UiO : Universitetet i Oslo

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Propagation characteristics of wireless channel – Chapter 2

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Contents

- 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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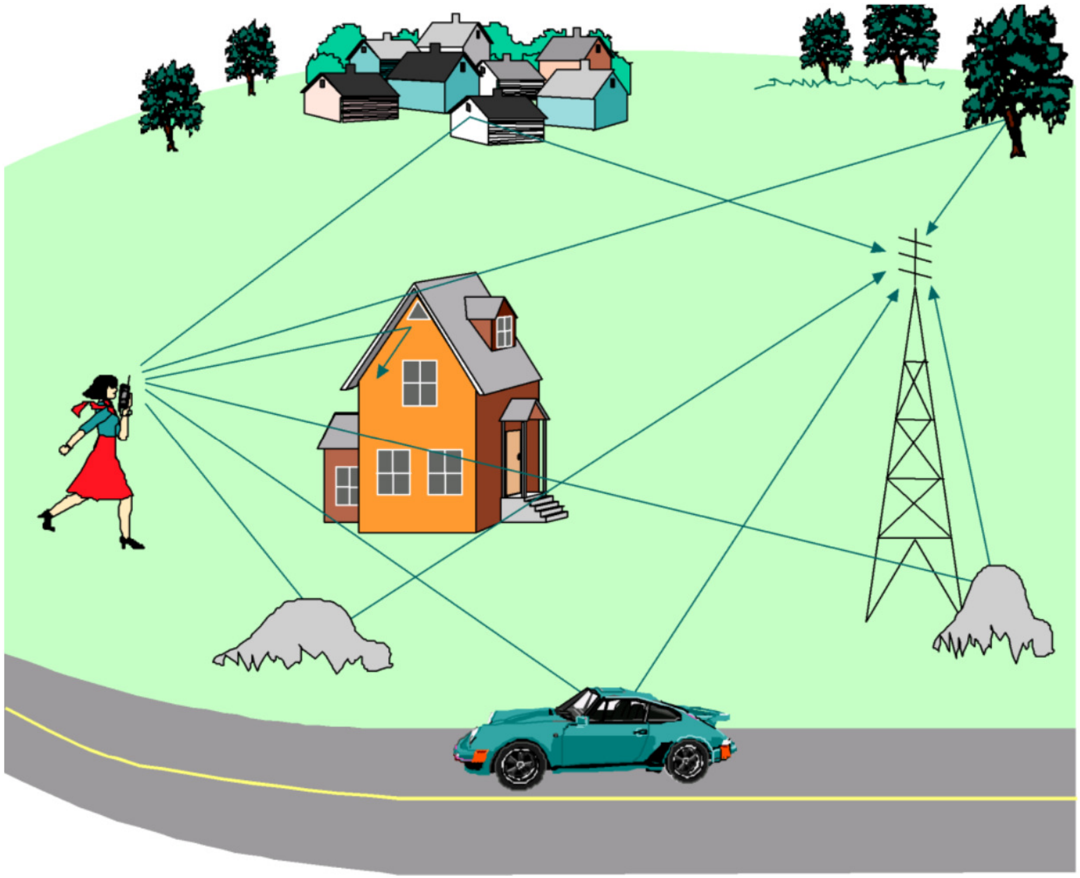
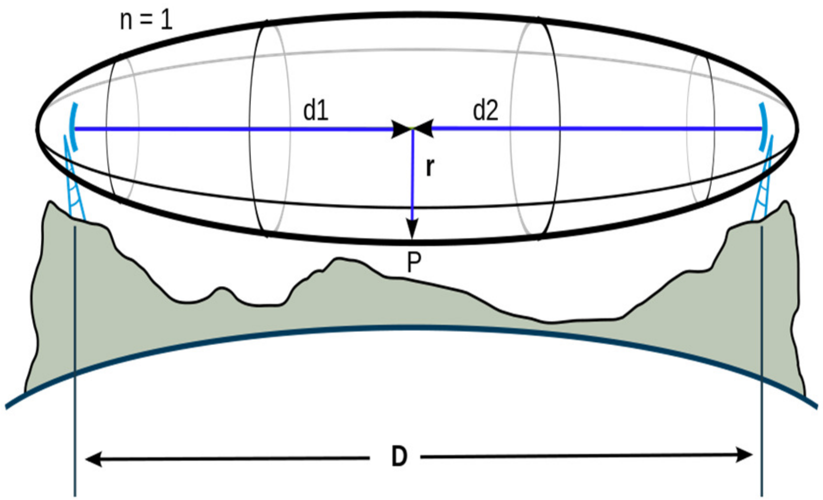
Radio channel

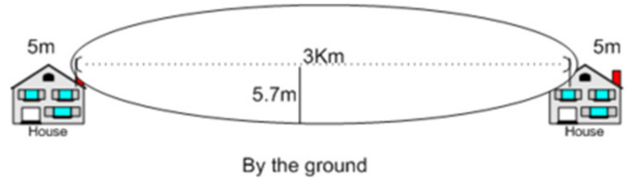
- The transmitted signal arrives at the receiver from different directions at different times over a number of ways
  - Line of sight (LOS) or
  - Non-line of sight (NLOS)

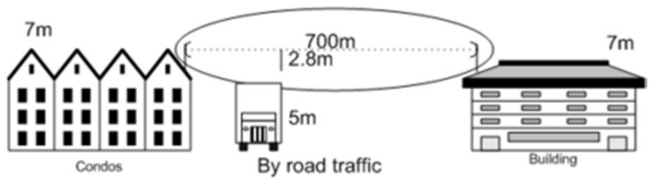


Fresnel zones



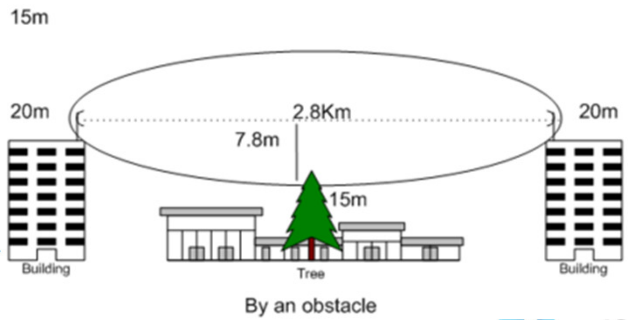
- Fresnel zones determine whether a given obstacle will cause a constructive or destructive interference at the receiver due to reflection
  - Reflection can enhance received signal if reflected and direct signals arrive in-phase
  - Its important to clear obstruction from first Fresnel zone
- The radius of Nth 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.





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

All units are meter



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

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

Fresnel zones

- 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):

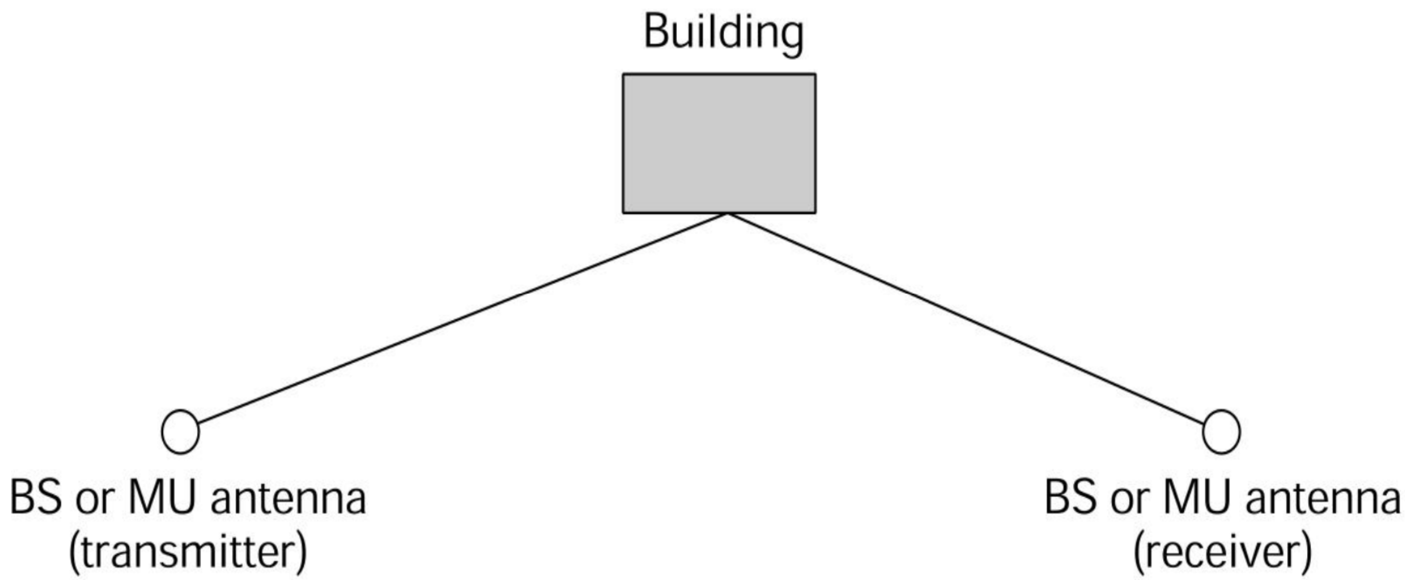
r = 17.31 sqrt(1 * (1000 * 1000) / (2437 * 2000))
r = 17.31 sqrt(1000000 / 4874000)
r = 7.84 meters

- 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

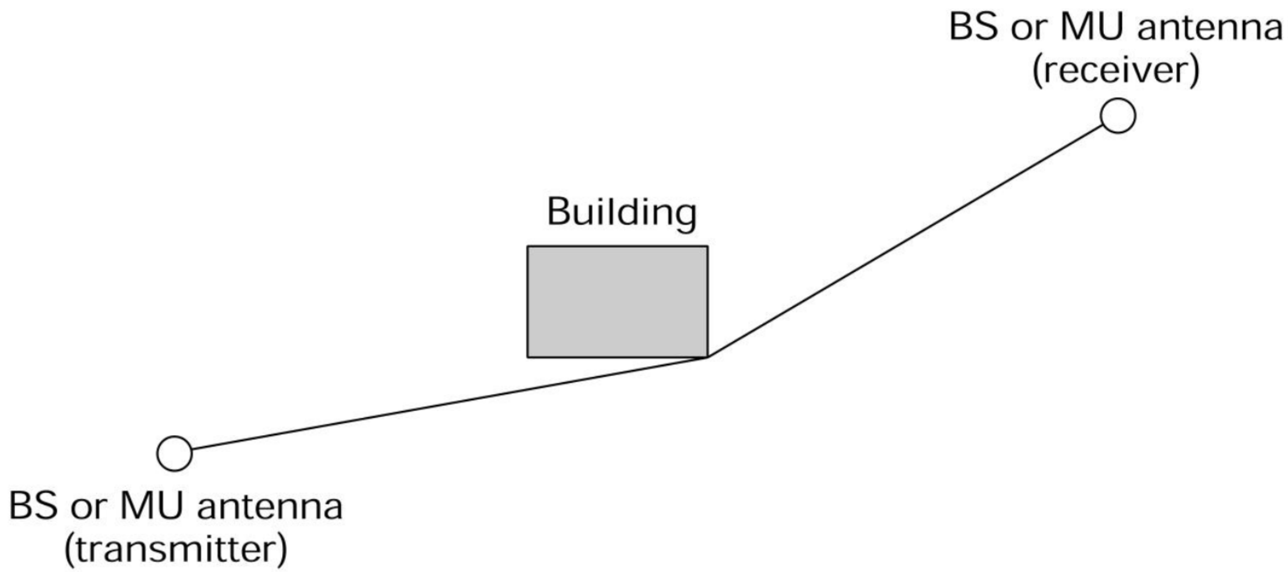
- How tall could a structure in the middle of a 2km point be to clear 60% (N=0.6) of the first Fresnel zone? Transmitter is transmitting at 2.437GHz (802.11b channel 6)

Reflection



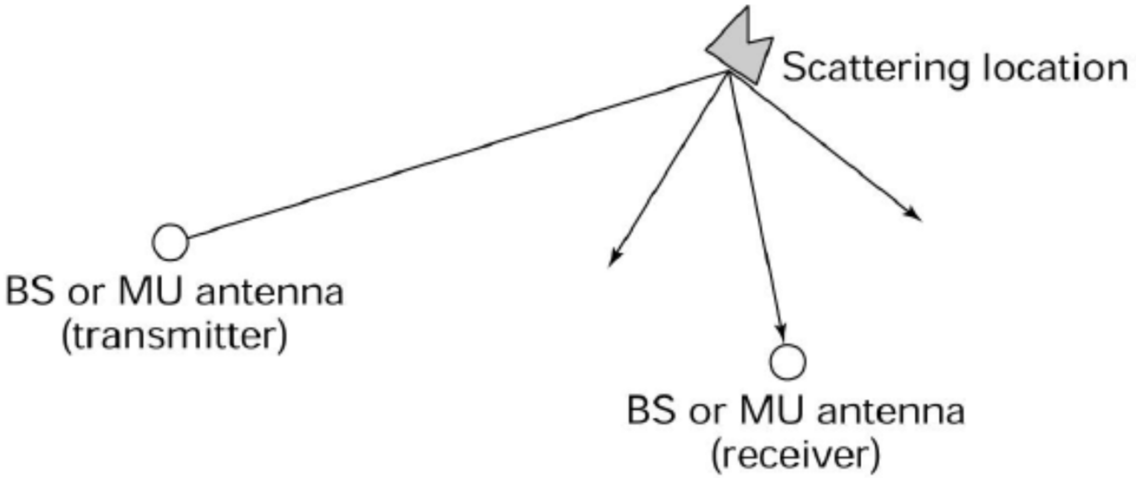
- Reflection occurs when a radio wave strikes a barrier with a dimension larger than the wave length of the radio wave
  - E.g. Buildings, ground, vehicles etc.

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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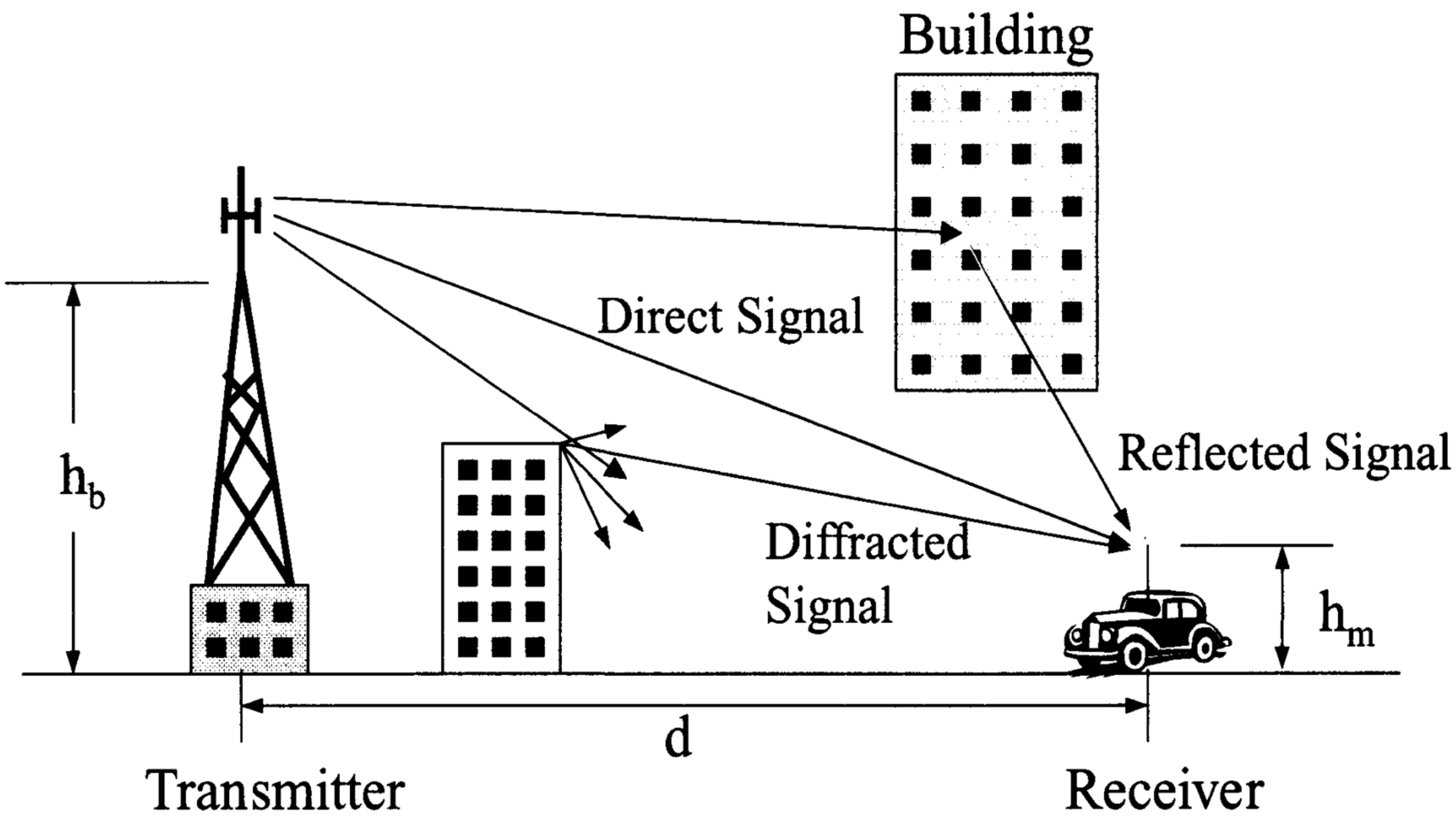
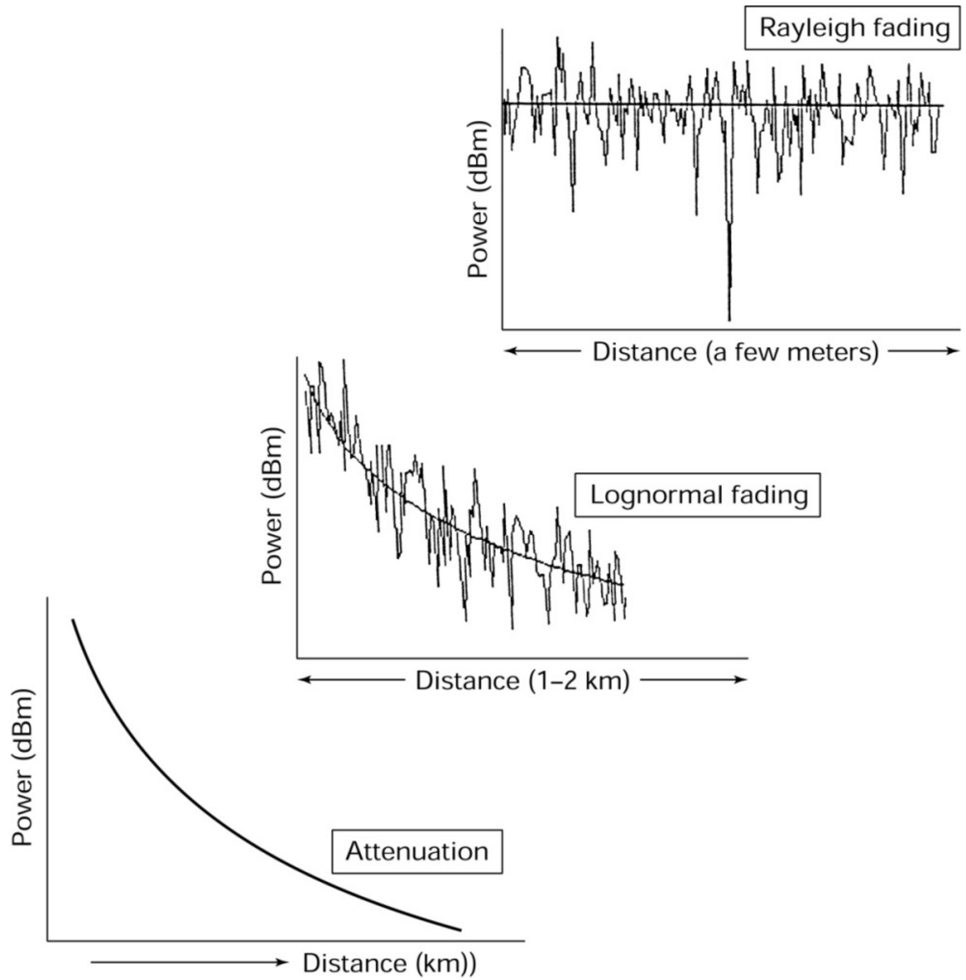
Attenuation and fading

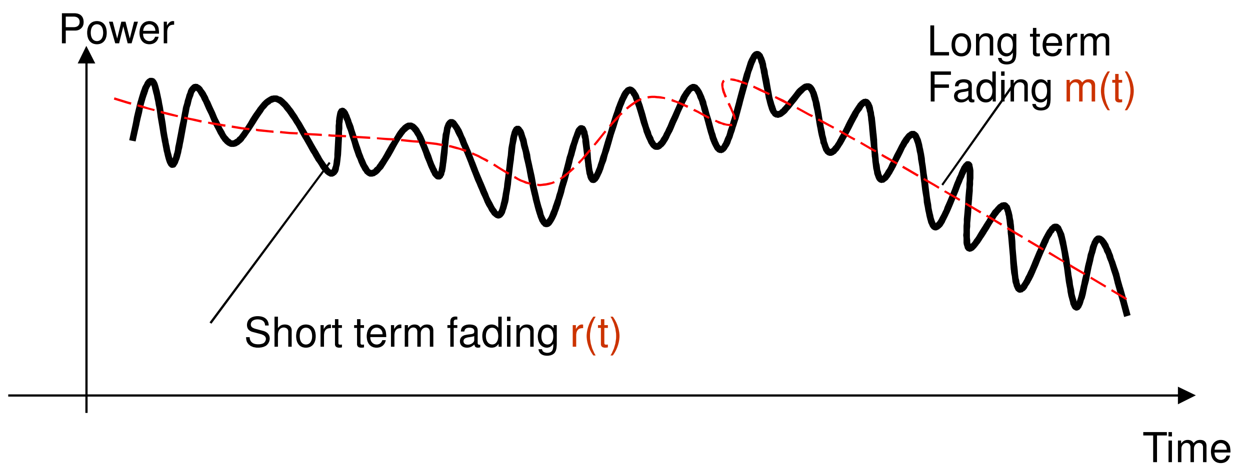


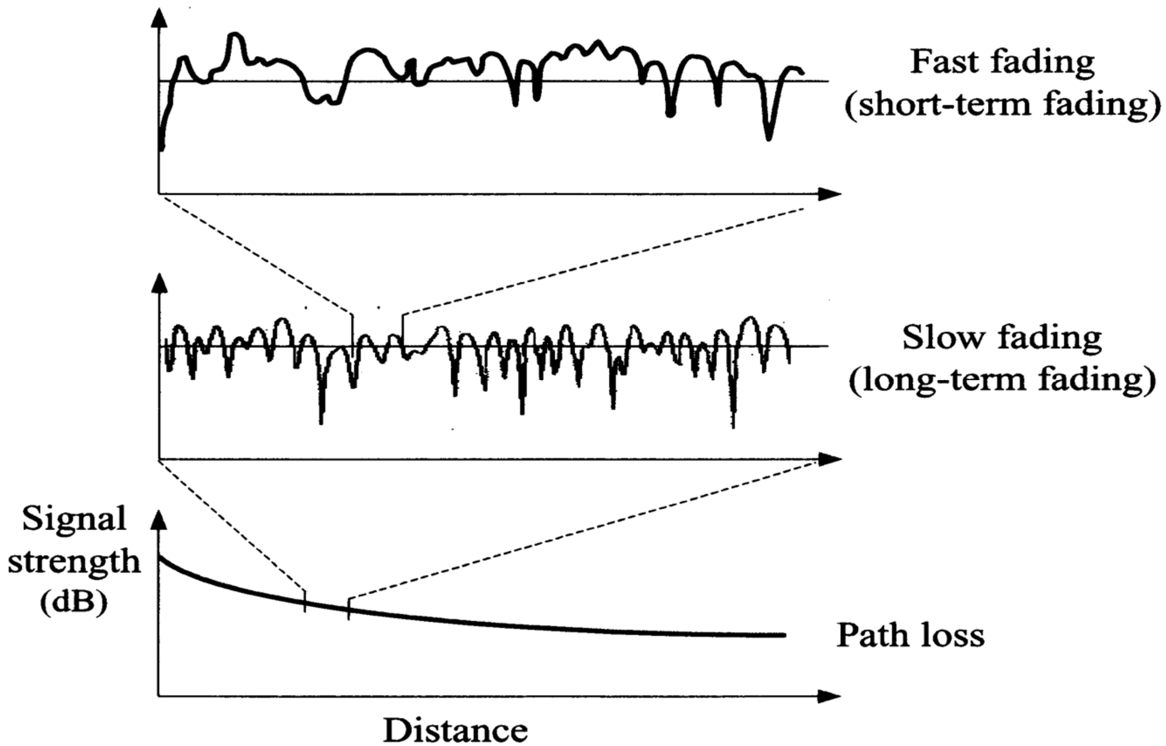
Attenuation and fading – spatial domain

- 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 modelled using log-normal distribution.



Attenuation and fading – time domain





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
- = 2 = 3 dB
- = 0.5 = -3 dB

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

- Decibel (dB) is a dimensionless unit

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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:

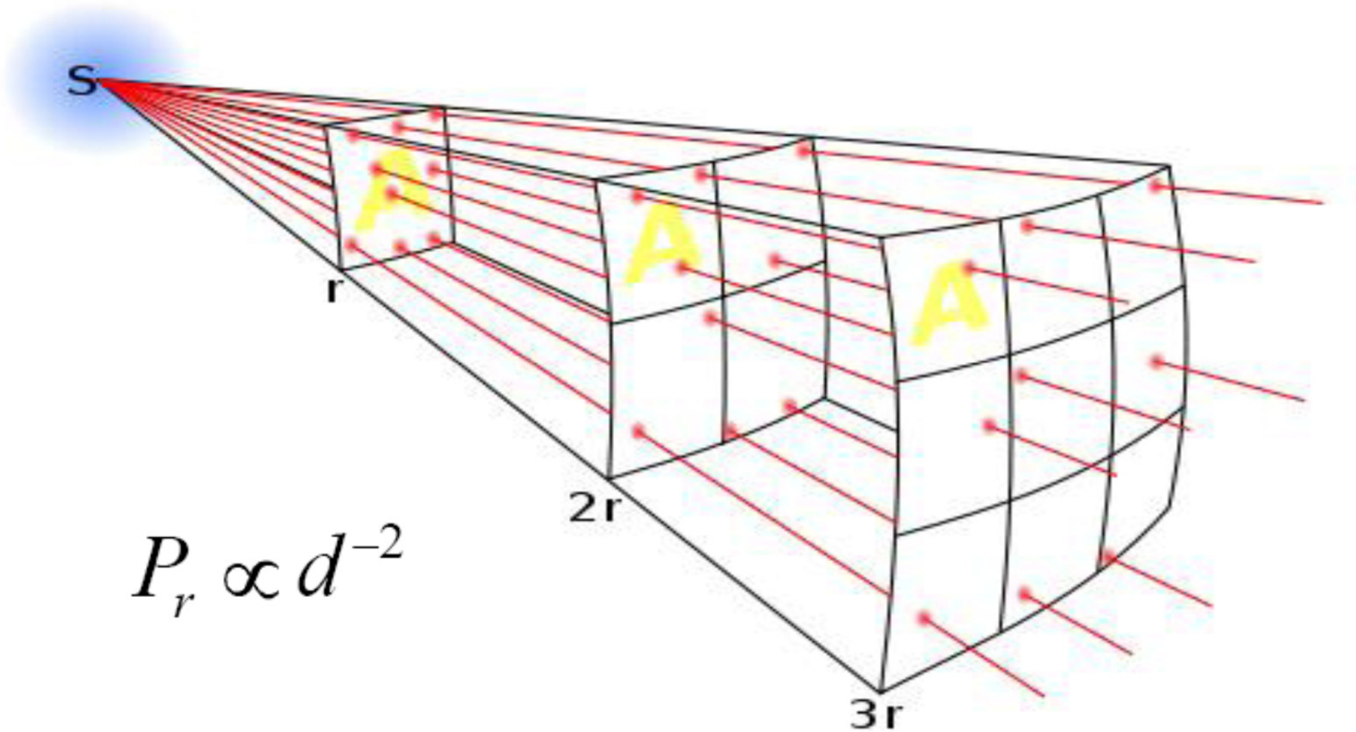
$$x = 10\log_{10}\left(\frac{P_a(mW)}{1\,mW}\right) \quad dBm$$

- Example:
  - P_a = 1 mW, x = 0 dBm
  - P_a = 1 W, x = 30 dBm, maximum output 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:



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

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Attenuation in free space

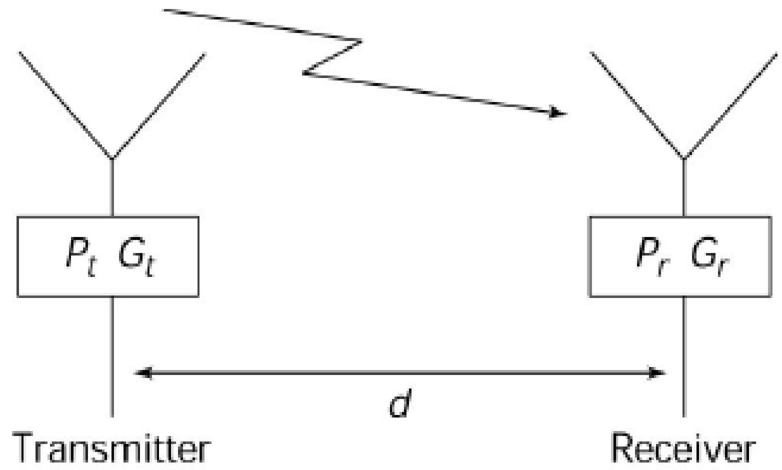
- Received power in free space can be expressed as:

$$P_r = \frac{P_t G_t G_r \lambda^2}{4\Pi^2 d^2 L} \quad (2.2)$$

P_t = transmit power

G_t, G_r = gain of transmitter, receiver antenna

L = other losses (e.g. filter loss, antenna loss)



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, it is identical to free space loss

- From the above equation, we can also write:

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

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Free space path loss

- Free space path loss:

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

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

d = distance from transmitter (m)

λ = signal wavelength (m)

f = signal frequency (Hz)

c = speed of light

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

where d in km and f in MHz

Attenuation in free space

- If received power is known in a reference distance dref , 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

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

Attenuation factor

- In real cases, attenuation is much higher because the signal propagation path is not really free space.
- With a general attenuation factor, the received power becomes:

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

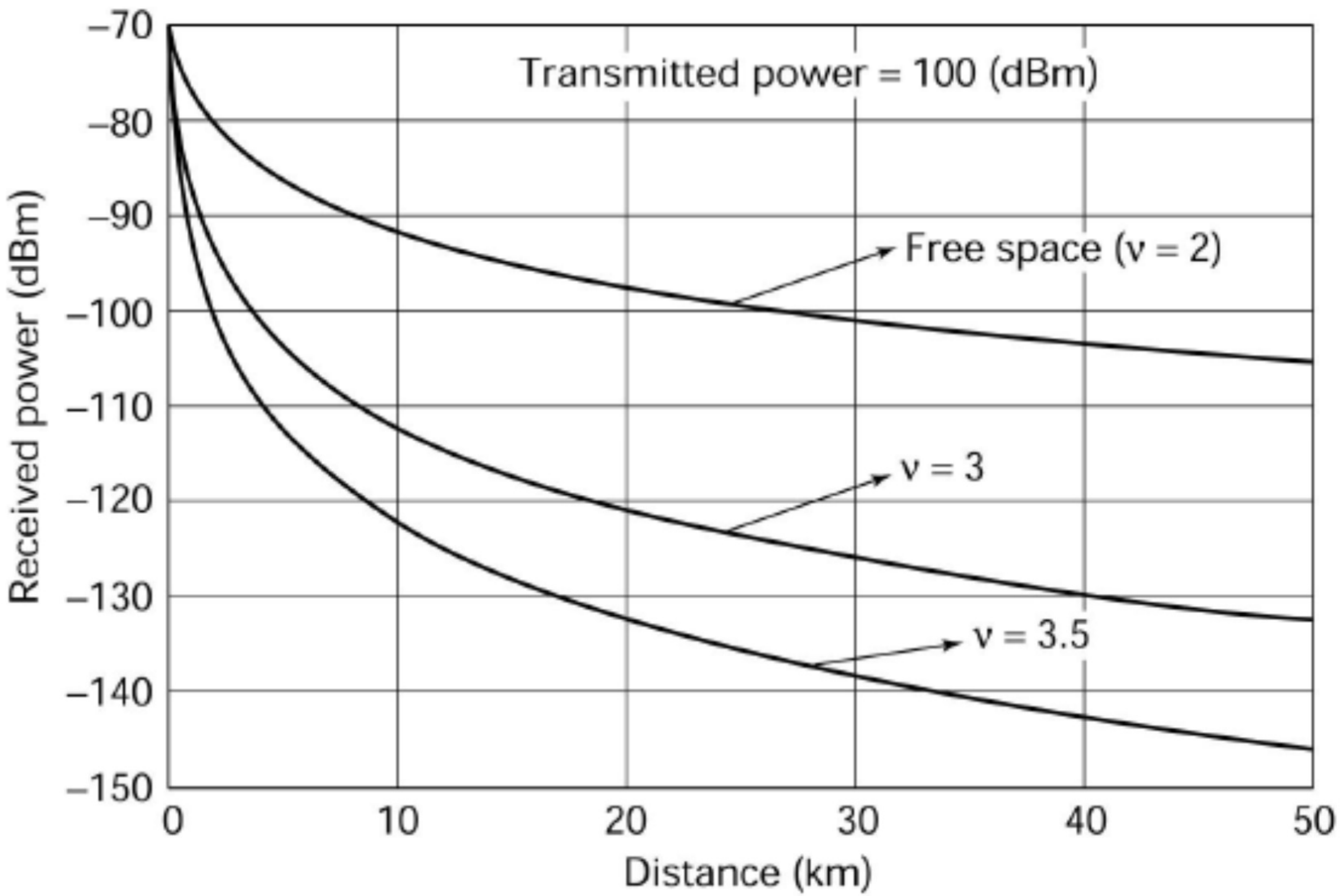
- ν = 2 for free space
- Typical values for urban areas are 3 - 5

- With received power known at a reference distance, one can write:

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

Attenuation factor

- Received as a function of distance for different values of ν:



Channel models

- Models are mathematical 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 behaviour rather most likely behaviour of the channel

  - Analytical or deterministic model: takes into account link specific geometry (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 – semi-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

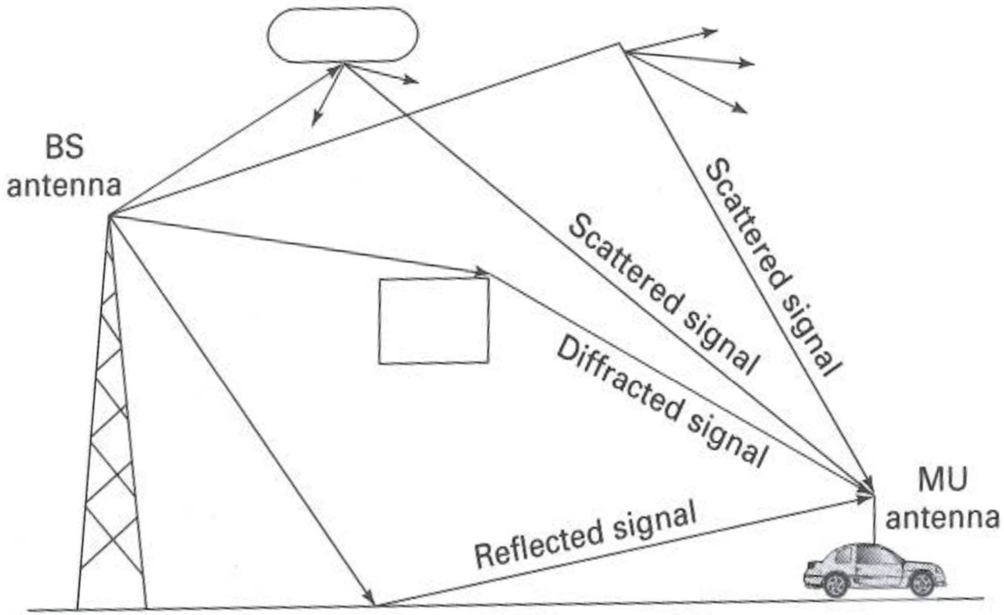


FIGURE 2.10 The most general case of signal reception, consisting of a direct path, a reflected path, a scattered path, and a diffracted path.

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 BS (b) and mobile terminal (mu) (km); $d \geq 1$ km
h_b = height of the BS antenna (m)
h_m = 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

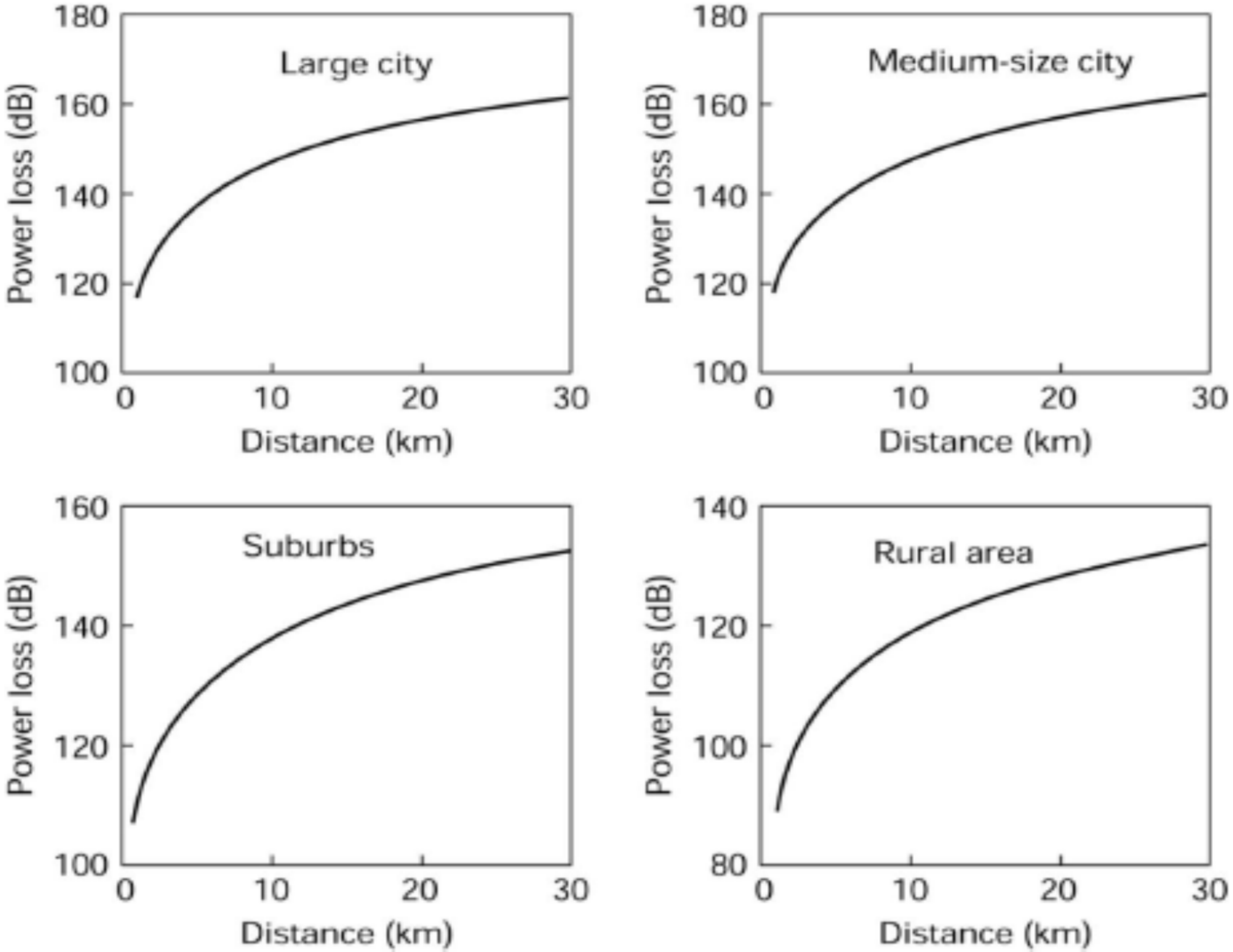


Figure shows loss calculation based on Hata model for four different environments given that f_0=900MHz, h_b=150m, h_{mu}=1.5m

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Indoor propagation model

- Models so far presented are not sufficient to predict signals in indoor
- Indoor propagation sees reflections, scattering, and diffraction due to walls, ceilings, furniture 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
- The zone configurations are based on:
  - The location of the base station
  - How the base station handles the traffic
  - Whether the base station is outside or inside the building

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: $\nu=2$ for LOS, $\nu>2$ for NLOS.

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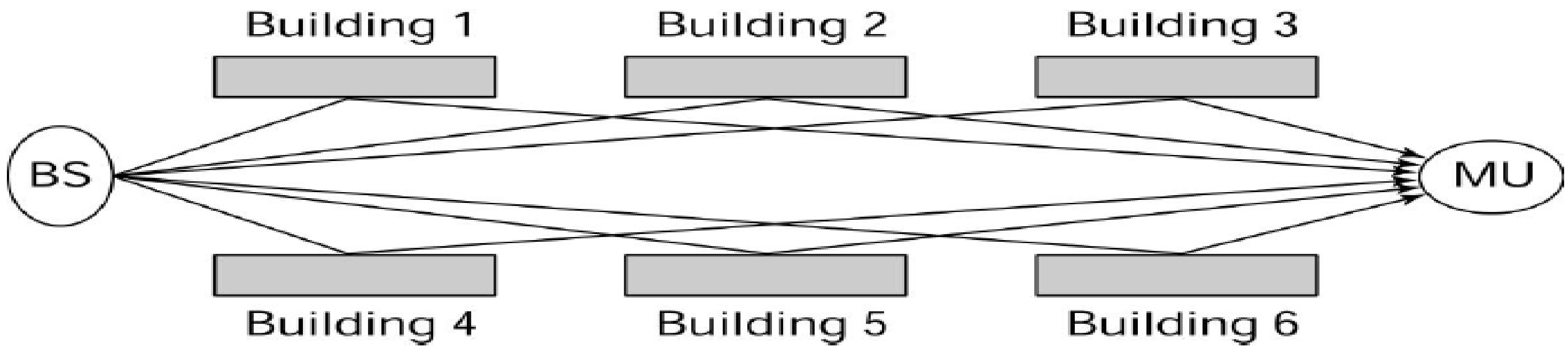
Fading

- In addition to propagation loss, attenuation may also fluctuate with geographical position, time and frequency which is referred as “fading” and usually modelled 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 $e_r(t)$:

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

$$where$$

$$a_i = \text{amplitude of the received component } i$$

$$p(t) = \text{transmitted signal shape}$$

$$t_i = \text{time taken by signal component } i \text{ to reach receiver}$$

$$N = \text{Number of paths taken by the signal}$$

Multipath fading

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

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

$$where$$

$$a_i = \text{amplitude of the received component } i$$

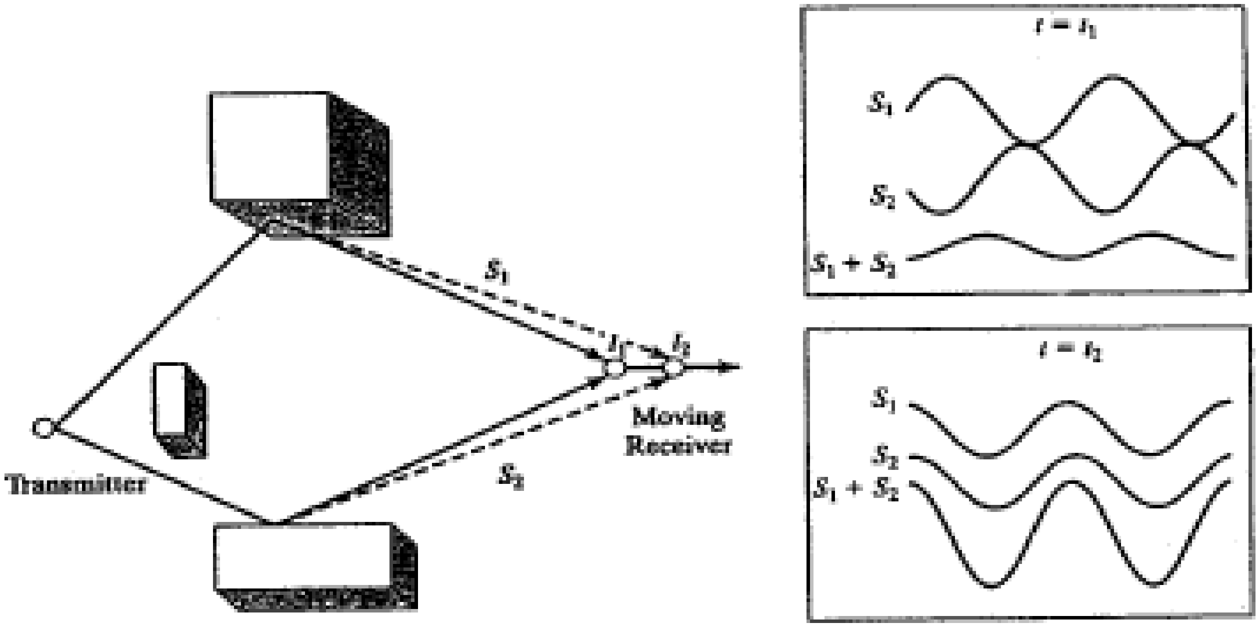
$$f_0 = \text{carrier frequency}$$

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

$$N = \text{Number of paths taken by the signal}$$

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

- *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\2, will be Rayleigh distributed

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

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

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

where

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

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

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

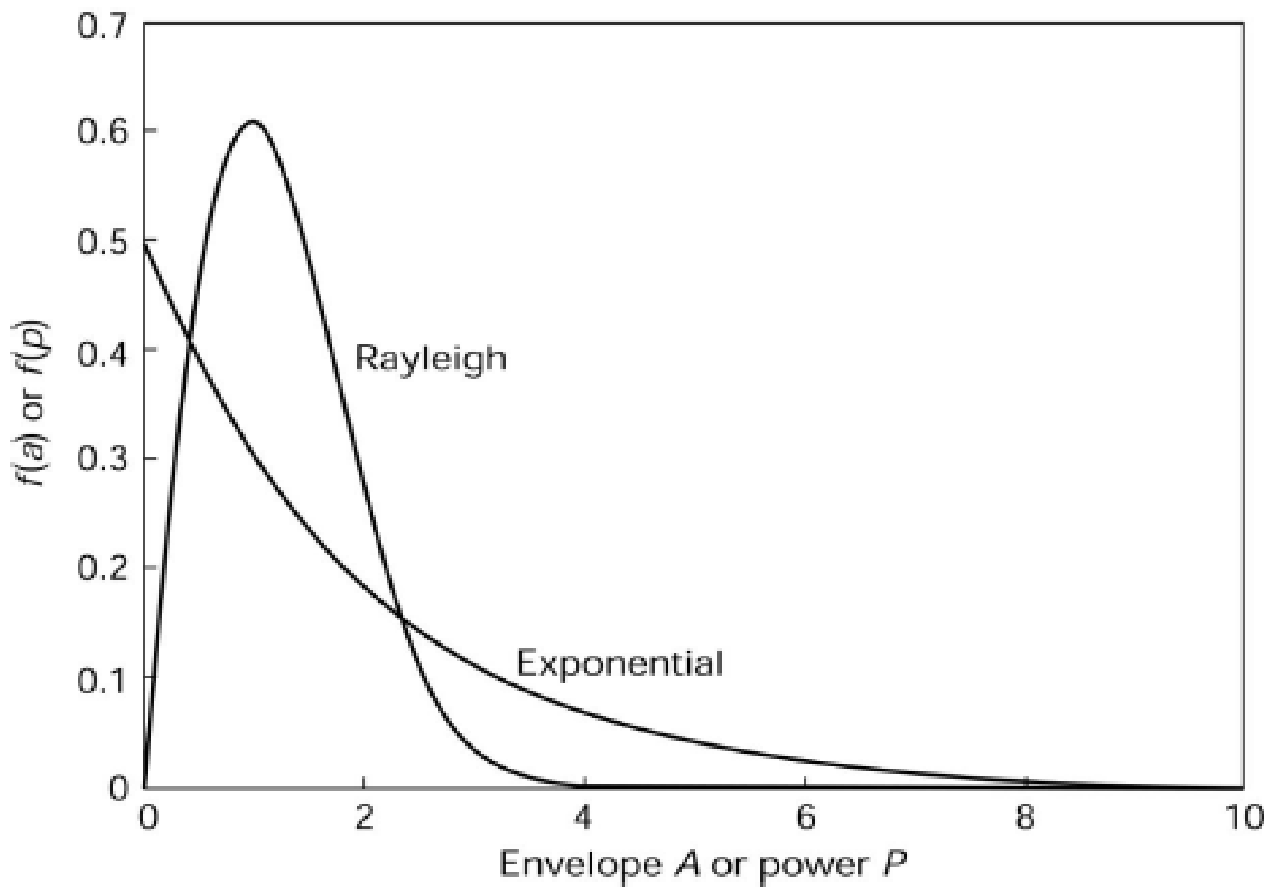
Power of received signal will be exponential distribution-

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

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

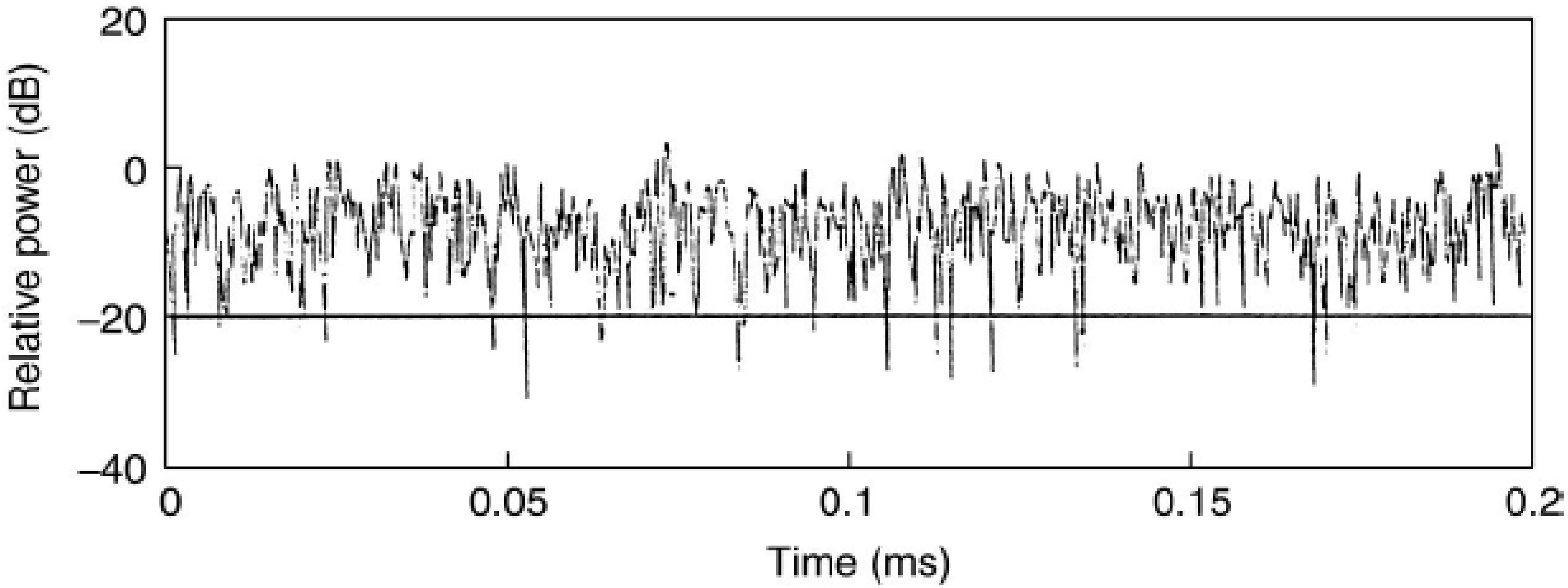
Rayleigh Model

- 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.



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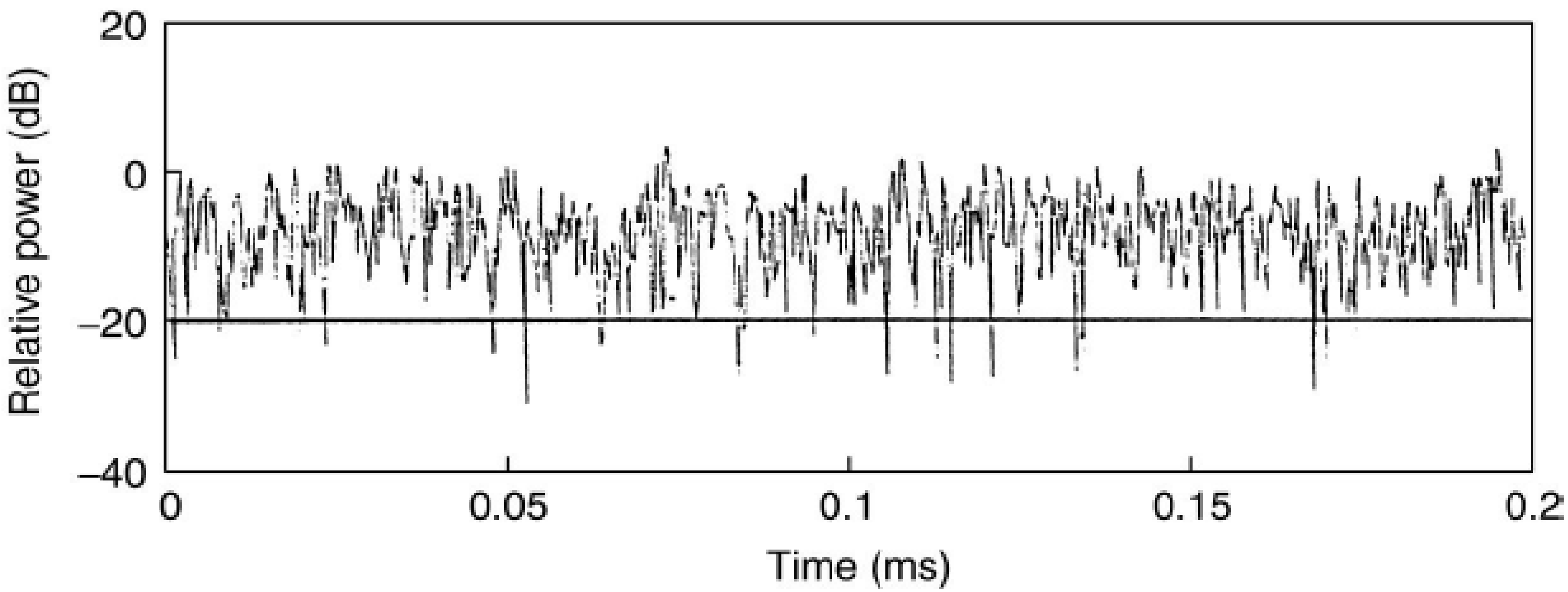
Outage

- Every receiver is designed to operate at an acceptable level only if a certain minimum power, P_{th}, 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



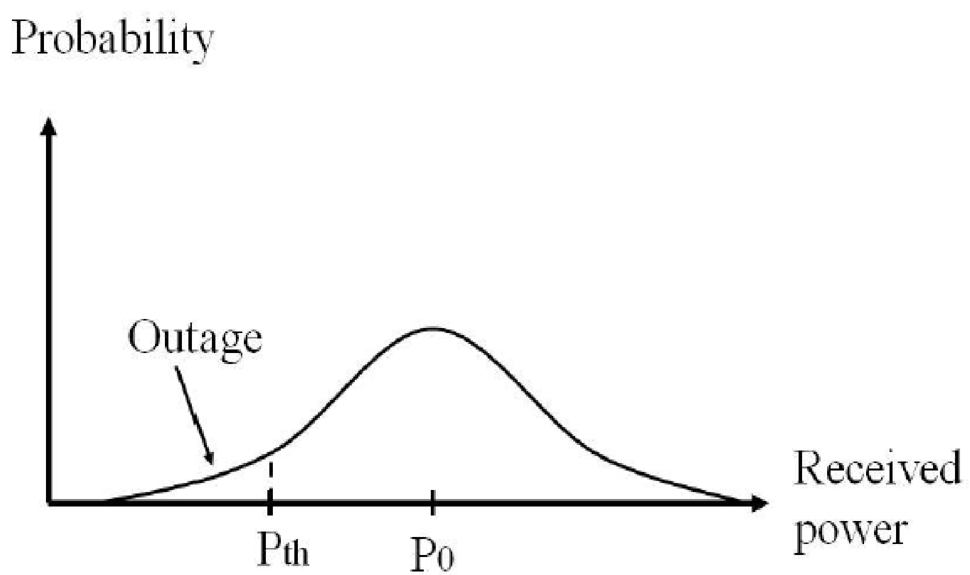
Outage

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 ρ_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

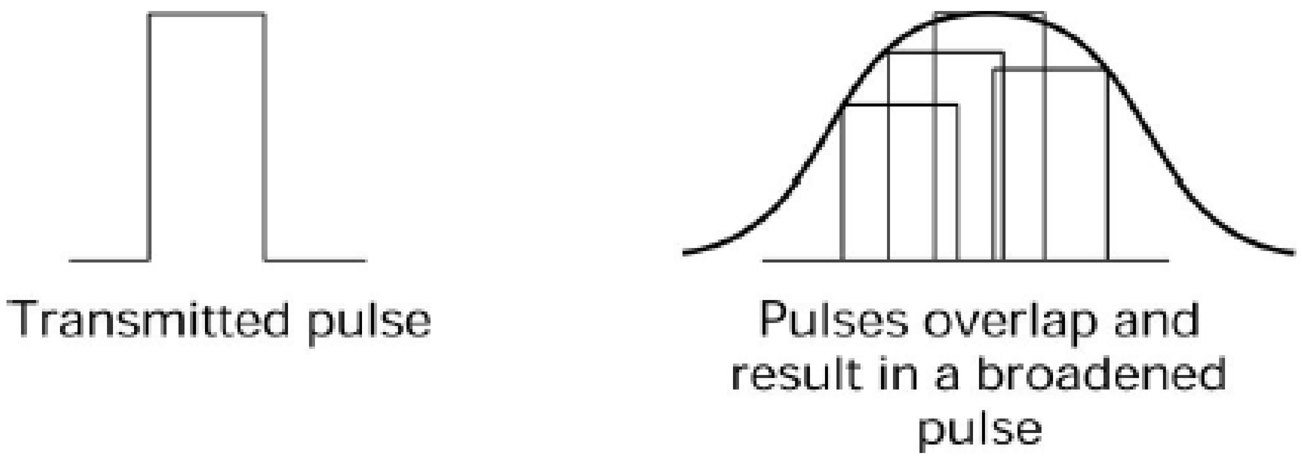


Outage

- 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)



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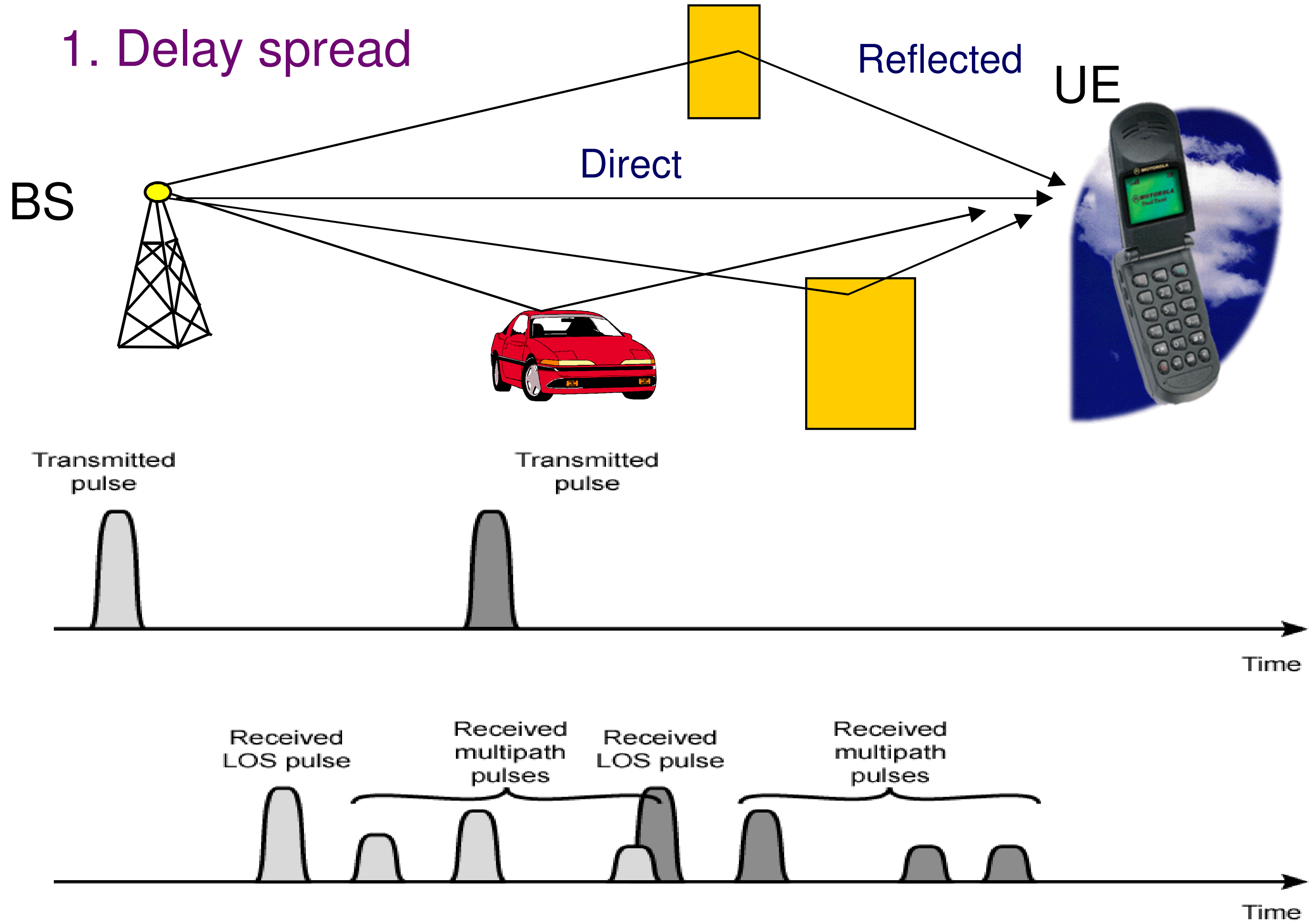
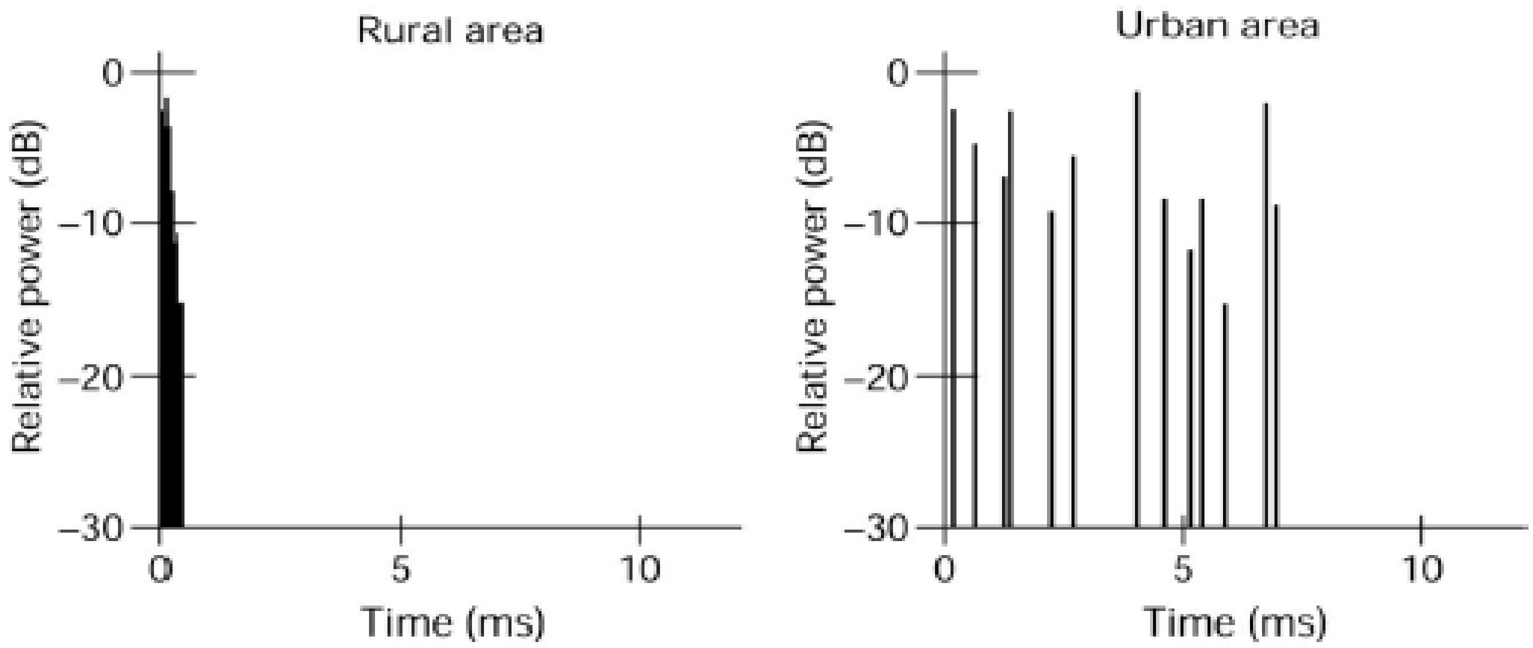
Multipath and Intersymbol interference



- 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 diverse 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-

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

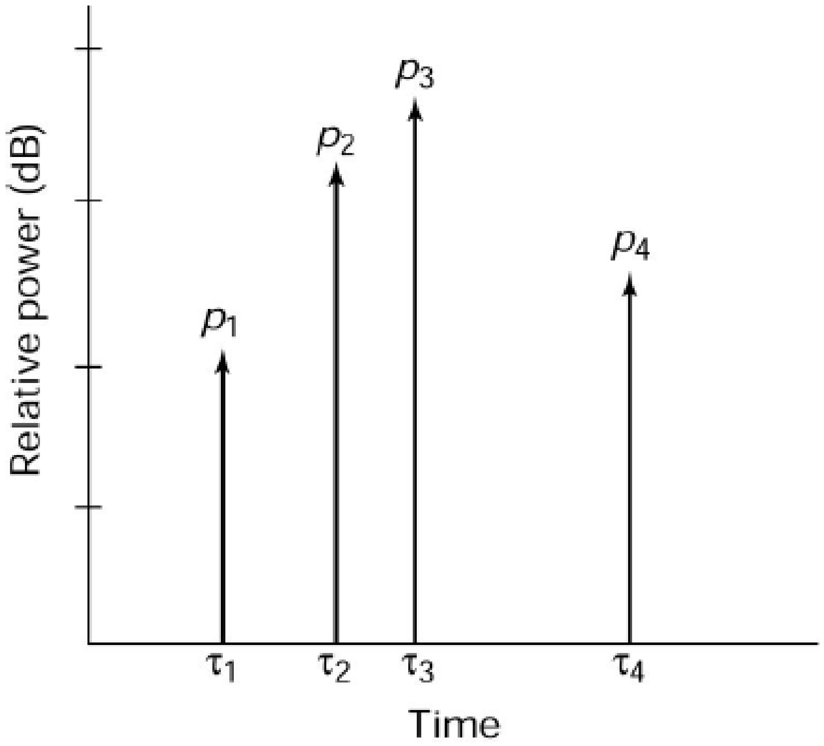
Where, average delay is-

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

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, $\boldsymbol{B_s}$ (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-

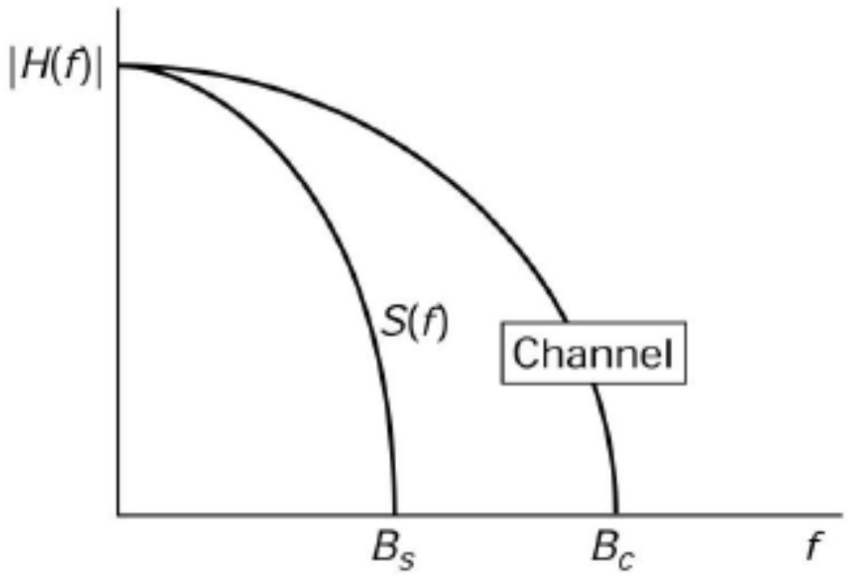
$$B_C = \frac{1}{5\sigma_d}$$

- 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

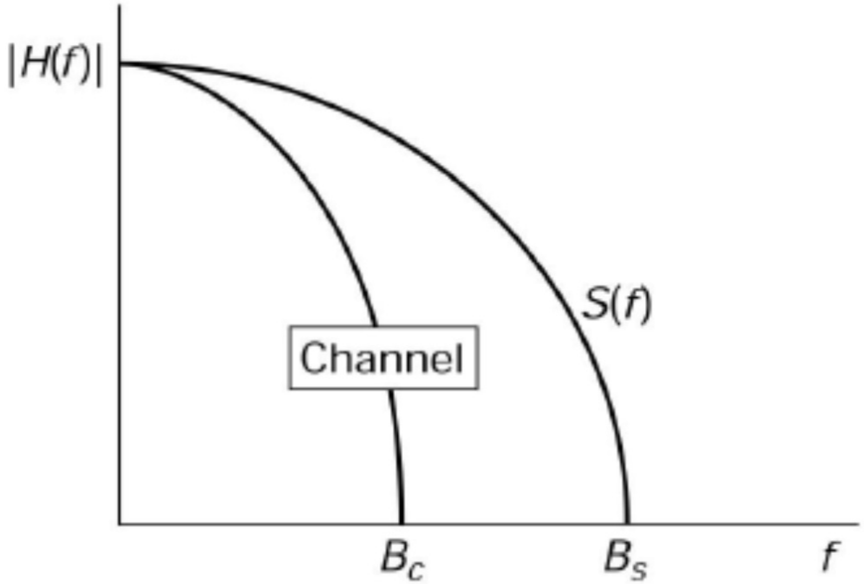
Flat fading channel

- If the channel bandwidth B_c is larger than message bandwidth B_s, all the frequency 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 frequency 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,

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

$$where$$

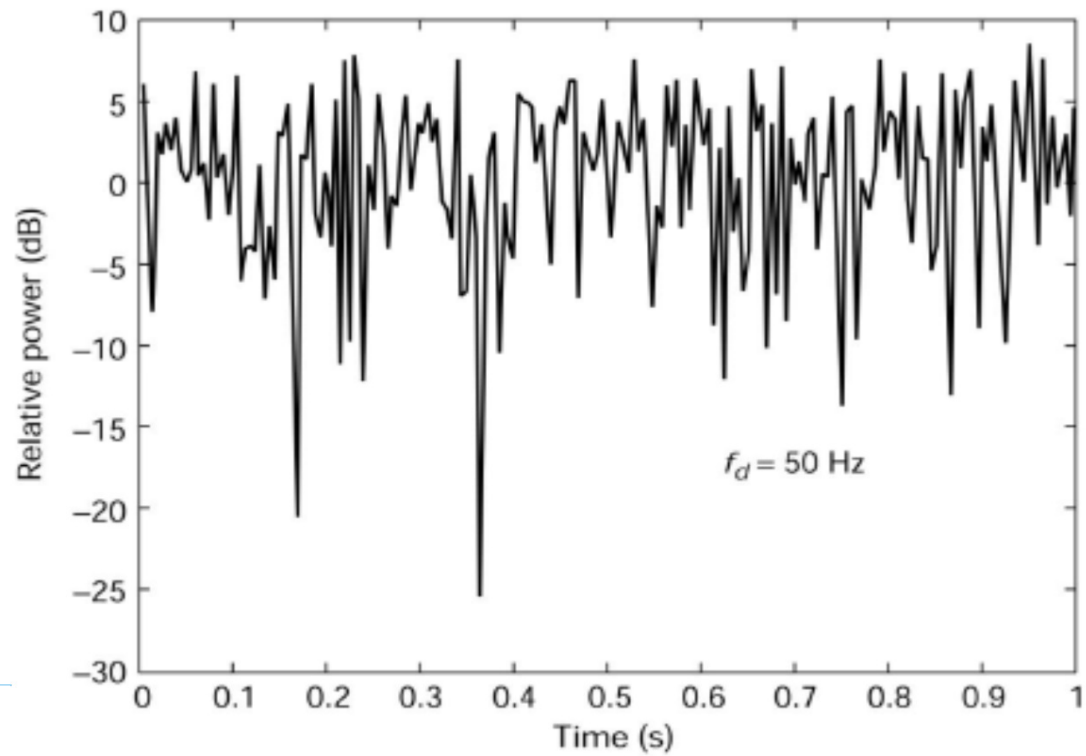
$$c = \text{velocity of electromagnetic wave in free space}$$

$$v = \text{velocity of the mobile unit(m/s)}$$

$$f_0 = \text{frequency of the signal}$$

Doppler effect

- This leads to two effects:
  - A level of variation at a rate that depends on the speed of the mobile
- • A frequency distortion resulting from the Doppler shift of the individual multi-path components (arriving at different angle)



Doppler effect

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

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

Coherence Time:

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

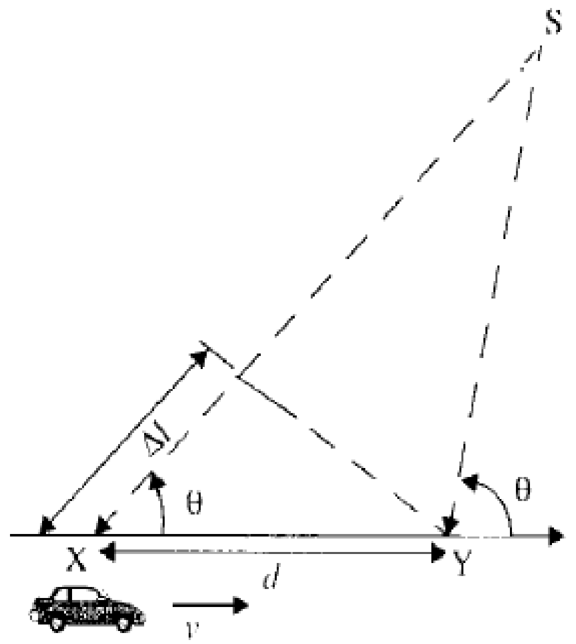


Illustration of Doppler effect.

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

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

Slow and Fast Fading

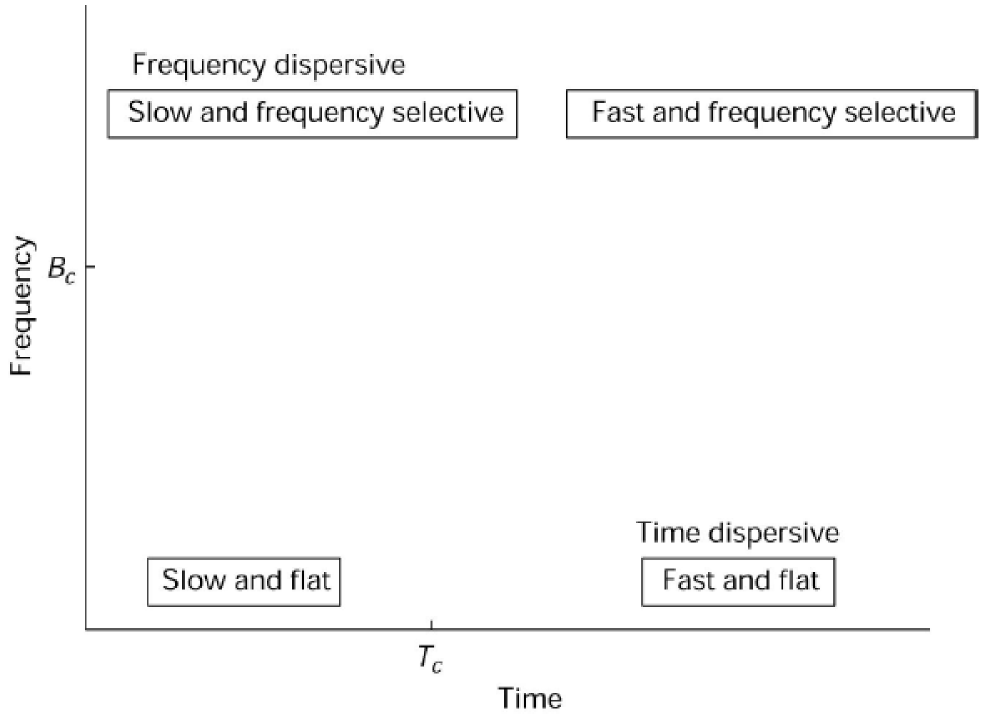
- Symbol period is smaller than coherence time, $T_s < T_c$
  - Slow fading
  - Symbol doesn't experience distortion

- Symbol period is larger than coherence time, $T_s > T_c$
  - Fast fading
  - Symbol undergoes distortion

Frequency dispersion versus 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 non-zero mean and Rician distributed envelope.

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

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

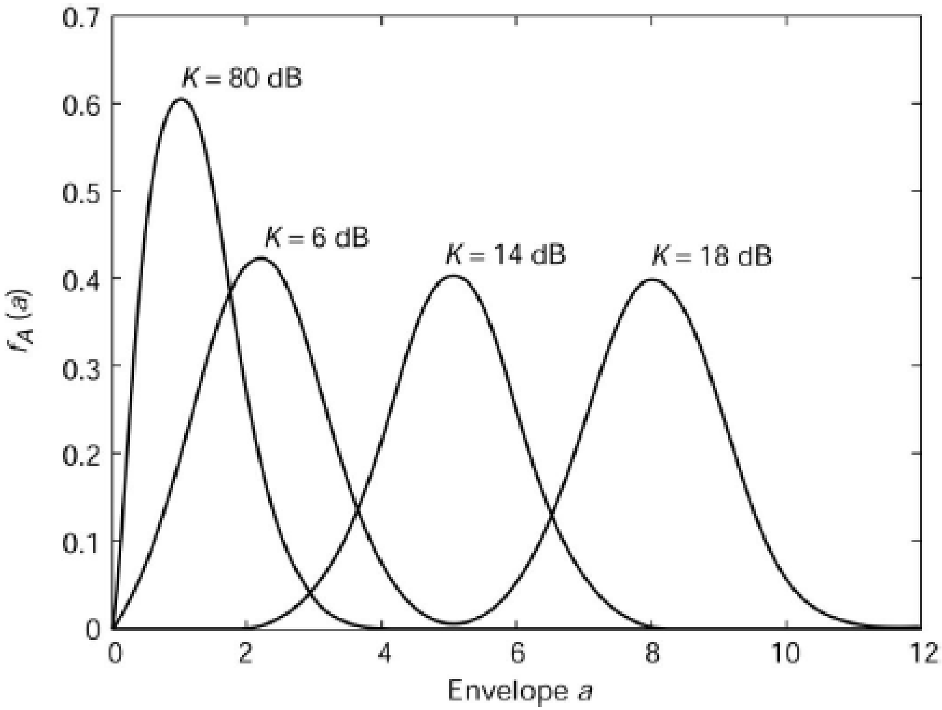
Where A_0 is the component from LOS part and $I_0(.)$ is the modified Bessel function.

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*=-∞ 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.

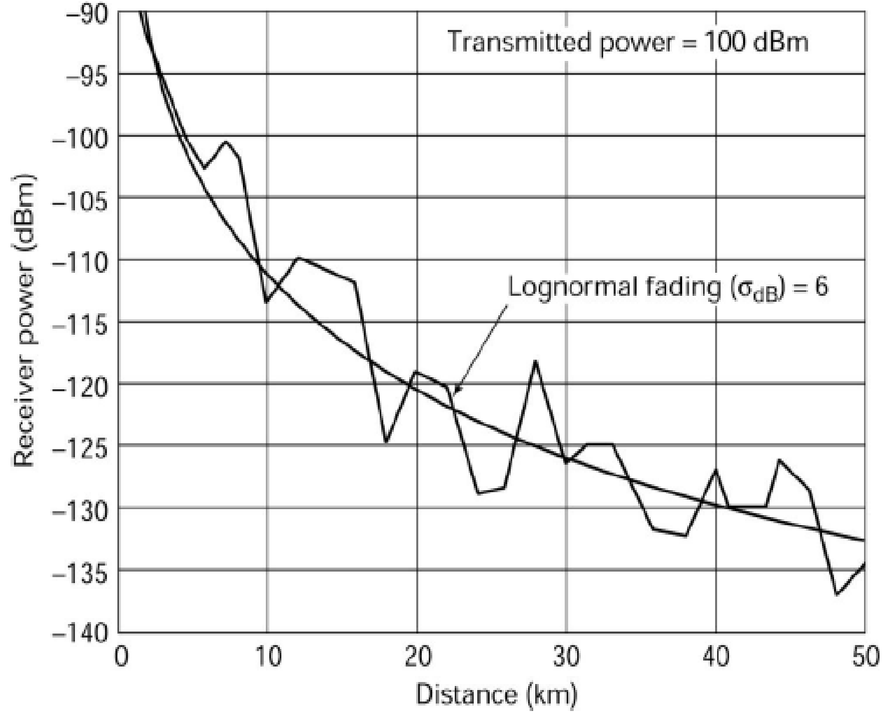
Lognormal fading

- 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".



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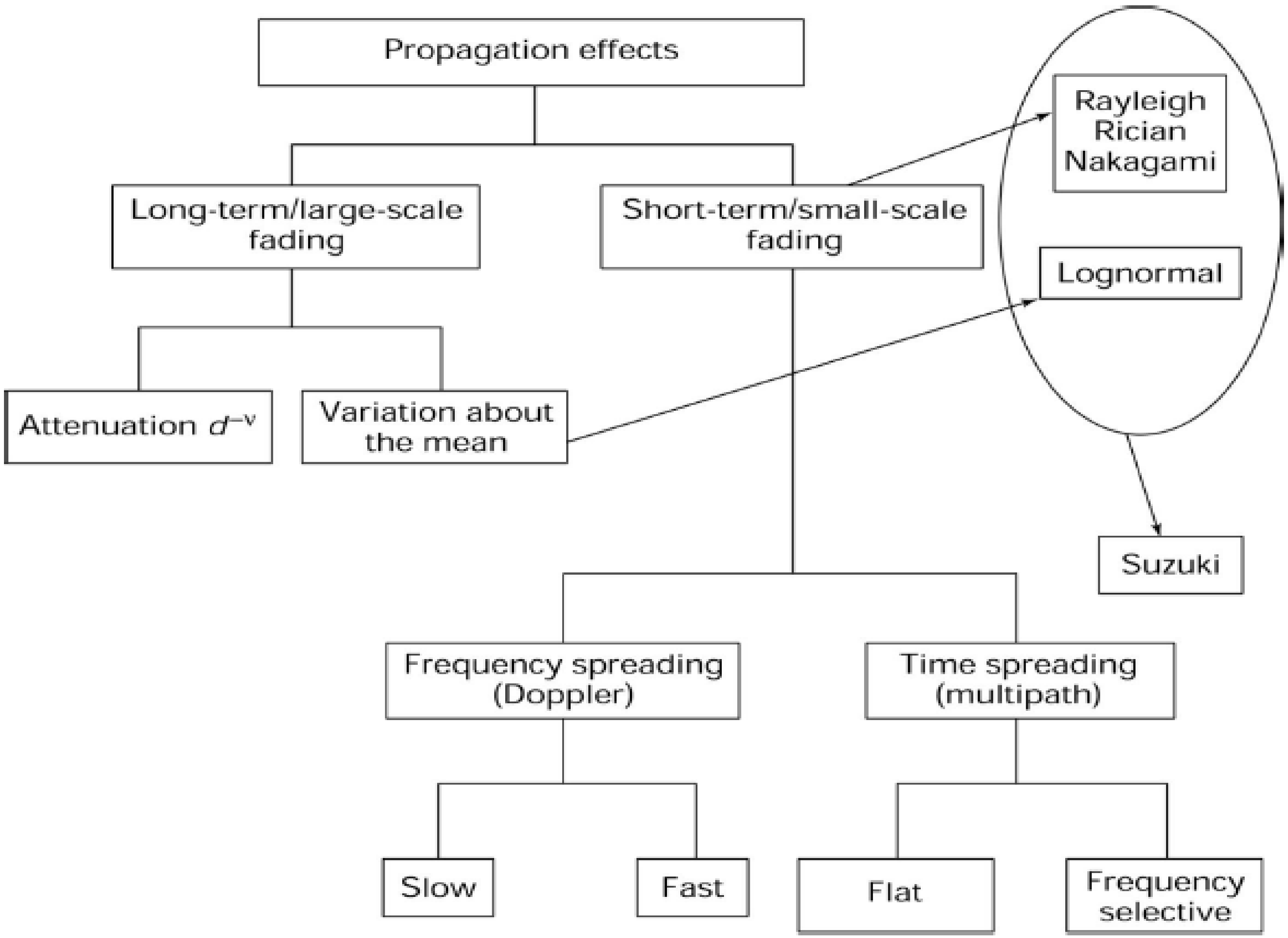
Summary of Fading



Summary (1)

- **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 d^{ν}, where ν 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 Doppler 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 exist between the transmitter and receiver
- **Short-term fading** can be described using *Rician distribution* if there is exists a direct path between the transmitter and receiver

Summary (2)

- **Short-term fading** due to multipath not only causes random fluctuations in the received power, but *also distorts the pulses* carrying the information
- If the **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 *Doppler 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.

Problems

- **Chapter 2: Propagation characteristics of wireless channel**

- **Problem 2**: The base station antenna is transmitting a power of 1W. The transmitter antena gain is unity while the receiver gain is 2. The system loss factor is unity (i.e. no loss). Find the received power in dBm at a distance of 5 km from the transmitter operating at 900 MHz in free space (Hint: Use eq. (2.2, slide 20))

- **Problem 11**: If the system goes into outage when when the received signal-to-noise ratio falls 5 dB below the average, calculate the outage probability in Rayleigh fading with an average signal-to-noise ratio of 5 dB. Note that the signal-to-noise ratio is exponentially distributed when Rayleigh fading is present.

- **Problem 14**: The maxium outage rate accepted in a wireless system subject to fading is 0.02. If the threshold SNR is 5 dB, what must be the minimum value of the average SNR?

- **Problem 16**: Calculate the mean delay and rms delay spread of a channel having the characteristics shown in figure P2.16. What is the coherence bandwidth 1/(5 rms delay)?