1.85 for this line of sight and the standard deviation is 1.01 dB. Let us summarize today's lecture where we have looked at certain channel measurement techniques and actual channel measurement campaigns.

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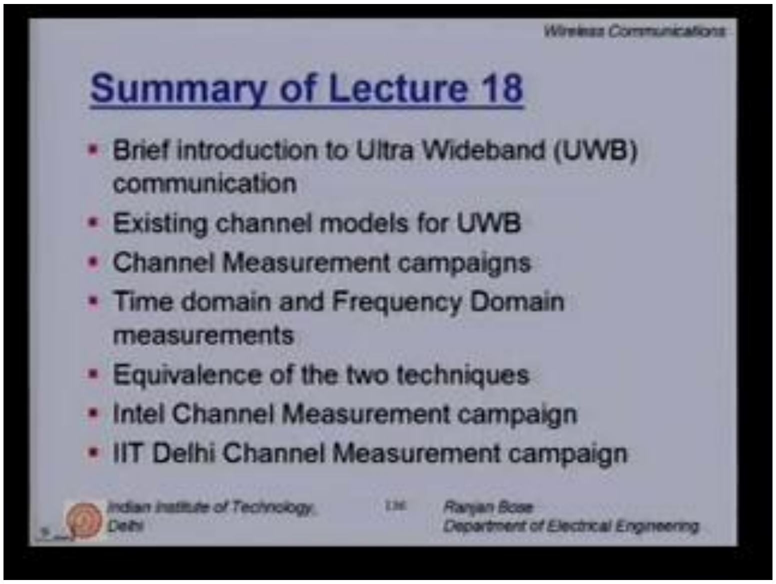

We started off with a brief introduction to the ultra-wideband communication system which was a test case. We first talked about the existing channel models for ultra-wideband communications. We then talked about the various channel measurement campaigns being carried out across the globe. We have realized that people have done time domain as well as frequency domain channel measurements. We also were relieved to see the equivalence of the two techniques and it corroborates the fact that you can either take measurements in the time domain or in the frequency domain. Specifically we discussed the Intel channel measurement campaign and IIT Delhi channel measurement campaign. We will conclude the lecture here.