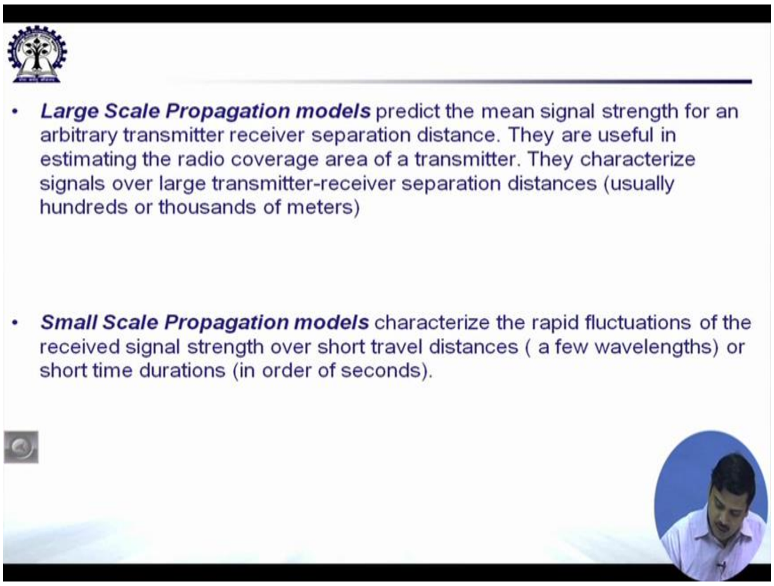
Fundamentals of MIMO Wireless Communication

Prof. Suvra Sekhar Das
Department of Electronics and Communication Engineering
Indian Institute of Technology, Kharagpur

Lecture - 06
Large Scale Propagation Models Path Loss

Welcome to the course on fundamentals of MIMO Wireless Communications, today we will talk about large scale propagation models, the reference books that have to be followed in this particular section would be wireless communication by Rappaport. We will usually go by the authors name and principles of mobile communication by Gordon Stuber. Now this does not necessarily restrict to these particular books there are many other books also these are the particular ones which I followed and I have used extensively in this particular part of the course.

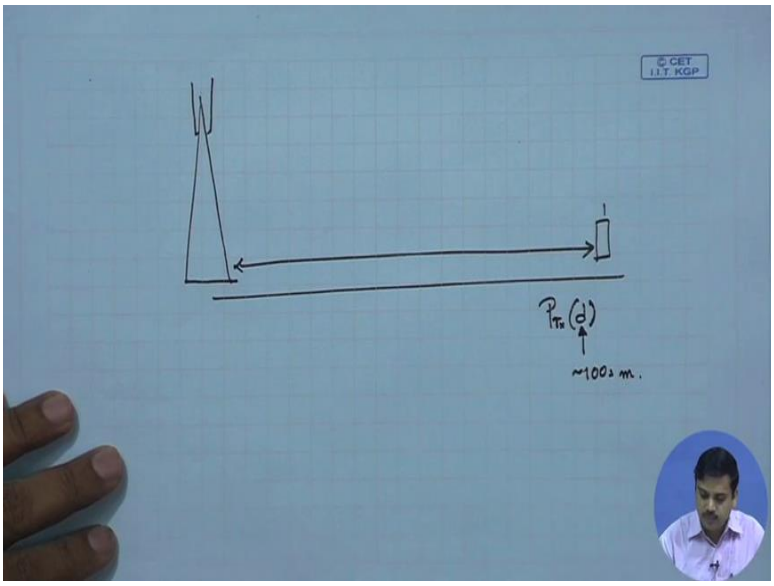
(Refer Slide Time: 01:01)



- ***Large Scale Propagation models*** predict the mean signal strength for an arbitrary transmitter receiver separation distance. They are useful in estimating the radio coverage area of a transmitter. They characterize signals over large transmitter-receiver separation distances (usually hundreds or thousands of meters)
- ***Small Scale Propagation models*** characterize the rapid fluctuations of the received signal strength over short travel distances (a few wavelengths) or short time durations (in order of seconds).

Large scale propagation models are basically those which predict the mean signal strength for an arbitrary transmitter receiver separation distance, they are usually used in a estimating that the radio coverage area of the transmitter. They characterize the signals over large transmitter receiver separation distances because we have seen this in briefly in the previous lecture that.

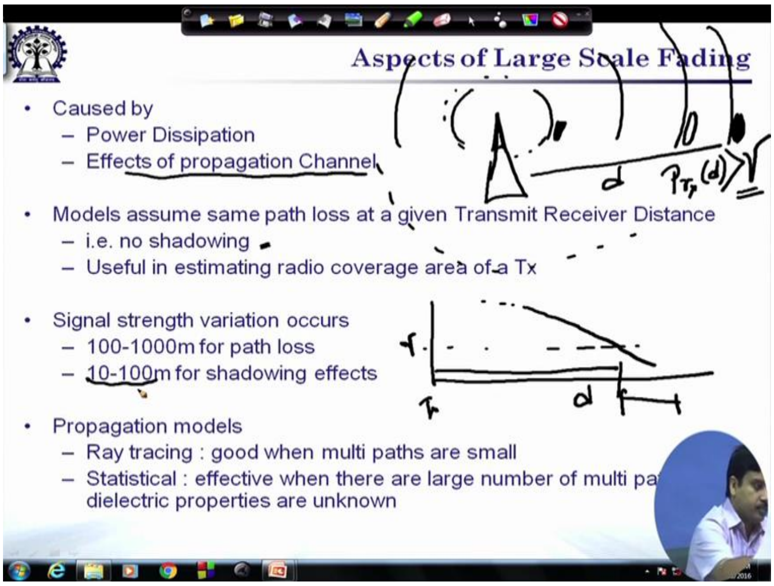
(Refer Slide Time: 01:31)



Suppose, there is a transmitter and there are receivers at a certain distance this particular model is going to predict the power that is received at a distance d from the transmitter to the receiver and these models are designed in such a way that, they captured the fluctuation of signal strength. When this d is significantly large in the orders of at hundreds of meters where as if we move in to the small scale propagation models they characterize rapid fluctuation of the received signal strength over a short interval of distance we have seen such a figure earlier where, we had separation distance on the x axis received signal strength and there was signal strength fluctuations along the distance while there was also the average received signal strength that was plotted in red colour in that particular figure.

So, this average received signal strength is the one which is usually captured by the large scale propagation models, where as these instantaneous fluctuations are the ones which are captured by small scale propagation models and the small scale propagation models captured fluctuations over few wave lengths, whereas large scale propagation model captures the fluctuation of signal strength when the separation distance is significantly large.

(Refer Slide Time: 03:08)



Aspects of Large Scale Fading

- Caused by
  - Power Dissipation
  - Effects of propagation Channel
- Models assume same path loss at a given Transmit Receiver Distance
  - i.e. no shadowing
  - Useful in estimating radio coverage area of a Tx
- Signal strength variation occurs
  - 100-1000m for path loss
  - 10-100m for shadowing effects
- Propagation models
  - Ray tracing : good when multi paths are small
  - Statistical : effective when there are large number of multi pa dielectric properties are unknown

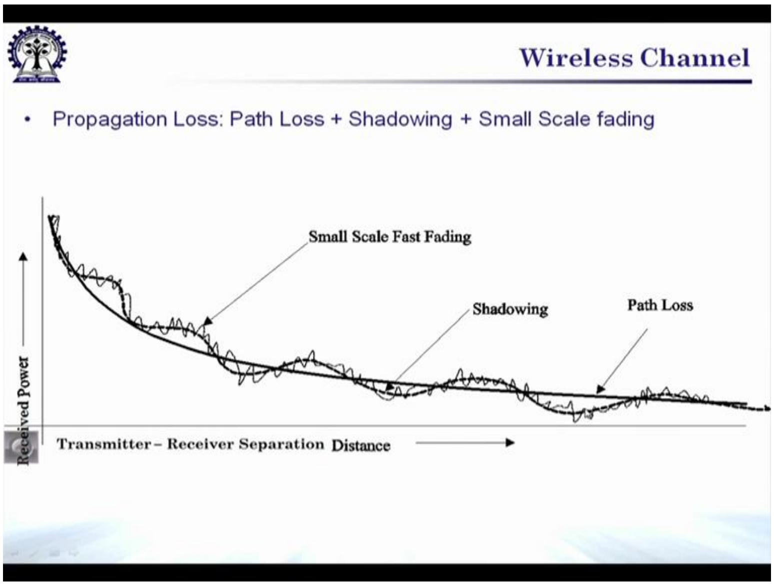
We will see details of such things now large scale propagations are effected by power dissipation as is here. So, by power dissipation what we mean is that the because of radiation well there is a transmitter signals are radiated all across at the receiver as we go on at large distance from the transmitter to the receiver. The receiver antenna size is fixed. So, we are capturing only a small fraction of the big envelop. So, when we are close to this distance we are capturing a significant fraction of this signal energy because the globe is like this, where as when we are far away we are capturing the same absolute area where as the globe has become bigger.

So, therefore, you are actually capturing a small fraction of the total energy as we increased the separation between the transmitter and the receiver these models they capture the effects of the propagation channel, we will see some of the effects of propagation channel in few lectures to come these models assume that path loss at a given transmitter receiver distance; that means, there is no shadowing we will discuss what is shadowing and it is of course, useful in estimating radio coverage area of the transmitter; that means, up to what distance is the received signal strength the received signal strength as a function of distance is greater than some threshold.

Now, when the signal level falls below such a threshold we say that the receiver is out of coverage. So, as we increase distance from transmitter, let say transmitter is located here as involved in the increase in the distance up to a certain point in distance d the signal strength remains above the threshold. So, if this is threshold gamma the received signal strength decreases in beyond certain point, it decreases below the threshold. So, this region is low coverage region where as this region is the coverage region such models helps in predicting this distance the maximum distance of separation as we have already said signal strength variation occurs for 100s or 1000s of meters and beyond within this small distance like 10 to 100s of meters there is a shadowing which we will see shortly.

Now, this propagation models as we are talking about said about of models they could be deterministic or they could be statistical by deterministic what we mean is that the signal strength at the receiver can be predicted by solving wave equations by statistical, what we mean is that there is a significant amount of measured data from the measured data there is curve fitting and there is a parametric model which we will see again shortly moving ahead this particular picture typically represents the fluctuation of signal strength versus distance.

(Refer Slide Time: 06:21)

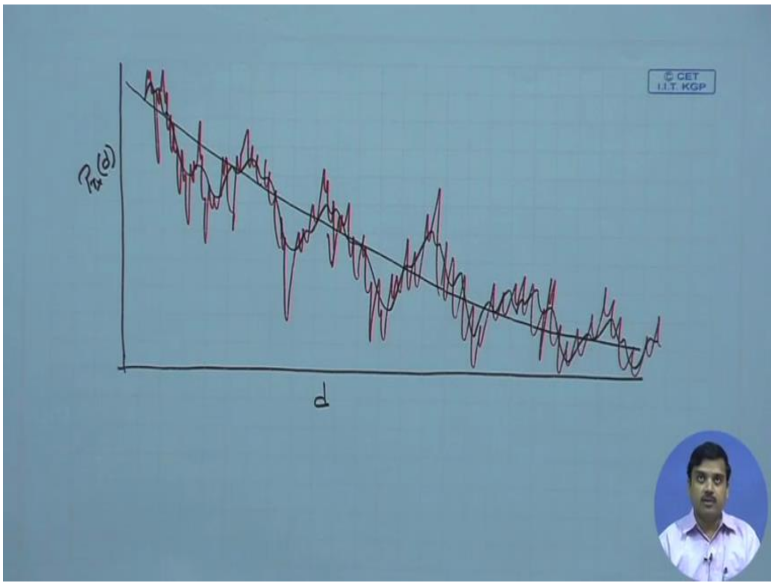


Wireless Channel

- Propagation Loss: Path Loss + Shadowing + Small Scale fading

If we draw it things might be little bit easier.

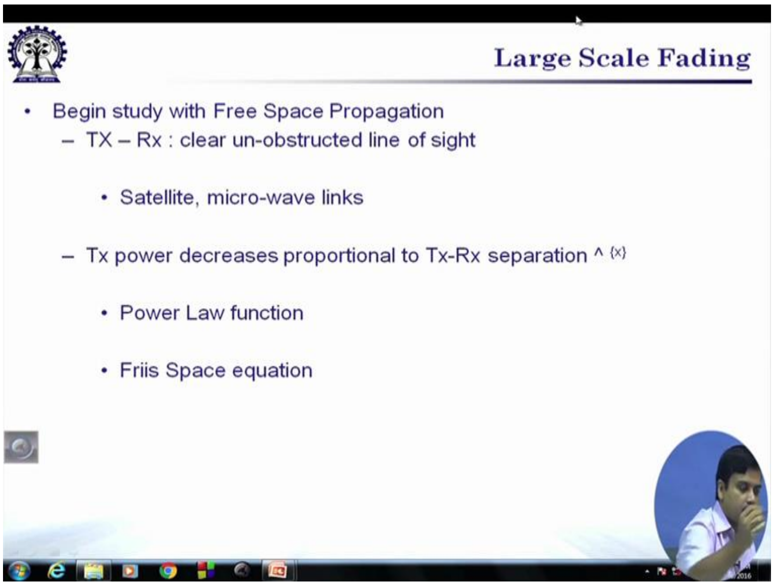
(Refer Slide Time: 06:35)



So, if we make received signal strength p receives as the function of distance and let say this is in dB m this is the separation distance. So, if we consider only large scale propagation models, what we will observe is the received signal strength almost monotonically decreases with increasing distance and this is because of the average received signal strength, where as on top of it we will find local fluctuations we will again see what are local fluctuations because of which signal strength the local average fluctuates.

On top of which there is instantaneous fluctuation of signal strength which is the small scale fading. So, in effect what we get at the receiver is the cumulative effect of these 3 phenomenons' that is the path loss shadowing and the small scale fading as this represented in this particular slide. So, the time fluctuations are due to small scale fading the slowly varying average as indicated or traced by this curser is because of shadowing and the average decrease in signal strength is due to path loss. So, this is the overall phenomenon and we need to understand these phenomenon again in this part of the course we will focus on these 2 parts we will do them briefly and we will spend the significant amount of time understanding the small scale fluctuations.

(Refer Slide Time: 08:18)

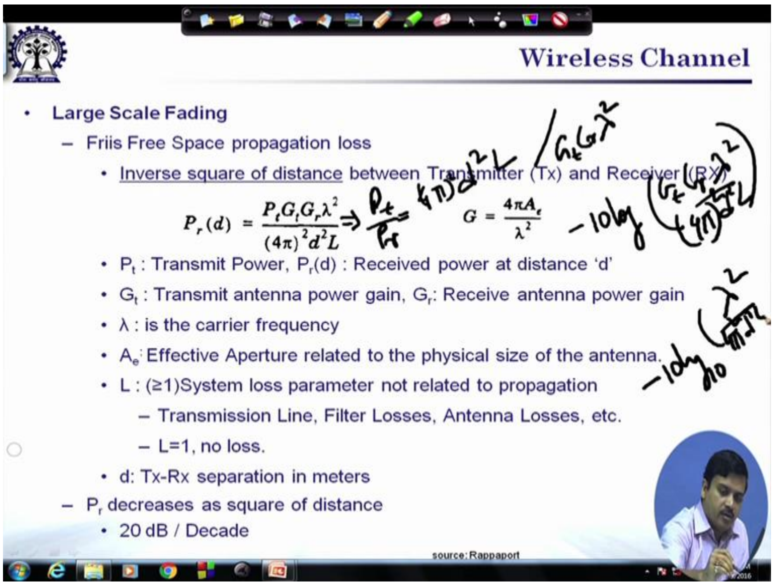


Large Scale Fading

- Begin study with Free Space Propagation
  - TX – Rx : clear un-obstructed line of sight
    - Satellite, micro-wave links
  - Tx power decreases proportional to Tx-Rx separation ^ {x}
    - Power Law function
    - Friis Space equation

So, we begin in the study of Friis Space Propagation models by Friis space propagate propagation models typically examples of such Friis space propagation models would be satellite link where between the transmitter and the receiver there is no obstruction microwave links there is line of sight. So, basically in these particular cases, we are talking about line of sight usually indicated by l o s and here they received power this is the received power this is r x decreases proportional to t x r x separation raised to some powers. So, basically d is the separation distance raised to the power of sum exponent as we will see. So, this is typically in this format it follows the power loop function and we will use the Friis, Friis space equation to solve this the problem, and find the expression of received signal strength moving ahead typically.

(Refer Slide Time: 09:27)



Wireless Channel

- Large Scale Fading
  - Friis Free Space propagation loss
    - Inverse square of distance between Transmitter (Tx) and Receiver (RX)

$$P_r(d) = \frac{P_t G_t G_r \lambda^2}{(4\pi)^2 d^2 L} \Rightarrow \frac{P_t}{P_r} = (4\pi)^2 d^2 L / G_t G_r \lambda^2 \qquad G = \frac{4\pi A_e}{\lambda^2} \qquad -10\log\left(\frac{G_t G_r \lambda^2}{(4\pi)^2 d^2 L}\right)$$

$$-10\log_{10}\left(\frac{\lambda^2}{(4\pi)^2 d^2}\right)$$

    - P_t : Transmit Power, $P_r(d)$: Received power at distance 'd'
    - G_t : Transmit antenna power gain, G_r: Receive antenna power gain
    - λ : is the carrier frequency
    - A_e: Effective Aperture related to the physical size of the antenna.
    - L : (≥1)System loss parameter not related to propagation
      - Transmission Line, Filter Losses, Antenna Losses, etc.
      - L=1, no loss.
    - d: Tx-Rx separation in meters
  - P_r decreases as square of distance
    - 20 dB / Decade

source: Rappaport

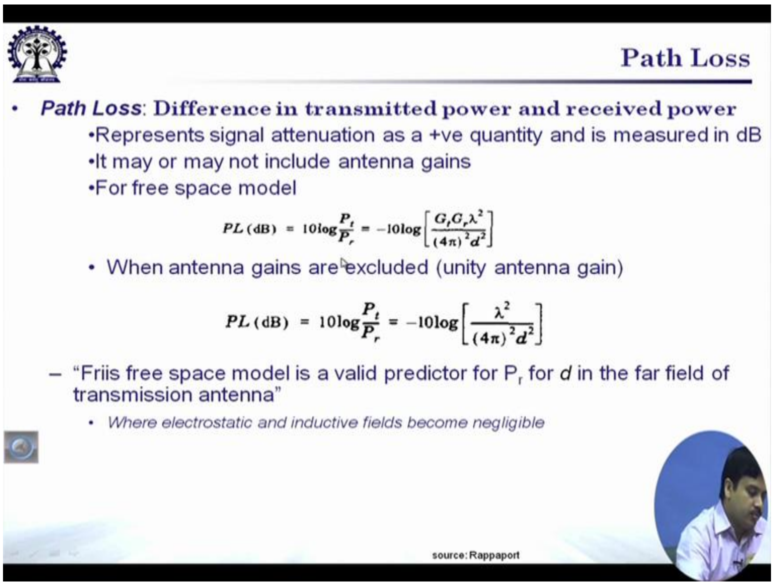
If you look at the Friis, Friis space equation the received signal strength at a particular distance d as indicated by this expression is proportional to the transmit power proportional to the antenna gain of the transmitter, it is proportional to the received antenna gain proportional to the wave length or inversely proportional to frequency inversely proportional to the distance of separation and l indicates system loses.

So, as described shortly p t is the transmit power P r d is the received power at the distance d where d is the separation between the transmitter and the receiver g t as indicated transmit power gain g r is a receive power gain lambda is the wave length and a e is the effective aperture.

So, if we have to calculate how you are going to get g through this expression we can find the antenna gain which is the function of effective aperture of the antenna and which is related to the physical size of the antenna as you increase the antenna size your gain increases, but they are of course, many details to antenna design l indicates system losses a losses would be coupling losses cables and many other aspects. So, typically one is there and the value of one equals to one would indicate an ideal system where there is no loss. So, if we go by these Friis space propagation model we are going to use this particular equation to calculate the received signal strength at a distance d well a transmitter power is mentioned if nothing is mentioned regarding the antenna gains, one can assume unity antenna gain otherwise if there are directional antenna then one has to use the antenna gains corresponding to that particular direction.

If we look at this particular model what we will figure out that the received signal strength is inversely proportional to the square of d; that means the power decreases 20 dB per decade when expressed in algorithm terms.

(Refer Slide Time: 12:09)



Path Loss

- *Path Loss*: **Difference in transmitted power and received power**
  - •Represents signal attenuation as a +ve quantity and is measured in dB
  - •It may or may not include antenna gains
  - •For free space model

$$PL\,(\mathrm{dB}) = 10\log\frac{P_t}{P_r} = -10\log\left[\frac{G_t G_r \lambda^2}{(4\pi)^2 d^2}\right]$$

  - When antenna gains are excluded (unity antenna gain)

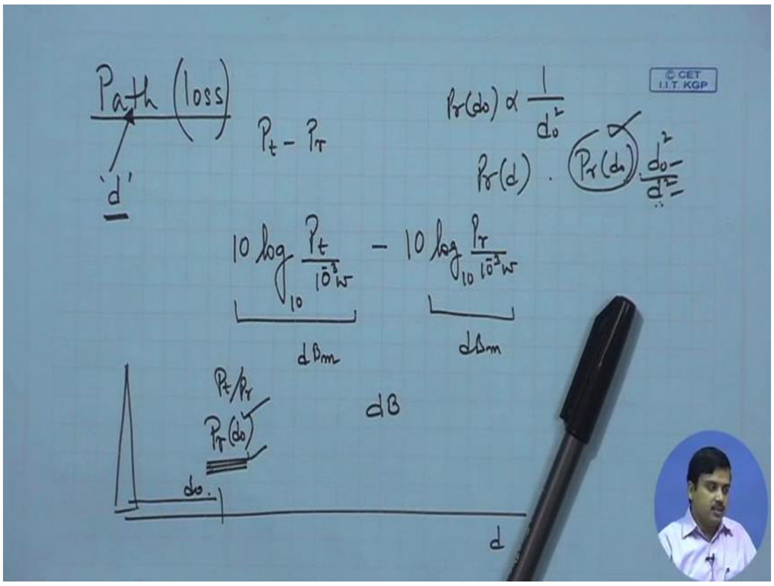
$$PL\,(\mathrm{dB}) = 10\log\frac{P_t}{P_r} = -10\log\left[\frac{\lambda^2}{(4\pi)^2 d^2}\right]$$

  - "Friis free space model is a valid predictor for P_r for *d* in the far field of transmission antenna"
    - *Where electrostatic and inductive fields become negligible*

source: Rappaport

So, path loss as is important parameter which will be used.

(Refer Slide Time: 12:21)



So, path loss is basically expression which is positive in quantity this is a very, very important term. So, it is positive in quantity and it may or may not include the antenna gain. So, when we talk of path loss it comes from the received signal strength in equation with respect to the transmitter is the function of transmitter receiver separation. So, this is a loss expression usually it is difference between the transmit power and the received power when expressed in the dB domain, and this is because of the path that is the separation between the transmitter and receiver that is d.

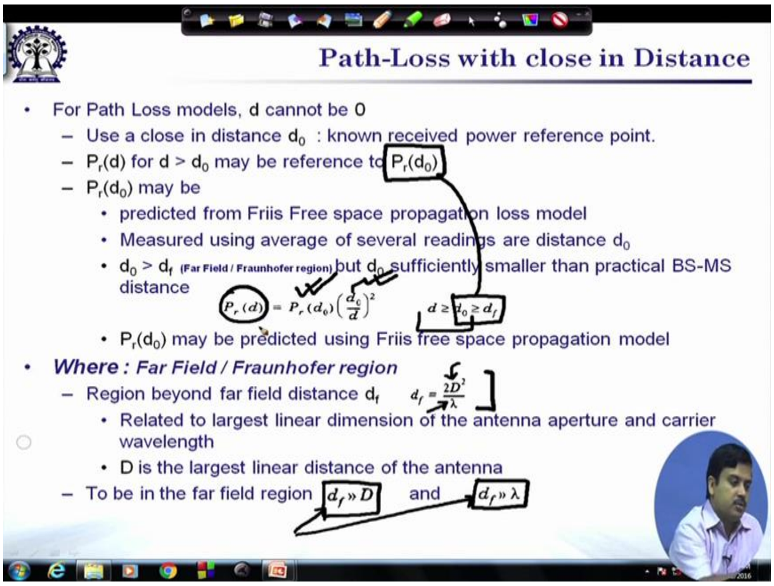
So, this particular count or this particular variable would be used significantly in predicting coverage for communication systems. Typically path loss is expressed as shown in this particular equation that pt in dB it is usually mentioned in the in the decibels is 10 log base 10 this log is usually in base 10 pt that is the transmit power divided by the receive power. So, if you open this up you are going to get 10 log base 10 of p t minus 10 log base 10 of p r. So, what we have is 10 log base 10 p t minus 10 log base 10 of Pr usually p t or Pr given in terms of milli watts. So, basically what we have over here is dB m dB in milli watts this is also given in dB milli watts.

So, when they are subtracted what you get the n result is dB if it is given in the linear scale of course, you have p t divided by p r. So, that is the ratio of the transmit power to the received power. So, which would be going to the denominator of the transmit power to calculate the received power. Now when antenna gains are excluded; that means, g t and g r the unity the equation becomes even simpler; that means, g t and g r have become now unity path loss would be 10 log of lambda squared by 4 pi d square coming from the Friis free space expression.

Now, be careful to note, we have a minus sign and therefore, inside the log things have got inverted because p t is here. So, an easy way to arrive at this expression would be p t divided by the expression that, we have over here is if we calculate from here p t divided by Pris equal to 4 pi d squared l divide by g t g r lambda that is what you see in the next expression now if you put a negative sign. So, basically this is a 4 pi squared d squared l divided by g t g r lambda squared and if you take a 10 log 10 and a negative sign. So, basically you are doing minus 10 log of you are putting it to the numerator g t g r lambda squared divided by 4 pi squared d squared l and when g t and g r are equal to unity, you have minus log base 10 lambda squared by 4 pi squared d squared l and that is what we have in the expression in the next slide.

So, that is the expression that is available with us which arrives directly from the Friis free space propagation model. Now this is a valid predictor for d in the far field of the antenna this means that we are at a sufficient distance from the antenna and where there are no electrostatic or inductive fields from the antenna further the other important thing, which you can see in particular expression is that in the denominator. We have d squared. So, if d takes on the value of 0 then, the path loss would go to very, very large number. So, this model is not valid for this model the receive signal strength would be infinity when d is 0. So, this model is not valid for d equals to 0.

(Refer Slide Time: 17:09)



Path-Loss with close in Distance

- For Path Loss models, d cannot be 0
  - Use a close in distance d_0 : known received power reference point.
  - $P_r(d)$ for $d > d_0$ may be reference to $\boxed{P_r(d_0)}$
  - $P_r(d_0)$ may be
    - predicted from Friis Free space propagation loss model
    - Measured using average of several readings are distance d_0
    - $d_0 > d_f$ (Far Field / Fraunhofer region) but d_0 sufficiently smaller than practical BS-MS distance

$$P_r(d) = P_r(d_0)\left(\frac{d_0}{d}\right)^2 \qquad d \geq \boxed{d_0 \geq d_f}$$

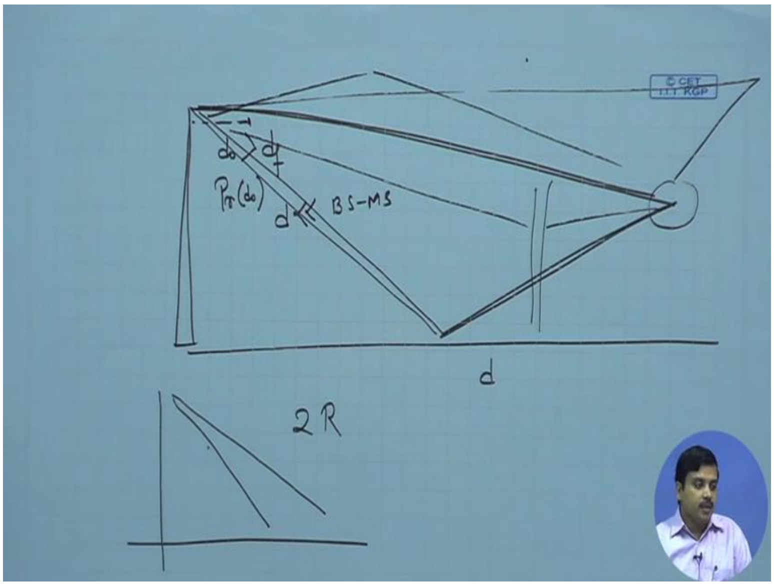
    - $P_r(d_0)$ may be predicted using Friis free space propagation model
- ***Where : Far Field / Fraunhofer region***
  - Region beyond far field distance d_f $\quad d_f = \frac{2D^2}{\lambda}$
    - Related to largest linear dimension of the antenna aperture and carrier wavelength
    - D is the largest linear distance of the antenna
  - To be in the far field region $\boxed{d_f \gg D}$ and $\boxed{d_f \gg \lambda}$

So, there are further improvements which are done in this particular model and to do this particular improvement some close in distance d is 0 has been used, now at d is 0 the received power P r d 0 is typically measured so; that means, suppose we are at a distance from the transmitter this is the transmitter this is d. So, if I make it 0 this one expression is going to fail.

So, we will identify some distance d0 at d0 received signal strength at d0 have to be measured a priori once this value is available then the received signal strength can be referenced to this particular d0 because in that case P r d 0 is proportional to 1 by d0 squared now d0 is known P r d 0 is known you have to get p received at d. When P r d 0 is given P r d 0 is known we have to multiply by d0 and divide by d square in that case this value is known to us. We are simply scaling the distance with these numbers and we will be able to get it of course, this d is restricted to be beyond a certain distance that is d0 as is as you seen in this expression. So, P r d 0 may be predicted from the Friis free space propagation loss model. So, basically using the earlier model we will find P r d 0 and it is measured using average of several readings. So, basically if the antenna is here we will be averaging at several readings will be taken at d0 and then P r d 0 would be calculated.

Once P r d 0 is calculated then we can calculate a calculate P r d following in this particular expression. So, for this it is required that the d0 must be greater than d f which is the far field or the Fraunhofer region, but d0 must be sufficiently smaller than practical base station and mobile station distance what does it mean?

(Refer Slide Time: 19:26)



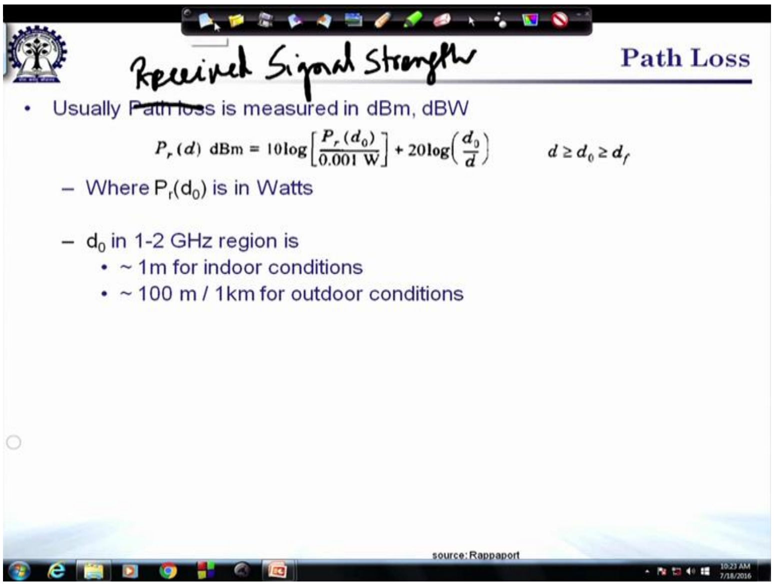
It means that the base station is here this is the d axis. So, we will measure it at certain separation d0 and call it P r d 0, which is the reference point this d0, this should be greater than the follow of a distance; that means, it should be in the far field and d should also be significantly less than a typical b s m s separation distance I mean, it cannot be very, very large it cannot be orders of kilometres it can be kilometres when base station separation distance would be like few tens of kilometres or so on.

So, going by this what we have over here is Pr received signal d is equal to P r d 0, where remember P r d 0 calculation has d0 in the denominator. So, if we multiply by d0 then, the d0 and d0 cancels up what you are left with is transmit power divided by d squared subject to the condition that d is greater than d0 and d0 is greater than d f; that means, this particular formula restricts the value of d from acquiring the value of 0. Therefore, vendoring the formula useful, P r d 0 may be predicted using Friis free space expression as we have said now if we concentrate on the far field region it can be calculated using the expression here.

So, it should be greater than 2d squared by lambda where, d is the largest linear dimension of the antenna and lambda is the wave length. So, d f is usually calculated in this form and to be in the far field we have to maintain the criteria the d f is greater than greater d and d f is greater than lambda. So, once you have calculated or found out what is d f following these expressions you have to ensure that d0 is greater than d f after you have found this one has to measure P r d 0.

Once P r d 0 has been measured; that means, this particular value is given and d0 is also given then we can calculate P r d that is received signal strength as a function of distance provided d is greater than d0 for d less than d0. This particular model cannot be used; every model has its own limitations and its usefulness. So, we should always remember when we taking a model we are careful with the set of assumption that comes to the particular model right moving ahead.

(Refer Slide Time: 22:28)



Received Signal Strength

Path Loss

- Usually ~~Path loss~~ is measured in dBm, dBW

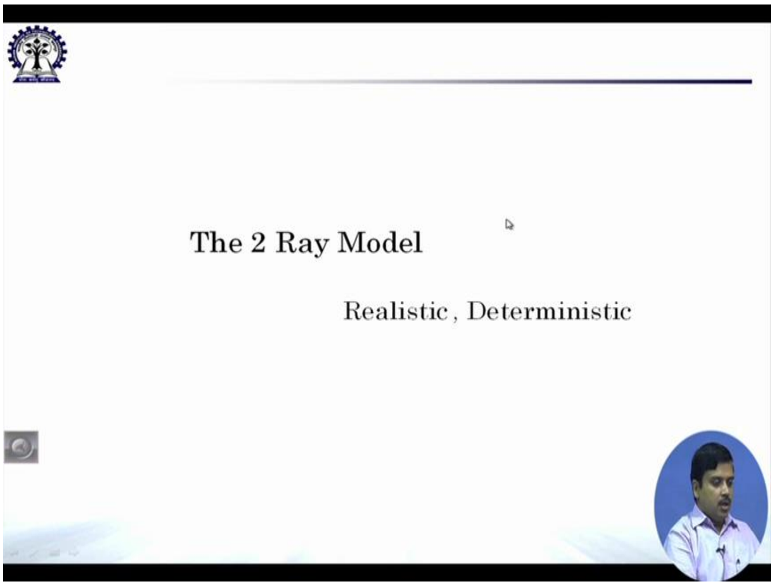
$$P_r(d)\ \text{dBm} = 10\log\left[\frac{P_r(d_0)}{0.001\ \text{W}}\right] + 20\log\left(\frac{d_0}{d}\right) \qquad d \ge d_0 \ge d_f$$

  - Where $P_r(d_0)$ is in Watts
  - d_0 in 1-2 GHz region is
    - ~ 1m for indoor conditions
    - ~ 100 m / 1km for outdoor conditions

source: Rappaport

So, what this particular expression now if we calculate the path loss the path loss is given in this expression sorry they received signal strength would be P r d in dB m as the received signal strength in d0 divided by 1 milli watt plus the logarithm of d0 by d there was 10 log d0 by d there was square above this 2 has come out. So, instead of 10 log we now have 20 log and d0 is typically one meter for indoor around 100 meters for outdoor it can be 1 kilometre if the separation distance of the transmitter will be few tens of kilometres sorry this particular thing is to be corrected it is not path loss this is the received signal strength is measured in dB m or dB w the received signal strength.

(Refer Slide Time: 23:42)

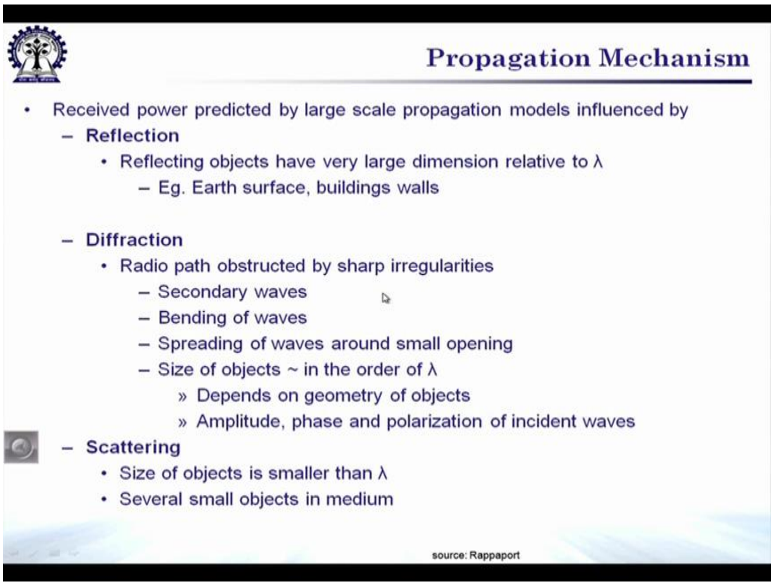


The 2 Ray Model

Realistic , Deterministic

So, as we move further we go into one of the important models which is the two ray model or which is little bit closer to realistic which is no longer free space equation it includes the propagation effects and this particular model is deterministic, but still it will give us some indication of the received signal strength.

(Refer Slide Time: 24:01)



Propagation Mechanism

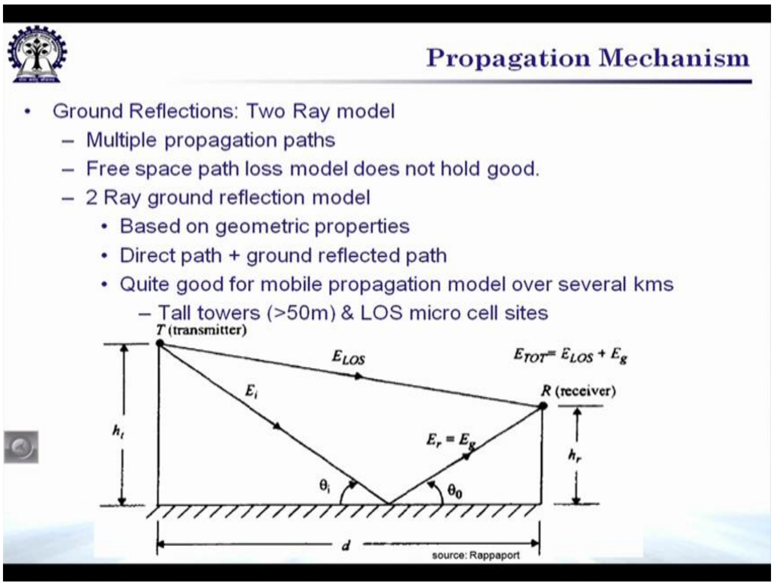
- Received power predicted by large scale propagation models influenced by
  - **Reflection**
    - Reflecting objects have very large dimension relative to λ
      - Eg. Earth surface, buildings walls
  - **Diffraction**
    - Radio path obstructed by sharp irregularities
      - Secondary waves
      - Bending of waves
      - Spreading of waves around small opening
      - Size of objects ~ in the order of λ
        - » Depends on geometry of objects
        - » Amplitude, phase and polarization of incident waves
  - **Scattering**
    - Size of objects is smaller than λ
    - Several small objects in medium

source: Rappaport

So, typical propagation phenomenon that happens when the signal propagates from the transmitter to the receiver as we have seen in a diagram before that could be line of site. We have calculated the expression of received signal strength when, there is line of site there could be reflection from the ground there could be reflection from buildings there could be diffraction from edges there could be scattering from land post or trees excreta when the cumulative signal comes to the receiver.

So, one of the simplest models that we would encounter is the two ray model which captures the direct line of site.

(Refer Slide Time: 24:53)



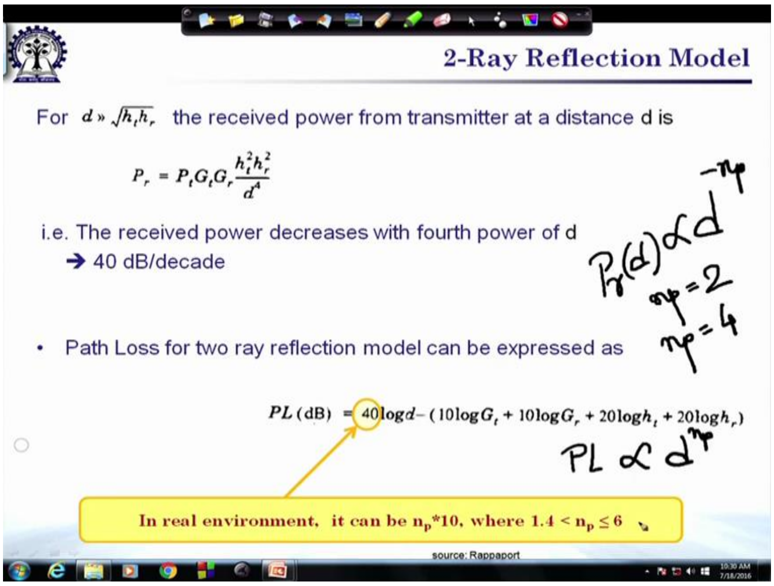
Propagation Mechanism

- Ground Reflections: Two Ray model
  - Multiple propagation paths
  - Free space path loss model does not hold good.
  - 2 Ray ground reflection model
    - Based on geometric properties
    - Direct path + ground reflected path
    - Quite good for mobile propagation model over several kms
      - Tall towers (>50m) & LOS micro cell sites

source: Rappaport

A reflected path later on we will see models which captures the different effects as shown in this particular slide. So, this is the famous 2 ray model and it has 2, two rays. So, basically one direct line of site one reflected and it is assumed that this separation distance is very, very large compared to the height of the transmitter and the receiver. So, there is a transmitting antenna height there is a received antenna height and the electric field because of line of site can be calculated electric field due to ground reflected ray can be calculated and the total signal strength at the receiver of the total e field would be vectorial addition of the line of site as well as the ground reflected ray.

(Refer Slide Time: 25:41)



2-Ray Reflection Model

For $d \gg \sqrt{h_t h_r}$ the received power from transmitter at a distance d is

$$P_r = P_t G_t G_r \frac{h_t^2 h_r^2}{d^4}$$

i.e. The received power decreases with fourth power of d

→ 40 dB/decade

- Path Loss for two ray reflection model can be expressed as

$$PL\,(\mathrm{dB}) = \boxed{40} \log d - (10 \log G_t + 10 \log G_r + 20 \log h_t + 20 \log h_r)$$

In real environment, it can be n_p*10, where $1.4 < n_p \le 6$

source: Rappaport

$P_r(d) \propto d^{-n_p}$

$n_p = 2$

$n_p = 4$

$PL \propto d^{n_p}$

So, when these 2 are added and a whole set of expressions are resolved what we end up is with the expression as shown in this particular slide here that the received signal strength is equal to the transmitted power multiplied by transmit antenna gain multiplied by received antenna gain, which we have seen before. Now we have few more additional terms we have the antenna height of the transmitter as well as we have the antenna height of the receiver. So, received signal strength as per this formula is dependent upon transmitter and receiver height or you can say that this particular model captures the effect of antenna height because typically we know initial level that as you increase the height of antenna your signal strength becomes better. So, this is one model captures sum of those effects whereas, the most interesting thing as we see that has happened because of the 2 ray model; that means, direct site direct line of site and the reflected path is that the denominator exponent which was d squared has, now become d to the power of 4.

Now, what does it indicate it simply indicates that previously, if the signal strength was falling around 20 dB per decade? Now it will fall at 40 dB per decade. So, it falls at a much-much faster rate than in the free space expression and what we have seen is only by taking 2 rays only by taking 2 rays between the transmitter and the receiver the received signal strength is now decreasing to the fourth power of d. Now when, there are multiple effects; that means, a scattering diffraction and many others this number will not necessarily be 4, but could be something else this is one of the simplistic model now, which captures somewhat close to reality and it gives numbers which are quite meaning full as we will see shortly in some of the results.

The path loss expression for the 2 ray model can be expressed as path loss in dB is 40 log d this is the separation between the transmitter and receiver and there is transmitter antenna gain, receive antenna gain, height of the transmitter and height of the receiver. Now one of the assumptions as mentioned is height of the transmitter and receiver must be much-much smaller than the separation distance and also has been indicated by this particular condition. So, this would also indicate that the angles are very, very small and they are almost at a gracing angle.

So, if we look at this expression in actual path loss expression what happens is this path loss exponent is no longer of a fixed value of earlier it was 20. Now it is 40 as can be read from this particular expression in real environments we can represent these numbers as shown over here n p multiplied by 10 or we generalise like 10 n p. So, that n p is the path loss exponent this is the path loss exponent and it lies anywhere, in the range of 1.4 to 6. Now this is not restrictive at all these numbers are from measurements and typically they would lie in the range of 1.4 to 6 as has been observed in many-many situations.

So, if we remember this expression typically path loss we can say is proportional to separation distance raised to the power of n p or received signal strength Pr as a function of d is proportional to the separation distance raised to the power of minus n p, what we have seen is for free space propagation model the n p is equal to 2 for 2 ray model. What we have seen is n p is equal to 4 in practice this n p can be vary between 1.4 and 6 as has been generally observed, but things could go worse on either directions under different conditions.

So, we stop this particular lecture in path loss we continue to study some more effects of large scale propagation model in the next lecture.