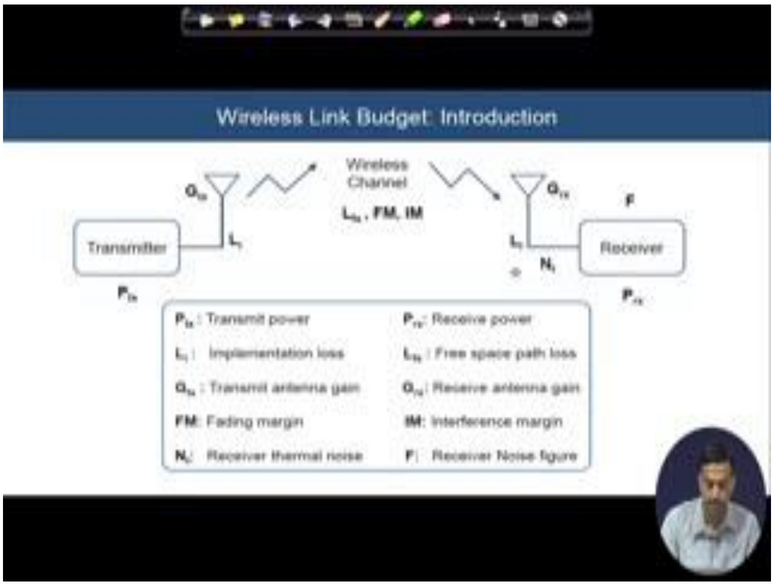
Spread Spectrum Communications and Jamming
Prof. Kutty Shajahan M
G S Sanyal School of Telecommunications
Indian Institute of Technology, Kharagpur

Lecture - 46
Tutorial – VI

Hello friends, today we will take up the tutorial-6 for week-8; and we will be discussing how to design and calculate the link budget for a typical wireless communication system.

(Refer Slide Time: 00:47)



Wireless Link Budget: Introduction

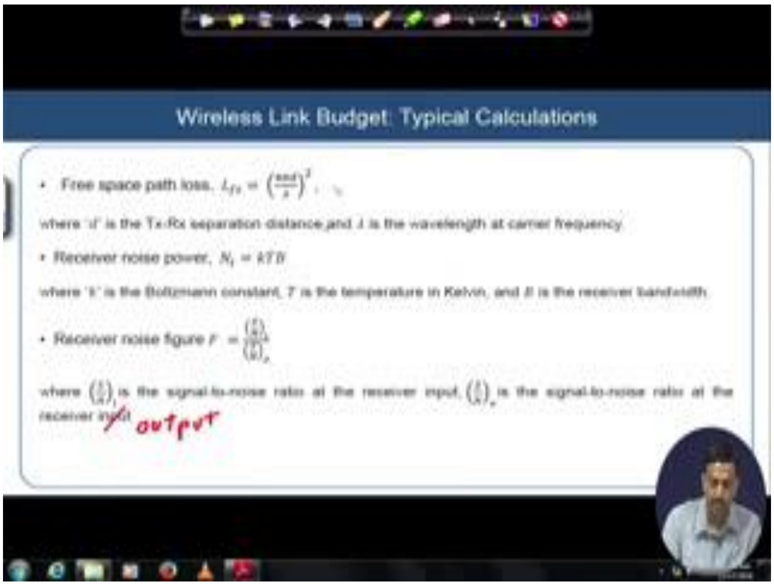
P_{tx} : Transmit power
P_{rx}: Receive power
L_i : Implementation loss
L_{fs} : Free space path loss
G_{tx} : Transmit antenna gain
G_{rx}: Receive antenna gain
FM: Fading margin
IM: Interference margin
N_t: Receiver thermal noise
F: Receiver Noise figure

So, as we see we have a transmitter which can transmit a wireless signal at with a transmit power of denoted by P t x; and the gain of the transmit antenna is denoted by G t x implementation losses which includes let say cable losses or feeder losses etcetera are consolidated and denoted by the term L subscript i. We have a wireless channel which has certain characteristics; and to begin with we have the term L f s which is nothing but the free space path loss which can be calculated based on an expression that we shall shortly see. Other considerations include what is called as a fading margin FM and the interference margin IM, so these are all basically loss factors along with implementation loss.

At a receiver end, we have a receive antenna with a gain G r x; again we have implementation losses. And we have invariably what is called as the thermal noise at receiver, which again can be calculated based on an expression that we shall shortly see.

We have the receiver noise figure, which will be defined. And we finally can obtain the receive power by adding all the gains to the transmit power and subtracting the losses. So, basically link project is calculation that enables us to design a wireless communication system given the parameters of the system some of which are included over here. So, let us proceed and see as to how this calculation is basically done.

(Refer Slide Time: 03:13)



Wireless Link Budget: Typical Calculations

- Free space path loss, $L_{fs} = \left(\frac{4\pi d}{\lambda}\right)^2$

where 'd' is the Tx-Rx separation distance and λ is the wavelength at carrier frequency

- Receiver noise power, $N_i = kTB$

where 'k' is the Boltzmann constant, T is the temperature in Kelvin, and B is the receiver bandwidth

- Receiver noise figure $F = \frac{\left(\frac{S}{N}\right)_i}{\left(\frac{S}{N}\right)_o}$

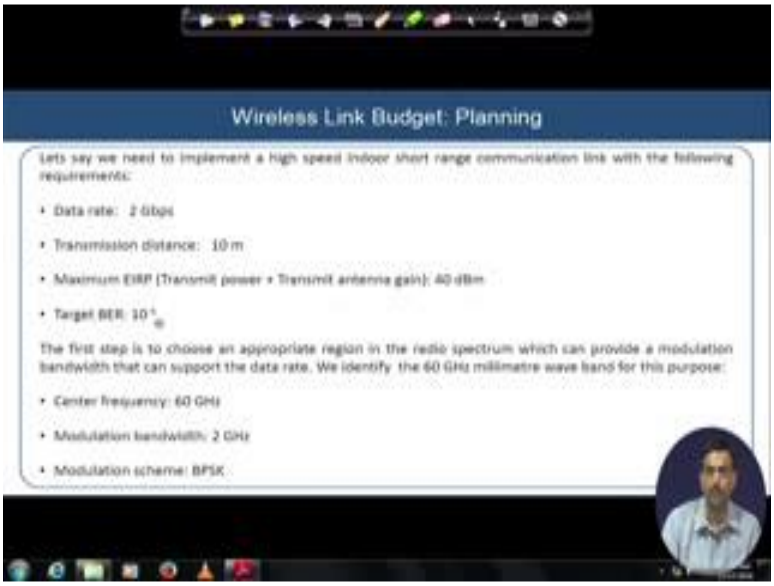
where $\left(\frac{S}{N}\right)_i$ is the signal-to-noise ratio at the receiver input, $\left(\frac{S}{N}\right)_o$ is the signal-to-noise ratio at the receiver ~~input~~ output

As I mentioned the free space path loss which figures over here, which is a basically the propagation loss that happens in a wireless channel is expressed by what is called as a popular free space transmission formula. So, it is a function of the separation distance between the transmitter and the receiver d, which means larger, it is span and is directly proportional. So, basically it means larger the distance more will be the propagation loss. So, this is inherent to any signal propagation phenomena. It is also inversely proportional to the wavelength of the signal at a given carrier frequency.

Secondly, I spoke about receiver noise, which is always present at the receiver. This is nothing but the thermal noise which can be expressed in terms of the Boltzmann constant k, the temperature T in a degree Kelvin, and the receiver bandwidth B in hertz. The receiver noise figure which is the property of a given receiver is defined as the signal-to-noise ratio at the input divided by signal-to-noise ratio at the output on fact I think I am sorry about this, this should be output.

And it is basically captures the amount of noise that is added in the receiver system itself. Like for example, in this case, we have the noise figure for this receiver. So, it is nothing but of the ratio of the signal-to-noise ratio at the input divided by signal-to-noise ratio at the output, which means it gives us an idea of how much noise is added by the receiver itself. And what that means is if F is greater than 1 that means, the signal-to-noise ratio at the input was more than that at the output which essentially as I said factors in the noise that is added in the receiver.

(Refer Slide Time: 05:50)



Wireless Link Budget: Planning

Lets say we need to implement a high speed indoor short range communication link with the following requirements:

- Data rate: 2 Gbps
- Transmission distance: 10 m
- Maximum EIRP (Transmit power + Transmit antenna gain): 40 dBm
- Target BER: 10 [illegible]

The first step is to choose an appropriate region in the radio spectrum which can provide a modulation bandwidth that can support the data rate. We identify the 60 GHz millimetre wave band for this purpose:

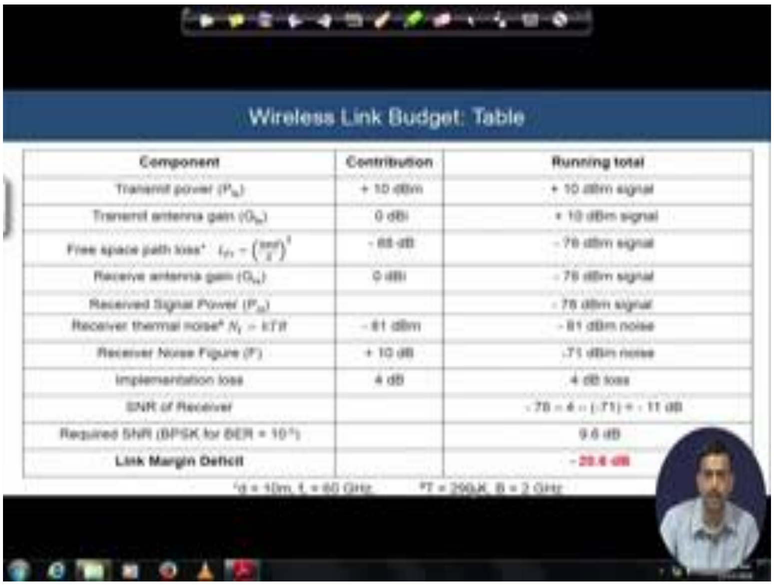
- Center frequency: 60 GHz
- Modulation bandwidth: 2 GHz
- Modulation scheme: BPSK

So, let us actually now see how this wireless link project planning is done. And let us take a specific example over here. So, we notice that we have to implement a high-speed indoor short range communication link. And the requirements are specified. For example, we need to support a data rate of as much as 2 Gbps. And we have a limited transmission distance which is nothing but a transmitter to receiver separation distance. And since it is short range, so we have only a distance of 10 meters; however, the data rate is quite high. The maximum EIRP that is the effective isotropic radiated power is of a term or is a quantity that is usually mandated by the regulatory authorities depending on the region in the world. So, basically f c c in the US, for example, of for 60 gigahertz transmission system that is in the millimeter wave band. So, this particular value is specifically for 60 gigahertz that is a millimeter wave band and that to indoor. So, this is the maximum which is mandated by the f c c.

Now, why we have taken this 60 gigahertz that I will come to shortly; let us say you now order to support this data rate at this given distance we also need to ensure that the BER of the system does not exceed 10 to the power of minus 5. So, keeping this target BER in mind, we are going to design the link budget, but considering that we have this kind of requirements of data rate transmission distance and maximum EIRP, we have to identify a proper region in the (Refer Time: 08:15) spectrum which will be able to support this kind of requirement.

And let us take as I said the millimeter wave spectrum with a centre frequency of 60 gigahertz. And it offers some modulation bandwidth around the centre frequency of about 2 gigahertz. The modulation scheme we will keep it simple and we will choose BPSK because in many case, we have a modulation bandwidth of 2 gigahertz and it is expected that BPSK will support a data rate of 2 Gbps. So, once we have zeroed in on a possible solution to meet this requirements. Let us see as to what kind of a wireless system a 60 gigahertz wireless system we require in order to meet or needs to be designed in order to meet at target BER of 10 to the power minus 5.

(Refer Slide Time: 09:18)



Wireless Link Budget: Table

Component	Contribution	Running total
Transmit power (P_{tx})	+ 10 dBm	+ 10 dBm signal
Transmit antenna gain (G_{tx})	0 dBi	+ 10 dBm signal
Free space path loss¹ $L_{FS} = \left(\frac{4\pi d}{\lambda}\right)^2$	- 88 dB	- 78 dBm signal
Receive antenna gain (G_{rx})	0 dBi	- 78 dBm signal
Received Signal Power (P_{rx})		- 78 dBm signal
Receiver thermal noise² $N_t = kTB$	- 81 dBm	- 81 dBm noise
Receiver Noise Figure (F)	+ 10 dB	-71 dBm noise
Implementation loss	4 dB	4 dB loss
SNR of Receiver		- 78 - 4 - (-71) = - 11 dB
Required SNR (BPSK for BER = 10^{-5})		9.6 dB
Link Margin Deficit		- 20.6 dB

¹d = 10m, f_c = 60 GHz ²T = 290 K, B = 2 GHz

So, in order to do that, let us take a look at this link budget table, which corresponds to this particular scenario. Now, actually the maximum EIRP which is at the addition of transmit power and antenna gain is mandated to be up to 40 dBm. But for the sake of implementation we will limit it to limit the transmit power itself to only 10 dBm most of the practical 60 gigahertz transmitter systems will operate in a range of P t x equal to 10 dBm to let say about 25 to 30 dBm. So, we will take the lower end of that. And as an example we will just assume that we have a transmit power of 10 dBm with 0 antenna gain that means, there is basically no antenna gain. And therefore 10 plus 0 which is P t x plus G t x which is nothing but EIRP.

So, let me just highlight that. So, this is nothing but the effective isotropic radiated power. So, as you can see we are well within the limits of our communication system which is a or rather the requirement which is a 10 dBm sorry 40 dBm - plus 40 dBm. So, we choose a transmit power of 10 dBm, and this a third column here give us a running total. So, we transmit with the power 10 dBm the antenna gain is 0. So, at the output of the transmitter are the signal power is 10 dBm. Note that I have not considered implementation losses here, because I will factor it later down the calculations.

The free space path loss is given by the formula as already mentioned that is a phase free space transmission formula. We have a distance d of 10 meters, so as you can see, if you substitute d equal to 10, and lambda basically there is a wavelength has to be calculated based on the carrier frequency also that is again a well known equation as we all know. That your lambda can basically we calculated as lambda equal to c divided by f c where c is nothing but the speed of light. So, this is a nothing but 3 into 10 to the power of 8 meters per second, and f c is already given as 60 gigahertz. So, this lambda can be substituted over here. And we calculate this free space loss in dB terms to be equal to minus 88 dB. So, this is a straight forward calculation in dB, it is nothing at 20 clock to the base 10 4 pi d by lambda

So, now the running total that is the previous signal power was 10 dBm, I have a free space loss of minus 88 dB. So, I subtract 10 from 88, and the result is minus 78 dBm. Please note that you can perform this subtraction between dBm and dB values provided the result is in dBm. So, it is a valid subtraction. So, 10 minus 88 gives you minus 78. Again assume that we have no a receiver antenna gain as well and so the signal power at a receiver antenna remains at minus 78 dBm. So, P r x basically is this value.

Now, we go onto calculate the noise. So, the thermal noise as I said is given by the expression k T B at the receiver. So, we substitute the value of Boltzmann constant the temperature in degree Kelvin is assumed to be a 290 k which is usually a standard value;

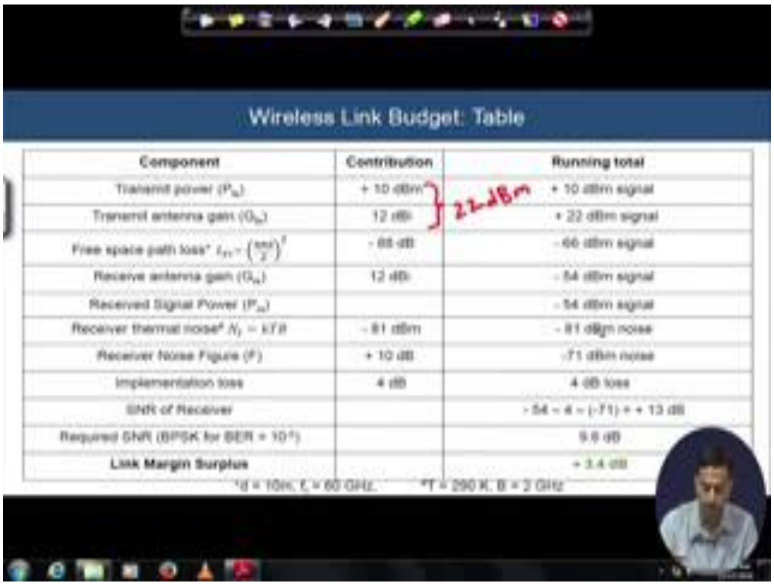
and the bandwidth as you already know which is already specified is 2 gigahertz. So, we substitute this value over here and we get the basically the noise value is minus 81, the signal value we have obtained up to this point that is up to minus 78 dBm. So, we are separately calculating noise in these two rows remember that.

We consider a noise figure of a 10 dB. So, addition of noise inside the receiver is factored over here. So, minus 81 plus 10 dB gives us a total noise a power value of minus 71, we have signal power of minus 78, noise power at the receiver of minus 71. And if you now consider a consolidated implementation loss of a 4 dB, we are in a position to calculate the signal-to-noise ratio at the receiver. So, signal is minus 78 as a dBm as already calculated we subtract the implementation loss of a 4 dB, and we further subtract because noise is in the denominator of the SNR expression. So, minus of whatever was the noise value which is minus 71 dBm. So, it turns out that the signal-to-noise ratio at the receiver in this particular case is minus 11 dB.

Now, we already know from a theory that for a target BER of 10 to the power of minus 5 BPSK mandates a SNR requirement of about 9.6 dB this, this can be obtained from basically the BER or the bit error rate curve versus SNR for a typical BPSK system. However, the SNR that our system returns is minus 11 d b. So, we can see that we are falling well short of the requirement of 9.6 dB, and the deficit which is nothing but the difference between this two terms that is come out by which we are falling short is about minus 12.6 dB which is quite a significant amount of deficit.

So, now the question is how can we make the system work. Because what is happening now is we have a situation where we were given the requirements and we first chose the spectrum or the region in the spectrum where we are going to operate. However, this particular link budget gives us a deficit. So, we have a couple of options now. To start with we can increase this transmit power, because the maximum transmit power plus G t x was specified to be about 40 dBm if you recall in this particular expression, so that was possible. So, this can be done by either increasing the transmit power or by incorporating an antenna which gives you a gain, either these two are possible, so that is what we are going to do next.

(Refer Slide Time: 17:27)



Wireless Link Budget: Table

Component	Contribution	Running total
Transmit power (P_{tx})	+ 10 dBm	+ 10 dBm signal
Transmit antenna gain (G_{tx})	12 dBi	+ 22 dBm signal
Free space path loss* $L_{FS} = \left(\frac{4\pi d}{\lambda}\right)^2$	- 88 dB	- 66 dBm signal
Receive antenna gain (G_{rx})	12 dBi	- 54 dBm signal
Received Signal Power (P_{rx})		- 54 dBm signal
Receiver thermal noise# $N_t = kTB$	- 81 dBm	- 81 dBm noise
Receiver Noise Figure (F)	+ 10 dB	-71 dBm noise
Implementation loss	4 dB	4 dB loss
SNR of Receiver		- 54 − 4 − (-71) = + 13 dB
Required SNR (BPSK for BER = 10^{-6})		9.6 dB
Link Margin Surplus		+ 3.4 dB

22dBm

*d = 10m, f_c = 60 GHz. #T = 290 K, B = 2 GHz

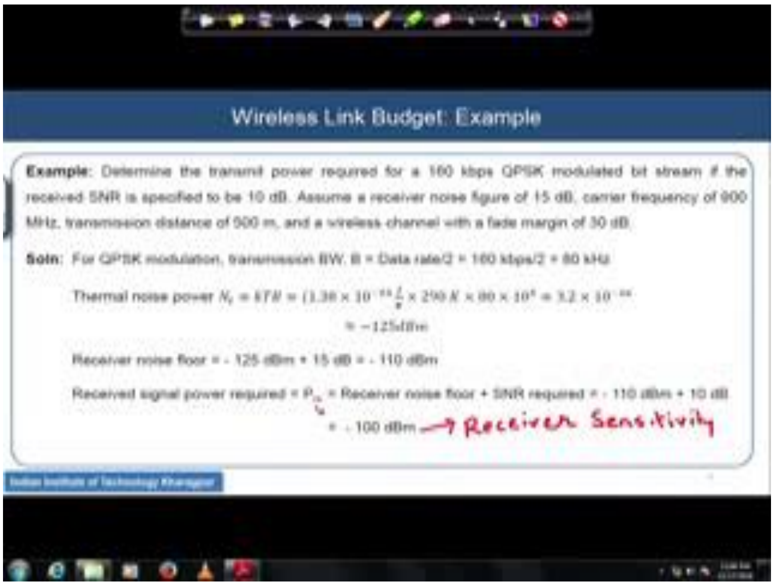
So, you can see that this table is similar to the previous table, but the only difference is we have added a 12 dBi gain at the antenna. So, we see now that the EIRP is turning out to be the addition of these two, so that is 22 dBm which is well within the limits of the 40dBm value, which was specified by which was the maximum EIRP specified basically. So, it is valid if you operate in this range there is no issue. The rest of the parameters remain the same; however, we can also include a receive antenna gain for illustrative purposes.

So, this is an additional gain which is possible a provided receiver has the capability in order to deliver an antenna gain that is if this smart antenna system is available at the receiver, which can provide this kind of a gain. So, what we say is the rest of the remaining rest of the calculations remaining the same. We have about 24 that is 12 plus 12 dBm gain which has now been which can now be harnessed in order have a feasible system a design of feasible system, which gives us a link margin surplus. You can clearly see the effect over here that the running total for the signal now turns out to be minus 54 dBm, and the noise value remaining the same, so is the implementation loss value as well. Since this signal power has now improved because of the transmitter and receiver antenna gains we have a surplus link margin of about 3.4 dB.

So, this goes to show how antenna gains can be crucial in this kind of a link, where the propagation loss is pretty high and it also highlights the importance of being forming where you can harness the antenna gain in order to improve the signal power. One thing that I have neglected over here is the oxygen absorption loss at 60 gigahertz which is a feature at that particular millimeter wave frequency, but considering that that loss is about 16 dB per kilometer and what we have is the transmission distance openly about 10 meters that loss is negligible. So, I have neglect neglected it in this in this particular analysis.

So, what can we do with this surplus link budget? So, the first and foremost thing that you can directly see is I can allow this loss that is the propagation loss to be more, which means for a fixed wavelength I can now in increase my transmission distance. Increasing transmission distance will give you an increase in propagation or free space loss. However, since we already have a link margin surplus we can support it provided it is within this value. Once again I would like to point out that we are still operating at EIRP of 22 dBm as per the mandate, it could have been as much as 40 dBm, so in which case we could have a higher link margin surplus. So, this is typically how what we see is the link budget for a high-speed short range communication system. Let me take another example. Now, where we need to calculated transmit power given this requirements and that is also done using link budget analysis.

(Refer Slide Time: 21:57)



Wireless Link Budget: Example

Example: Determine the transmit power required for a 160 kbps QPSK modulated bit stream if the received SNR is specified to be 10 dB. Assume a receiver noise figure of 15 dB, carrier frequency of 900 MHz, transmission distance of 500 m, and a wireless channel with a fade margin of 30 dB.

Soln: For QPSK modulation, transmission BW, B = Data rate/2 = 160 kbps/2 = 80 kHz

Thermal noise power $N_t = kTB = (1.38 \times 10^{-23} \frac{J}{K} \times 290\,K \times 80 \times 10^3 = 3.2 \times 10^{-16}$

$= -125\text{dBm}$

Receiver noise floor = - 125 dBm + 15 dB = - 110 dBm

Received signal power required = P_{rx} = Receiver noise floor + SNR required = - 110 dBm + 10 dB

= - 100 dBm → Receiver Sensitivity

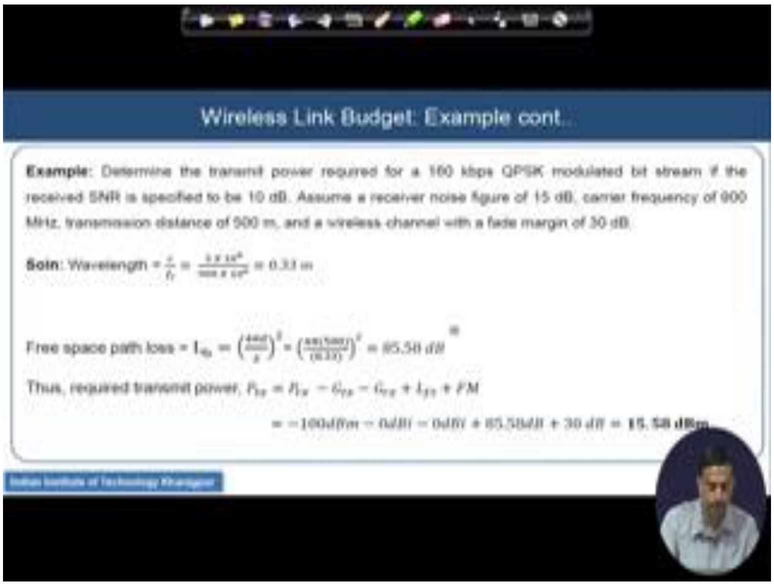
Indian Institute of Technology Kharagpur

So, we have an example where we need the transmit power to be determined for a QPSK modulated bit stream. And the data rate specified is 160 kbps and the requirement is that the received SNR should be at least 10 dB. The noise figure at the receiver is specified to be 15 dB. And the carrier frequency is assumed to be 900 megahertz. We have a transmission distance of about 500 meter, and a wireless channel which now has a fade margin of 30 dB. This fade margin term was not highlighted in the previous a table and example, because there we were talking about an indoor channel. So, this is more like an outdoor channel with a transmission distance of 500 meters.

So, what we do is we first find out the transmission bandwidth B required and for the QPSK modulated stream B are aware that the transmission bandwidth is a half the data rate, and it turns out to be 80 kilohertz. Based on this B, we calculate the noise power using the Boltzmann constant, and the standard temperature of 290 degree Kelvin. So, it turns out that the noise is minus 125 dBm. We have a receiver noise floor therefore of minus 125 dBm plus the noise figure in the receiver. So, the total noise at the receiver is minus 110 dBm. And we need a signal power which would be above this noise floor if reliable detection has to be done. So, we calculate the signal power as this noise floor plus the SNR that is required for detection which is specified over here and it is 10 dB. So, this is a value which is been given to you. So, therefore, we add the SNR to the receiver noise floor, and we see that the power required at the receiver is minus 100 dBm.

So, generally this kind of an analysis where we consider only the receiver noise floor, which includes the thermal noise and the noise figure and we consider the SNR requirement based on some given data. This kind of a required signal power also means the receiver should be sensitive enough in order to receive this kind of power. So, this is also generally termed as receiver sensitivity. So, the receiver sensitivity for this system is 100 dBm. Based on this value, we will now find out as to what is the transmit power which is required in order to realize this kind of a sensitivity. So, what we do is we are already told that we have a 900 megahertz centre frequency.

(Refer Slide Time: 25:22)



Wireless Link Budget: Example cont..

Example: Determine the transmit power required for a 160 kbps QPSK modulated bit stream if the received SNR is specified to be 10 dB. Assume a receiver noise figure of 15 dB, carrier frequency of 900 MHz, transmission distance of 500 m, and a wireless channel with a fade margin of 30 dB.

Soln: Wavelength = $\frac{c}{f_c} = \frac{3\times10^8}{900\times10^6} = 0.33$ m

Free space path loss = $L_{fs} = \left(\frac{4\pi d}{\lambda}\right)^2 = \left(\frac{4\pi(500)}{(0.33)}\right)^2 = 85.58\ dB$

Thus, required transmit power, $P_{tx} = P_{rx} - G_{tx} - G_{rx} + L_{fs} + FM$

$= -100 dBm - 0 dBi - 0 dBi + 85.58 dB + 30\ dB =$ **15.58 dBm**

Indian Institute of Technology Kharagpur

So, we calculate the wavelength based on it using the formula c by f c. And we turns out that the wavelength is 0.33 meters. And we now invoke the definition for free space path loss and use this value of wavelength and the transmission distance of a 500 meters in order to calculate the free space path loss which turns out to be 85.58 in this case. So, finally, we put together all the times we know that the receive power basically is the transmit power plus the gain plus that is the antenna gain at the transmitter and receiver minus the free space path loss minus the fade margin, which is the basically value accounting for single fading in the wireless channel.

So, the transmit power taking the terms on to the other side the transmit power turns out to be equal to the received power minus the gains plus the free space path loss plus the fade margin. And the value calculated using the values calculated above are 15.58 dBm. So, what we see is that we have made use of the link budget parameters like the free space path loss and the thermal noise power and of course, the noise figure in order to calculate the required transmit power for a system whose received SNR is specified to be equal to a certain value. And this is another way of using link budget in order to design wireless systems. So, in this case, a minimum transmit power of 15.58 dBm is required in order to implement this wireless communication system. So, we end this tutorial over here. What we have seen in this tutorial is relevance of the link budget in order to design a feasible implementable wireless communication system.

Thank you.