Chapter 3

Mobile Radio Propagation:
Large-Scale Path Loss

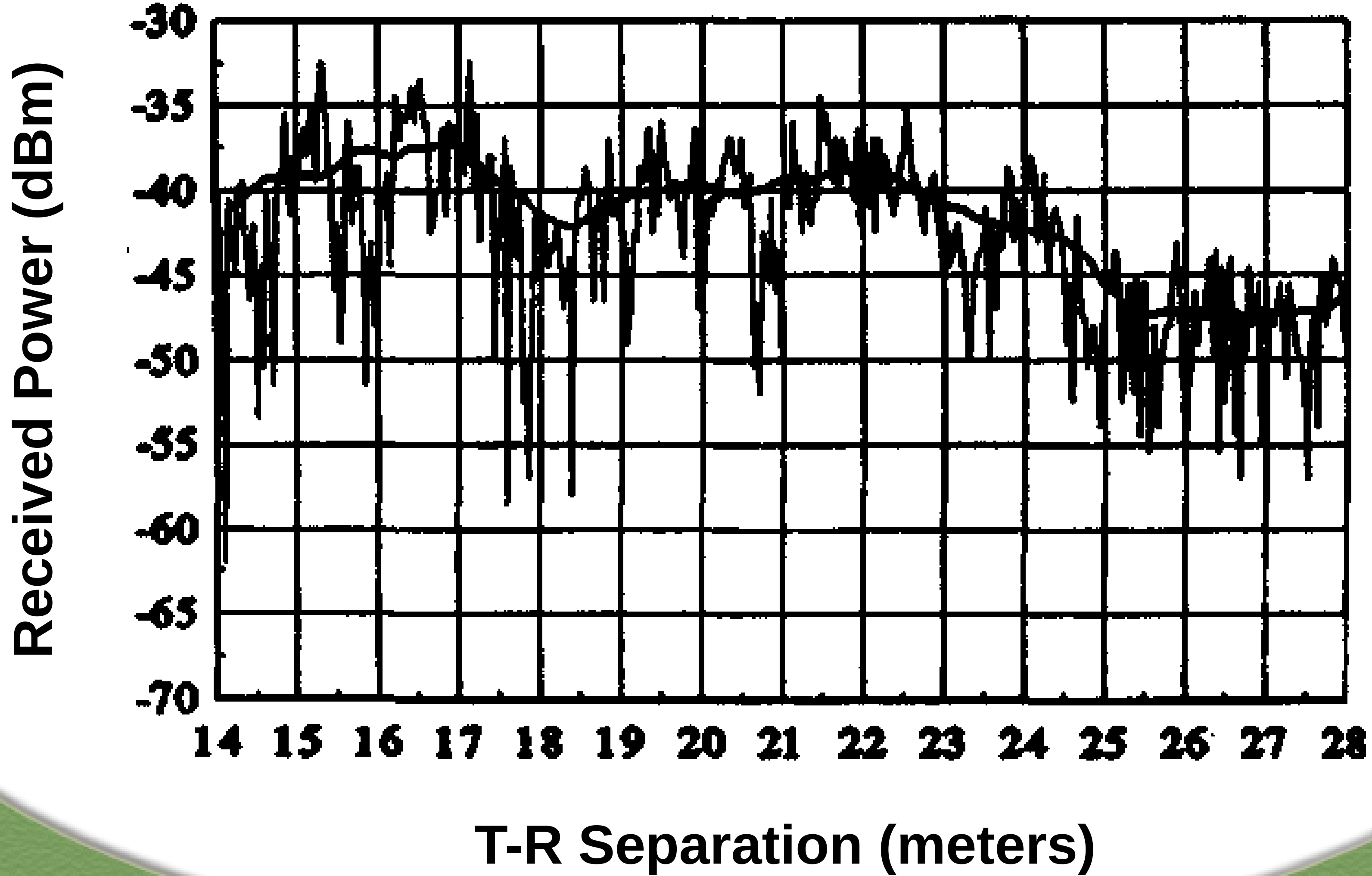
Research the variation law of wireless signal in different scale ranges, and establish the corresponding models

Large-Scale

Small-Scale

- Research method : Forming specific statistical models based on theoretical analysis and practical measurement

Two types of Fading



Two types of Fading

First Question :

What is the attenuation law of the mean power of wireless signal, over large propagation distances ?

—— Large-scale path loss

Second Question :

How to characterize the rapid fluctuations of the received signal strength, over a short distance or time duration ?

—— Small-scale fading

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2. Three Basic Propagation Mechanism
3. Practical Link Budget Design Using Path Loss Models
4. Outdoor Propagation Models
5. Indoor Propagation Models

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2. Three Basic Propagation Mechanism
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Free Space Propagation Model

Free space

A clear, unobstructed Line-of-Sight (LOS) path between the transmitter and receiver.

An example: the satellite communication systems

Free Space Propagation Model

(PP.93)

In free space, the received power is predicted by Friis equation

$$P_r(d) = \frac{P_t G_t G_r \lambda^2}{(4\pi)^2 d^2 L}$$

$P_r(d)$: received power with a distance d between the *Tx* and *Rx*

P_t : transmitted power

G_t : transmitting antenna gain

G_r : receiving antenna gain

λ : wavelength of the electromagnetic wave

L : System loss factor L (L>=1), usually due to transmission line attenuation, filter losses, and antenna losses in communication systems (L=1 indicates no loss in the system hardware)

EIRP & ERP

$$P_r(d) = \frac{\boxed{P_t G_t} G_r \lambda^2}{(4\pi)^2 d^2 L}$$

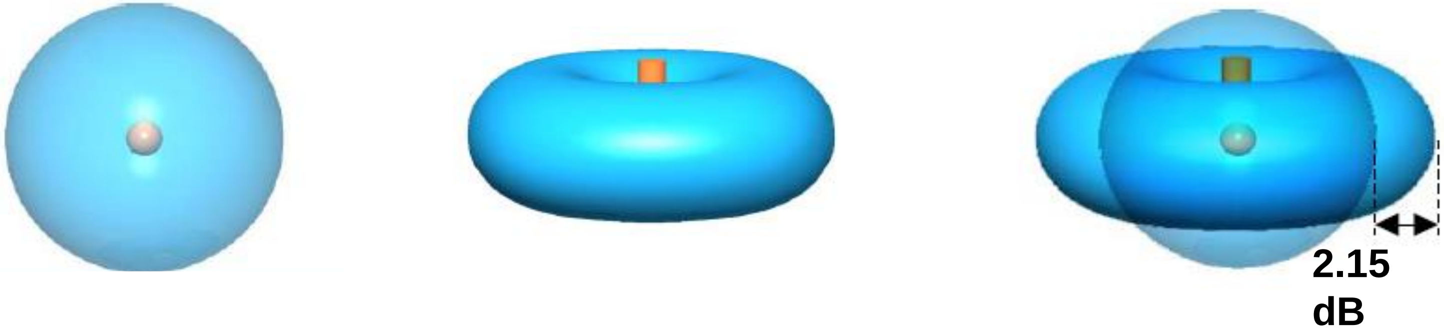
- **EIRP: Effective Isotropic Radiated Power.**

  It denotes the maximum radiated power as compared to an isotropic radiator.

- **ERP: Effective Radiated Power.**

  It denotes the maximum radiated power as compared to a half-wave dipole antenna.

EIRP & ERP



- **In practice, antenna gains *G* are given in units of**
  dBi (dB gain with respect to an isotropic antenna) or
  dBd (dB gain with respect to a half-wave dipole).

$$EIRP = P_t G_t$$

dBi = dBd + 2.15 dB **EIRP = ERP + 2.15 dB**

Far-field Region

"Fraunhofer Region"

$$P_r(d) = \frac{P_t G_t G_r \lambda^2}{(4\pi)^2 d^2}$$

- **The Friis equation is valid only when**

$$d > d_f$$

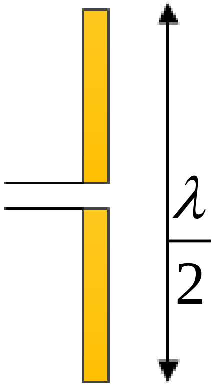
- **The far-field distance d_f is defined as**

$$d_f = \frac{2D^2}{\lambda}$$

D **: largest dimension of transmitting antenna aperture**

λ **: carrier wavelength**

half-wave dipole antenna

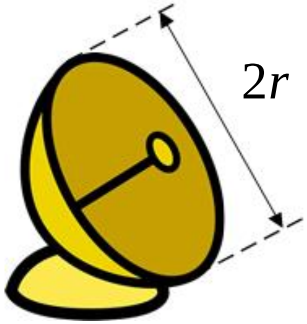


$$D = \frac{\lambda}{2}$$

$$\Downarrow$$

$$d_f = \frac{\lambda}{2}$$

parabolic antenna



$$D = 2r$$

$$\Downarrow$$

$$d_f = \frac{8r^2}{\lambda}$$

9dBi antenna & 3dBi antenna

Path Loss

The *path loss* represents signal attenuation as a positive difference (in dB) between the effective transmitted power and the received power.

Path Loss

$$P_r(d) = \frac{P_t G_t G_r \lambda^2}{(4\pi)^2 d^2}$$

- The path loss for the free space model when antenna gains are included is given by quantity measured in dB, is defined as the

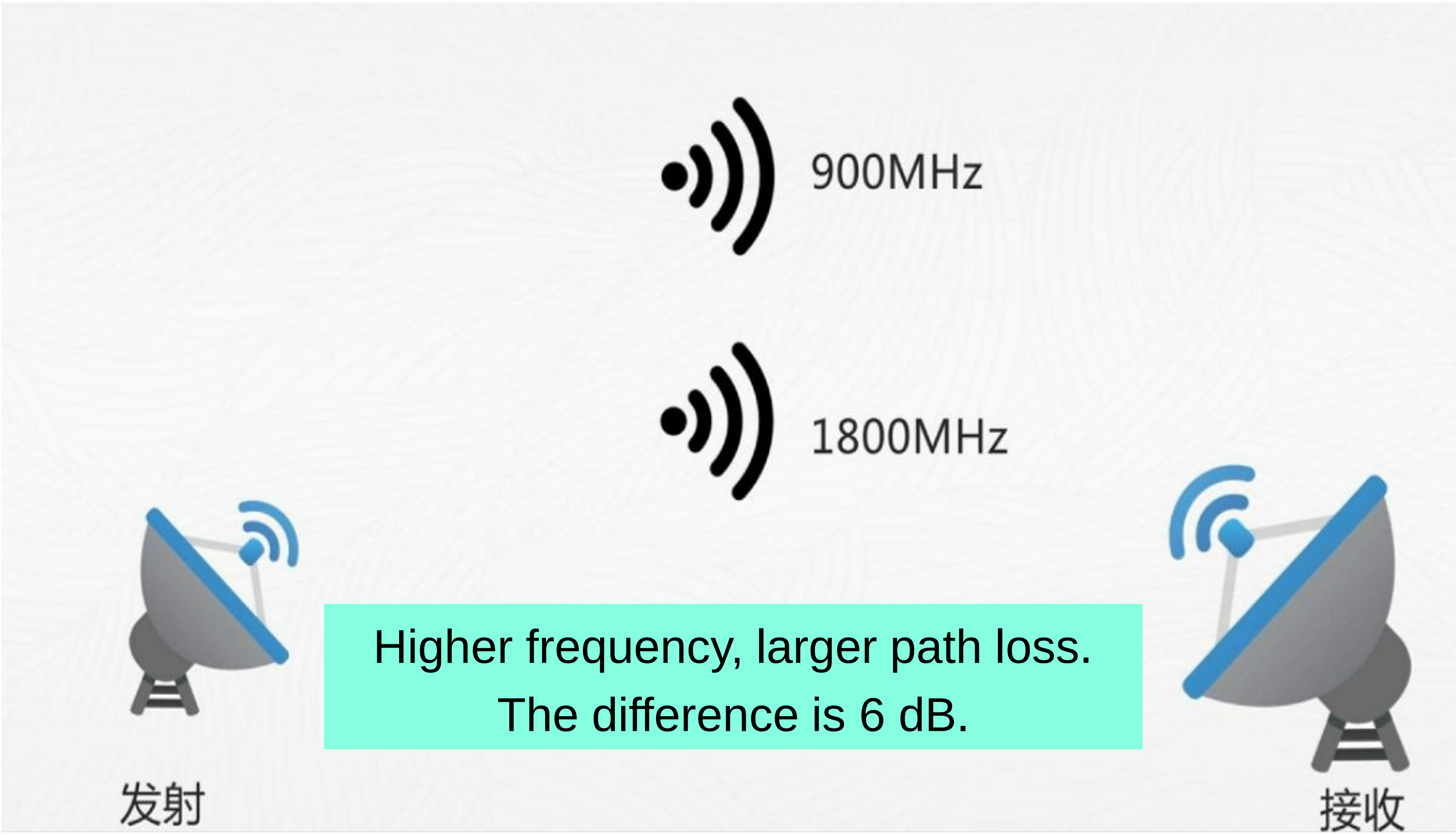
$$PL(dB) = 10\log\frac{P_t}{P_r} = -10\log\left[\frac{G_t G_r \lambda^2}{(4\pi)^2 d^2}\right]$$

- When antenna gains are excluded, the antennas are assumed to have unity gain, and path loss is given by

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

$$PL(dB) = 32.44 + 20\lg f + 20\lg d \quad (f : \mathrm{MHz},\ d : k\mathrm{m})$$

Path Loss



Higher frequency, larger path loss.
The difference is 6 dB.

Path Loss

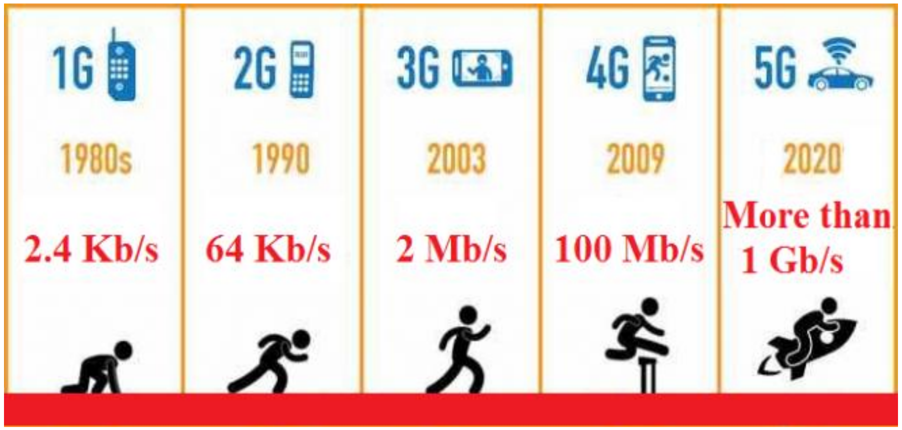
Larger distance, larger path loss.

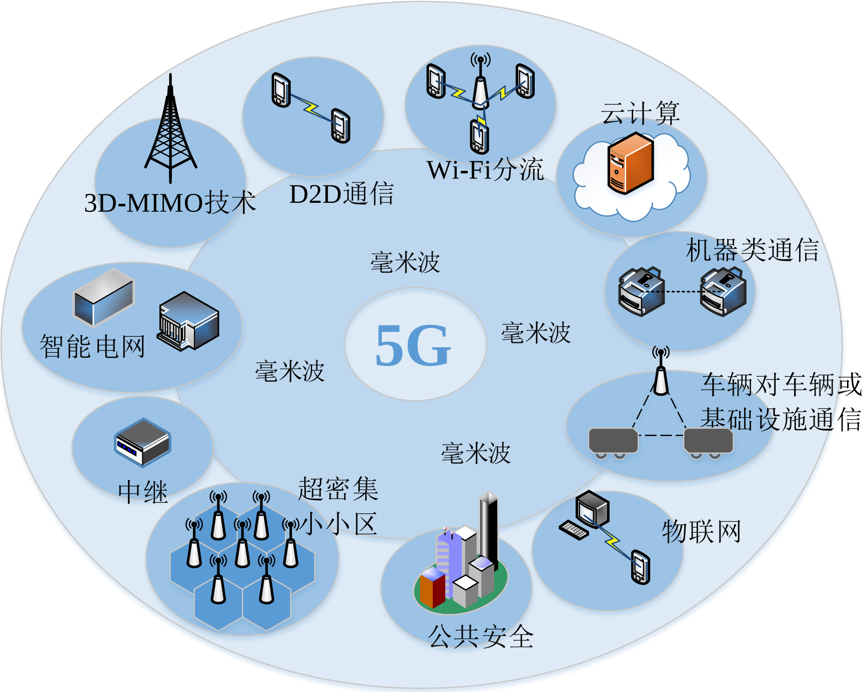
The growth rate is 20dB/decade .

发射

接收

Question





Path loss :

4G *VS*. 5G (Millimeter-wave)

Reference Distance

$$P_r(d) = \frac{P_t G_t G_r \lambda^2}{(4\pi)^2 d^2}$$

- It is clear that equation does not hold for d=0. For this reason, large-scale propagation models use a known received power reference point. The received power, Pr(d), at any distance $d>d_0$, may be related to Pr at d_0 .

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

- If P_r is in units of dBm or dBW, the received power is given by

$$P_r(d) = P_r(d_0) - 20\lg(\frac{d}{d_0})$$

$$PL(d) = 10\lg\frac{P_t}{P_r(d)} = PL(d_0) + 20\lg(\frac{d}{d_0})$$

Reference Distance

$$P_r(d)\ \mathrm{dBm} = P_r(d_0)\ \mathrm{dBm} - 20\lg\left(\frac{d}{d_0}\right) \qquad d \geq d_0 \geq d_f$$

$$PL(d)\ \mathrm{dB} = PL(d_0)\ \mathrm{dB} + 20\lg\left(\frac{d}{d_0}\right)$$

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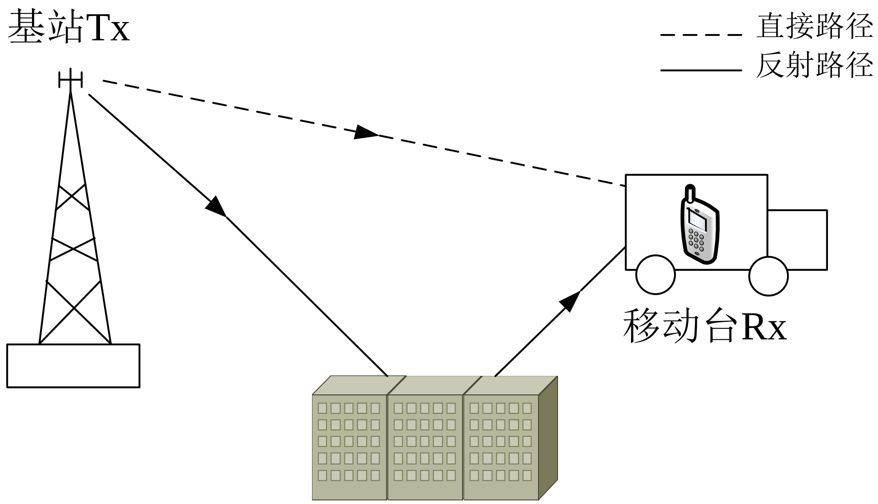
Three Basic Propagation Mechanisms

(PP.99)

- **Reflection**
- **Diffraction**
- **Scattering**

Reflection

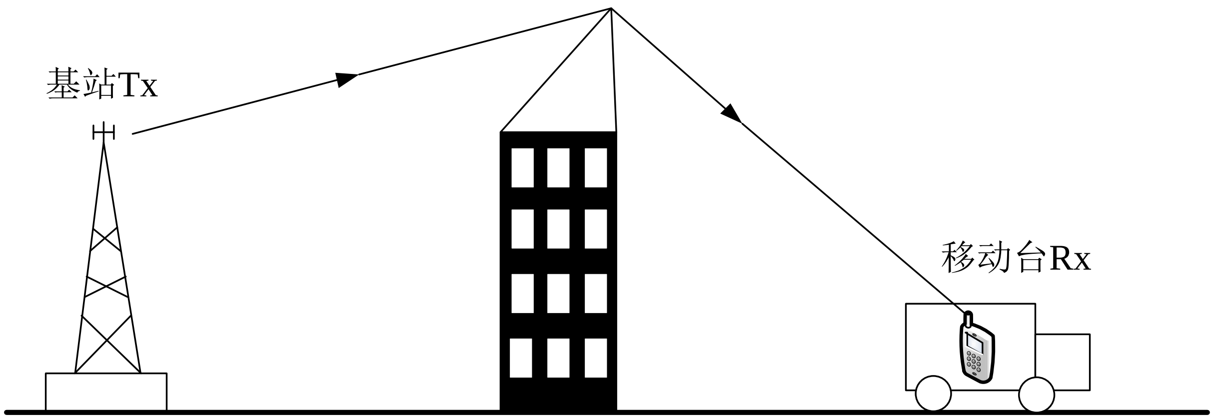
Reflection : occurs when a propagating wave impinges upon an object which has very large dimensions when compared to the wavelength of the wave.



***Reflection occurs from the surface of the earth and from buildings and walls*.**

Diffraction

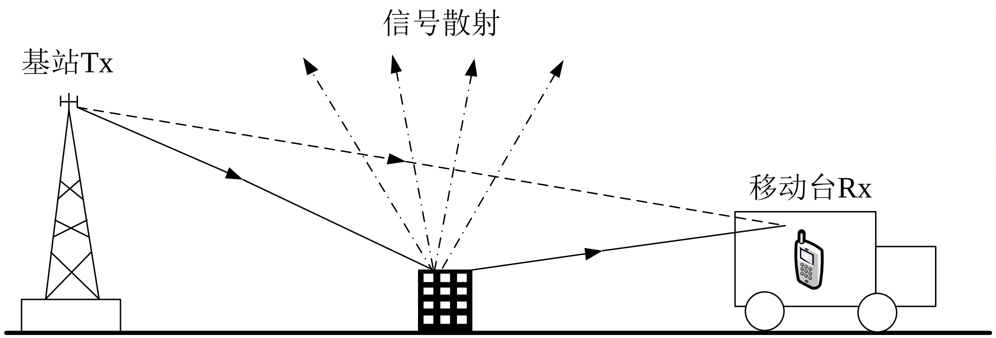
Diffraction : occurs when the radio path between the transmitter and receiver is obstructed by a surface that has sharp irregularities (edges).



The secondary waves are present, giving rising to a bending of waves around the obstacle.

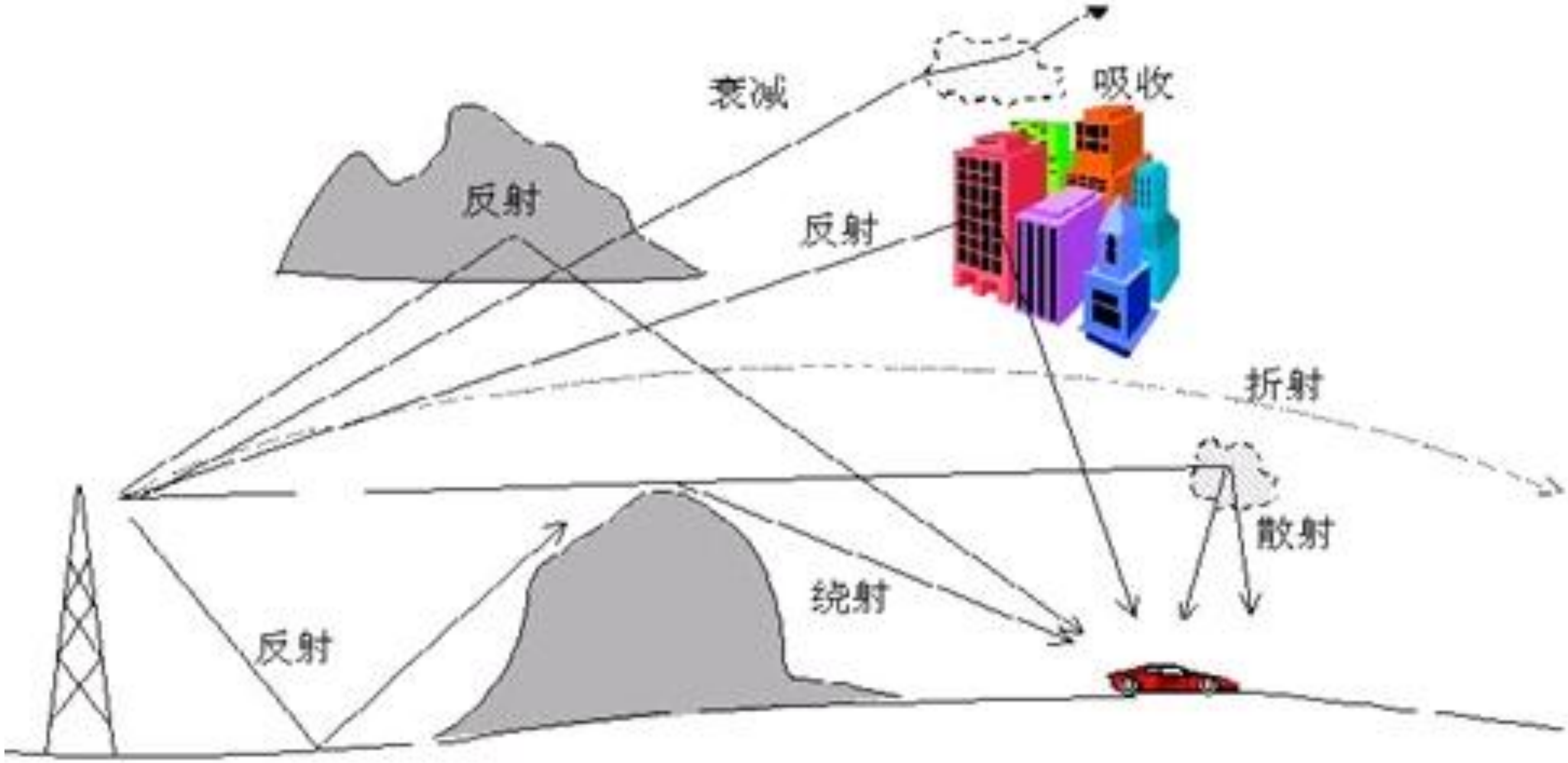
Scattering

Scattering : occurs when the medium through which the wave travels consists of objects with dimensions that are small compared to the wavelength, and where the number of obstacles per unit volume is large.



***Scattered waves are produced by rough surfaces, small objects, or other irregularities in the channel*.**

Radio Propagation Mechanism



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Log-distance path loss model

(PP.121)

Both theoretical and measurement-based propagation models indicate that average received signal power decreases logarithmically with distance, whether in outdoor or indoor channels. The average large-scale path loss for an arbitrary T-R separation is expressed as a function of distance by using path loss exponent *n*.

$$\overline{PL}(d) \propto \left(\frac{d}{d_0}\right)^n$$

$$\overline{PL}(d) = \overline{PL}(d_0) + 10n\log(\frac{d}{d_0})$$

n is the path loss exponent which indicates the rate at which the path loss increases with distance

d_0 is the close-in reference distance

d is the T-R separation distance

$$\overline{Pr}(d)\ \text{dBm} = \overline{Pr}(d_0)\ \text{dBm}\ -\ 10n\log(\frac{d}{d_0})$$

Relation between *PL* and *Pr*

$$\left.\begin{aligned}\overline{Pr}(d)\ \text{dBm} &= \overline{Pr}(d_0)\ \text{dBm} - 10n\lg\left(\frac{d}{d_0}\right)\\ \overline{PL}(d)\ \text{dB} &= \overline{PL}(d_0)\ \text{dB} + 10n\lg\left(\frac{d}{d_0}\right)\end{aligned}\right\} \Rightarrow$$

$$\overline{PL}(d) - \overline{PL}(d_0) = \overline{Pr}(d_0) - \overline{Pr}(d)$$

Table 3.2: Path-loss exponents

ENVIRONMENT	Path loss exponent, *n*
Free space	2
Ideal specular reflection	4
Urban cells	2.7-3.5
Urban cells, shadowed	3-5
In building, line-of-sight	1.6-1.8
In building, obstructed path	4-6
In factory, obstructed path	2-3

Example 1

If a transmitter produces power: Pt=50w, receive sensitivity (minimum usable signal level) is -100dbm. Assume d_0=100m, with a 900MHz carrier frequency, n=4, G_t=G_r=1. Find the coverage distance d.

$$P_r(d_0) = \frac{P_t G_t G_r \lambda^2}{(4\pi)^2 d_0^2 L} = \frac{50(1)(1)(1/3)^2}{(4\pi)^2(100)^2(1)} = (3.5 \times 10^{-6})\ \mathrm{W} = 3.5 \times 10^{-3}\ \mathrm{mW}$$

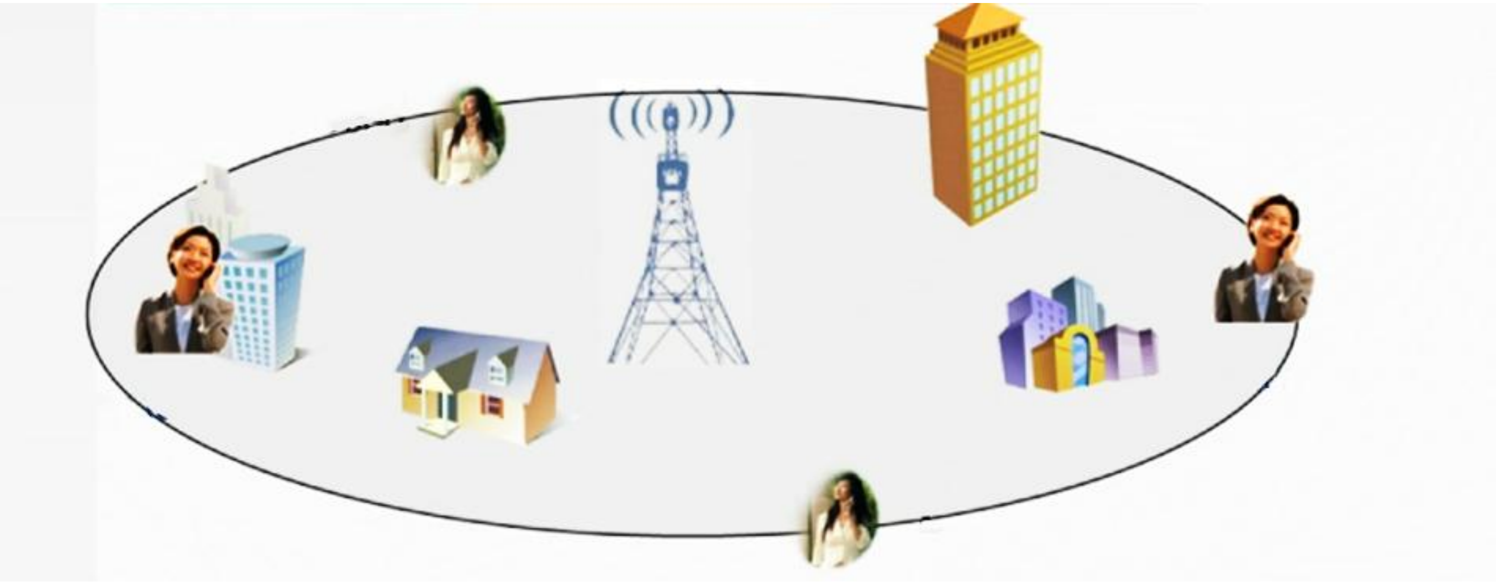
$$P_r(d_0)\,(\mathrm{dBm}) = 10\log P_r(\mathrm{mW}) = 10\log(3.5 \times 10^{-3}\ \mathrm{mW}) = -24.5\ \mathrm{dBm}$$

$$10n\lg\left(\frac{d}{d_0}\right) = \overline{Pr}(d_0) - \overline{Pr}(d) = -24.5 - (-100) = 75.5\ \mathrm{dB}$$

If n=4, $\log(d/d_0)$ =75.5/40 =1.8875, d/d_0 =77.18, d=7718m

$$\overline{Pr}(d) = \overline{Pr}(d_0) - 10n\lg\left(\frac{d}{d_0}\right)$$

Environment parameter



Effects of random shadowing

The strength of received signal is finally a logarithmic normal distribution when the Mobile station is far from the Base station.

Log-normal Shadowing

(PP.122)

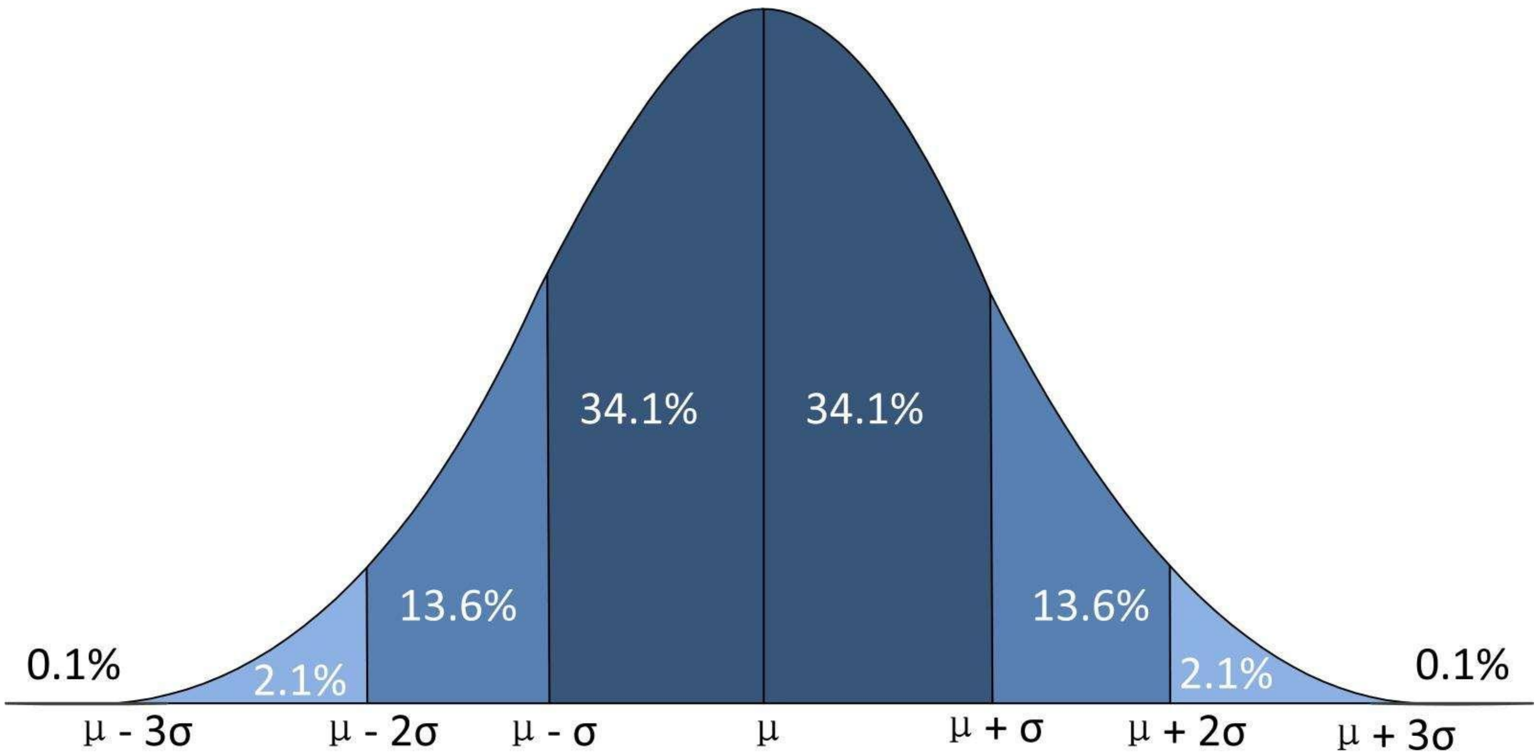
The model in Equation (4.68) does not consider the fact that the surrounding environmental clutter may be vastly different at two different locations having the same T-R separation. This leads to measured signals which are vastly different than the *average* value predicted by the Equation (4.68).

$$PL(d)[dB] = \overline{PL}(d) + X_\sigma = \overline{PL}(d_0) + 10n\log(\frac{d}{d_0}) + X_\sigma$$

$$\Pr(d)[dBm] = \overline{\Pr}(d) + X_\sigma = \overline{\Pr}(d_0) - 10n\log(\frac{d}{d_0}) + X_\sigma$$

Normal Distribution

$$X_\sigma \sim N(\mu, \sigma) \qquad \mu = 0$$



Log-normal Shadowing

(PP.123)

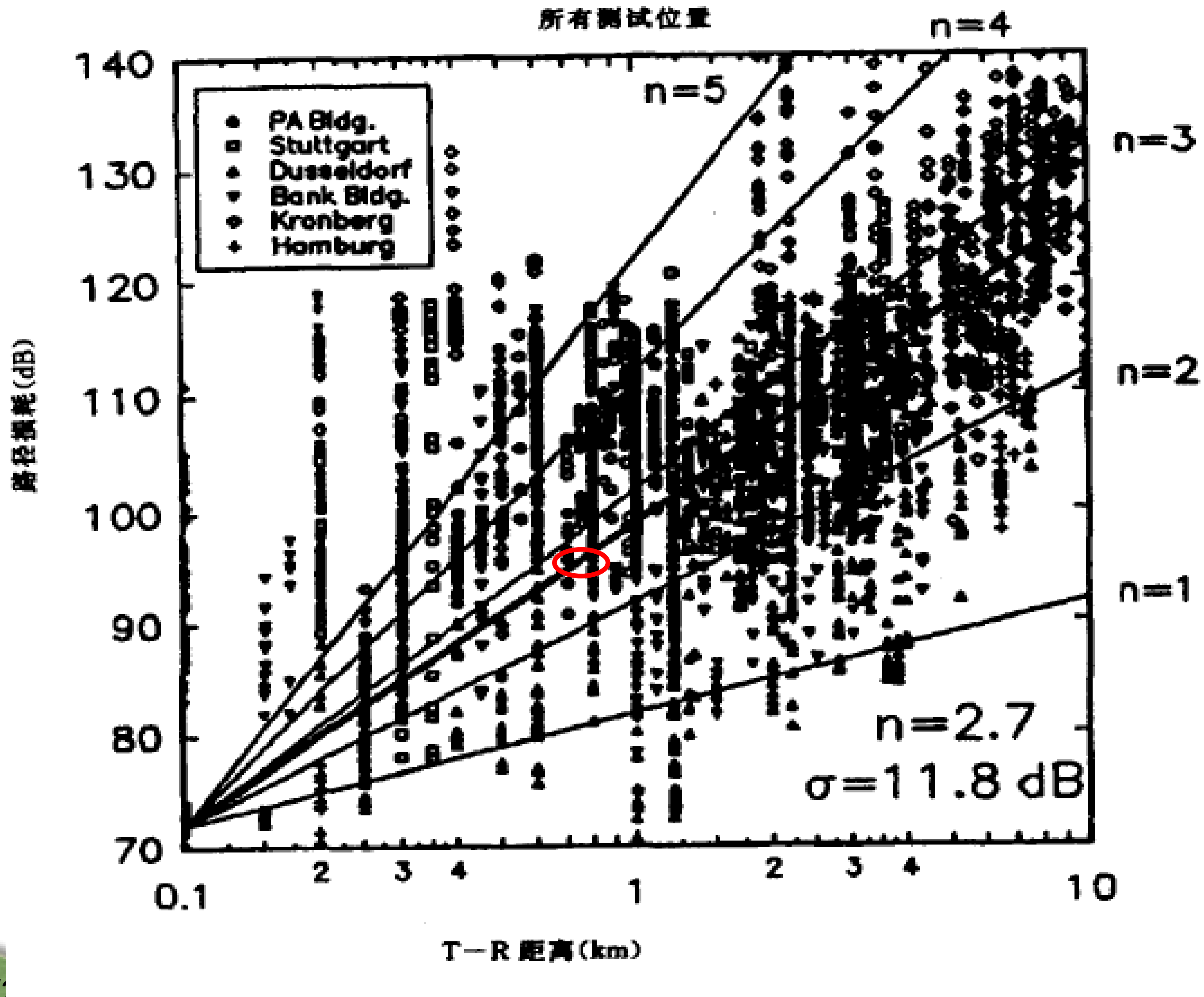


图 3.17 德国许多城市测试数据和相应的 MMSE 路径损耗模型分布图

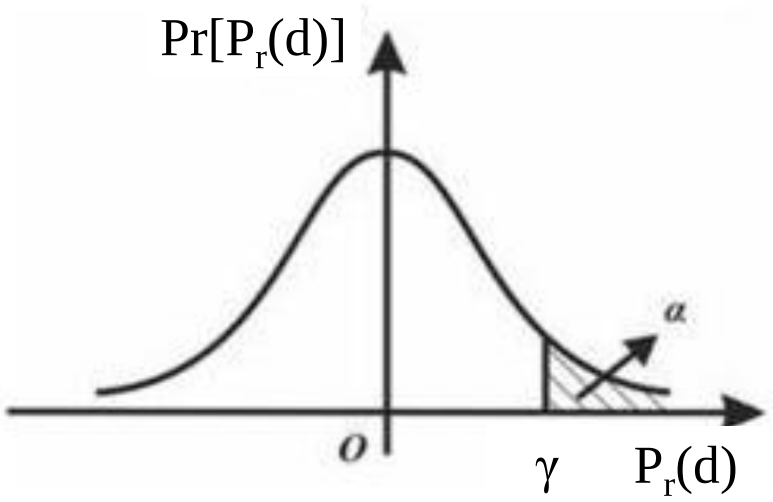
Log-normal Shadowing

- Due to environmentally scattered fields along a path, signal levels received at distance d fluctuate randomly around the mean value given by the path-loss exponent $n \Rightarrow$ some cell locations may be below a desired receive level, γ
- It turns out that the path-loss at a distance d, $PL(d)$ measured in decibel, is Gaussian distributed with standard deviation σ => shadow effect gives a log-normal distribution of receive power

$$\boxed{P_r(d) \sim N(\overline{P_r}(d), \sigma)}$$

Q-Function

$$P_r(d) \sim N(\overline{P_r}(d), \sigma)$$



$$Pr[P_r(d) > \gamma] = Q\left(\frac{\gamma - \overline{P_r(d)}}{\sigma}\right)$$

$$Pr[P_r(d) < \gamma] = Q\left(\frac{\overline{P_r(d)} - \gamma}{\sigma}\right)$$

- The Q-function may be used to determine the probability that the received signal level will exceed (or fall below) a particular level.

Q-Function

(PP.411)

- The Q-function is defined as

$$Q(z) = \frac{1}{\sqrt{2\pi}}\int_{z}^{\infty}\exp\left(-\frac{x^2}{2}\right)dx = \frac{1}{2}\left[1 - erf\left(\frac{z}{\sqrt{2}}\right)\right]$$

$$Q(z) = 1 - Q(-z)$$

表 D.1 Q 函数列表

z	Q(z)	z	Q(z)
0.0	0.50000	2.0	0.02275
0.1	0.46017	2.1	0.01786
0.2	0.42074	2.2	0.01390
0.3	0.38209	2.3	0.01072
0.4	0.34458	2.4	0.00820
0.5	0.30854	2.5	0.00621
0.6	0.27425	2.6	0.00466
0.7	0.24196	2.7	0.00347
0.8	0.21186	2.8	0.00256
0.9	0.18406	2.9	0.00187
1.0	0.15866	3.0	0.00135
1.1	0.13567	3.1	0.00097
1.2	0.11507	3.2	0.00069
1.3	0.09680	3.3	0.00048
1.4	0.08076	3.4	0.00034
1.5	0.06681	3.5	0.00023
1.6	0.05480	3.6	0.00016
1.7	0.04457	3.7	0.00011
1.8	0.03593	3.8	0.00007
1.9	0.02872	3.9	0.00005

Example 2

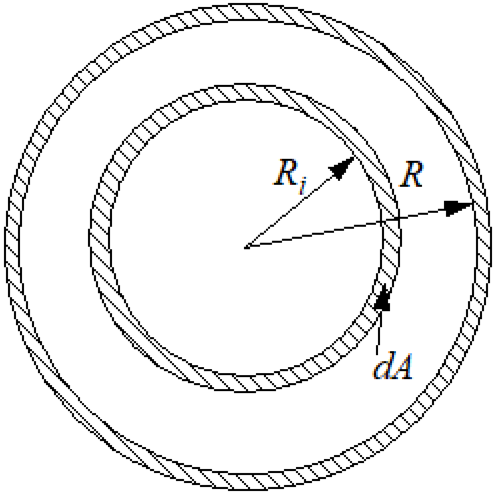
- A local average signal strength field measurements , the measured data fit a distant-dependent mean power law model having a log-normal distribution about the mean. Assume the mean power law was found to be $P_r(d) \propto d^{-3.5}$. If a signal of 1mW was received at d_0=1m from the transmitter, and at a distance of 10m, 10% of the measurements were stronger than -25dBm, define the standard deviation σ , for the path loss model at d=10m.

$$\Pr\left[P_r(d) > \gamma\right] = Q\left(\left\{\gamma - \overline{P_r}(d)\right\} / \sigma\right)$$

$$\overline{Pr}(d) = \overline{Pr}(d_0) \; - \; 10n\lg\left(\frac{d}{d_0}\right)$$

Percentage of Coverage Area

- U(γ) denotes the percentage of area with a received signal that is equal or greater than γ.

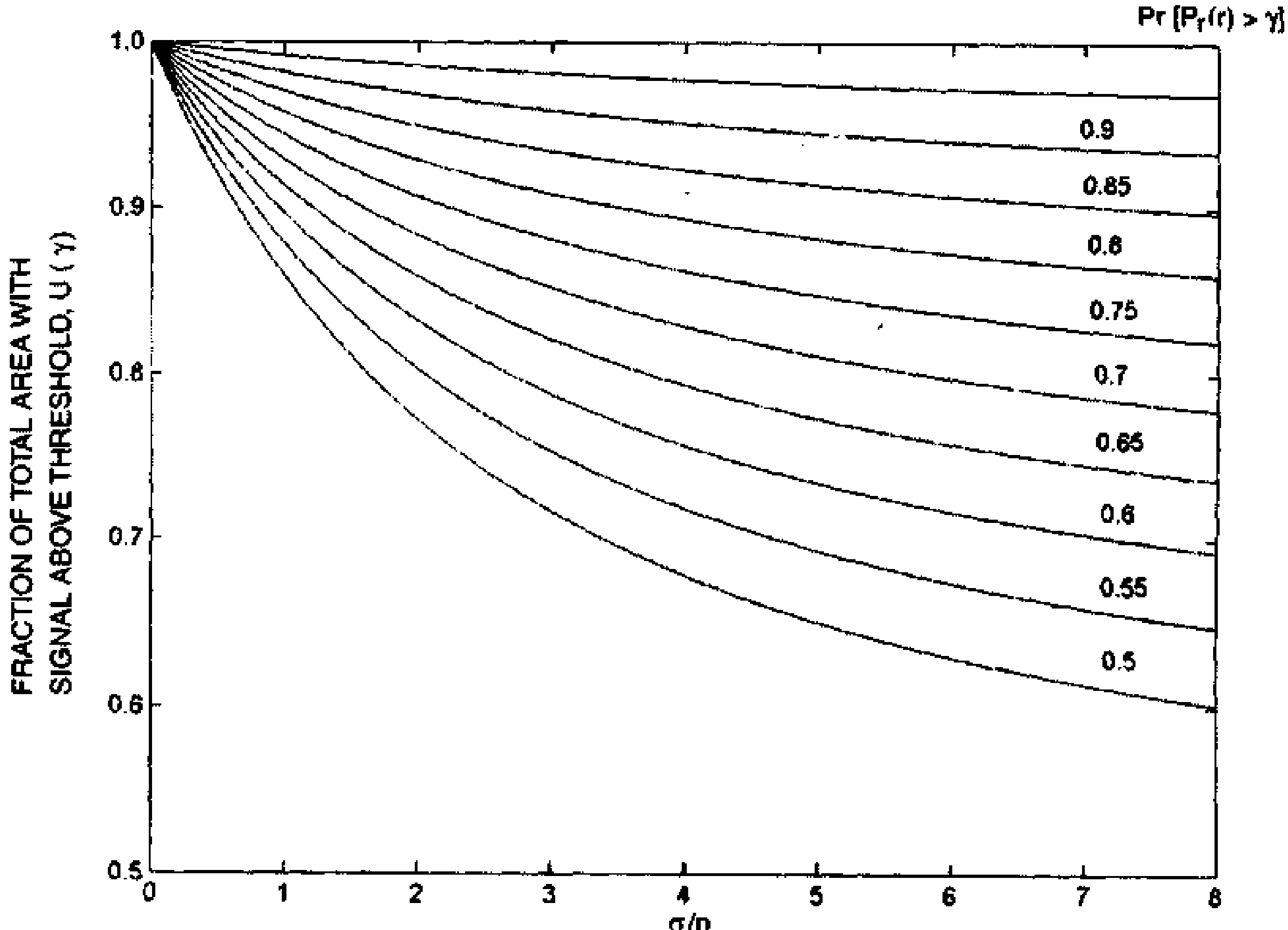


$$U(\gamma) = \frac{1}{\pi R^2}\int Pr[P_r(r) > \gamma]\,dA = \frac{1}{\pi R^2}\int_0^{2\pi}\int_0^{R} Pr[P_r(r) > \gamma]\,r\,dr\,d\theta$$

U-Function

(PP.125)

$U(\gamma)$ as a function of probability of signal above threshold on the cell boundary.



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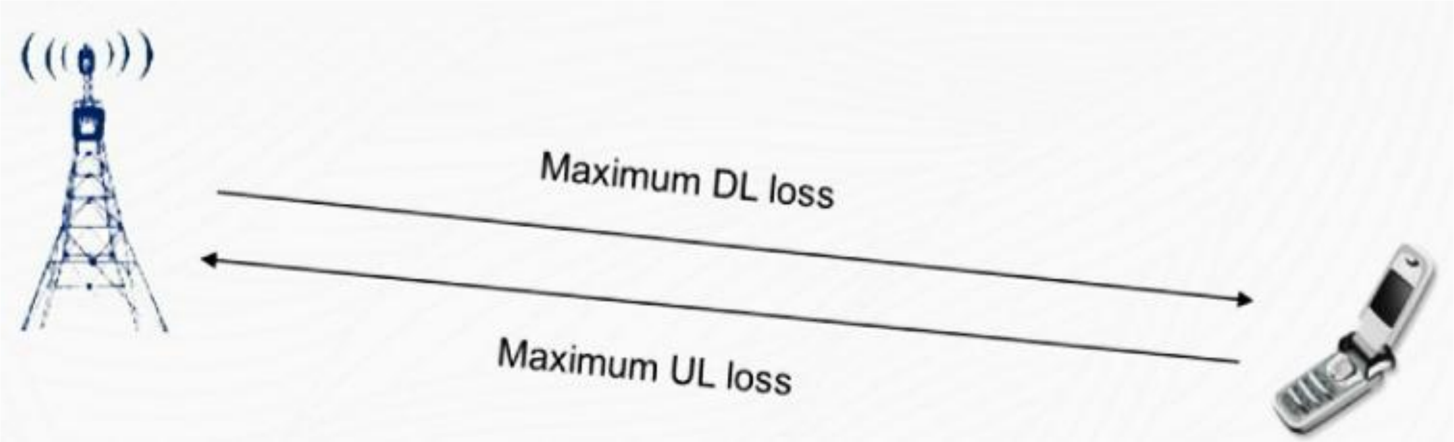
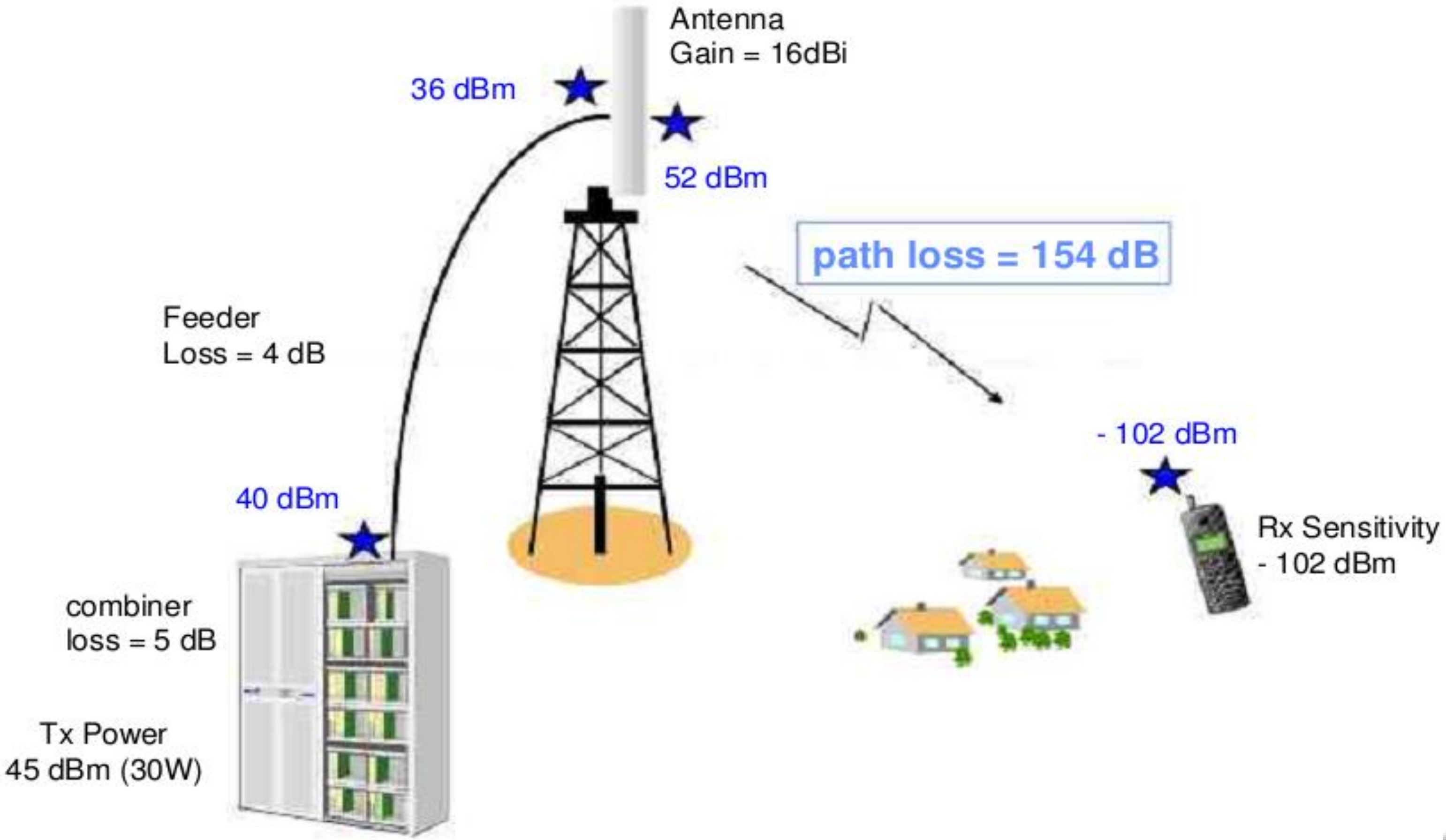
Link Budget Objective



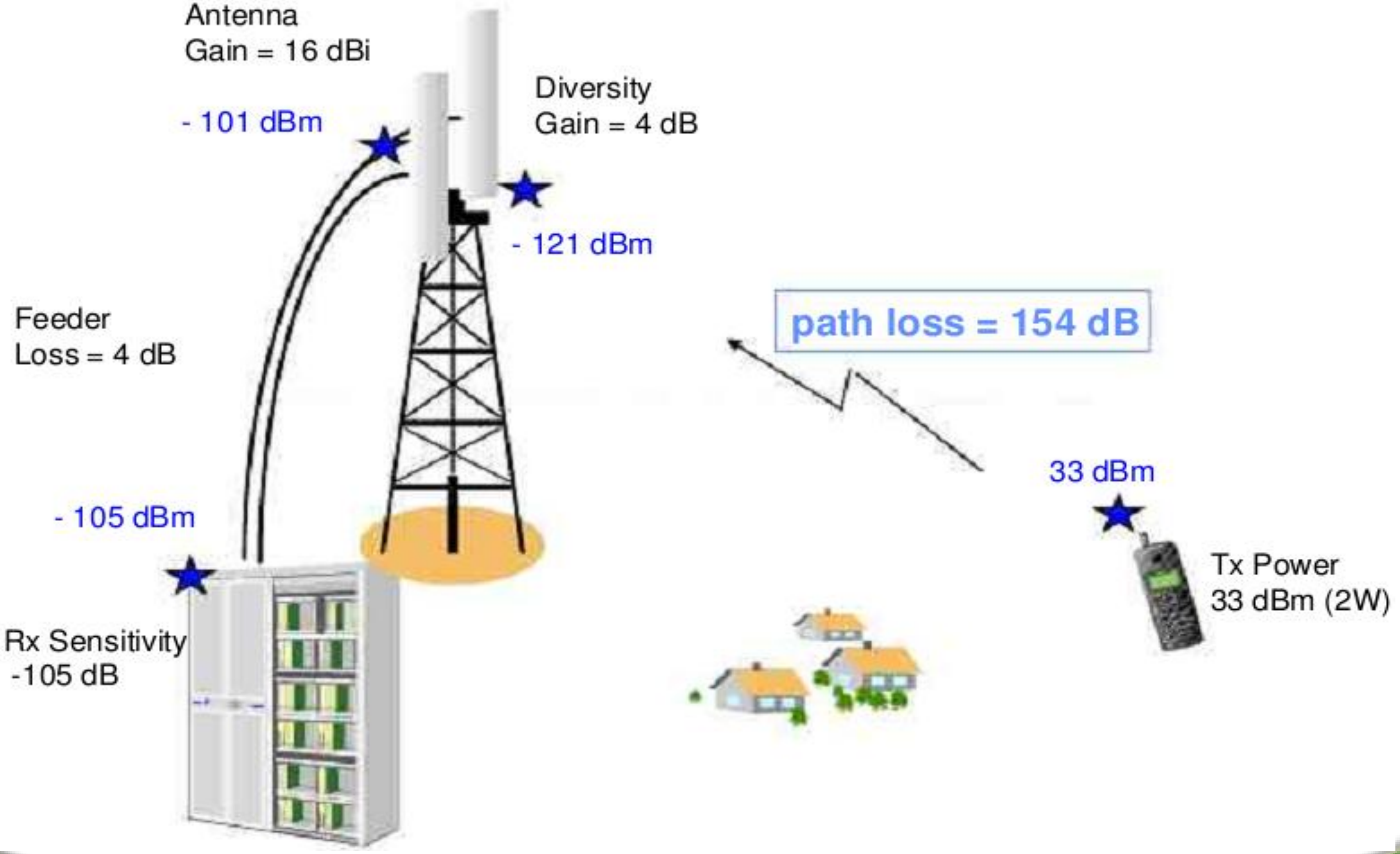
- Link budget refers to the calculation of the total gain and loss over the whole communication link, i.e. maximum propagation loss allowed in the link during a call connection with acceptable call quality.

- The Base Transceiver Station (BTS) coverage can be determined by using the link budget and the propagation model.

Downlink Budget



Uplink Budget



Example 3 (PP.125)

$$\Pr(d)[dB] = \overline{\Pr}(d) + X_\sigma = \overline{\Pr}(d_0) - 10n\log(\frac{d}{d_0}) + X_\sigma$$

Four received power measurements were taken at distances of 100 m, 200 m, 1 km, and 3 km from a transmitter. These measured values are given in the following table. It is assumed that the path loss for these measurements follows the model in Equation (4.69.a), where d_0 = 100 m:

(a) Find the minimum mean square error (MMSE) estimate for the path loss exponent *n*;

(b) Calculate the standard deviation about the mean value;

(c) Estimate the received power at $d = 2$ km using the resulting model;

(d) Predict the likelihood that the received signal level at 2 km will be greater than -60 dBm;

(e) Predict the percentage of area within a 2 km radius cell that receives signals greater than -60 dBm, given the result in (d).

Distance from Transmitter	Received Power
100 m	0 dBm
200 m	–20 dBm
1000 m	–35 dBm
3000 m	–70 dBm

(a) Find the MMSE estimate for the path loss exponent *n*

- **Mean Square Error, MSE (均方误差):**

$$\text{MSE} = \frac{1}{N}\sum_{i=1}^{N}\left(x_{mesured,i} - x_{predicated,i}\right)^2$$

- **MMSE (Minimum Mean Square Error)是一种使均方误差最小的估计函数，也称最优估计。**

$$\overline{Pr}(d) = \overline{Pr}(d_0) - 10n\lg\left(\frac{d}{d_0}\right)$$

$$J(n) = \sum_{i=1}^{N}\left(x_{mesured,i} - x_{predicted,i}\right)^2$$

$$= (0-0)^2 + (-20-(-3n))^2 + (-35-(-10n))^2 + (-70-(-14.77n))^2$$

$$= 6525 - 2887.8n + 327.153n^2$$

setting $\frac{dJ(n)}{dn} = 654.306n - 2887.8 = 0 \rightarrow n = 4.4$

(b) Calculate the standard deviation about the mean value

The sample variance $\sigma^2 = J(n)/4$ at $n = 4.4$ can be obtained as follows.

$$J(n) = (0+0) + (-20+13.2)^2 + (-35+44)^2 + (-70+64.988)^2$$
$$= 152.36.$$
$$\sigma^2 = 152.36/4 = 38.09\,\mathrm{dB}^2$$

therefore

$\sigma = 6.17$ dB, which is a biased estimate.

(c) Estimate the received power at *d* = 2 km using the resulting model

$$\overline{Pr}(d) = \overline{Pr}(d_0) - 10n\lg(\frac{d}{d_0})$$

The estimate of the received power at *d* = 2 km is

$$\overline{P}_r(d = 2\ \text{km}) = 0 - 10(4.4)\log(2000/100) = -57.24\ \text{dBm}$$

A Gaussian random variable having zero mean and 6.17 dB standard deviation could be added to this value to simulate random shadowing effects at d=2 km.

(d) Predict the likelihood that the received signal level at 2 km will be greater than -60 dBm

The probability that the received signal level will be greater than -60 dBm is given by

$$Pr[P_r(d) > \gamma] = Q\left(\frac{\gamma - \overline{P_r}(d)}{\sigma}\right)$$

$$Pr[P_r(d) > -60 \text{ dBm}] = Q\left(\frac{-60 + 57.24}{6.17}\right)$$

$$= Q(-0.44) = 1 - Q(0.44) = 1 - 0.326 = 67.4\%$$

表 D.1 Q 函数列表

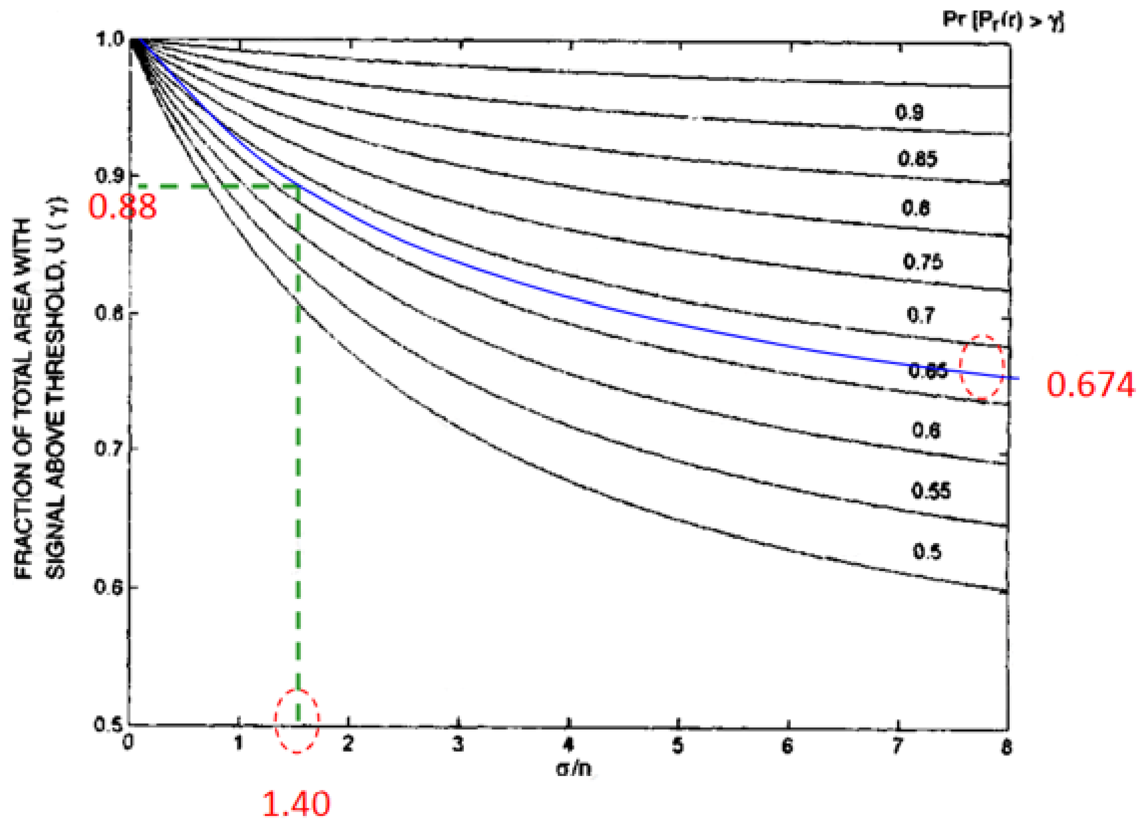
z	$Q(z)$	z	$Q(z)$
0.0	0.50000	2.0	0.02275
0.1	0.46017	2.1	0.01786
0.2	0.42074	2.2	0.01390
0.3	0.38209	2.3	0.01072
0.4	0.34458	2.4	0.00820
0.5	0.30854	2.5	0.00621

(e) Predict the percentage of area within a 2 km radius cell that receives signals greater than -60 dBm, given the result in (d).

Since 67.4% of the users on the boundary receive signals greater than -60 dBm, then 88% of the cell area receives coverage above –60dbm.

$$\sigma / n = 6.17 / 4.4 = 1.40$$

$$Pr[P_r(d) > -60 \text{ dBm}] = 0.674$$



Summary

- 如何根据大量的实际测量值来建立大尺度路径损耗模型；
- 如何根据给定模型来分析一定距离下的路径损耗；
- 如何根据统计模型来估计在一定距离和范围内满足给定通信质量要求的概率；
- 利用建立的大尺度路径损耗模型，来指导实际中无线通信系统的链路预算设计。

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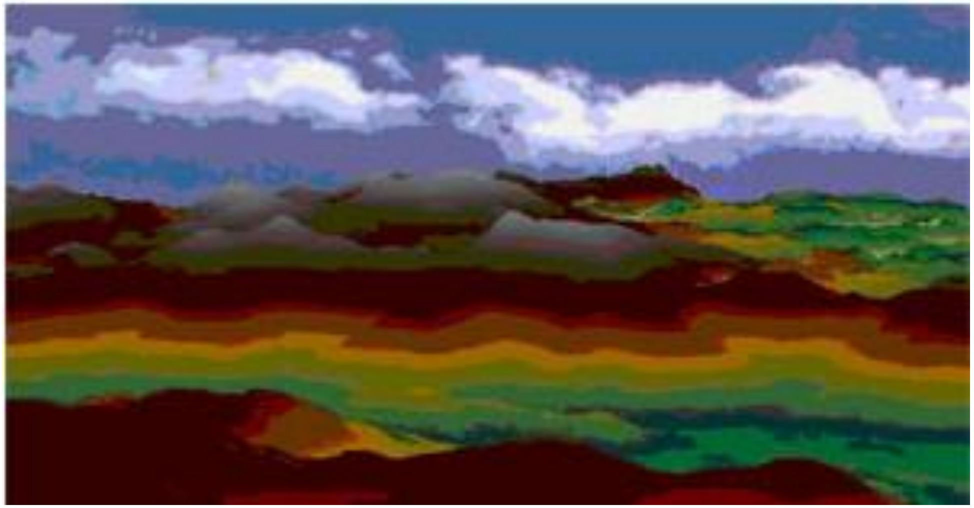
Radio propagation models facilitate studies of radio transmissions under different environments of implementation of the radio system.

Radio propagation models can be classified in to two categories:

1. Outdoor Propagation Models
2. Indoor Propagation Models

Outdoor Propagation Models

- Okumura Model (150-1920MHz,1km-100km)
- Hata Model (150-1500MHz,1km-20km)
- Egli Model (40-400MHz,0-64km)



Okumura Model

(PP.131)

$$L_{50}(\mathrm{dB}) = L_F + A_{mu}(f,d) - G(h_{te}) - G(h_{re}) - G_{AREA}$$

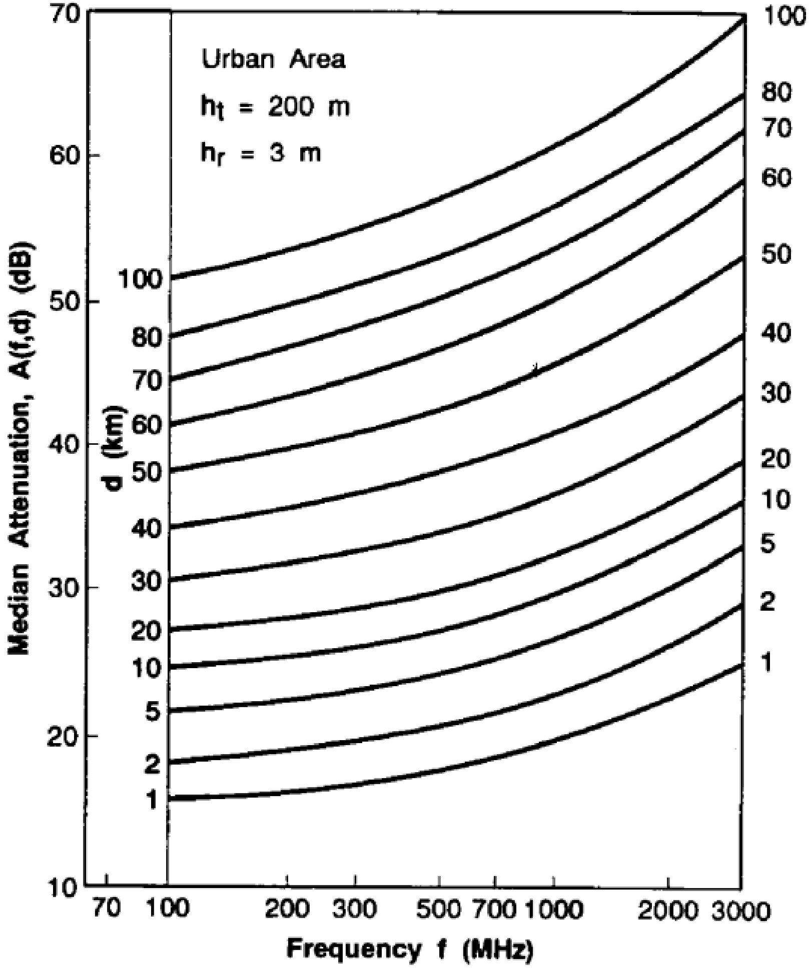
- L_{50}: the median value of propagation path loss
- L_F : the free space propagation loss
- $A_{mu}(f, d)$: the median attenuation relative to free space
- $G(h_{te})$: the base station antenna height gain factor
- $G(h_{re})$: the mobile antenna height gain factor
- G_{AREA}: the gain due to the type of environment

✓ Be wholly based on measured data and do not provide analytical explanation.

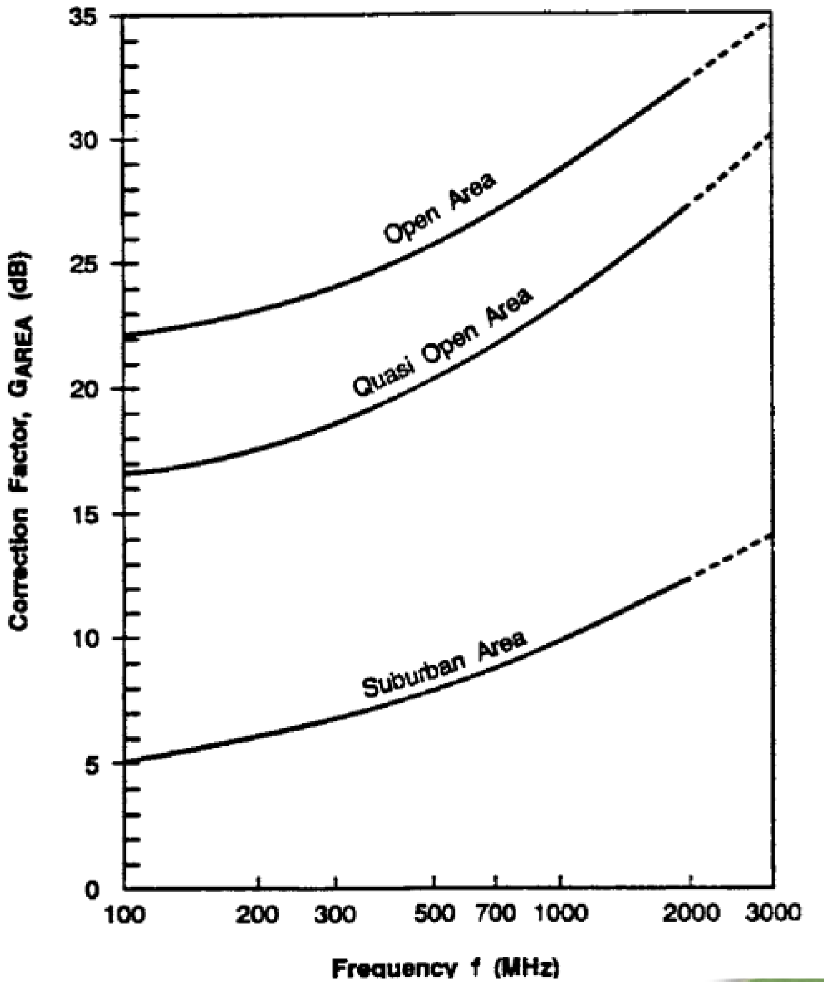
✓ The disadvantage with this model is its slow response to rapid change in terrain.

Okumura median attenuation and correction

$A_{mu}(f, d)$



G_{AREA}



(PP.151-152)

Example 4 **(PP.134)**

Find the median path loss using Okumura's model for $d = 50$ km, $h_{te} = 100$ m, $h_{re} = 10$ m in a suburban environment. If the base station transmitter radiates an EIRP of 1 kW at a carrier frequency of 900 MHz, find the power at the receiver (assume a unity gain receiving antenna).

$$L_{50}(\mathrm{dB}) = L_F + A_{mu}(f, d) - G(h_{te}) - G(h_{re}) - G_{AREA}$$

HATA model & COST –231 extension

(PP.134-135)

- HATA model

$$L_{50}(urban)(\mathrm{dB}) = 69.55 + 26.16\log f_c - 13.82\log h_{te} - a(h_{re}) + (44.9 - 6.55\log h_{te})\log d$$

  - f_c: the frequency (in MHz) from 150 MHz to 1500 MHz
  - h_{te}: the effective transmitter antenna height (30m ~ 200m)
  - h_{re}: the effective receiver antenna height (1m ~ 10m)
  - d: the T-R separation distance (in km)
  - $a(h_{re})$: the correction factor for effective mobile antenna height which is a function of the size of the coverage area

- COST –231 extension

$$L_{50}(urban) = 46.3 + 33.9\log f_c - 13.82\log h_{te} - a(h_{re}) + (44.9 - 6.55\log h_{te})\log d + C_M$$

Example 5

In the suburban of a large city, d = 10 km, h_{te} = 200 m, h_{re} = 2 m , carrier frequency of 900 MHz, using HATA' s model find the path loss.

$$a(h_{re})[dB] = 3.2[\log 11.75(h_{re})]^2 - 4.97$$
$$= 3.2[\log 11.75(2)]^2 - 4.97 = 1.05 dB$$

$$L_{50}(urban)[dB] = 69.55 + 26.16\log 900 - 13.82\log 200 - 1.05$$
$$+ (44.9 - 6.55\log 200)\log 10 = 143.80 dB$$

$$L_{50}(dB) = 143.80 - 2[\log(900/28)]^2 - 5.4 = 133.86 dB$$

Chapter 3

1. Free Space Propagation Model
2. Three Basic Propagation Mechanism
3. Practical Link Budget Design Using Path Loss Models
4. Outdoor Propagation Models
5. **Indoor Propagation Models**

Indoor propagation models

- First studied by Bell Laboratories and BT Laboratories, for instance for wireless LANs and cordless phones
- Highly dependant on building materials, lay-out, etc.
- Again, log-normal shadowing law applies (Rappaport, pp. 127-131)
- Becoming very important for modern use of picocells for communications in offices, etc., (UMTS, wireless Internet access)!

Feature of Indoor Radio Channel

- The distances covered are much smaller, and the variability of the environment is much greater for a much smaller range of T-R separation distances. It has been observed that propagation within buildings is strongly influenced by specific features such as the layout of the building, the construction materials, and the building type.
- Indoor radio propagation is dominated by the same mechanisms as outdoor : reflection, diffraction, and scattering. However, conditions are much more variable.

Path attenuation factors

(PP.138-141)

- Partition Losses in the same floor
- Partition Losses between Floors(floor attenuation factors, FAF)

Log-distance Path Loss Model

- Indoor path loss has been shown by many researchers to obey the distance power law

$$PL(d)[dB] = \overline{PL}(d_0) + 10n\log(\frac{d}{d_0}) + X_\sigma$$

Where the value of *n* depends on the surroundings and building type, and *X* represents a normal random variable in dB having a standard deviation. This is identical in form to the log-normal shadowing model of outdoor path attenuation model.

Attenuation Factor Model

$$\overline{PL}(d)[\mathrm{dB}] = \overline{PL}(d_0)[\mathrm{dB}] + 10n_{SF}\log\left(\frac{d}{d_0}\right) + FAF[\mathrm{dB}] + \sum PAF[\mathrm{dB}]$$

Where n_{SF} represents the exponent value for the “same floor” measurement. The path loss on a different floor can be predicted by adding an appropriate value of FAF.

Signal Penetration into buildings

- Measurements showed that penetration loss decreases with increasing frequency. Specifically, penetration attenuation values of 16.4dB, 11.6dB, and 7.6dB were measured on the ground floor of a building at frequencies of 441MHz, 896.5MHz, and 1400Mhz, respectly.

Summary

1. Free Space Propagation Model
2. Three Basic Propagation Mechanism
3. Practical Link Budget Design Using Path Loss Models
4. Outdoor Propagation Models
5. Indoor Propagation Models

Exercises

If the base stations use 20 W transmitter powers and 10 dBi gain omnidirectional antennas, determine the cell coverage distance d.

Let $n = 4$ and the standard deviation of 8 dB hold as the path loss model for each cell in the city. Also assume that a required signal level of -90 dBm must be provided for 90% of the coverage area in each cell, and that each mobile uses a 0dBi antenna. Assume $d_0 = 1$ km. (Q(0.7)=0.25, fc=900MHz)