UiO : Universitetet i Oslo

UNIK4230: Mobile Communications
Spring 2013

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Propagation characteristis of wireless channel

Date: 07.02.2013

Agenda

Radio wave propagation phenomena

- Reflection
- Refraction
- Diffraction
- Scattering

Signal attenuation

- Attenuation and fading
- Path loss
- Hata model

Indoor propagation

More on fading

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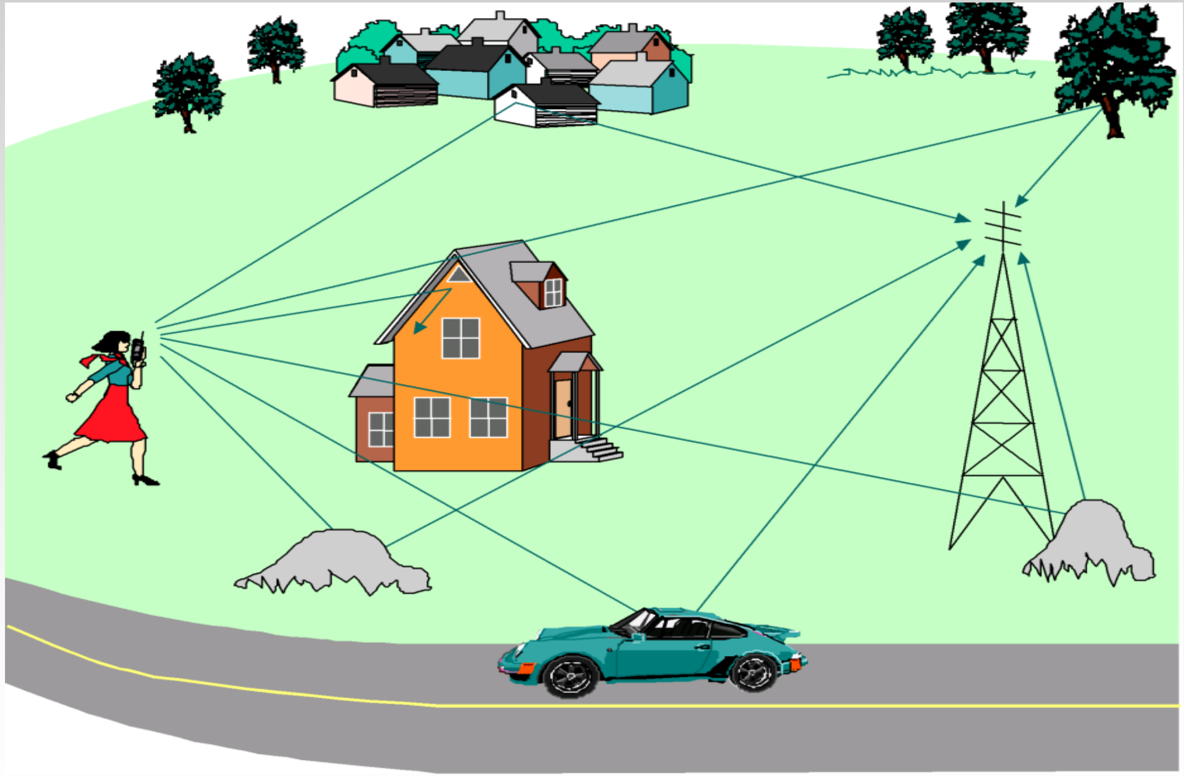
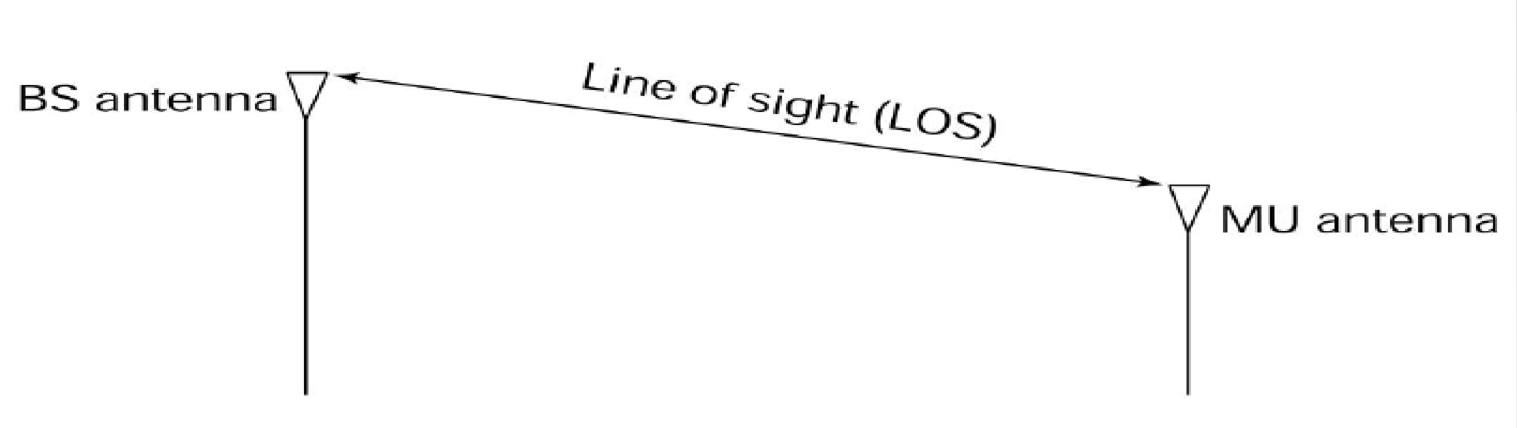
Radio channel

The transmitted signal arrives at the receiver from different directions at different times over a number of ways

- Line of sight (LOS) or
- Non-line of sight (NLOS)



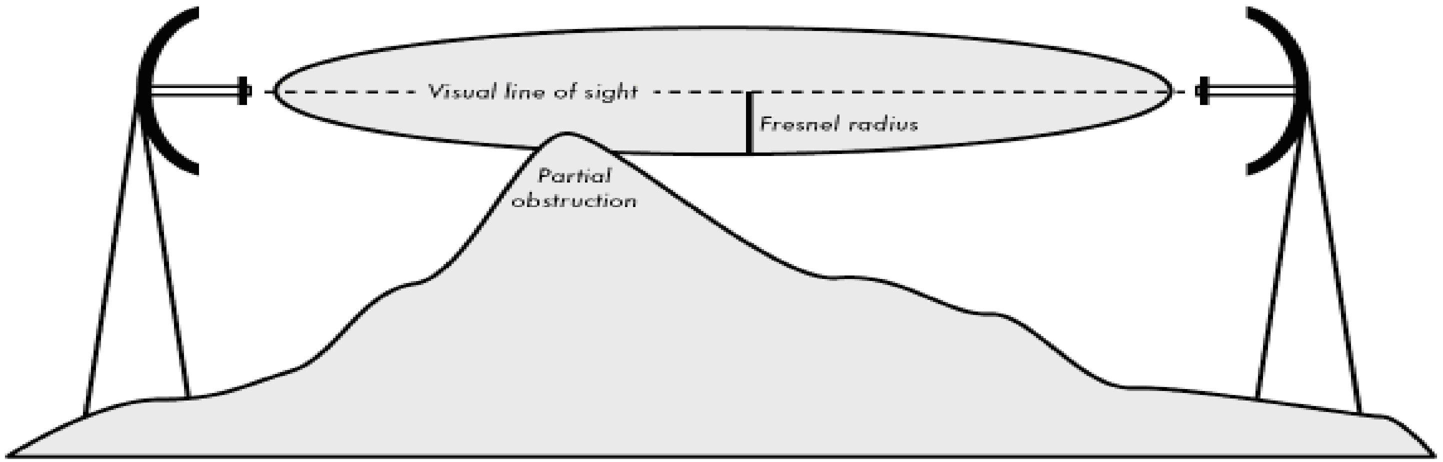
Line of sight propagation



Unobstructed line of sight propagation between the transmitter and receiver

- Lower attenuation
- There must be no obstruction on LOS
- Objects not even on direct LOS can interfere radio transmission (see Fresnel Zone)

Fresnel zones



The Fresnel zone is partially blocked on this link, although the visual line of sight appears clear..

$$F_n = \sqrt{\frac{n\lambda d_1 d_2}{d_1 + d_2}}$$

All units are meter

1st Fresnel zone while D in Km and f in GHz

$$r = 8.657\sqrt{\frac{D}{f}}$$

Fresnel zones determine whether a given obstacle will cause a constructive or desctructive interference at the receiver due to reflection

- Reflection can enhance received signal if reflected and direct signals arrive in-phase
- Its important to clear obstruction from first Fresnel zone

The radius of first Fresnel zone, r = 17.31 * sqrt(N(d1*d2)/(f*d)) ...where r is the radius of the zone in meters, N is the zone to calculate, d1 and d2 are distances from obstacle to the link end points in meters, d is the total link distance in meters, and f is the frequency in MHz.

Fresnel zones

For example, let's calculate the size of the first Fresnel zone if the first Fresnel zone in the middle of a 2km link, transmitting at 2.437GHz (802.11b channel 6):

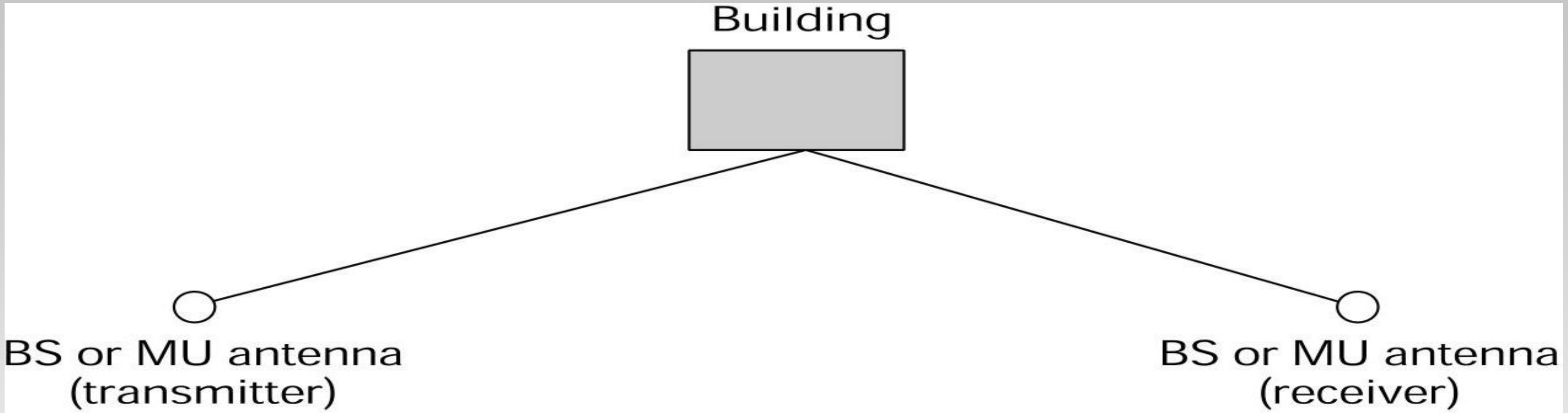
r = 17.31 sqrt(1 * (1000 * 1000) / (2437 * 2000))
r = 17.31 sqrt(1000000 / 4874000)
r = 7.84 meters

Assuming both of our towers were ten meters tall, the first Fresnel zone would pass just 2.16 meters above ground level in the middle of the link.

Fresnel zone: exercise

How tall could a structure in the middle of a 2km point be to clear 60% (N=0.6) of the first Fresnel zone? Transmitter is transmitting at 2.437GHz (802.11b channel 6)

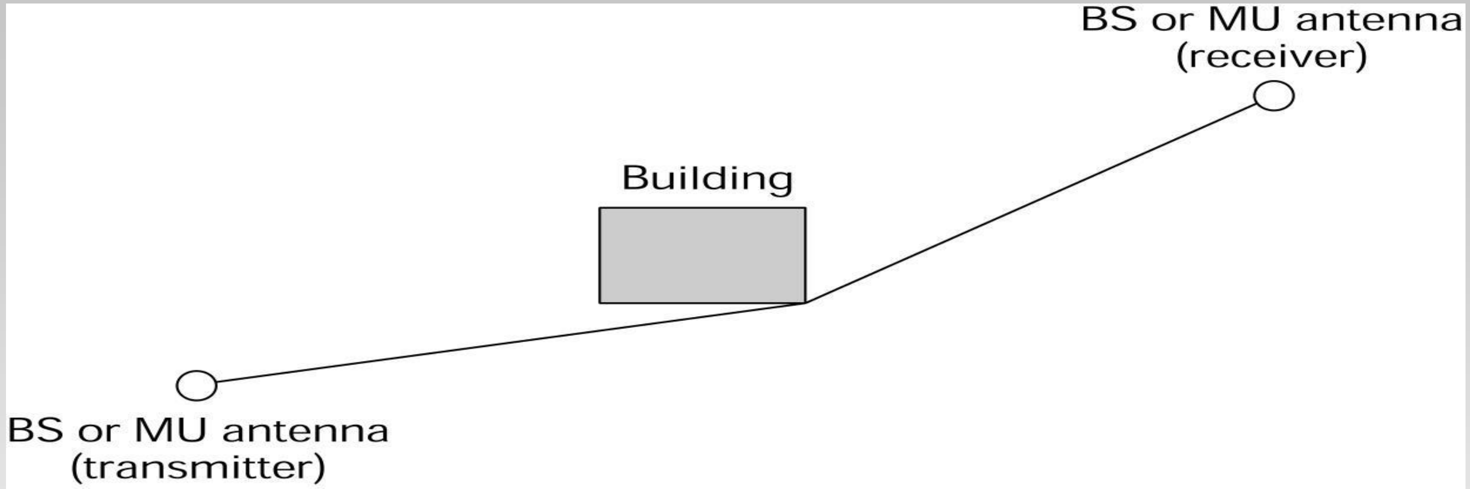
Reflection



Reflection occurs when a radio wave strikes a barrier with a dimension larger than the wave length of the radio wave

- E.g. Buildings, ground, vehicles etc.

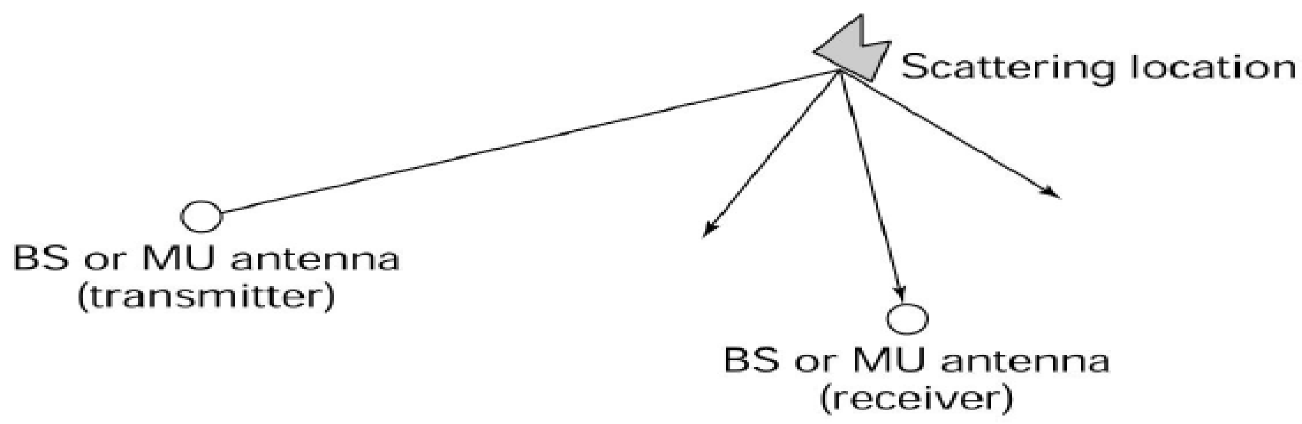
Diffraction



Diffraction occurs when the radio wave hits an obstacle with sharp irregularities, edge, small gap

- Size of the object (e.g. edge) must be comparable to or smaller than the wavelength of the radio wave
- E.g. Bending around the object (typically corner of the houses or hills)

Scattering



Scattering occurs when the radio wave strikes the obstacles with dimension smaller than the wave length of the radio wave

- E.g. Vegetation, street signs etc.

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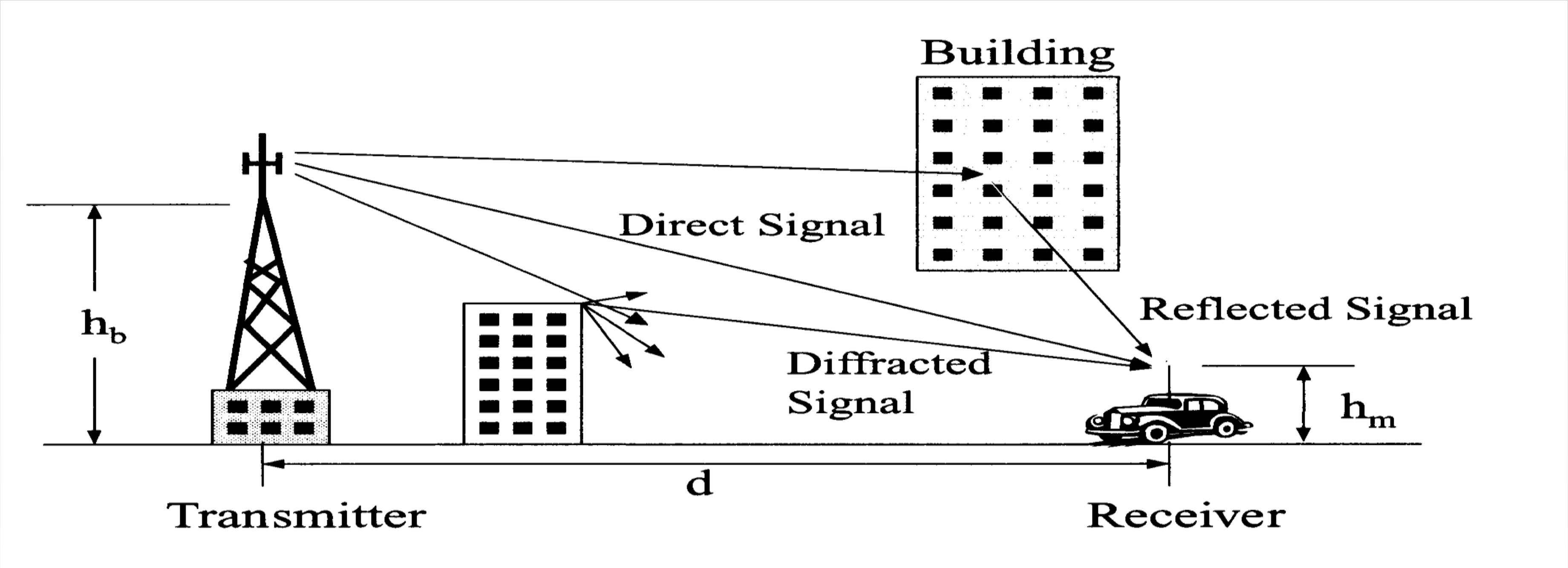
Indoor propagation

More on fading

Attenuation and fading

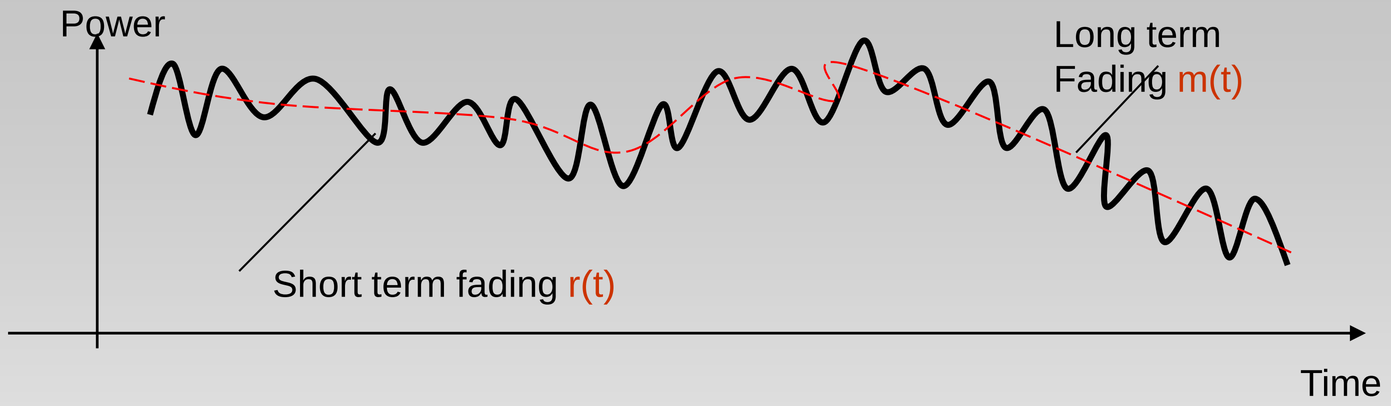


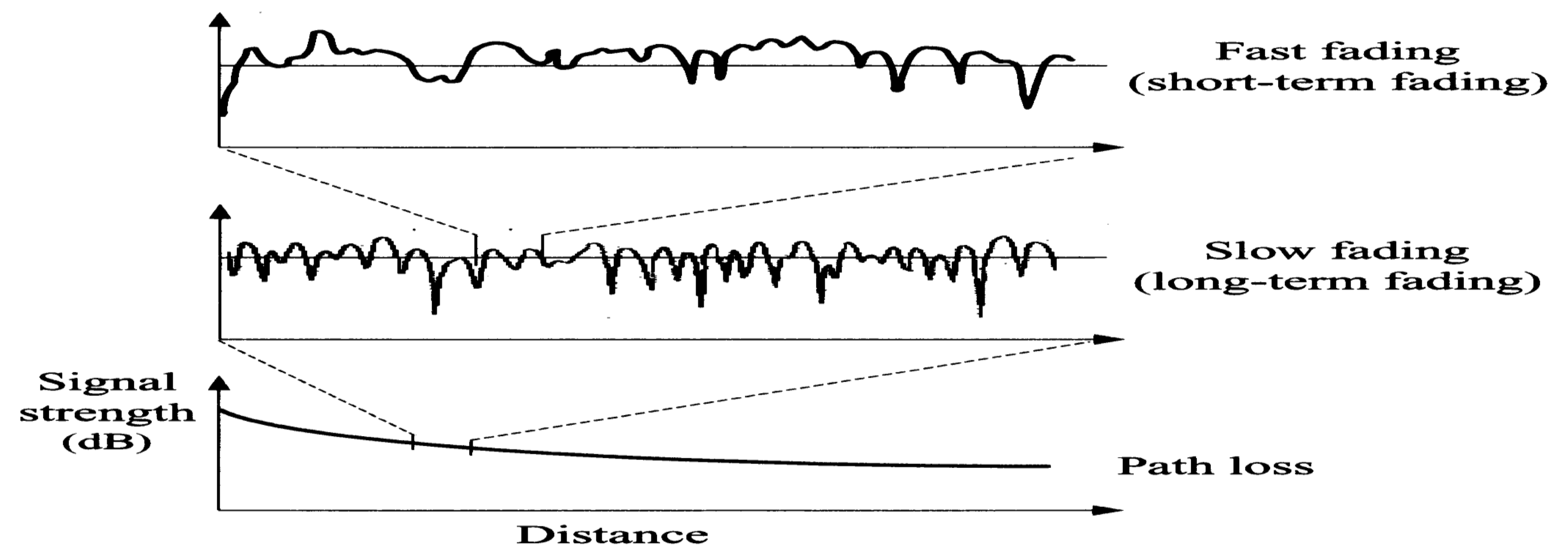
Attenuation and fading

Fading is deviation of attenuation a radio wave experience over certain propagation media.

- Distance dependent attenuation
- Fast fading: Rapid fluctuation of signal over a small areas. Fast fading occurs due to multipath propagation
  - Fast fading is characterized by Rayleigh and Rician distribution.
  - Rayleigh distribution: It assumes infinite reflected path with all possible attenuation and no direct path. E.g. It is used to characterize worst case urban or indoor communications
  - Rician distribution: It assumes a direct path from TX to RX as well as infinite reflected paths. E.g. Used to characterize satellite communication channels
- Slow fading: It is long-term fading effect caused by large obstruction (shadowing) such as large building or hills
  - Shadowing is modeled using log-normal distribution.

Attenuation and fading





About the term dB

Widely used to measure e.g. gain, attenuation, signal to noise ratio (SNR) etc.

The ratio of power value P_a to another power value P_b is calculated as:

$$X_{dB} = 10\log_{10}\left(\frac{P_a}{P_b}\right) \quad dB$$

Example:

Ratio = 0.1 = -10 dB

= 1 = 0 dB

= 10 = 10 dB

= 100 = 20 dB

Decibel (dB) is a dimensionless Unit

$$P_a = 10^{\frac{X_{dB}}{10}} P_b \; watt \; given \; P_b \; in \; watt$$

About the term dBm

dBm (decibel-milliwatt) is the power unit in dB referenced to 1 mW.

It measures absolute power in radio, microwave and fiber option network.

- dBm can measure both very small and very large values in short form

To measure an arbitrary power P_a as x dBm:

$$x = 10\log_{10}\left(\frac{P_a(mW)}{1mW}\right) \quad dBm$$

Example:

P_a = 1 mW, x = o dBm

P_a = 1 W, x = 30 dBm, maximum outout power of GSM 1800 mobile phone

x = 33 dBm, P_a = 2 W

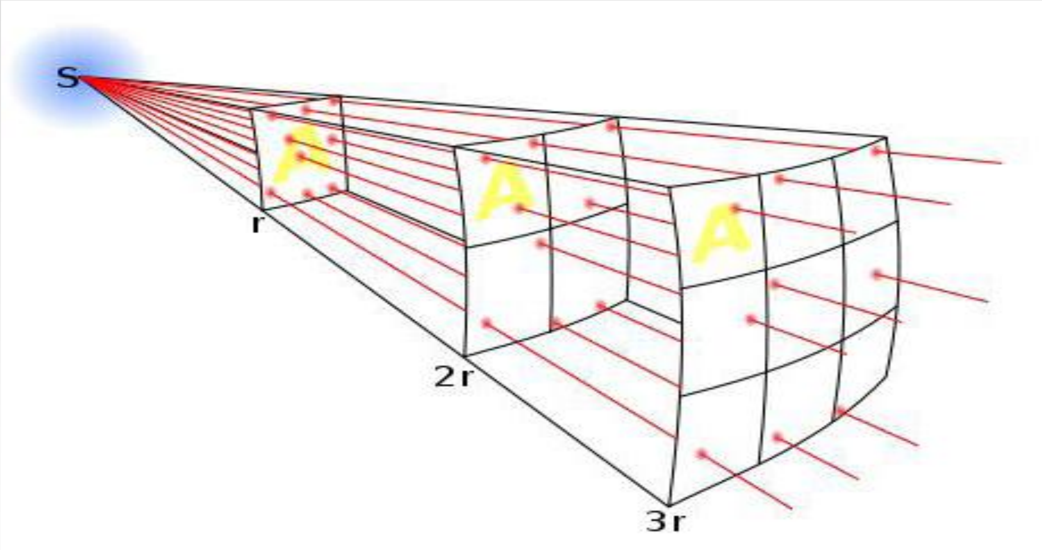
x = 80 dBm, P_a = 100 KW, P_{tx} of FM radio transmitter with 50km range

dBm is an absolute measure of power in mW

Attenuation in free space

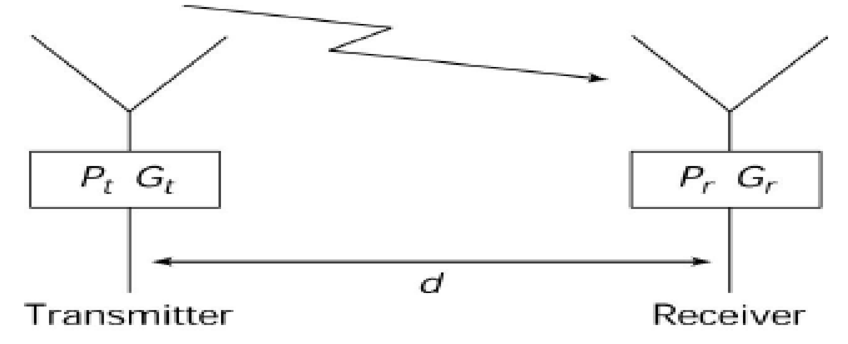
When there is line of sight between transmitter and receiver, received power follows inverse square law:

$$P_r \propto d^{-2}$$



Attenuation in free space

Received power in free space can be expressed as:



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

$$P_t = transmit\ power$$

$$G_t, G_r = gain\ of\ transmitter, receiver\ antenna$$

$$L = other\ losses\ (e.g.\ filtertap\ , antennatap\ )$$

Attenuation in free space

Free space path loss:

$$L = \left(\frac{4\Pi d}{\lambda}\right)^2 = \left(\frac{4\Pi df}{c}\right)^2$$

$$L_{dB} = 20Log_{10}\left(\frac{4\Pi d}{\lambda}\right)$$

$d = dis\tan ce\ from\, transmitter\,(m)$

$\lambda = signal\ wavelength\,(m)$

$f = signal\ frequency\,(Hz)$

$c = speef\ of\ light$

$$L_{dB} = 32.44 + 20\log_{10}(f) + 20Log_{10}(d)$$

$$where\, d\ in\, km\, and\ f\ in\, MHz$$

Attenuation in free space

If received power is known in a reference distance d_{ref} , received power in an arbitrary distance can be calculated:

$$P_r(d) = P_r(d_{ref})\left(\frac{d_{ref}}{d}\right)^2$$

In dBm

$$P_r(d)[dBm] = 10\log_{10}(P_r(d_{ref})) + 20\log_{10}\left(\frac{d_{ref}}{d}\right)$$

Path loss

If transmitted and received power are known, path loss can be calculated:

$$L(dB) = 10\log_{10}\left(\frac{P_t}{P_r}\right)$$

if both transmitter and receiver has no gain, its identical to free space loss

From the above equation, we can also write:

Path Loss (dB) = Transmit Power (dBm) – Received Power (dBm)

Attenuation factor

In real case attenuation is much higher because signal propagation path is not really free space.

With attenuation factor, received power:

$$P_r \propto d^{-\nu}$$

v=2 for free space

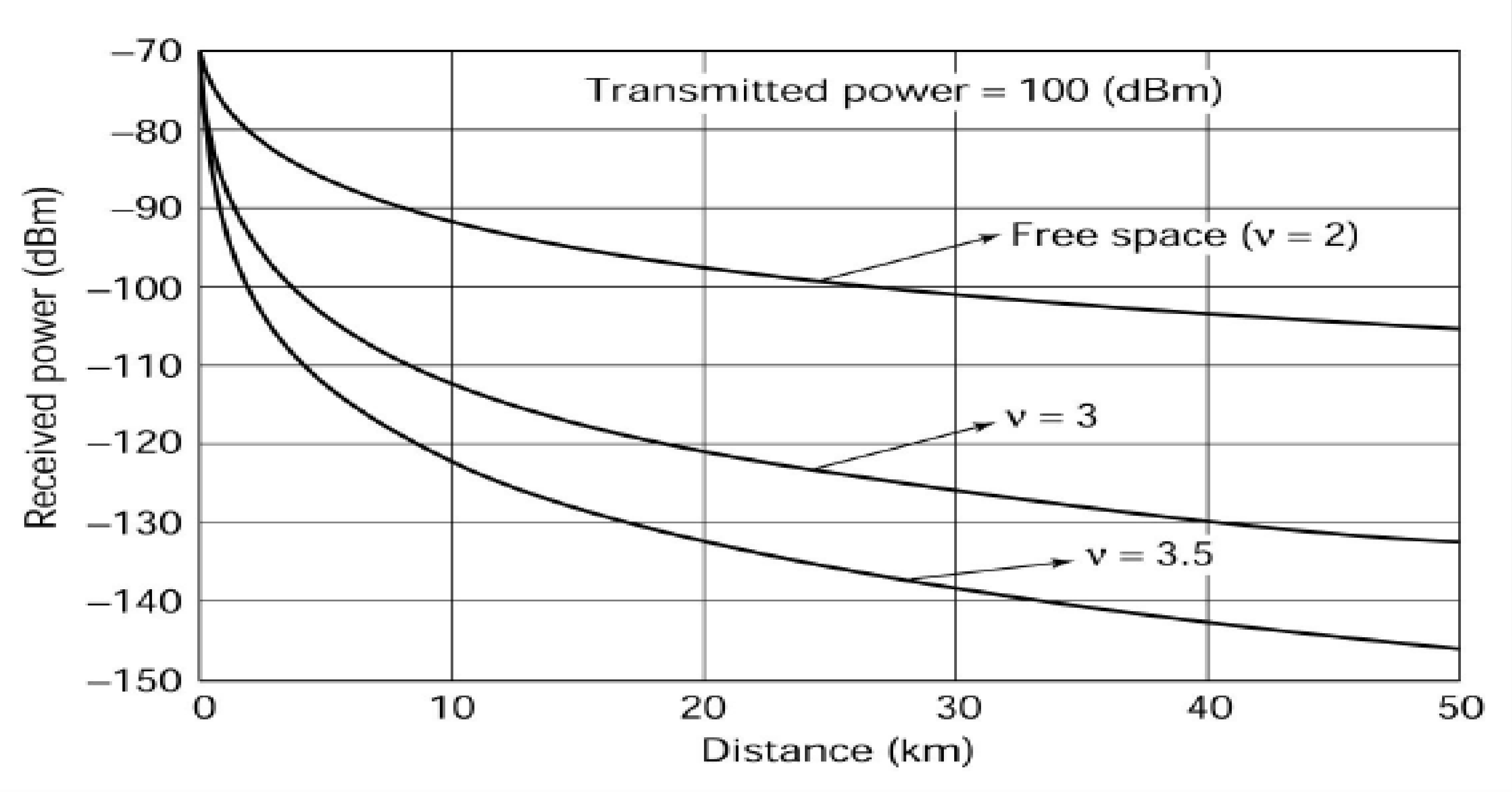
Typical values for urban areas are 3-5

With reference distance one can write:

$$P_r(d)[dBm] = 10\log_{10}(P_r(d_{ref})) + 10.\nu.\log_{10}\left(\frac{d_{ref}}{d}\right)$$

Attenuation factor

Received as a function of distance for different values of v:



About channel model

Models are mathemetical description of attenuation that are used for system design, system simulation or radio planning purposes

Two types of channel model:

- Empirical model: developed based on large collection of data for a specific scenario (e.g. Urban, sub-urban); do not point out exact behavior rather most likely behavior of the channel

- Analytical model: takes into account link specific geometri (e.g. curve of hills, edges, big buildings etc.)

In Practice often takes combination with site-specific correction factors used in addition to empirical models

Okumura model

Combining all these causes (reflection, scattering, and diffraction), Okumura et al. (1968) proposed channel model

The model includes correction factor to account for terrain.

But correction factors have to be incorporated for every scenario

- Hata (1980) proposed a model to overcome the problem

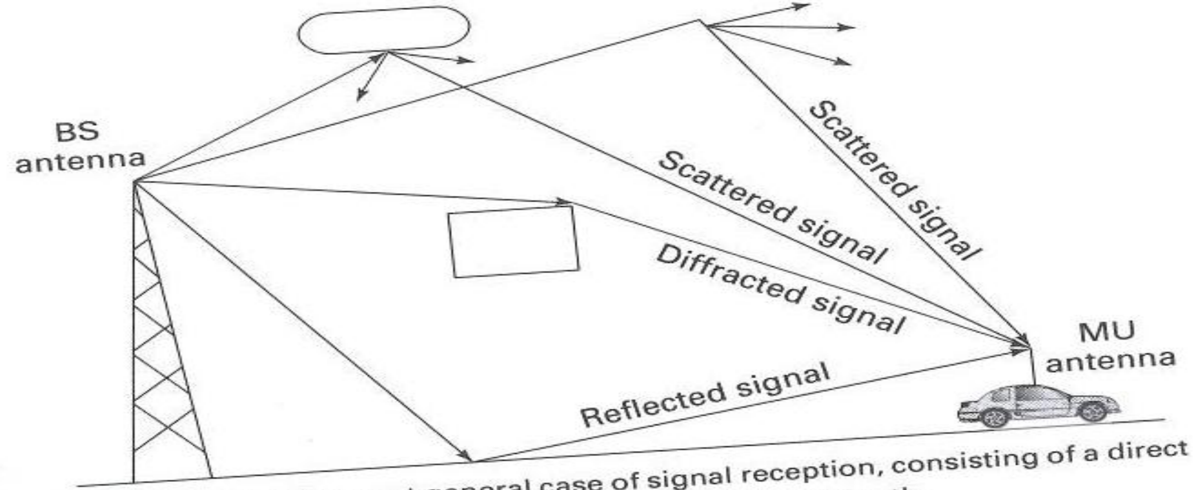


FIGURE 2.10 The most general case of signal reception, consisting of a direct path, a reflected path, a scattered path, and a diffracted path.

Hata model

- In Hata model, path loss in urban areas is given by:

$$L_p(dB) = 69.55 + 26.16\log_{10}(f_0) + (44.9 - 6.55\log_{10} h_b)\log_{10} d - 13.82\log_{10} h_b - a(h_{mu})$$

$where$

$f_0 = carrier\ \ frequency\ (MHz)$

$d = separation\, between\ BTS\ and\ MU\ (km);\ d \geq 1\, km$

$h_b = height\ of\ the\ BTS\ antenna\ (m)$

$h_{mu} = height\ of\ the\ MU\ antenna\ (m)$

$a(h_{mu}) = correction\ \ factor\ \ for\ MU\ antenna\ height$

  - For large cities, the correction factor $a(h_{mu})$ is given by:

$$a(h_{mu}) = 3.2[\log_{10}(11.75 h_{mu})]^2 - 4.97 \qquad f_0 \geq 400\, MHz$$

  - For small and medium cities, the correction factor $a(h_{mu})$ is given by:

$$a(h_{mu}) = [1.1\log_{10}(f_0) - 0.7]h_{mu} - [1.56\log_{10}(f_0) - 0.8]$$

Hata model

For suburban and rural areas following correction factors are used:

$$L_{sub}(dB) = L_p - 2[\log_{10}(\frac{f_0}{28})]^2 - 5.4$$

$$L_{rur}(dB) = L_p - 4.78[\log_{10}(f_0)]^2 + 18.33\log_{10} f_0 - 40.94$$

$$where\, L_p \; is\; the\; loss\; in\; small - to - medium\; citites\,.$$

Hata model

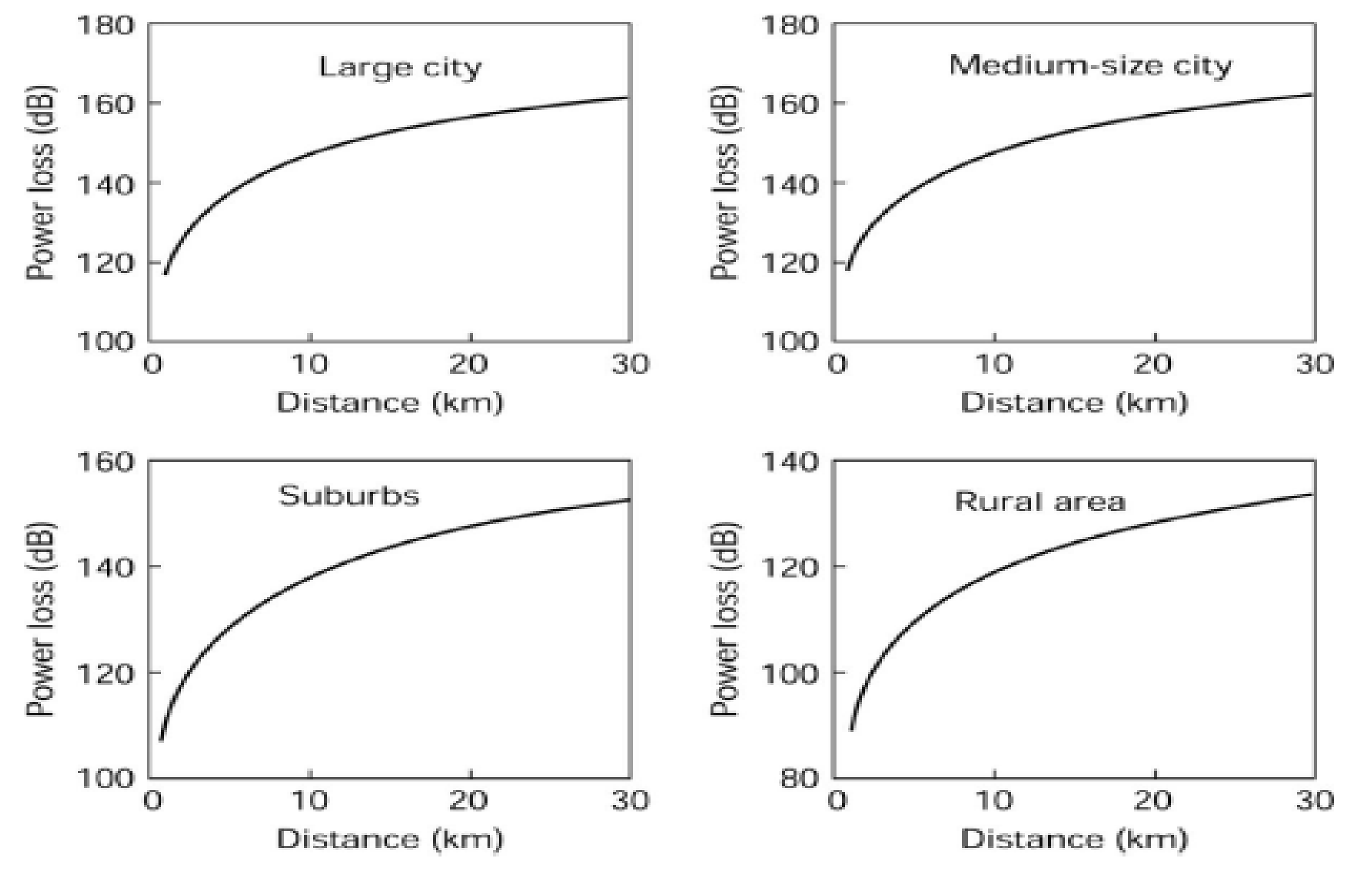


Figure shows loss calculation based on hata model for four different environments given that f_0=900MHz, h_b=150m, h_{mu}=1.5m

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Indoor propagation model

Models so far presented are not sufficient to predict signals in indoor

Indoor propagation sees reflect, scatter, and diffract due to walls, ceilings, furnitures etc. (i.e. many obstacles)

Best approach to model indoor: classify these environments into different `zone’ configurations

- Extra large zone
- Large zone
- Middle zone
- Small & microzone

Indoor propagation model

Extra large zone:

A BTS outside building takes all the traffic in the buildings

Loss = path-dependent losses (from BTS to building) + penetration-dependent losses (penetration of various floors & walls)

Large zone:

Large buildings with small density of users

The building is covered by a single indoor BTS located within the building itself

General formula of path loss can be used. L(d) = L0 (d0) [d0/d]v

Loss is determined whether users are in the same floor as BTS (attenuation factor 2-3 if Tx and Rx on the same floor, it will be greater than 3 if they are on different floors)

Indoor propagation model

Middle zone:

Bulding structure is large and heavily populated (e.g. shopping malls)

A number of BTSs serve the users

Loss = Free space path loss + floor loss + wall loss + reflection loss

Small zone and microzone:

Buildings having many walls and partitions

Loss depends on the material of the walls and partitions

Need the provision of one BTS for each room

Usually heavy traffic in each room

Large-zone model can be used with appropriate path loss exponent: v=2 for LOS, v>2 for NLOS.

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More on fading

Fading

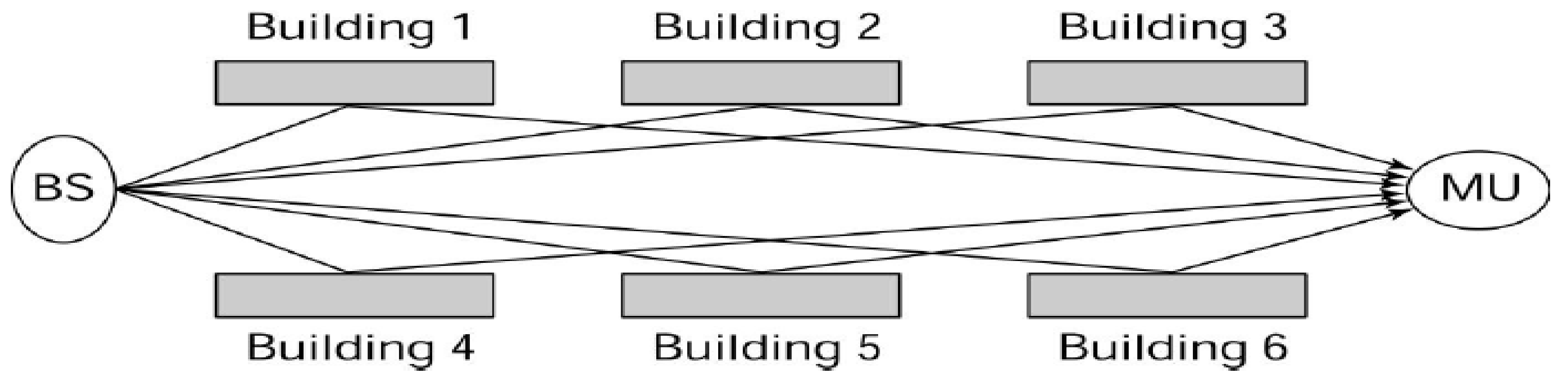
- In addition to propagation loss, attenuation may also fluctuate with *geographical position*, *time* and *frequency* which is referred as “fading” and usually modeled as *random* process.
- Propagation fluctuates around mean value
- Fading describes this signal fluctuation around mean value
- Primary cause of fading is signal traversing multiple path. Another reason is the shadowing from large objects along the wave propagation

Fading can be described in three ways:

- Multipath
- The statistical distribution of the received signal envelope (e.g. Rayleigh)
- Duration of fading (e.g. long-term, short-term)

Multipath fading

- Signal leaves the transmitting antenna and can take different paths to reach the receiver (due to reflection, diffraction, scattering etc.)
- Receiver gets superposition of the multiple transmitted signal, each taking different path
- Each copy will experience differences in *attenuation*, *delay* and *phase shift* after reaching at receiver



Multipath fading

Signal components arrive at receive antenna are independent of each other

- Hence, signal received at the antenna can be expressed as the vector sum of the signal components

Assuming Rx stationary & no direct path exists (Tx-Rx), the received signal e_r(t):

$$e_r(t) = \sum_{i=1}^{N} a_i \, p(t - t_i)$$

$$\begin{aligned}
&where \\
&a_i = amplitude\ of\ the\ received\ component\ i \\
&p(t) = transmitted\ signal\ shape \\
&t_i = time\ taken\ by\ signal\ component\ i\ to\ reach\ receiver \\
&N = Number\ of\ paths\ taken\ by\ the\ signal
\end{aligned}$$

Multipath fading

Instead of using sum of delayed components, received signal can also showed using phasor notation:

$$e_r(t) = \sum_{i=1}^{N} a_i \cos(2\Pi f_0 t + \phi_i)$$

$$where$$

$$a_i = amplitude\ of\ the\ received\ component\ i$$

$$f_0 = carrier\ \ frequency$$

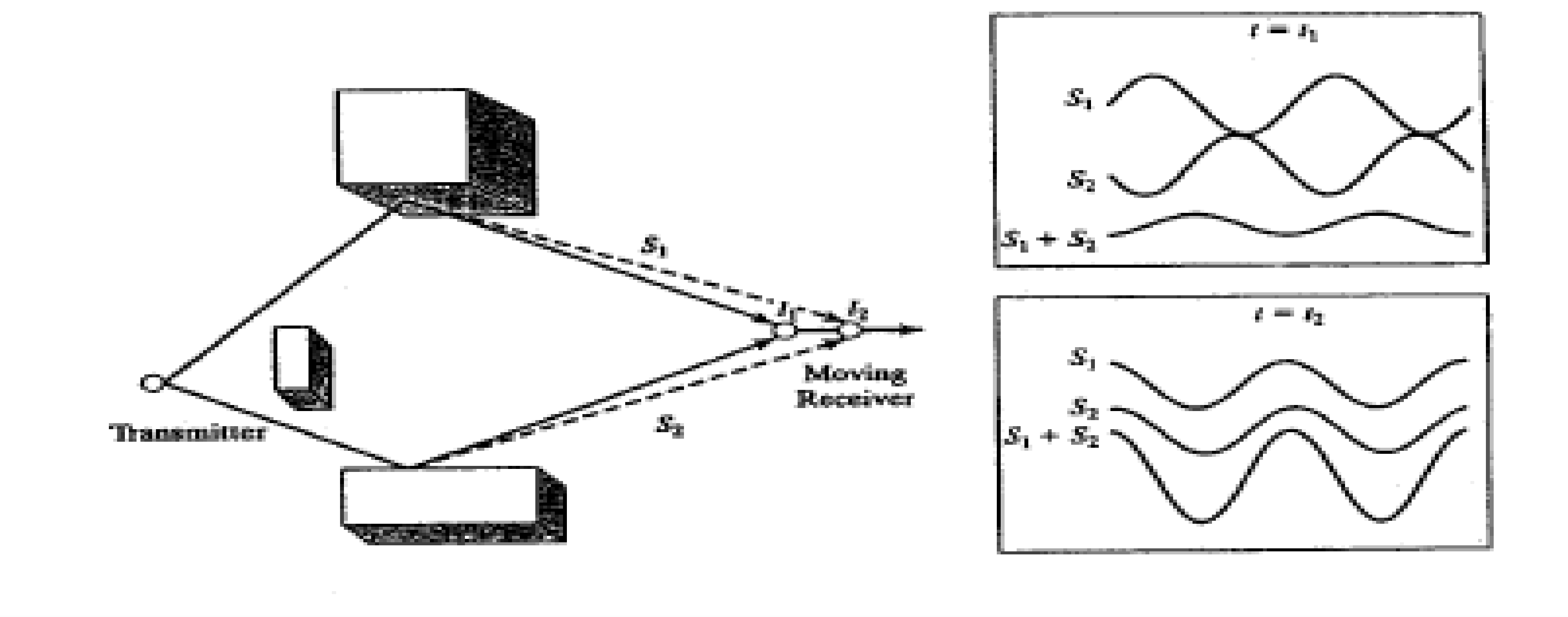
$$\phi_i = Phase\ of\ i^{th}\ signal\ component$$

$$N = Number\ of\ \ paths\ taken\ by\ the\ signal$$

Multipath fading

Resulting signal is the random summation of different signals (cosine shaped signals)

- Leads to a random variation depending on the relative phase between signal components
- Creates constructive and destructive summation



Rayleigh Model

$$e_r(t) = \sum_{i=1}^{N} a_i \cos(2\Pi f_0 t + \phi_i)$$

$$= \cos(2\Pi f_0 t)\sum_{i=1}^{N} a_i \cos(\phi_i) - \sin(2\Pi f_0 t)\sum_{i=1}^{N} a_i \sin(\phi_i)$$

$$= X\cos(2\Pi f_0 t) - Y\sin(2\Pi f_0 t)$$

where

$$X = \sum_{i=1}^{N} a_i \cos(\phi_i), \quad Y = \sum_{i=1}^{N} a_i \sin(\phi_i)$$

- X and Y are independent and identically distributed Gaussian random variable
- Under this condition envelop of the received signal A, given by $(X^2+Y^2)^{1\backslash 2,}$ will be Rayleigh distributed

Probability density function (pdf) of Rayleigh distribution is given by-

$$f_A(a) = \frac{a}{\sigma^2}\exp\left(-\frac{a^2}{2\sigma^2}\right)\cdot U(a)$$

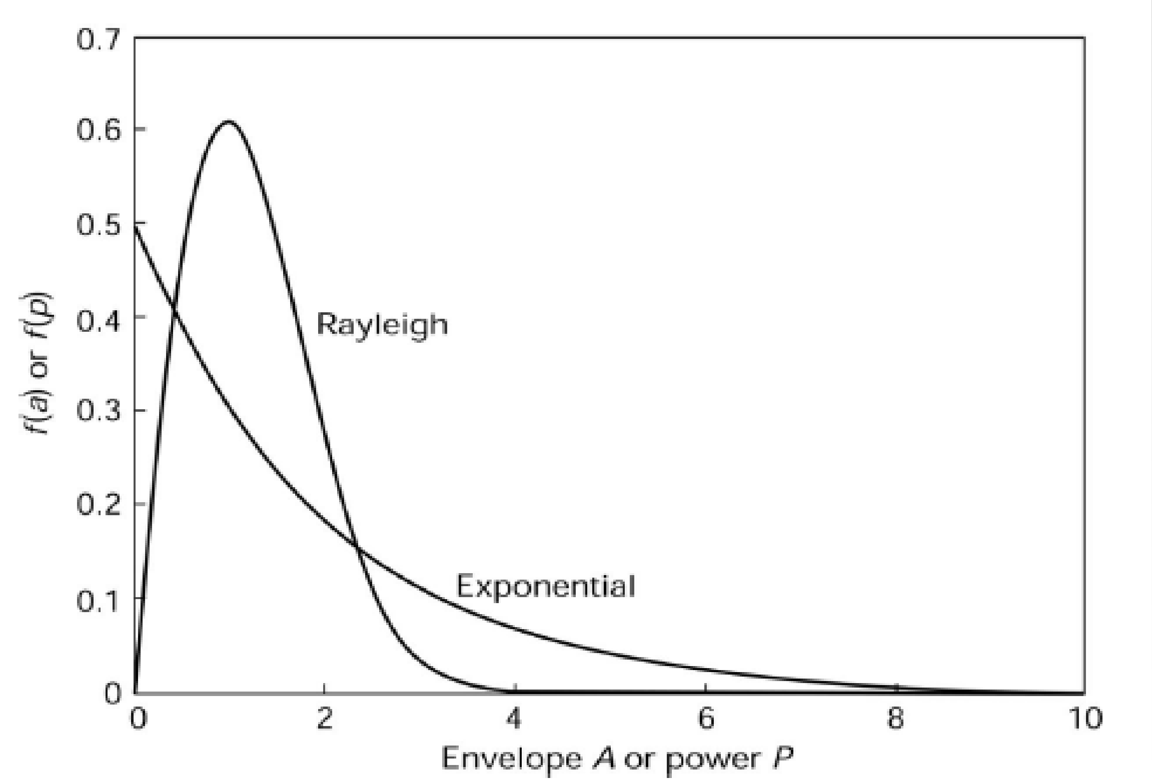
Power of received signal will be exponential distribution-

$$f_P(p) = \frac{1}{2\sigma^2}\exp\left(-\frac{p}{2\sigma^2}\right)\cdot U(p)$$

Where σ^2 is the variance of random variable X (or Y) and U (.) is the Unit Step Fuction.

Rayleigh Model

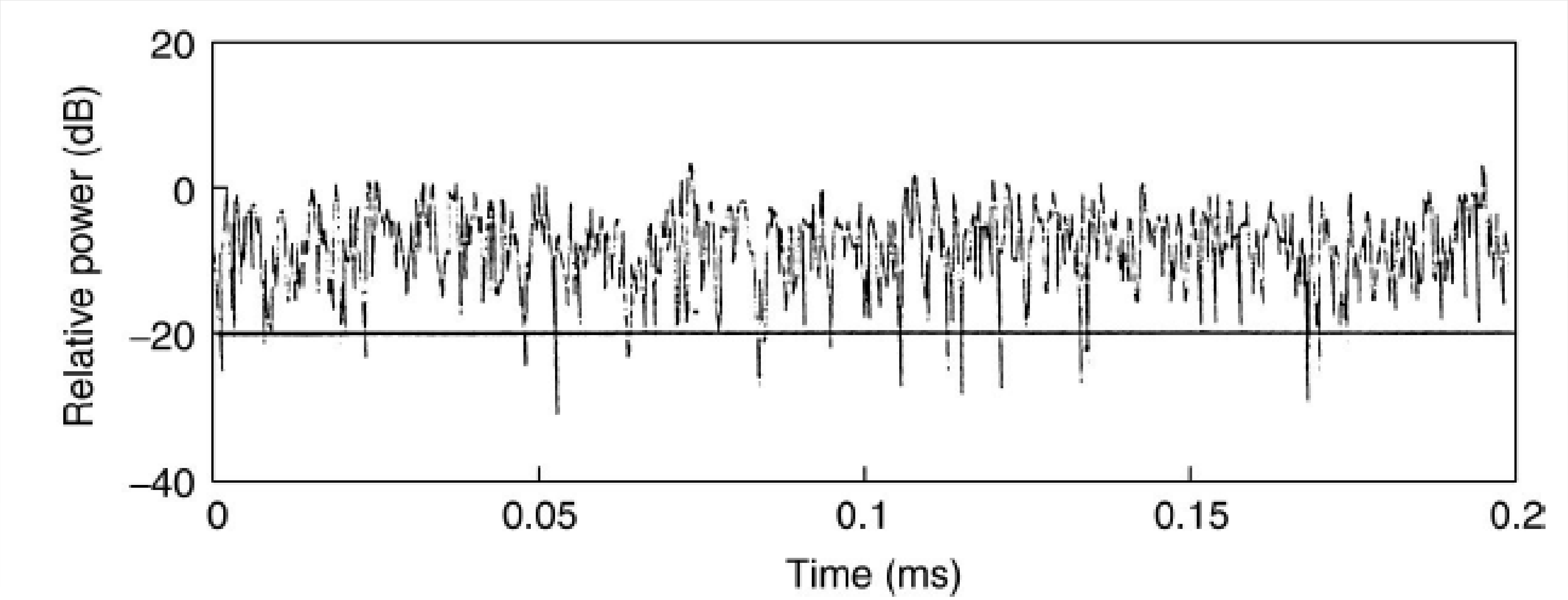
- Rayleigh distribution represents worst case fading as no LOS is considered.
- This is the most used signal model in wireless communication.



Rayleigh Model

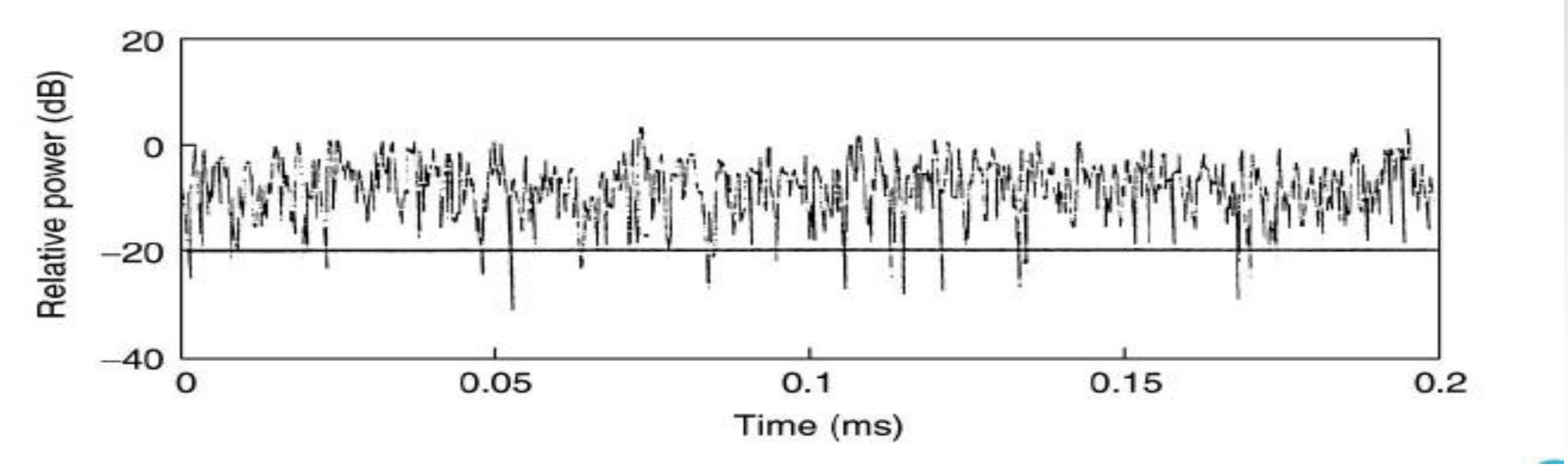
A typical radio signal received in Rayleigh faded channel is shown below

- Variation can be 20 dB (factor of 100)
- Received signal is random even without considering noise. This is due to multipath and randomness of phase.



Outage

- Every receiver is designed to operate at an acceptable level only if a certain minimum power, P_{thr}, is being received
- The receiver will be in outage whenever power goes below this threshold value. Also termed as “deep fade”.
- Outage is the implication of fading; following system goes into outage if the threshold is set to -20 dB of relative power



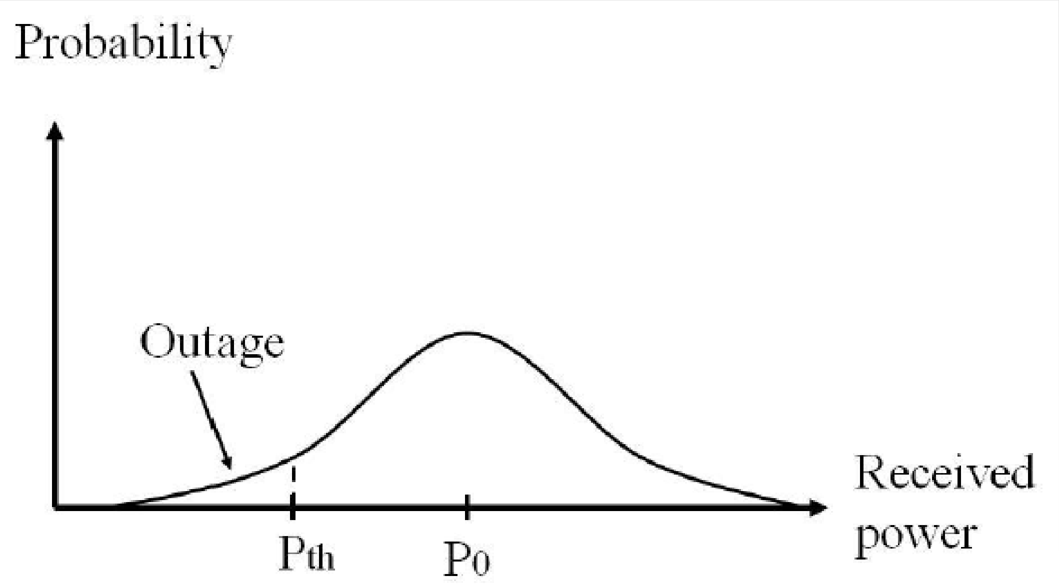
Outage

The outage probability is given by-

$$P_{out} = \int_0^{p_{th}} f(p)dp = \int_0^{p_{th}} \frac{1}{p_0} \exp\left(-\frac{p}{p_0}\right) dp = 1 - \exp\left(-\frac{p}{p_0}\right)$$

Where p_0 is the average power and given by $2\sigma^2$

- One of the adverse consequence of fading is the existing of outage
- When outage occurs, the performance of the wireless system becomes unacceptable



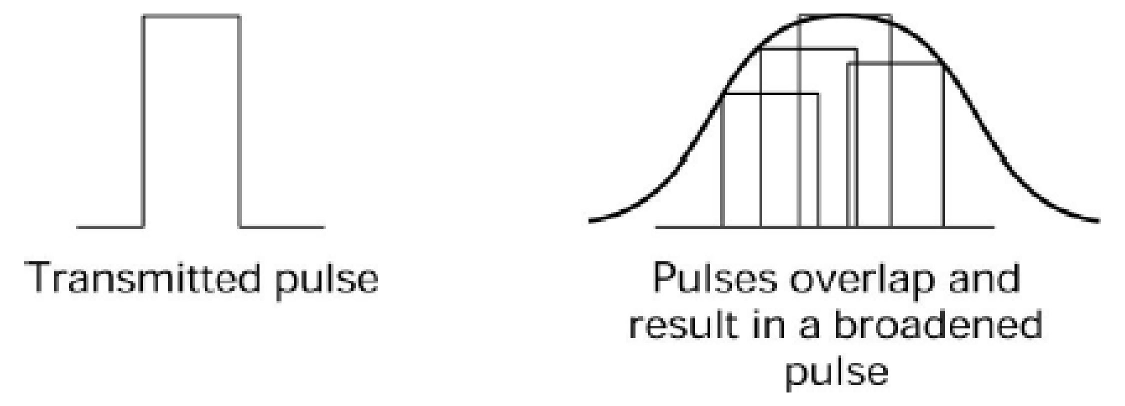
Outage (2)

Example 2.5

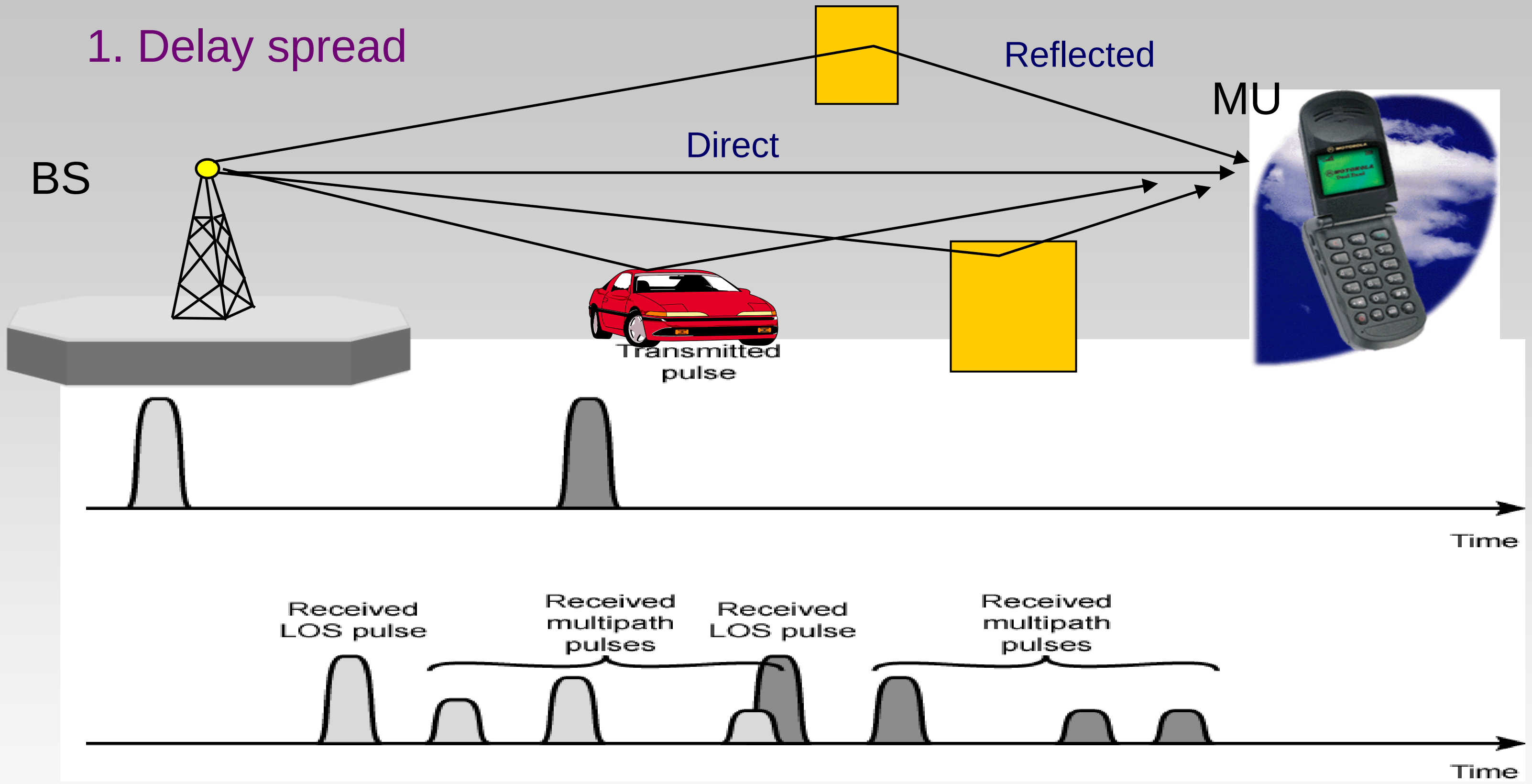
If the minimum required power for acceptable performance is 25 micro watt, what is the outage probability in a Rayleigh channel with an average received power of 100 micro watt?

Multipath and Intersymbol interference

- So far we discussed about the fluctuations of received signal due to fading but-
- Fading may affect the shape of the received signal pulse
- Figure: four different paths, pulse arrives at four different times at the receiver
- Envelope of the overlapping pulse showed a broadened pulse – leads to intersymbol interference (ISI)



Multipath and Intersymbol interference



- Intersymbol interference (ISI) occurs if the delay spread of the channel exceeds the symbol time (or the sampling interval)
- Cancellation of ISI is done via an equalizer at the receiver

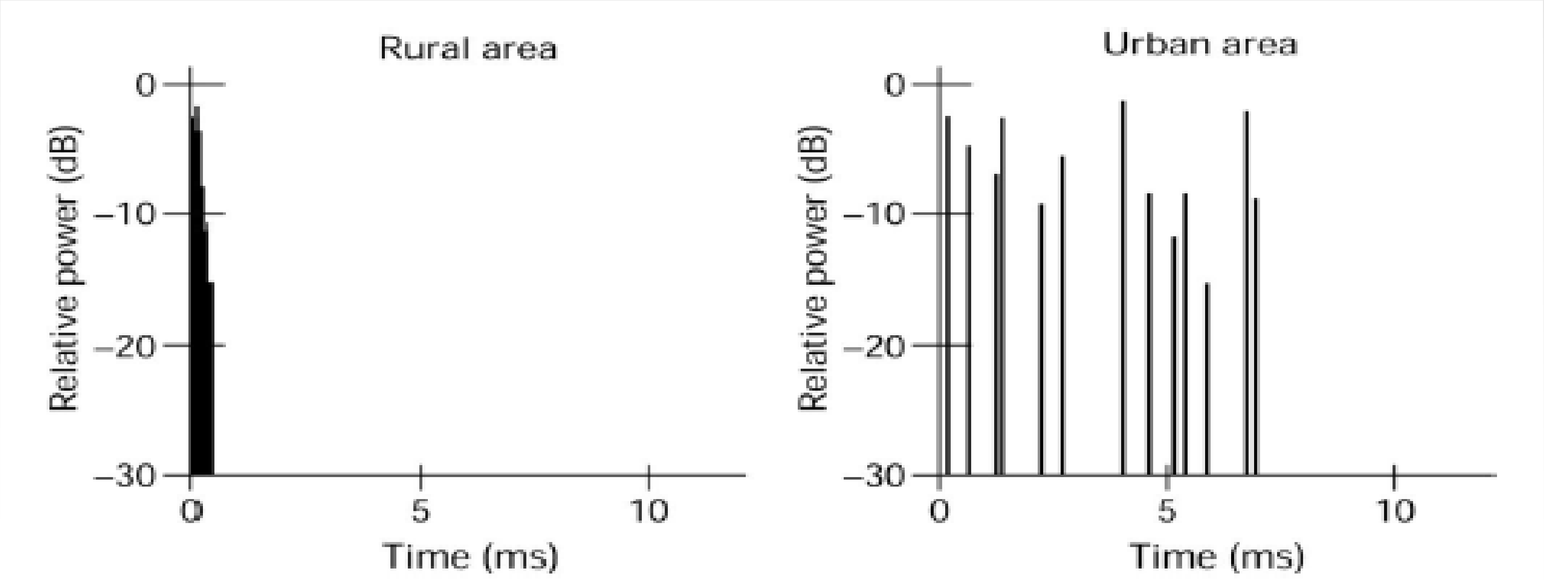
Impulse response

Impulse corresponding to multiple paths arrive at the receiver at different times and with different power depending on the nature of the channel (e.g. reflection, defraction, scattering etc.)

These arrival times of signal with different powers can be used to define the impulse response of the channel

Figure:

- rural areas – due to fewer tall structure, multiple paths are closed to each other
- Urban areas – multiple paths are more diversed and received signals are spread out



Impulse response

Figure shows an Impulse response of a multipath fading channel where Pi is the power and τ_i is the delay of i component.

rms delay spread is given by-

$$\sigma_d = \sqrt{\langle \tau^2 \rangle - \langle \tau \rangle^2}$$

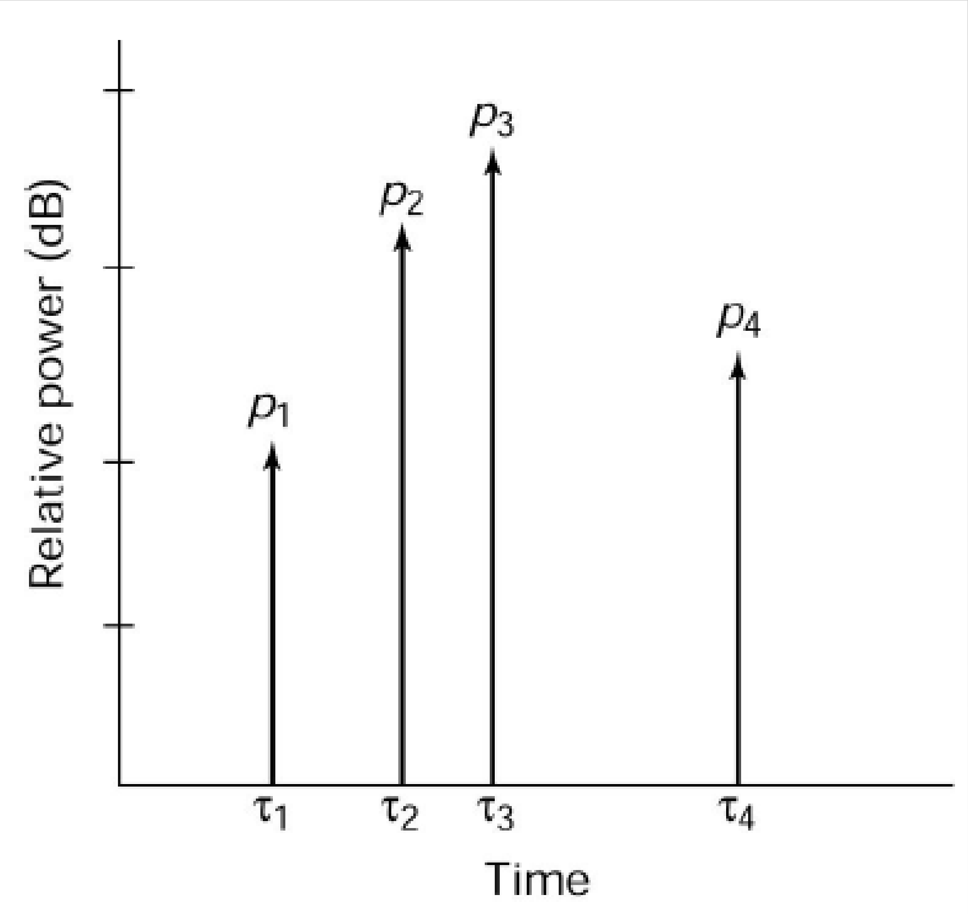
Where, average delay is-

$$\langle \tau \rangle = \frac{\sum_{i=1}^{N} p_i \tau_i}{\sum_{i=1}^{N} p_i}$$

Mean square delay is-

$$\langle \tau^2 \rangle = \frac{\sum_{i=1}^{N} p_i \tau^2}{\sum_{i=1}^{N} p_i}$$

Example 2.6



Symbol rate and bandwidth

There is a direct correlation between symbol rate, R (symbol/s) and information bandwidth, B_s (Hz) in a radio connection:

$$R \propto B_s$$

Means,

High symbol rate (bit rate) -> high bandwidth (broadband)

Low symbol rate (bit rate) -> low bandwidth (narrowband)

The channel bandwidth is given by-

$$B_C = \frac{1}{5\sigma_d}$$

This channel bandwidth can be identified as the *coherence bandwidth* of the channel.

Large spreading of signal → small channel bandwidth

Small spreading of signal → high channel bandwidth

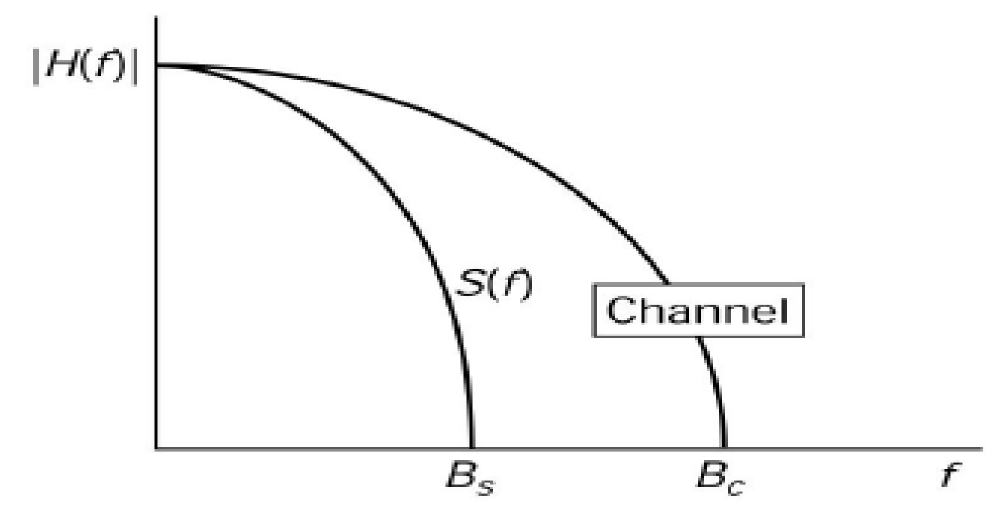
Flat fading channel

If the channel bandwidth B_c is larger than message bandwidth B_s, all the frequecy components in the message will arrive at the receiver with little or no distortion

ISI will be neligible

The channel will be defined as **flat fading channel**

Rural areas can be characterized as nearly flat fading channel



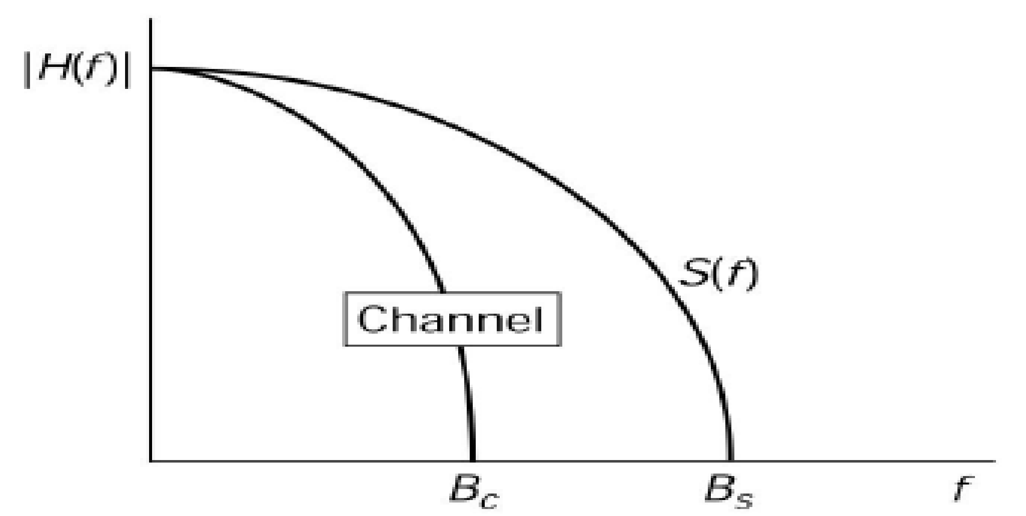
Frequency selective channel

If the message bandwidth B_s is larger than channel bandwidth B_c, different frequecy components in the message will arrive at the receiver at different time

Resulting pulse broadening – ISI

The channel is classified as **frequency selective channel**

The flat fading channel can become frequency selective channel if the information is transmitted with higher and higher bandwidth



Doppler effect

So far, we assumed mobile phone being stationary

The motion of the mobile unit results a **doppler shift** in the frequency of the received signal

The maximum doppler shift is expressed as,

$$f_d = f_0 \frac{v}{c}$$

$$where$$

$$c = velocity\ of\ elctromagnetic\ wave\, in\ \ free\ space$$

$$v = velocity\ of\ the\ mobile\ unit\,(m/s)$$

$$f_0 = frequency\ of\ the\ signal$$

Doppler effect

Taking all the direction into account, the instantaneous frequency of the doppler shifted signal is:

$$f_{in} = f_0 + f_d \cos(\theta)$$

Coherenc Time:

$$T_C \approx \frac{9}{16\pi f_d}$$

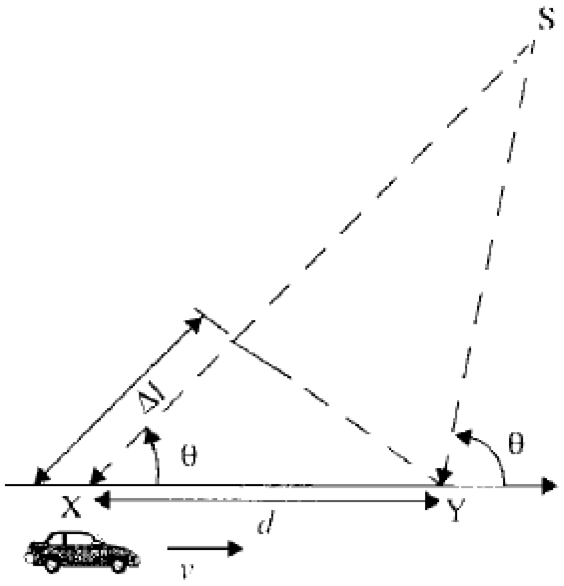


Illustration of Doppler effect.

Slow and fast fading can be also explained by coherence time, Tc-

- If pulse duration is smaller than Tc, then it is unlikely to undergo distortion→ slow fading
- If pulse duration is larger than Tc, then will be distorted→ fast fading

Slow and Fast Fading

Symbol period is smallar than coherence time, Ts < Tc

- Slow fading
- Symbol doesn’t experience distortion

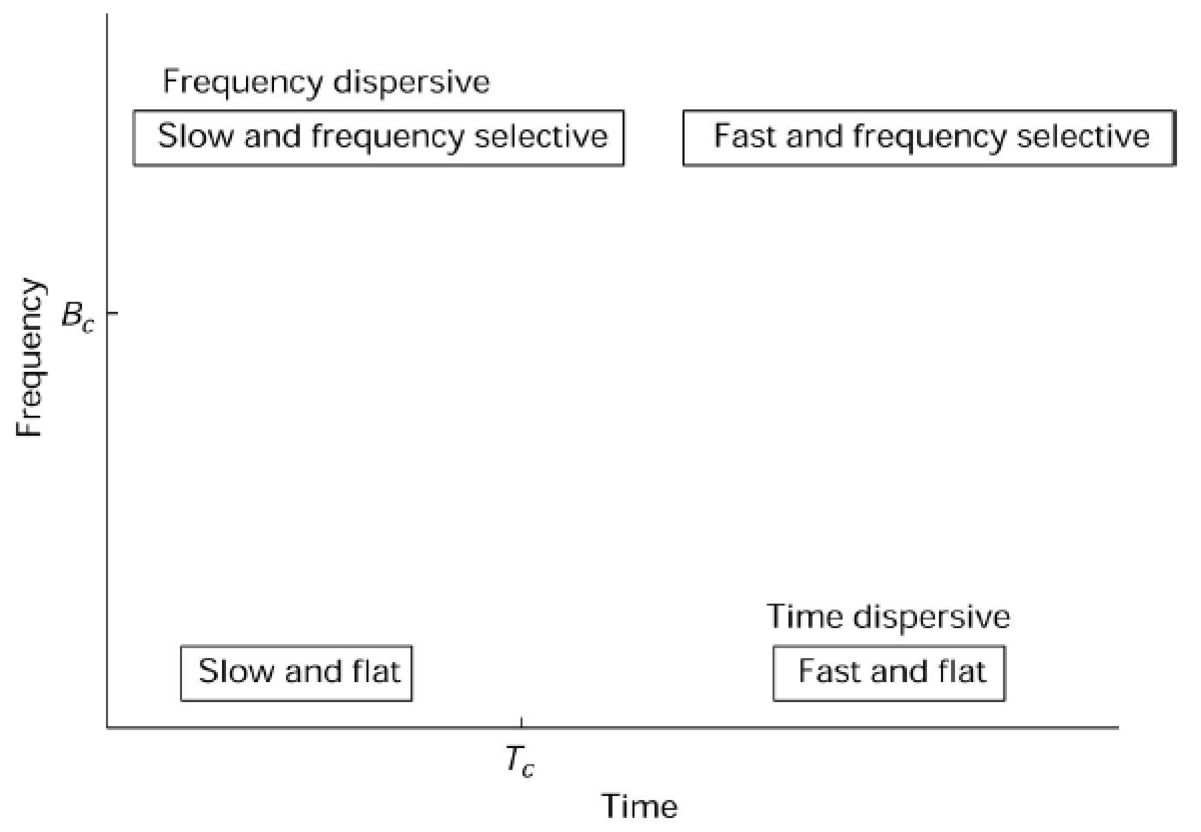
Symbol period is larger than coherence time, Ts > Tc

- Fast fading
- Symbol undergoes distortion

Frequency dispersion verses Time dispersion

- Fading can occur in frequency domain (due to multipath) and in time domain (due to movement of MU)

- At low data rate and when MU has low mobility then channel is slow and flat
- If data rate is high but MU is moving slowly then channel is slow but frequency selective
- If however, data rate is high and MU is moving at high speed then channel will be both fast and frequency selective. Channel will be both time and frequency dispersive.



Rician Model

- Rician model considers a LOS path in the received signal in addition to number of random paths
- This LOS adds a deterministic component in the received signal and makes Gaussian random variable of nonzero mean and Rician distributed envelope.

The power distribution fucntion (pdf) of Rician distribution is given by-

$$f_A(a) = \frac{a}{\sigma^2} \exp\left(-\frac{a^2 + A_0{}^2}{2\sigma^2} \right) \cdot I_0\left(\frac{aA_0}{\sigma^2} \right)$$

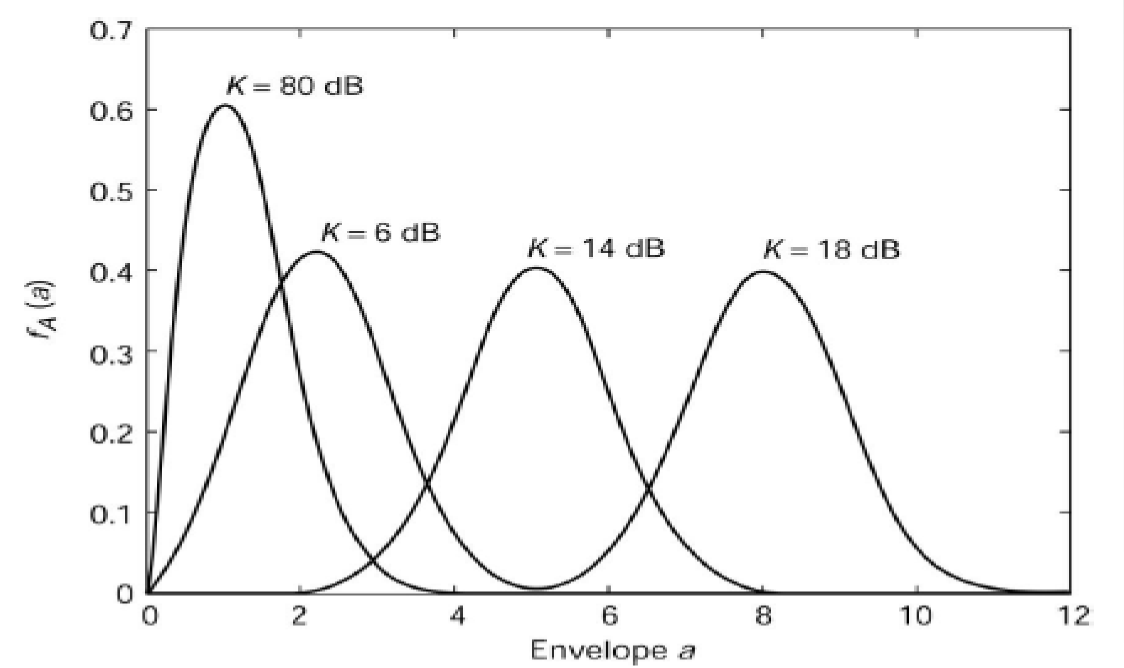
Where Ao is the component from LOS part and Io(.) is the modified Bessel function.

Rician Model

- Rician probability distribution function is characterized by the power of ratio of direct component to the power of other random paths (diffuse component), K(dB):

$$K(dB) = 10\log_{10}\left(\frac{A_0^{\;2}}{2\sigma^2}\right)$$

- For $K=-\infty$ there is no direct path and the Rician distribution becomes Rayleigh distribution
- For higher and higher value of K, the Rician distribution becomes almost Gaussian
- In general, Rician distribution has less signal variation compare to Rayleigh because of existence of LOS component and reduces the effect of fading



Rayleigh and Rician Model

- Rayleigh fading model assumes there is no line of sight (LOS) or most applicable when there is no dominant propagation along the LOS.

- Rician fading occurs when one of the paths, typically a line of sight signal is much stronger than the others. That means it assumes a LOS

- Hence, Rayleigh model can be also considered a special case of Rician model

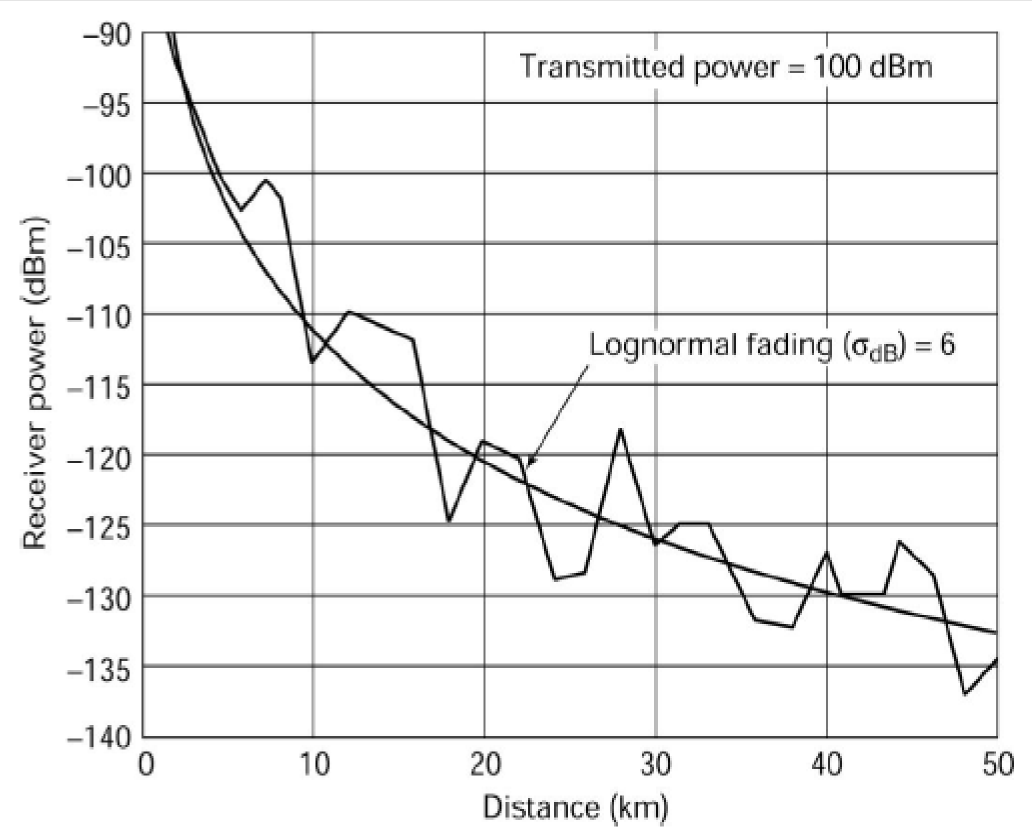
Lognormal fading

- Fading described so far falls under “short-term” fading. However, received signal also undergoes “long-term” fading as discussed earlier

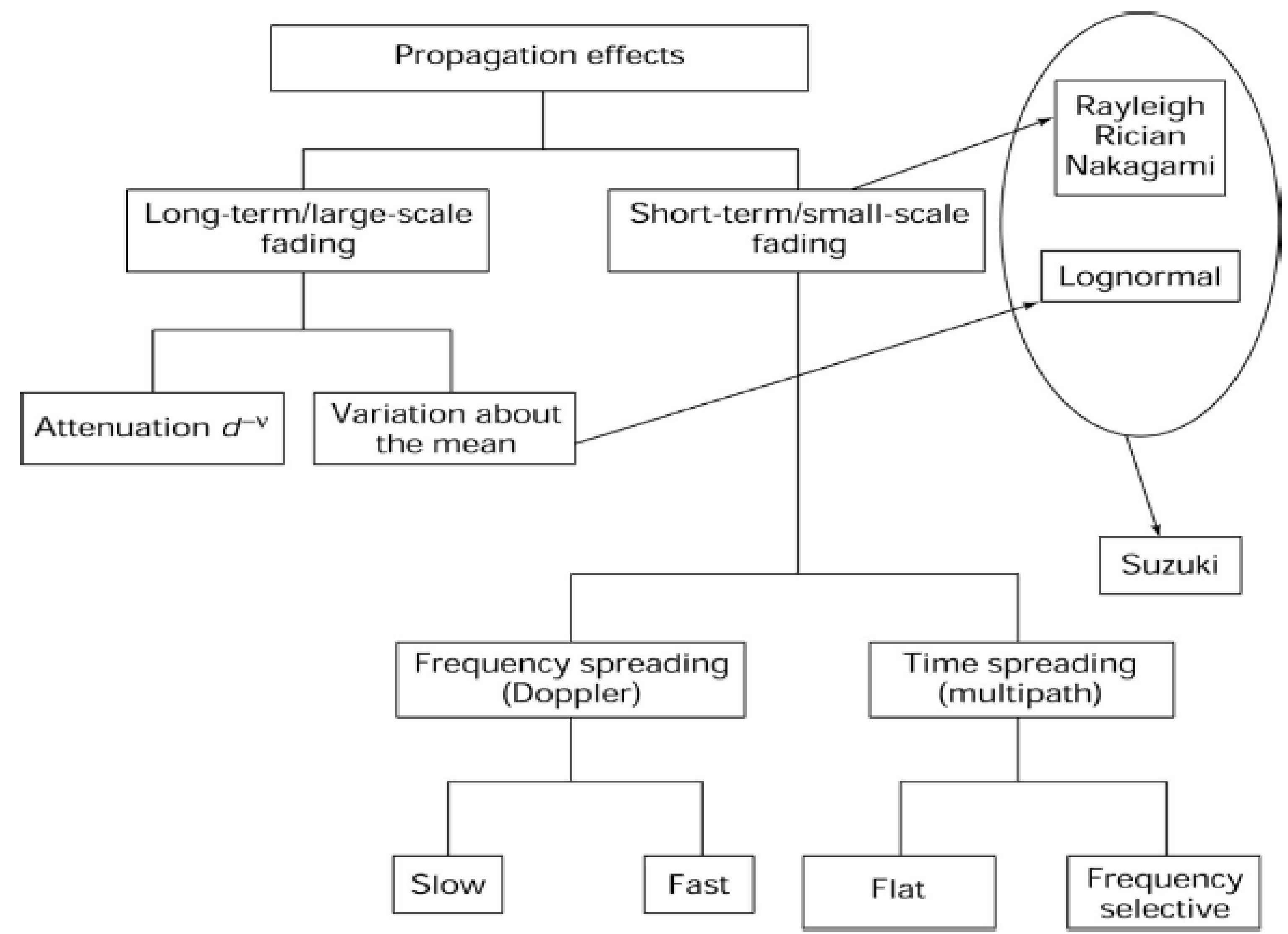
- Long-term fading occurs where propagation takes place in an environment with tall structures (e.g. trees, building)

- Under these conditions, the signal likely to have multiple reflected and scattered before taking multiple paths to the receiver

- Long-term fading is also referred as “shadowing”.



Summary of Fading



Problems

Chapter-2: Propagation characteristics of wireless channel

- Problem 2
- Problem 11
- Problem 14
- Problem 16

Summary

- Attenuation is a result of reflection, scattering, diffraction and refraction of the signal by natural and man-made structure
- The received power of radio signal is inversely proportional to the (distance)^v, where v is the loss parameter (2 for free space and 2-4 for other environments)
- The loss in outdoor can be modeled by Hata Model
- Indoor propagation models are based on the characteristics of interior of building, materials and other factors and described in terms of various zone model
- The random fluctuations in the received power are due to fading
- Multipaths and Dopper effect contribute to short-term fading and multiple reflections, scattering lead to long-term fading (shadowing)
- Short-term fading can be described using Rayleigh distribution if no direct paths exists between the transmitter and receiver
- Short-term fading can be described using Rician distribution if there is a direct paths exists between the transmitter and receiver

Summary

- Short-term fading due to multipath not only causes random fluctuations in the received power, but also distorts the pulses carrying the information
- If bandwidth of the channel is higher than the bandwidth of the message, the signal is characterized by “flat fading” and no pulse distortion. In opposite case, the result is “frequency selective fading” channel.
- If there is relative motion between transmitter and receiver the result is Dopper fading.
- In general, worst case fading occurs when it is both fast and frequency selective fading
- Both short-term and long-term fading leads to outage. The system goes outage when the SNR or received signal goes below a certain level or threshold.