Chapter 3 Communication Channels and Noises

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3.1 Introduction

- The study of signal transmission is important to digital communications because it provides prediction models for estimating the power required for reliable communications,and also provides clues to receiver techniques for compensating the impairment introduced through the transmission channel .
- A communication channel provides the connection between the transmitter and receiver . The physical channel may be a pair of copper wires that carry the electrical signal ,or an optical fiber that carry the information on a modulated light beam , or a free space over which the information-bearing signal is radiated by the use of an antenna, Other media that can be characterized as communication channel are data storage media , such as magnetic disks and optical disks ,etc. .

3.2 Twisted- Pair Wires and Coaxial Cables

- The telephone network makes use of wirelines for voice signal transmission , as well as data and video transmission.

  Twisted –pair copper wires and coaxial cables are basically guided electromagnetic channels that provide relatively modest bandwidths.

- Telephone wires generally used to connected a user (subscriber) to the central office , known as local loop) has a bandwidth of several hundred kilohertz (kHz). On the other hand , coaxial cable has a usable bandwidth of several megahertz (MHz) . Signals transmitted through such channels are distorted in both amplitude and phase, in addition to the additive noise.

3.2.1 Telephone channel

- Wireline telephone channels are also prone to cross-talk interference from physically adjacent channels.
- Both twisted-pair wireline and coaxial cable can be modeled as a transmission line and expressed by a two-port network as shown by Fig .3.1 . The input current and voltage are related to the output current and voltage by the chain matrix (or ABCD matrix) as

$$\begin{bmatrix} V_1 \\ I_1 \end{bmatrix} = \begin{bmatrix} A & B \\ C & D \end{bmatrix} \begin{bmatrix} V_2 \\ I_2 \end{bmatrix}$$

- In Fig. 3.1 , the physical characteristics of the transmission line are represented by the four parameters : the conductance G in mhos per unit length , the capacitance C in farads per unit length , the inductance in henries per unit length , and the resistance R in ohms per unit length .
- The chain matrix of a uniform transmission line is given by

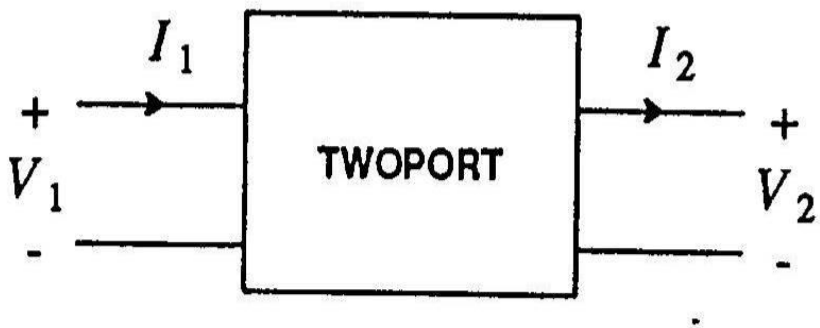
$$\begin{bmatrix} A & B \\ C & D \end{bmatrix} = \begin{bmatrix} \cosh(\gamma L) & Z_0 \sinh(\gamma L) \\ (1/Z_0)\sinh(\gamma L) & \cosh(\gamma L) \end{bmatrix}$$

where $Z_0 = \sqrt{(R + j\omega L)/(G + j\omega C)}$

$$\gamma = \sqrt{(R + j\omega L)(G + j\omega C)}$$

- Fig.3.2 Shows the impulse responses of the twisted-pair wirelines of different lengths.

Fig.3.1 Two-port network and transmission line equivalent circuit



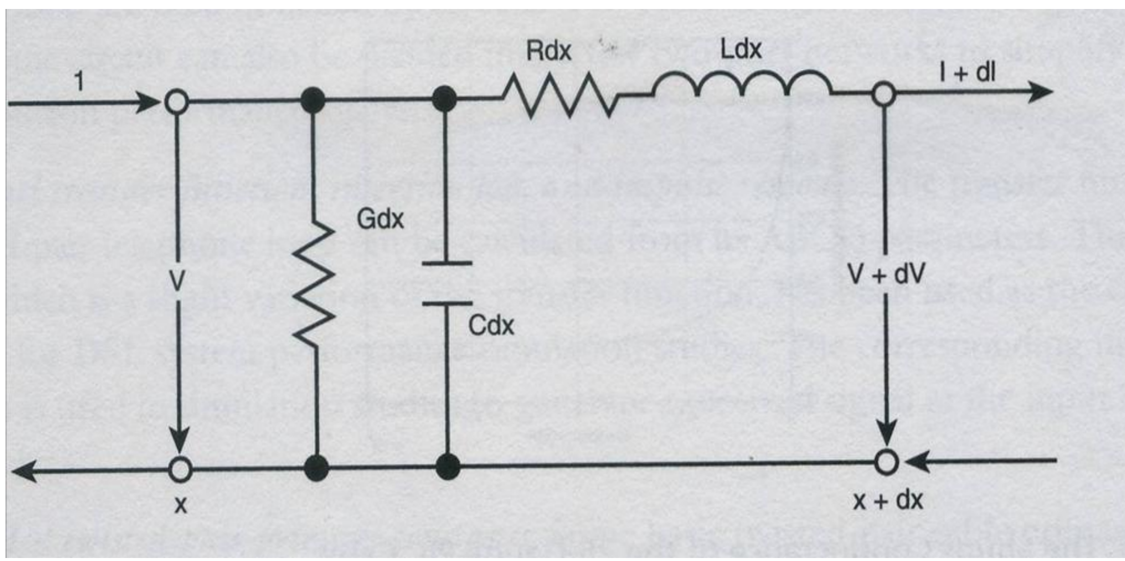
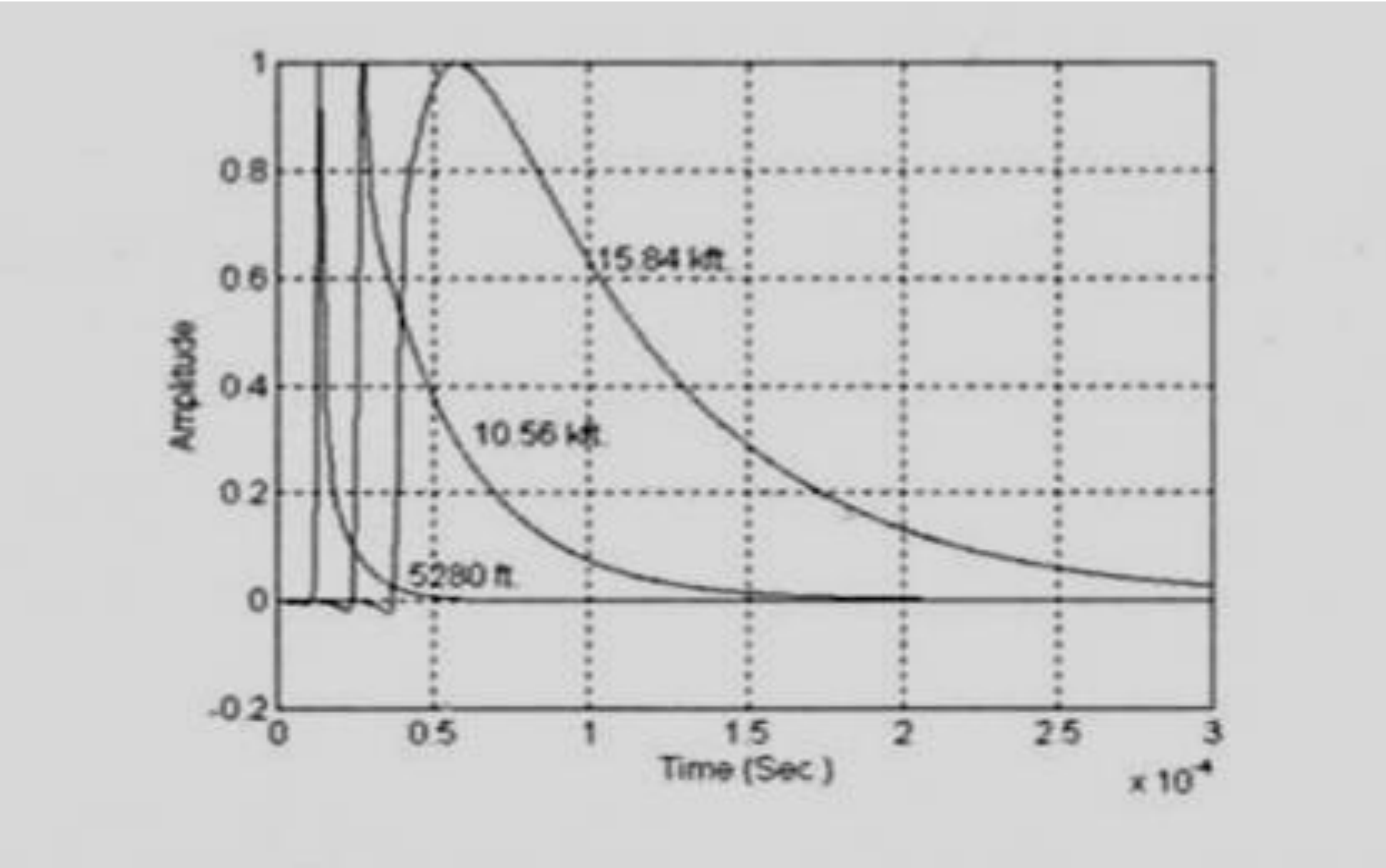


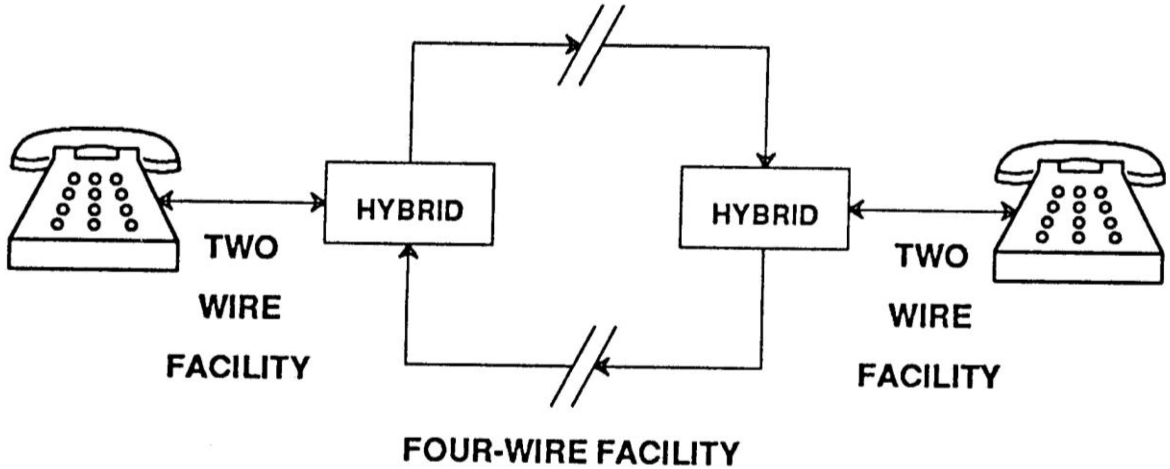
Fig.3.2 Impulse responses for twisted-pair loops of different lengths



- ## Delay and Echo

Delay and echo are two important impairments in telephone channels. A simplified telephone channel is shown in Fig.3.3 . The twisted wire pair connecting the central office with customer premise , known as local loop, is used for bidirectional two-way transmission . At the central office , a circuit , known as hybrid , separates the two direction s of transmission. Longer distance facilities are four-wire , thus the two directions of transmission are physically separated. The hybrid is basically a bridge circuit with three ports (terminal pairs) as shown in Fig.3.3 . If the bridge is not perfectly balanced , the transmitter port of the hybrid becomes coupled to the receiver port , thereby giving riseto an echo due to leakage of the nera-end (local) transmitted sognal to the near-end (local(receiver. To cancel the unwanted echo ,echo canceller is included in the transceiver. Far-end echo also has its origin of non-ideal operation of the far-end hybrid .

Fig.3.3 (a) A simplified model of telephone channel (b) Hybrid circuit



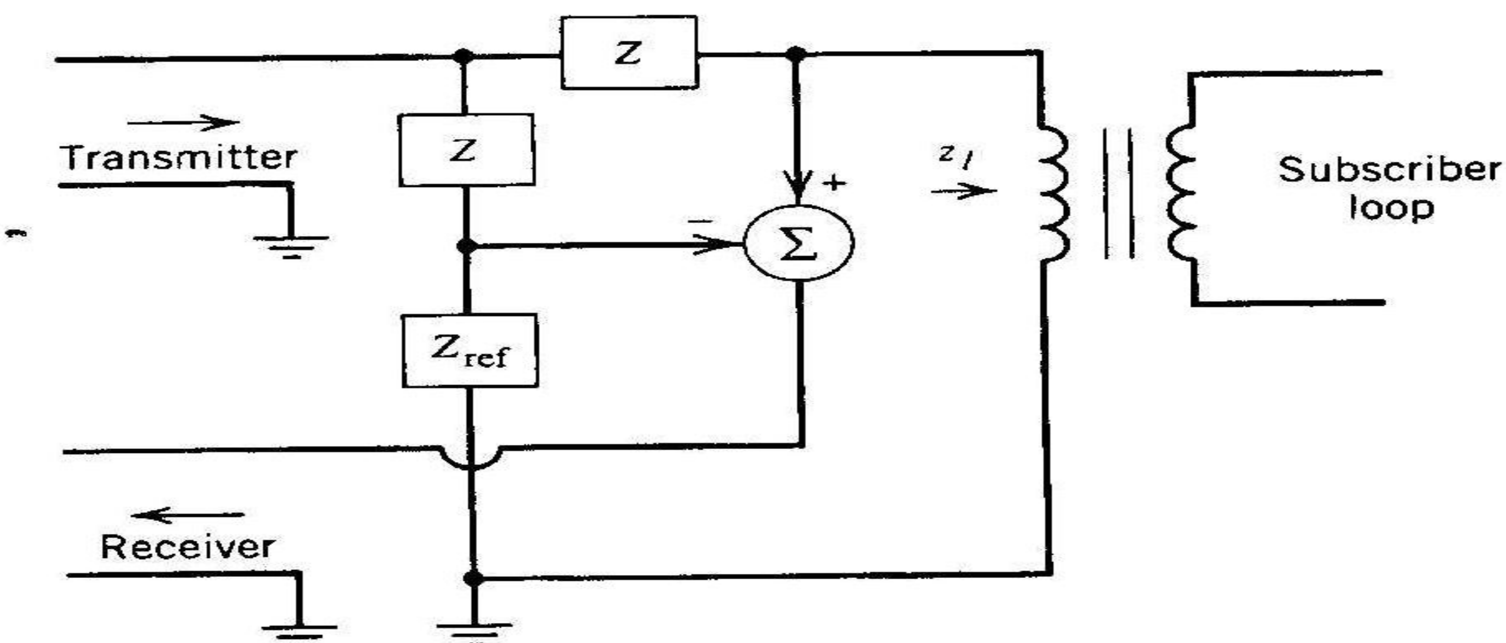
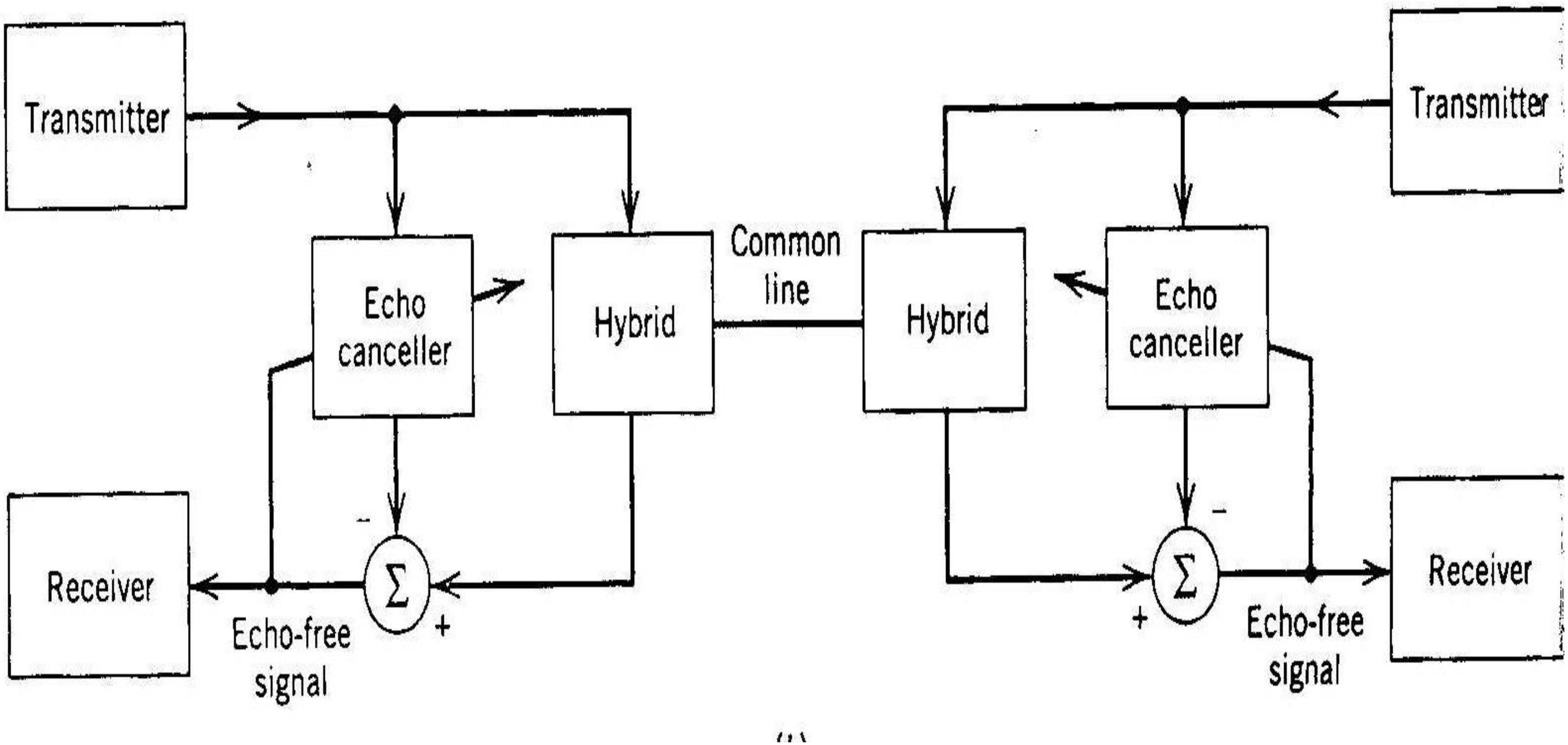


Fig.3.4 Full duplex telephone channel with echo canceller



- **Crosstalk**

There are two basic cross-talk mechanisms as illustrated in Fig.xx : near-end crosstalk (*NEXT*) and far-end crosstalk (*FEXT*) .

NEXT represents a crosstalk of a local transmitter into a local receiver , and experiences an attenuation which can be modeled by

$$| H_{NEXT}(j\omega) |^2 = K_{NEXT} | \omega |^{1.5}$$

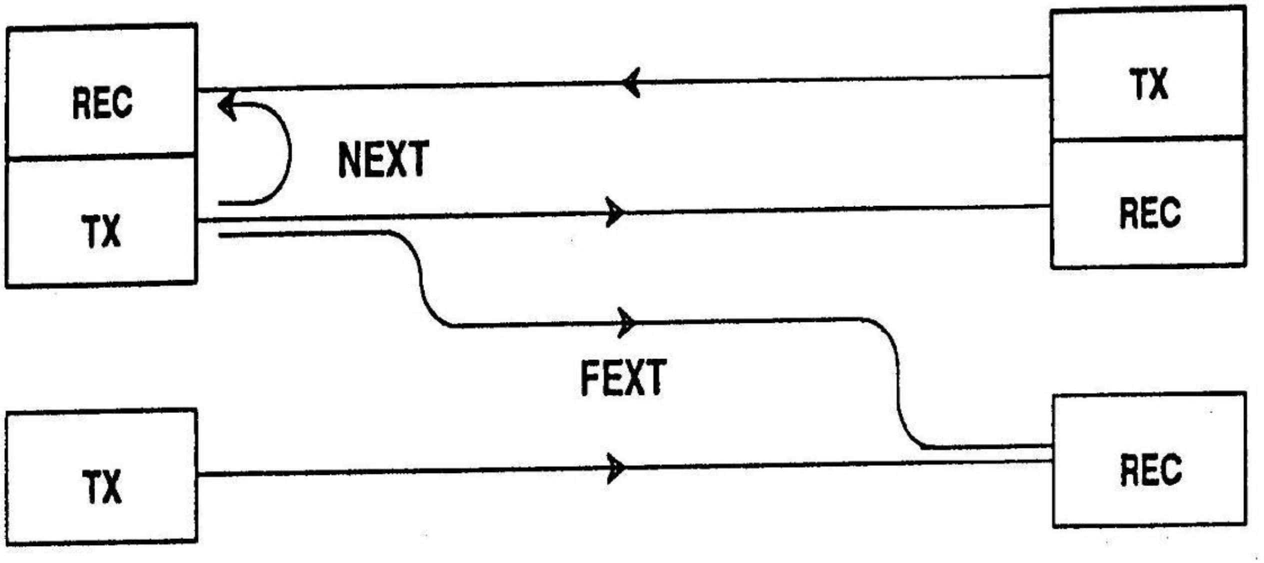
where $H_{NEXT}(j\omega)$ is the transfer function experienced by the crosstalk.

FEXT represents a crosstalk of a local transmitter into a remote receiver , with an attenuation given by

$$| H_{FEXT}(j\omega) |^2 = K_{FEXT} | C(j\omega) |^2 | \omega |^2$$

where $C(f)$ is the loss of the cable.

Fig.3.5 Illustration of far-end crosstalk and near-end crosstalk



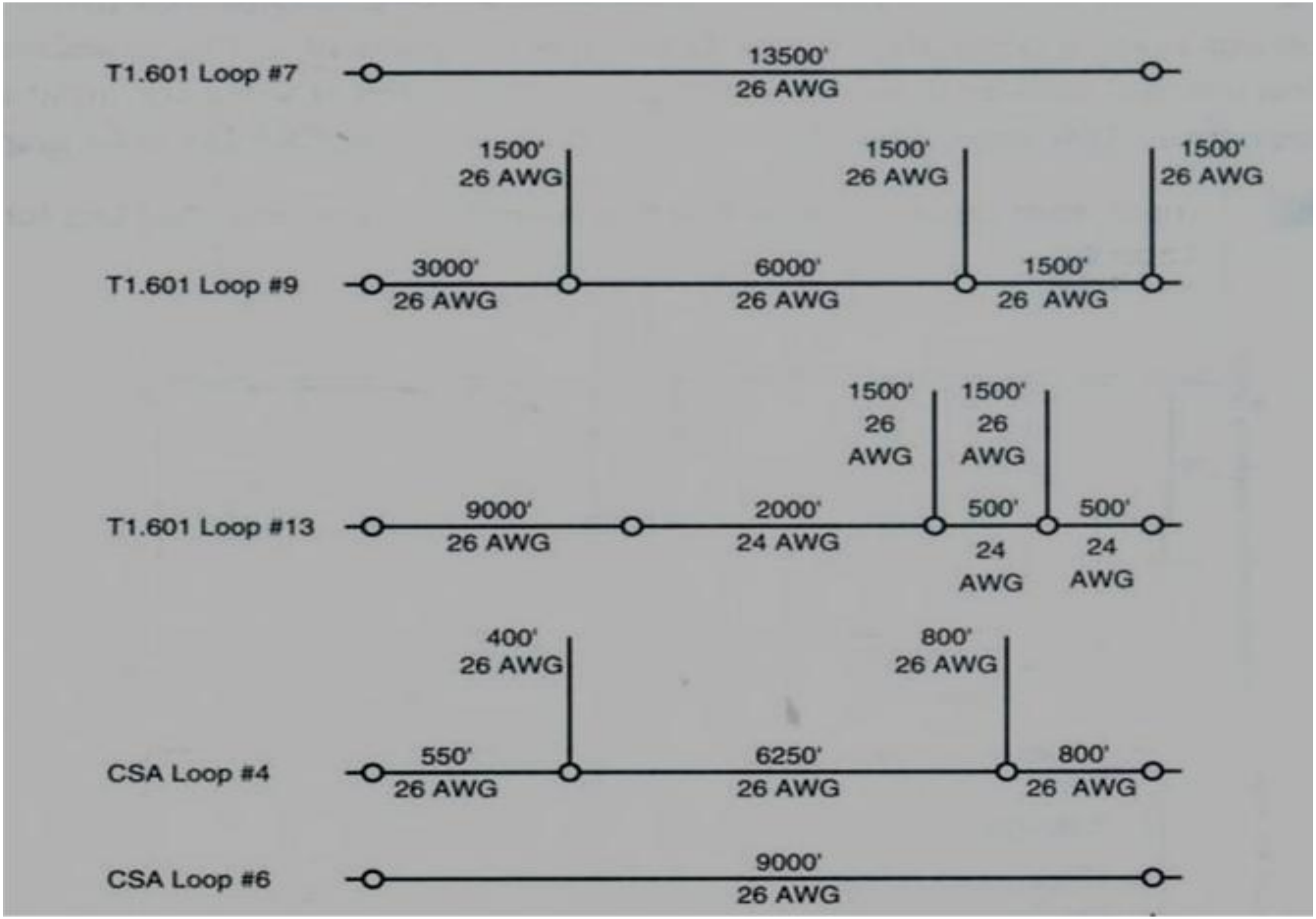
3.2.2 Digital Subscriber Line (DSL)

- **Digital Subscriber Line (DSL) is a family of technologies that provides digital data transmission over the wires of a local telephone network .**
- **Many DSL technologies have been developed in the recent years to enable using the wide installed base of copper (twisted pair) cables laid by the telephone companies . for high-speed digital transmission. Asymmetric Digital Subscriber Line *(ADSL),* is the most commonly installed technical variety of DSL.**
- **The data throughput of consumer DSL services typically ranges from 256 Kb/s to 24 Mbit/s in the direction to the customer (downstream), depending on DSL technology, line conditions, and service-level implementation.**

- In ADSL, the data throughput in the upstream direction, (i.e. in the direction to the service provider) is lower, hence the designation of *asymmetric* service. ADSL supports up to 8 Mbps in the downlink direction and up to 1 Mbps in the uplink direction.

  In Symmetric Digital Subscriber Line (SDSL) service, the downstream and upstream data rates are equal.

Fig.3.6 Some test-loops for ADSL



3.3 Optical Fiber

- The optical fiber is capable of transmitting light for long distance with high bandwidth and low attenuation .It also free from external interferences , and has immunity from inter4ception by external means.
- The use of an optical dielectric waveguide for high performance communication was first suggested by Kao and Hockham in 1966.
- Optical fibers offer the communication system desugner a channel bandwidth that is several orders of magnitude larger than coaxial cable channels.
- Fig.3.7 illustrates the configuration of an optical fiber waveguide
- Fig.3.8 shows the loss spectrum of an ultra low-loss single mode fiber

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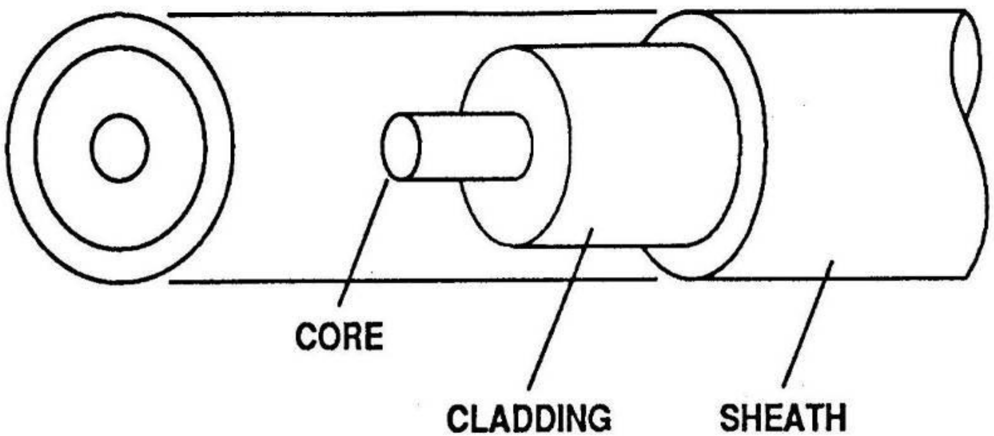
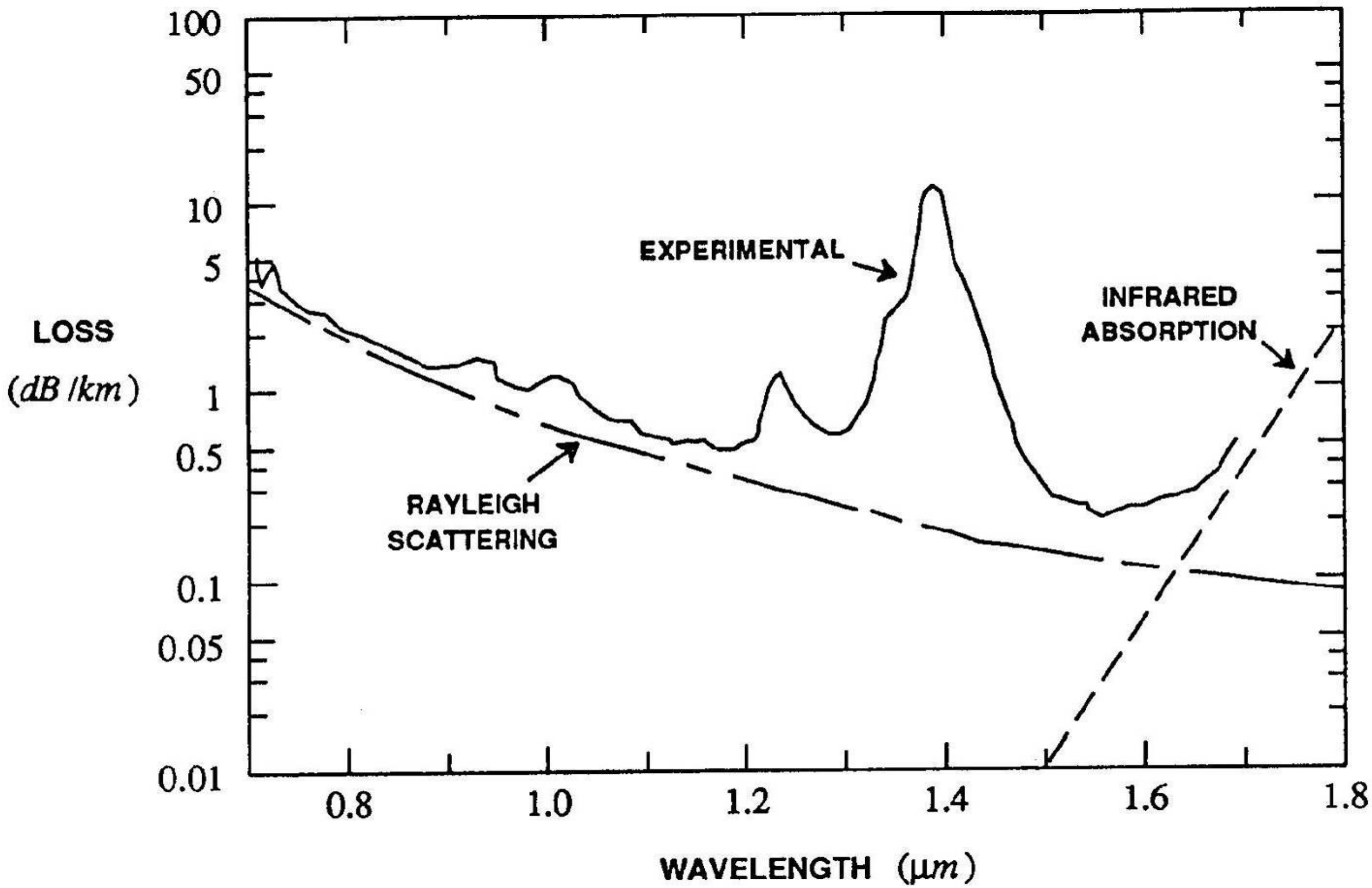
Fig.3.7 Structure of optical fiber



An optical fiber waveguide. The core and cladding serve to confine the light

Fig.3.8 Loss spectrum of an ultra-low-loss single mode fiber



3.4 Wireless Channels

- In wireless communications , electromagnetic energy is coupled to the propagation medium by an antenna which serves as the radiator. The physical size and the configuration depend primarily on the frequency of operation.
- The information signal transmitted over the wireless channel may be corrupted by the additive noise, interferences , multipath fading , distortion and attenuation, etc. .
- The propagation effects and other signal impairments are often collected to form a channel's characteristics .
- For physical models, four modes of propagation are considered :

  (i) free-space (line –of-sight) propagation

  (ii) reflection

  (iii) diffraction

  (iv) scattering

- **Often, the received signal is the combination of many of these modes of propagation. Due to multiple reflections from various objects, the EM waves travel along different paths of varying lengths.**

  The interaction between these waves causes multipath fading at a specific location.
- **Statistical models take an empirical approach, measuring propagation characteristics in a variety of environments and then developing a model based on the measured statistics for a particular class of environment. These models are easier to describe and use than the physical models, but do not provide the same accuracy.**
- **Noise and interference are unwanted electrical signals interfering with the desired signal .**

- **AWGN Channel : Additive white Gaussian noise channel .**

  With this model, zero-mean noise having a Gaussian distribution is added to the signal.

  The noise is usually assumed to be white over the bandwidth of interest. That is, samples of the noise process are uncorrelated with each other.

  The noise has a flat two-sided power spectral density $N_o/2$ (watts/Hz) across the frequency range $-\infty < f < \infty$

- **For fixed satellite communication in which there is a direct line-of sight path between the transmitter on satellite and the receiver, the additive white Gaussian noise channel often provides a reasonably good model.**

3.5 Wireless Channel Models and Characteristics

3.5.1 Free-Space Propagation

- **Wireless transmission is characterized by the generation, in the transmitter, of an electrical signal representing the desired information, the propagation of corresponding radio wave through space, and a receiver that estimates the transmitted information from the received signal.**
- **The transmission system is characterized by the antennas that convert between electrical signals and radio waves, and the propagation of the radio waves through space.**
- **The free space propagation model is used to predict received signal strength when the transmitter and the receiver have a clear, unobstructed line-of-sight path between them.**

3.5.1.1 Isotropic Radiation

An isotropic antenna transmits radio waves equally in all directions. It is also called omnidirectional antenna. In reality, an isotropic antenna does not exist, and all antennas have some directivity associated with them.

- **The power captured by the receiving antenna depends on the size and orientation of the antenna with respect to the transmitter. The power received by an antenna of *effective* area or absorption cross section A_e is given by**

$$P_R = (P_T / 4\pi d^2)\, A_e \qquad (3.1)$$

The *antenna efficiency* is defined as

$$\eta = A_e / A \qquad (3.2)$$

where *A* *is the physical area of the antenna .*

- **From electromagnetic theory, the effective area of an isotropic radiation is given by $A_{iso} = \lambda^2 / 4\pi$**

Therefore ,we obtain

$$P_R = P_T / (4 \pi d / \lambda)^2 = P_T / L_p \qquad (3.3)$$

where P_T is the transmitted power,

P_R is the received power,

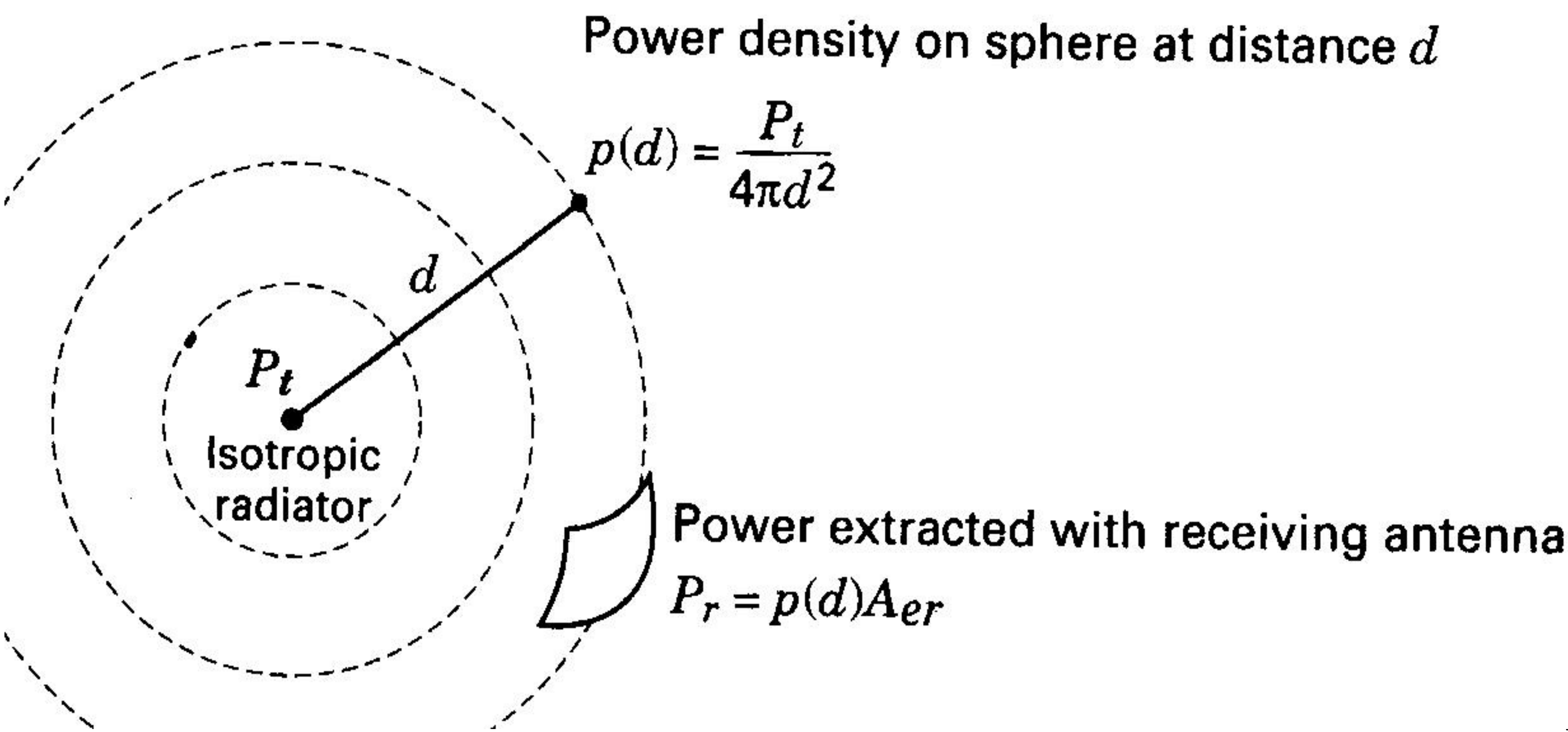
$L_p = (4 \pi d / \lambda)^2$ is the path loss

λ is the wavelength of radiation

d is the distance between the transmitting and receiving antennas. $d >> \lambda$.

Fig.3.9 Isotropic Radiation

$$A_{er} = \frac{\text{total power extracted}}{\text{incident power flux density}}$$



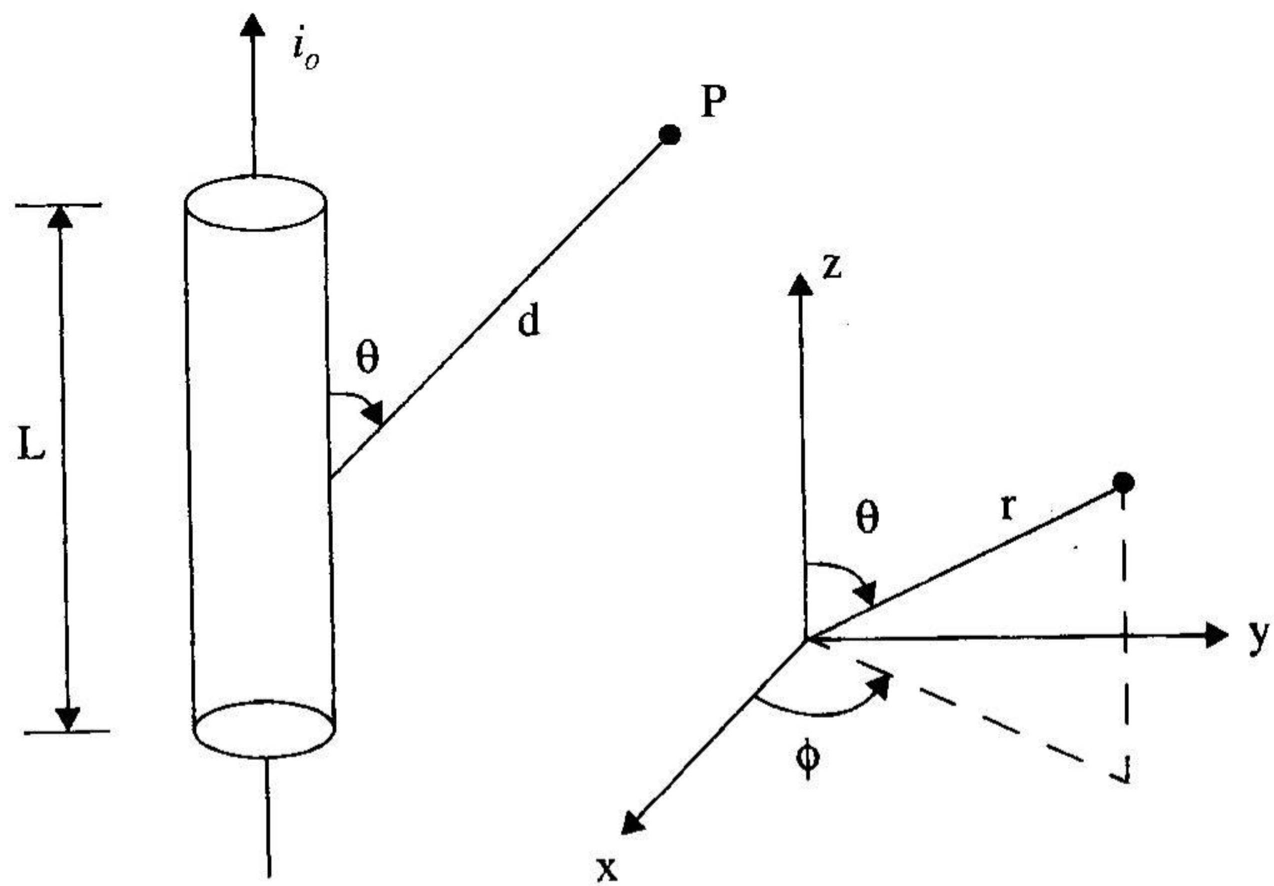
3.5.1.2 Directional Radiation

i. Most antennas are not isotropic.
Instead, they have gain or directivity G (θ, ψ) that is a function of the azimuth angle ψ and elevation angle θ.

ii. The transmit gain of an antenna is defined as

G = { power flux density in direction (θ, ψ) } ／
{ power density of an isotropic antenna for the same transmit power }

Fig.3.10 Linear Radiator



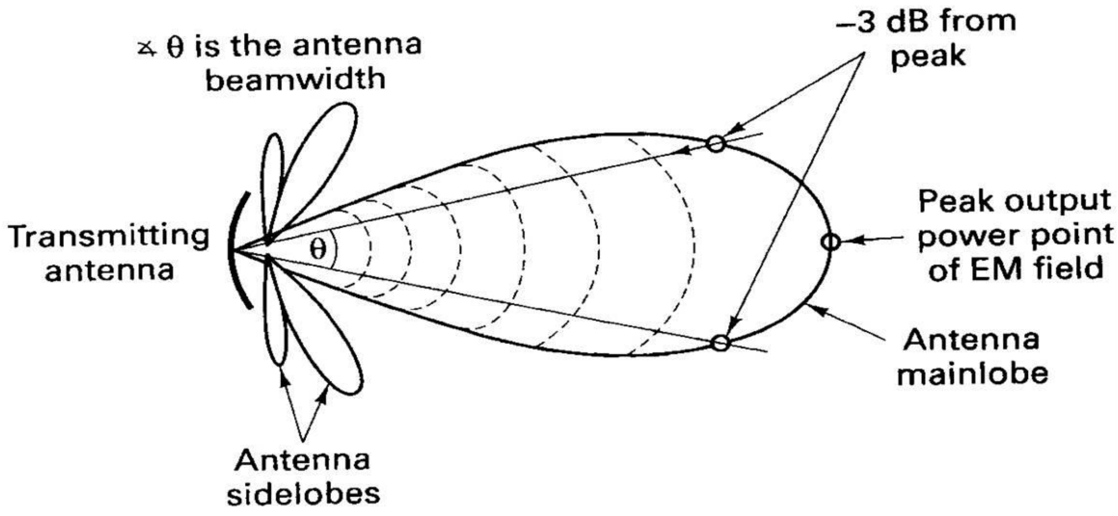
3.5.1.3 Equivalent Isotropic Radiation Power (EIRP)

For directional antenna , the equivalent isotropic radiation power (EIRP) is defined as

$$\text{EIRP} = P_T \, G_t$$

where G_T is the antenna gain of the transmitting antenna.

Fig.3.11 Directional Antenna Pattern



- **Parabolic Antenna Gain**

For a parabolic (dish-shaped) antenna, the antenna (maximum) gain is

$$G = A_e / A_{iso} = (\eta \pi D^2 / 4) / (\lambda^2 / 4\pi)$$
$$= \eta (\pi D / \lambda)^2 \qquad (3.6)$$

where $\eta = A_e / A$ is the antenna efficiency, D is the diameter of the dish.

- **Antenna efficiency indicates how well the antenna converts incident EM (radiation) energy into usable electrical energy .**

  For parabolic antennas, the efficiency typically ranges from 45% to 75% .

3.5.1.4 Friis Equation

a. When non-isotropic antennas are used, the free-space loss relating the received and transmitted power can be expressed by the Friis equation :

$$P_R = P_T * G_T * G_R / L_p \qquad (3.4)$$

where G_t is the transmitting antenna gain,
G_r is the receiving antenna gain,
L_p is the path loss .

This equation can be expressed, in dB relation, as

$$P_R\,(dB) = P_T\,(db) + G_T\,(dB) + G_R\,(dB) - L_p\,(dB) \qquad (3.5)$$

b. The Friis equation is the fundamental *link budget equation.*
It relates power received to power transmitted, taking account the loss in the radio link.
Closing the link refers to the requirement that the right-hand-side provide enough power at the receiver to detect the transmitted information reliably.

3.5.1.5 Receiver Sensitivity

- Receiver sensitivity is a parameter that indicates the minimum signal level required at the antenna terminals in order to provide reliable communications.
  It depends on the factors : receiver design, modulation format, and transmission rate.
  Receiver sensitivity is often expressed in dBm
- Illustrative example : (Haykin p.15)

  A commercial mobile receiver for data transmission may be specified with a sensitivity of - 90 dBm, what is the radius of the service area of the receiver at a transmission frequency of 800 MHz ? Assuming that the transmitter antenna transmits 100 mw signal.

  Ans . 9.2 Km (free-space path model)

3.5.2 Terrestrial Propagation Mechanisms

- Reflections, Diffraction, and Scattering are three basic propagation mechanisms which impact signal propagation in wireless communication systems .
- Reflection occurs when a propagating radio wave impinges upon an object which has a large dimensions compared to the wavelength of the radio wave.

  In terrestrial propagation , reflections occur from the Earth surface and from buildings and walls .

- Diffraction occurs when the radio path between the transmitter and receiver is obstructed by a surface that has sharp edges. Waves propagate in different directions with edge as the secondary source, even behind the obstacle. Thus signal can be received even when there is no unobstructed LOS from the transmitter.

- **Scattering occurs when the size of an obstacle is on the order of the wavelength of the radio signal. An incoming signal is scattered into several weaker outgoing signals.**

  In practice, foliage, traffic signs, and lamp posts induce scattering in the wireless communication systems.

  The actual received signal in a mobile radio environment is often stronger than what is predicted by reflection and diffraction models alone. This is because when a radio wave impinges on a rough surface , the reflected energy is spread out in all directions due to scattering. This might provide additional radio energy at a receiver.

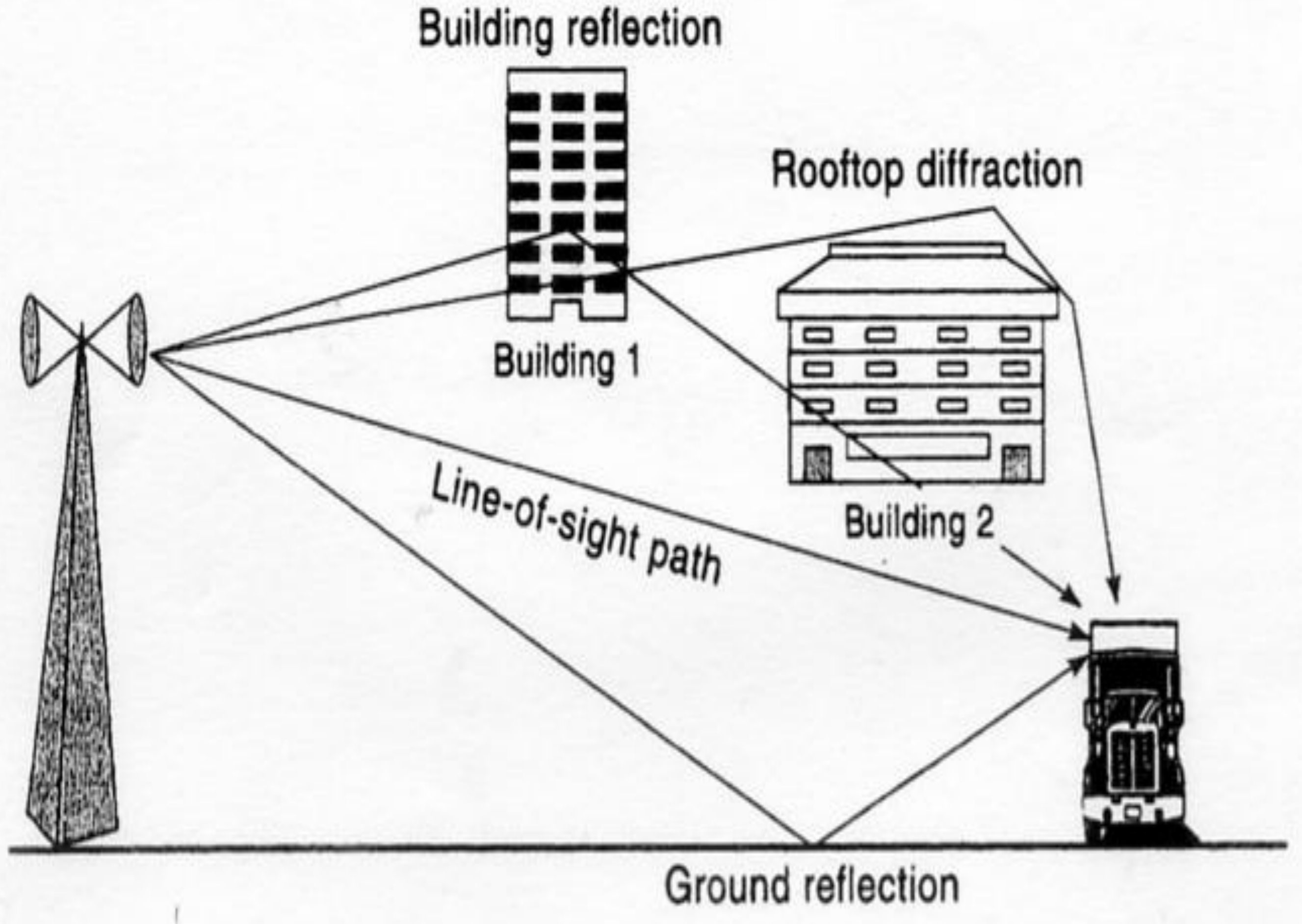
3.5.3 Statistical Models of Terrestrial Propagation

- In a statistical approach, the propagation characteristics are empirically approximated on the basis of measurements in certain general types of environments, such as urban, suburban, and rural.

The statistical approach is broken into two components :

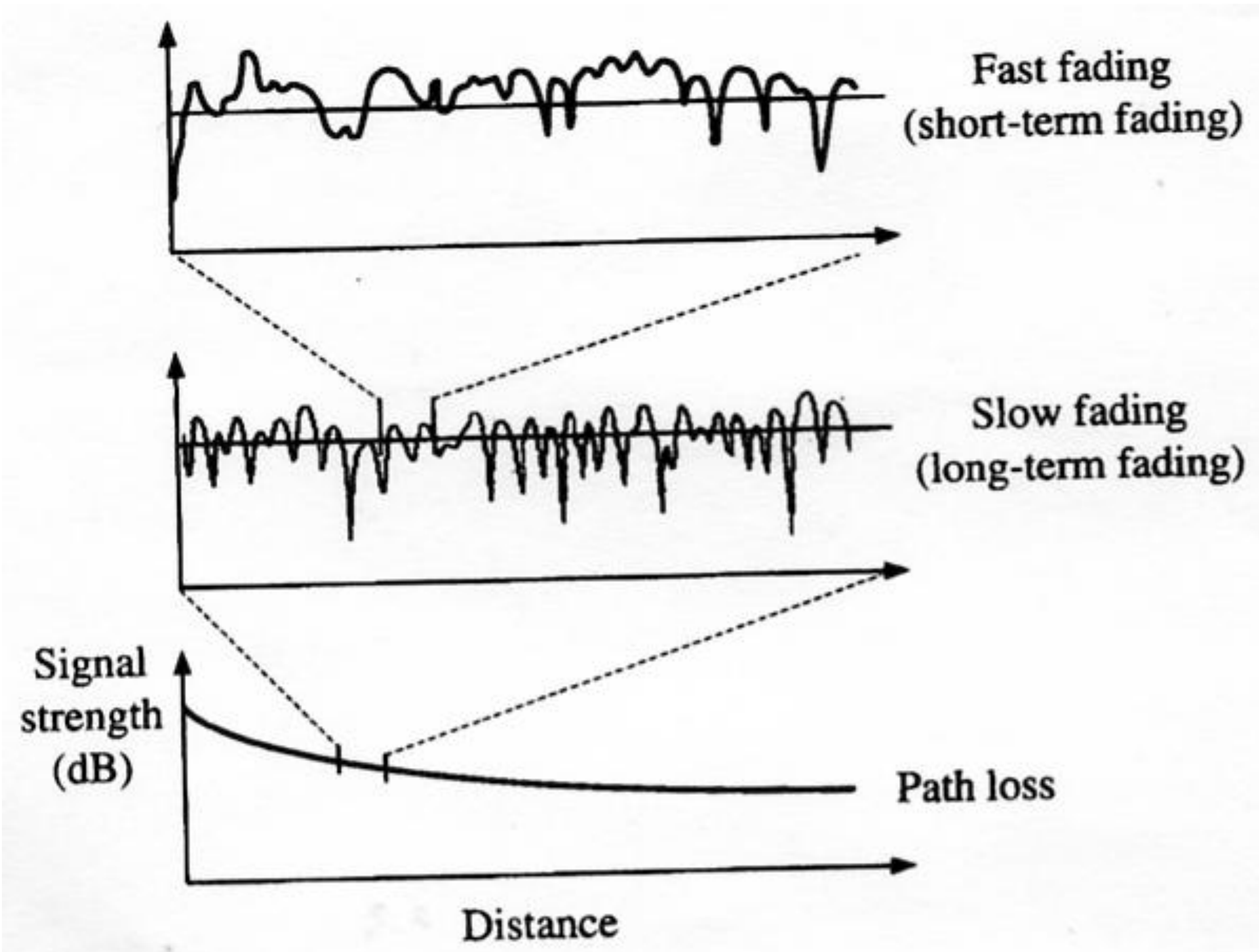
an estimate of the *median path loss* and *local variations.*

Fig.3.12 Outdoor Radio Propagation



Radio propagation mechanisms in an outdoor area.

Fig.3.13 Fading Signal



3.5.3.1 Median Path Loss

A general model, based on empirical measurements, for the path loss in various environment can be expressed by

$$P_R = P_T \,.\, (1/\beta_0) \,.\, (d_0 / d)^n \qquad (3.14)$$

and

$$L_p = \beta_0 + 10\, n \log (d / d_0) \qquad (3.15)$$

where d_0 is the reference distance (typically 1 meter)

β_0 is the measured path loss at reference distance

n is the path loss exponent

d is the distance between transmitter and receiver.

Some sample values for n in the model are given as follows.

Free space, $n = 2$; Flat rural, $n = 3$;

Rolling rural, $n = 3.5$;

Suburban, $n = 4$; Dense urban, $n = 4.5$

Note : More accurate path loss models have been developed , including the well-known Okumura-Hata models.

3.5.3.2 Shadowing

- **A signal transmitted through a wireless channel will typically experience random variation due to blockage from objects in the signal transmission path , depending on the environment and the surroundings, and the location of the obstructive objects.**

  The received signal strength will vary around the median value. This variation due to location is often referred to as shadowing or slow fading

- **The variation about median can be model as a lognormal distribution f ,**

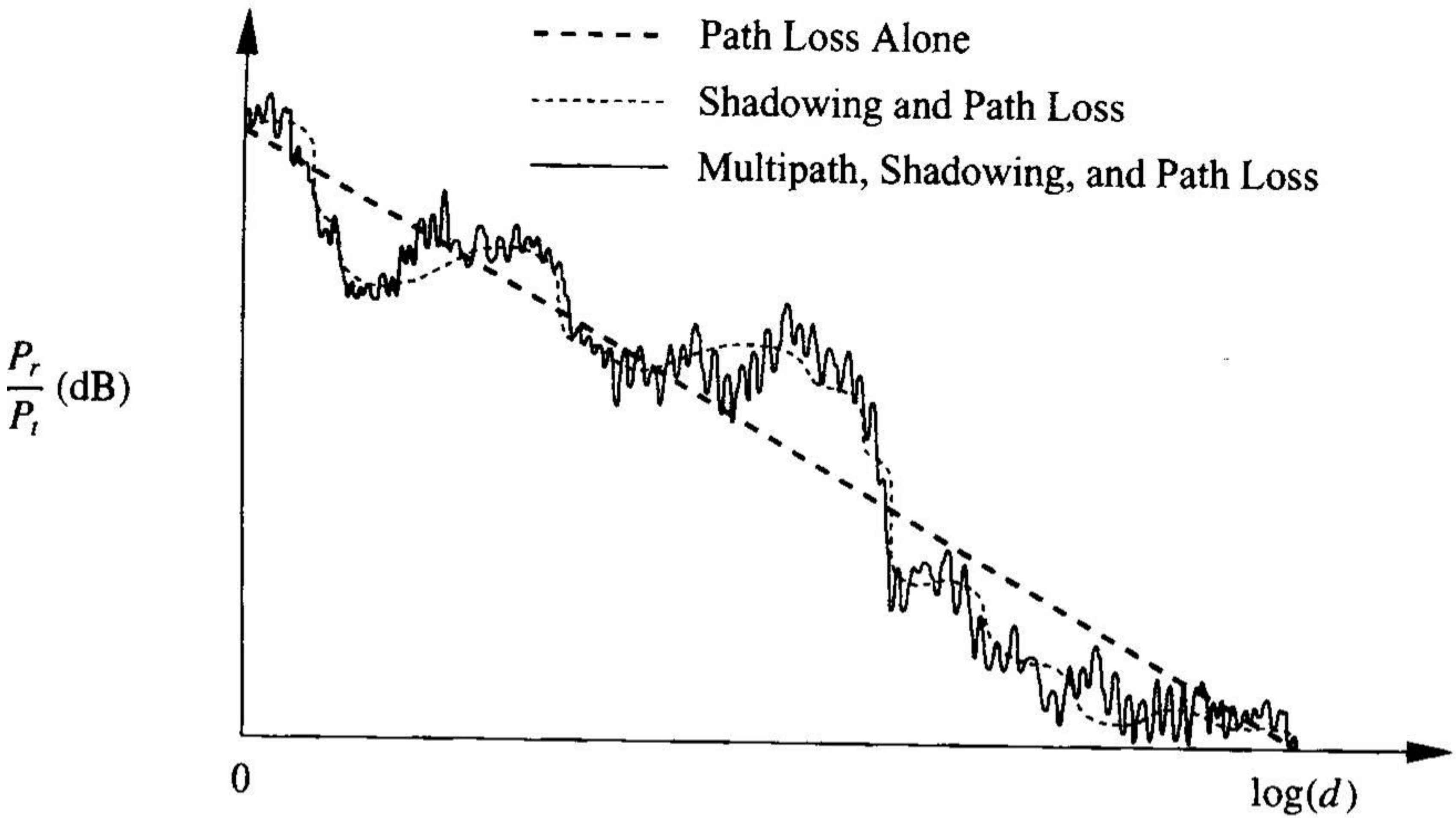
$$f(\chi_{dB}) = \{ 1 / \sqrt{(2\pi\sigma_{dB}^2)} \} \; exp \; \{ -(\chi_{dB} - \mu)^2 / 2\sigma_{dB}^2 \} \qquad (3.16)$$

where μ is the median value of the path loss (in dB) at a specific distance r from the transmitter.

Typical values for the standard deviation σ_{dB} range from 5 to 12 dB .

The above equation is known as the lognormal model for local shadowing.

Fig.3.14 Path loss, Shadowing and Multipath vs. Distance



■ Combined Path Loss and Shadowing

$$P_R = P_T - [\beta_0 + 10\, n \log (d / d_0) + \chi_{dB}]$$

where x_{dB} is a Gaussian random variable with zero mean and variance σ_{dB}^2

With shadowing，the received power at any given distance from the transmitter is log-normally distributed with some probability of falling below

P_{min} , .

We define the outage probability p_{out} to be the probability that the receiver at a given distance d falls below P_{min} :

$$p_{out} = 1 - Q \{ [P_{min} - P_T + \beta_0 + 10\, n \log (d / d_0)] / \sigma_{dB} \}$$

- The Q-function $Q(x)$ is defined as

$$Q(x) = \{ 1/ \sqrt{(2\pi)} \} \int_x^{\infty} exp (- x^2 / 2) \, dt$$

$$Q(x) = 1 - Q(-x)$$

- For x=1.3 , Q(x) = 0.09680 ; x=1.2 , Q(x) =0.11507 about 10%
  x=1.5 , Q(x) = 0.06681 ;
  x =1.6 , Q(x) = 0.05480 ; x= 1.7 , Q(x) = 0.04457 about 5%
  x=2.0 Q(x) = 0.02275 x =2.1 , Q(x) = 0.01786
  x= 2.3 , Q(x) = 0.01072; x =2.4 , Q (x) = 0.00824 about 1%
  x =2.5 , Q(x) = 0.00621
  x = 3.0 , Q(x) = 0.00135 ; x =3.1 , Q(x) = 0.00097 about 0.1 %

Example :

Find the outage probability at 150 m for a wireless channel based on the combined path loss and shadowing model $n=3.7$, β_0 =31 dB , d_0 = 1 m and σ_{dB} = 4 dB .

Assume that a transmit power P_1 = 10 mw =10 dBm and the minimum power required at the receiver is P_{min} = -110 dBm

Solution :

$$p_{out} = 1- Q\{[P_{min} - P_T + \beta_0 + 10\, n \log(d/d_0)]/\sigma_{dB}\}$$

$$= 1 - Q\{[110 - 10 + 31 + 37 \log(150)]/4\}$$

$$= 1- Q\{-2.125)$$

$$= Q(2.125) = 0.017 = 1.7\ \%$$

3.5.4 Local Propagation Effects with Mobile Radio

- In most mobile communication systems, the mobile antenna is well below the surrounding buildings. Thus, most communication is via scattering of electromagnetic wave from surfaces or diffraction over and around buildings.

  These multiple propagation paths, or multipath, have both slow and fast aspects : slow fading and fast fading.

- Slow fading arises from the fact that most of the large reflectors and diffraction objects along the transmission path are distant from the terminal. The motion of the terminal relative to these distant objects is small.

  Consequently, the corresponding propagation changes are slow. These factors contribute to the median path loss between a fixed transmitter and a fixed receiver.

The statistical variation of these mean loss due to the variation of the intervening terrain, vegetation, etc. was modeled as a lognormal distribution for terrestrial applications.

The slow fading process is also known as shadowing or lognormal fading.

- Fast fading is due to scattering of the signal by objects near transmitter. In mobile radio, the rapid fluctuations in the spatial and temporal characteristics caused by local multipath are known as fast fading (short-term fading due to fast spatial variations.

3.5.4.1 Rayleigh Fading

- For receivers far from the transmitters, there are no direct radio wave between them, the probability distribution of signal amplitude of every path is a Gaussian distribution and their phase distribution has a uniform distribution within ($0, 2\pi$) radians . Therefore , the probability distribution of the envelope for the composite signals is a Rayleigh distribution and its probability distribution function (pdf) is given by

$$f_R(r) = (r/\sigma^2) \exp(-r^2/2\sigma^2) \quad , \; r > 0 \qquad (3.18)$$

where r is the envelope of fading signal and σ is the standard deviation.

The pdf of the phase distribution of the composite signal is given by

$$p(\theta) = 1/(2\pi) , \quad 0 \leqq \theta \leqq 2\pi \qquad (3.19)$$

- The **mean** value of the Rayleigh distribution is given

by $E[R] = \int r f_R(r)\, dr = \sigma\sqrt{(\pi/2)}$

and the **mean-square** value is given by

$$E[R^2] = \int r^2 f_R(r)\, dr = 2\sigma^2 = R_{rms}^2$$

The **cumulative** probability distribution function is given by

$$Prob(r < R) = \int r f_R(r)\, dr = 1 - \exp(-R^2 / 2\sigma^2)$$

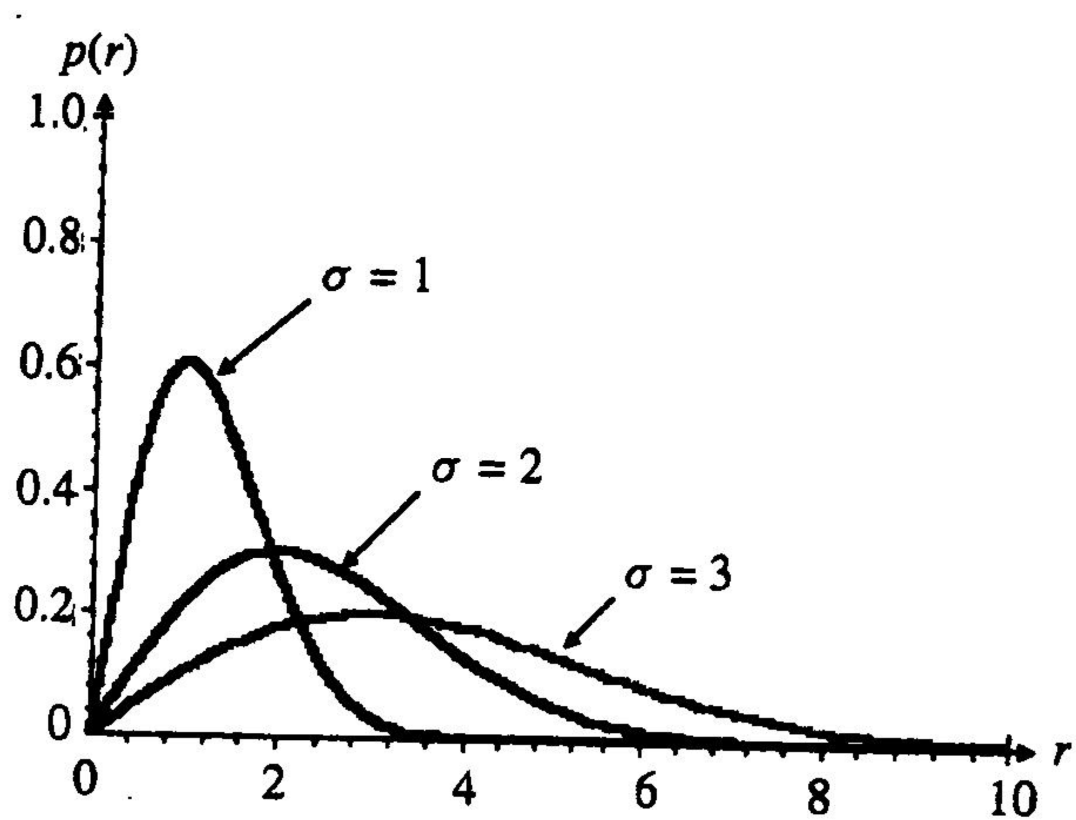
Fig.3.14(a) plots the Rayleigh distribution.

Fig.3. 14(b) shows the Rayleigh amplitude distribution.

The **median** of the distribution is R_{rms} ,which implies that there is constructive interference ($R > R_{rms}$) for 50 % of the locations.

From this figure, we can see that deep fades of **20 dB** or more ($R < 0.1\ R_{rms}$) occur only rarely (with a probability of 1 %)

Fig. 3.14 (a) Rayleigh Distribution



The pdf of Rayleigh distribution when σ = 1, 2, and 3.

3.5.4.2 Rician Fading

- In the case that there is a specular or direct radio path between transmitter and receiver, the probability distribution of the envelope of the composite signal is a Rician distribution and its pdf is given by

$$f_R(r) = (r/\sigma^2)\ \exp\ \{\ -(r^2+\beta^2)/2\sigma^2\ \}\ *$$
$$I_0(\beta r/\sigma^2)\ ,\quad r \geqq 0 \qquad (3.20)$$

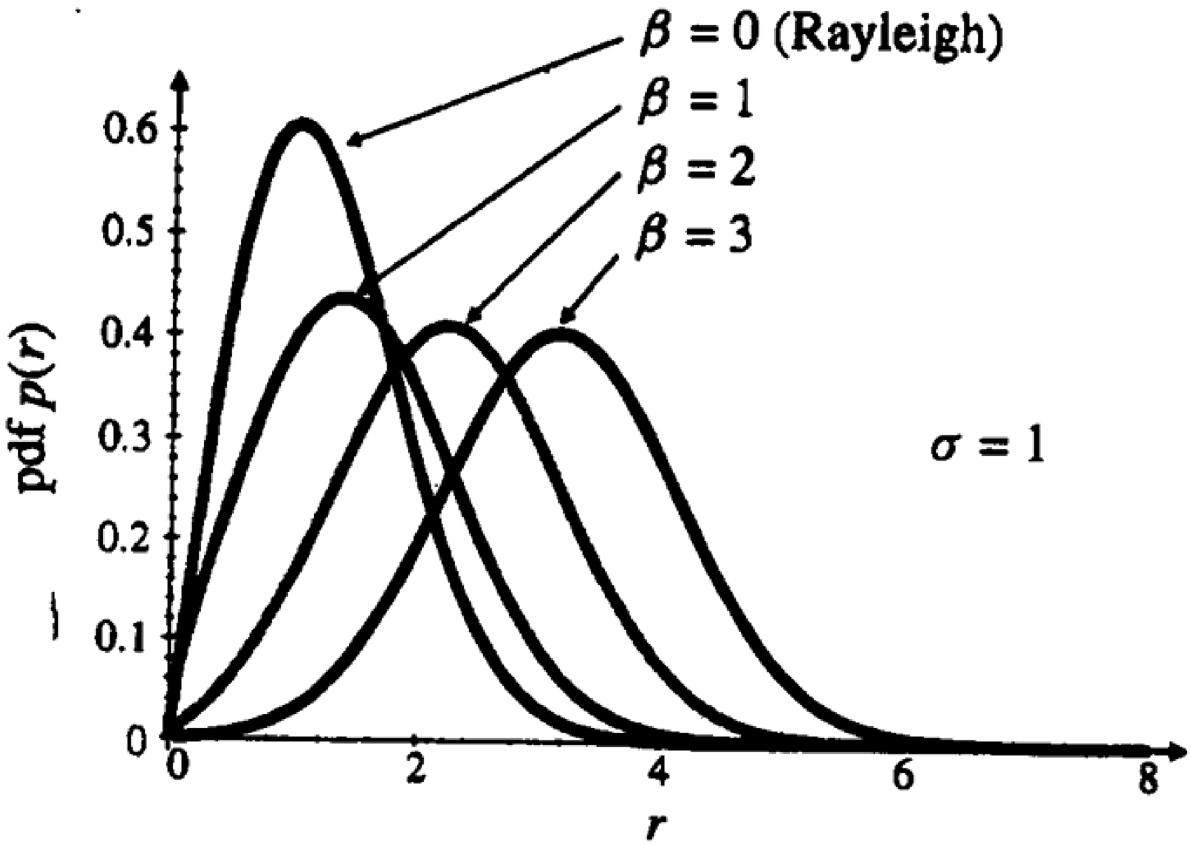
where r is the envelope of fading signal and σ is the standard deviation , β is the amplitude of direct signal , and $I_0(x)$ is the zero-order modified Bessel function of the first kind.

$$I_0(x) = 1/\ (2\pi) \int \exp(\ x\cos\theta)\ d\theta$$

$$\fallingdotseq e^x / \sqrt{(2\pi x)} \qquad (3.21)$$

- **When β is very large , the above equation *p (r)* can be approximated by a Gaussian distribution. When β is very small, *p (r)* can be approximated by a Rayleigh distribution.**
- **The ratio of the power in the direct path to the power in the reflected paths is referred to bas the Rician factor K.**

Fig. 3.16 Rician Probability Density Function



The pdf of the onvelope of composite signals according to Rician distribution.

3.5.5 Doppler Shift

- If a receiver is moving toward the source, then the zero-crossing of the signal appear faster, and consequently, the received frequency is higher. The opposite effect occurs if the receiver is moving away from the source . The resulting change in frequency is known as the Doppler shift .

- If the receiver (receiving terminal) is moving at the speed v and the direction of radiation are at an angle Ψ , the maximum Doppler shift is given by

$$f_D = (v / c) f_0 \qquad (3.22)$$

The received frequency f_r is given by

$f_r = f_0 + f_D \cos \Psi$ if the receiver is moving toward the source

$= f_0 - f_D \cos \Psi$ if the receiver is moving away from the source

3.5.6 Clarke's Model of Fast Fading

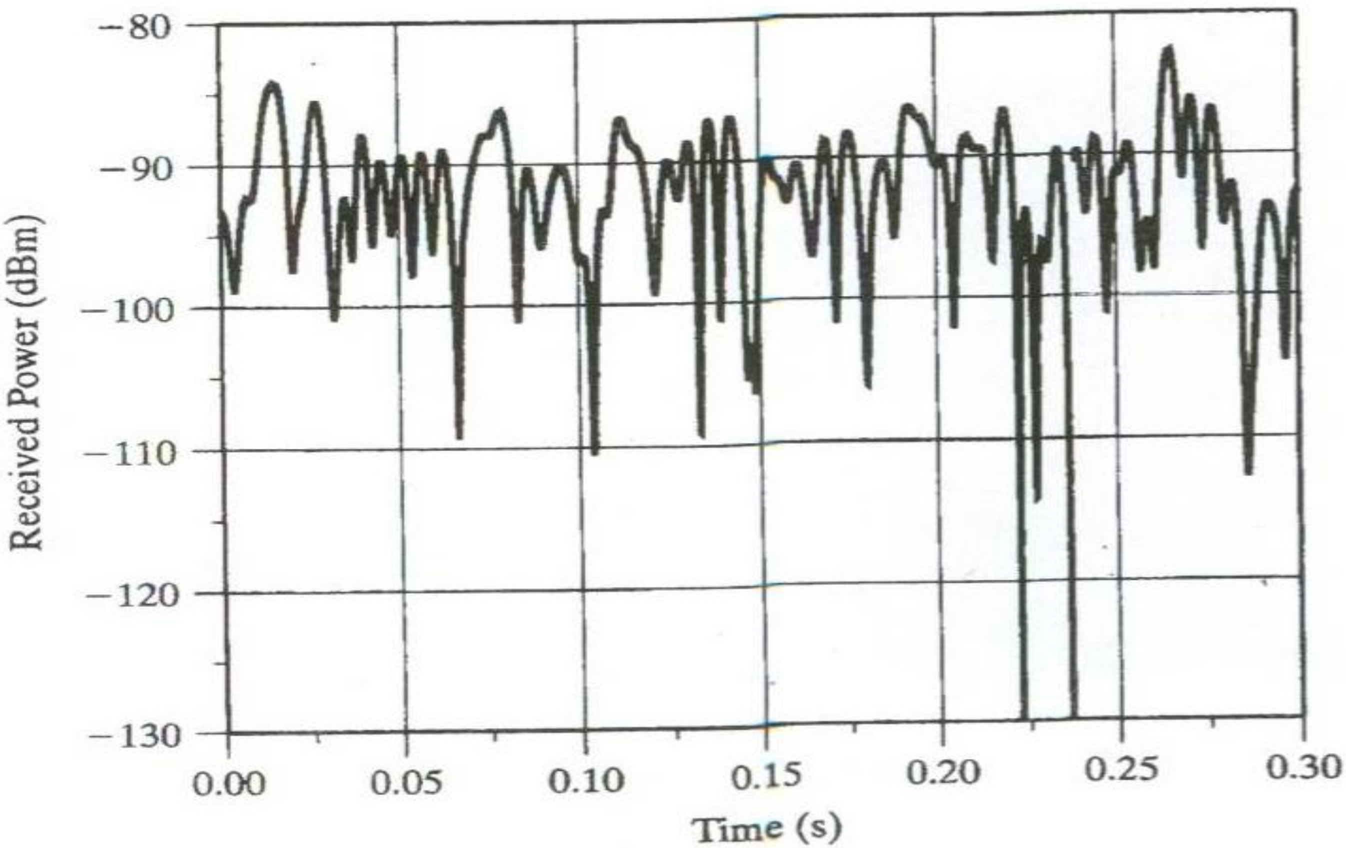
- If we measure the received signal strength as a function of time for a mobile terminal, we may observe a rapid variation in the signal strength about a median value.

  This phenomenon is known as fast fading.

  From the previous discussion on stationary receiver, we would expect the signal power at different locations to have a Rayleigh distribution.

  Fig.3.18 shows a sample trace of the received signal power for a terminal moving at 100 *km/hr* in a Rayleigh fading environment.

Fig.3.18 Rayleigh Fading Signal



- **Clarke Model**

Assuming that the transmitted signal reaches a moving receiver via multiple paths, the complex envelope of N signal- rays is expressed by

$$\tilde{E}(t) = \Sigma_{n=1}^{N} E_n \exp[\, j\,(2\pi f_n t + \psi_n\,)] \qquad (3.23)$$

All rays are assumed to arrive from a horizontal direction.
Since the receiver is moving, each ray has a different Doppler shift f_n. The rays are assumed to come from arbitrary angles ψ_n and the relative phase of each ray is iid.

(i) Time dependency of fading phenomenon

The autocorrelation of the complex envelope is expressed as

$$R_E(\tau) = E\,[\,E(t)\,E^{*}(\,t+\tau)\,] \qquad (3.24)$$

where the asterisk * denotes complex conjugate and τ is a time offset .

After some mathematical manipulations, we obtain the autocorrelation of the complex envelope, given by

$$R_E(\tau) = P_0 \mathbf{E}[\exp(-j 2\pi f \tau)]$$

$$= P_0 J_0(2\pi f_D \tau) \qquad (3.25)$$

where $P_0 = \Sigma_{n=1}^{N} \mathbf{E}[E_n^2]$ **is the average received power , and** $J_0(x)$ **is the *zeroth-order* Bessel function of the first kind.**

$$J_0(x) = (1/\pi) \int_0^{\pi} \exp(-j x \cos\theta)\, d\theta \qquad (3.26)$$

(ii) Power Spectrum of Fading Process

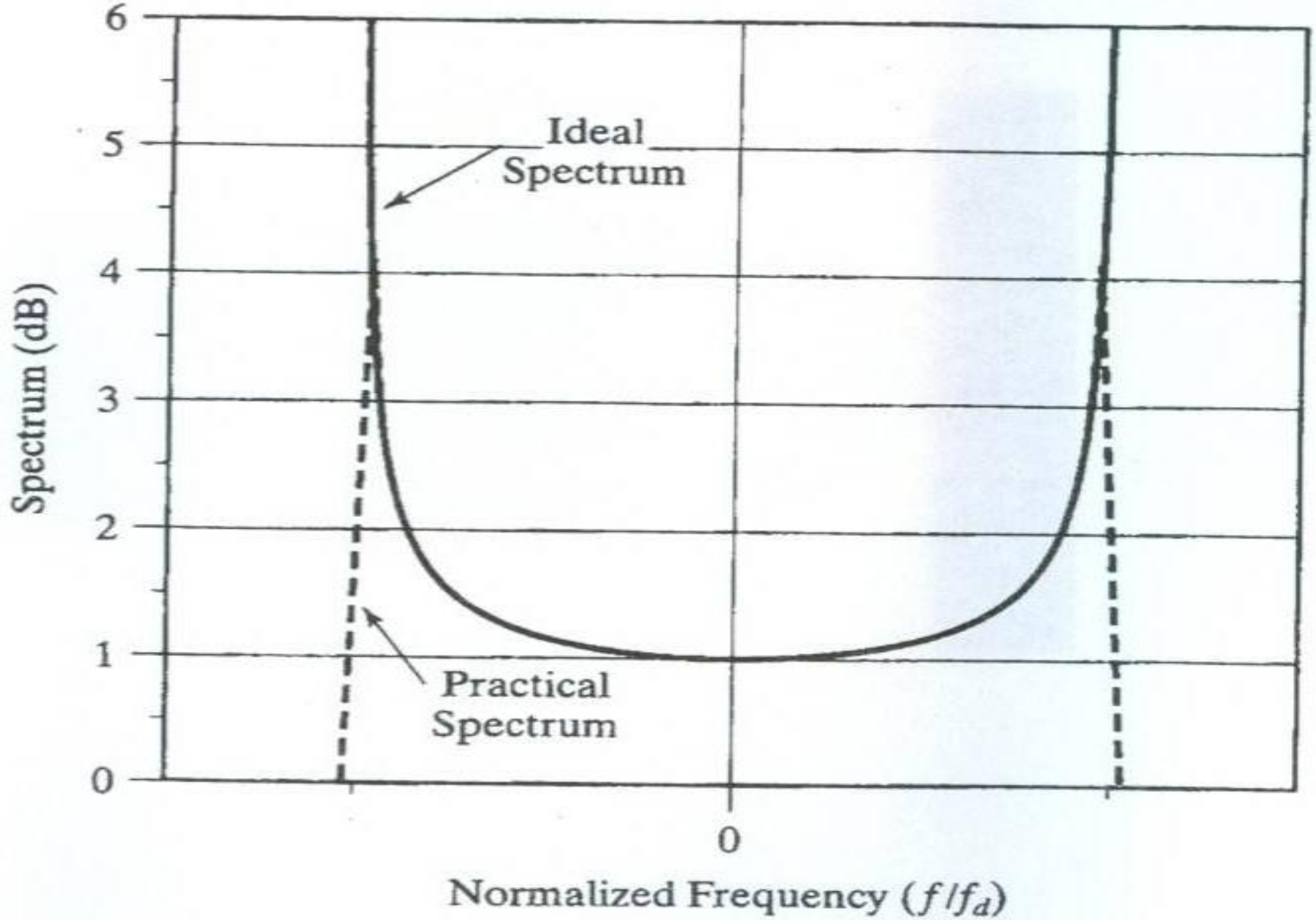
The Fourier transform of the autocorrelation function of the envelope is given by

$$S_E = F\,[R_E(\tau)\,]$$

$$= \begin{cases} P_0 / \sqrt{[1- (f/f_D)^2]}, & f < f_D \\ 0, & f > f_D \end{cases} \qquad (3.27)$$

Fig.2.20 plots Eq.(2.27) for $P_0 = 1$. The power spectrum is zero at frequencies greater than the Doppler shift f_D.

Fig.3.19 Doppler Spectrum



- **Empirical measurements tend to support the Clarke model for mobile terrestrial communications , with a Doppler bandwidth related to the frequency of transmission and mobile velocity.**
- **In a multipath environment, when the time delay between the various signal paths is a significant fraction of the transmitted signal's symbol period , a transmitted symbol may arrive at the receiver during the next symbol period and cause intersymbol interference (ISI).**

3.5.7 Indoor Propagation

- **With the growth of cellular telephone usage, these appliances are being used more and more in indoor locations such shopping malls, office buildings, train stations, and airports.**

  It is important that wireless design take into account the propagation characteristics in these high density locations.
- **An in-building site-specific propagation model that includes the effect of building type as well as the variations caused by obstacles has been used to accurately deployed indoor and campus wireless networks.**

- **A simple model for the indoor path loss is given by**

$$L_p(dB) = \beta_0\,(dB) + 10\,n\,\log_{10}(d/d_0) + \sum_{p=1}^{P} WAF(p) + \sum_{q=1}^{Q} FAF(q) \qquad (3.28)$$

where *n* represents the exponent value for the " same floor" measurement , WAF is the wall attenuation factor, FAF is the floor attenuation factor, and P an Q are the number of walls and floors ,respectively, separating the transmitter and the receiver.

Equation 3.28 is also known as the Motley- Keenan model [Motley and Keenan, 1988]

3.5.8 Channel Classifications

- Wireless channels can be categorized by the wave propagation effects as large-scale effects and small-scale effects.

  1. **Large-scale effects** are due to the general terrain and the density and height of buildings and vegetation. These effects are characterized statistically by the median path loss and lognormal shadowing. Both of these phenomena have a behavior that varies relatively **slowly** with time.
  2. **Small-scale effects** are due to the local environment , nearby trees, buildings, etc., and the movement of the radio terminal through that environment. They have been characterized statistically as **fast** Rayleigh fading.

- **Two kinds of dispersion of mobile channelsons are :**

  a. Time dispersion --- The mobile channel introduces delay spread into the received signal. That is, received signal has a longer duration than that of the transmitted signal, due to the different delays of the signal paths.

  b. Frequency dispersion ----The mobile channel introduces Doppler spread into the received signal. That is, the received signal has a larger bandwidth than that of the transmitted signal, due to the different Doppler shifts introduced by the components of the multiple path .

- **Time-Selective Channel**

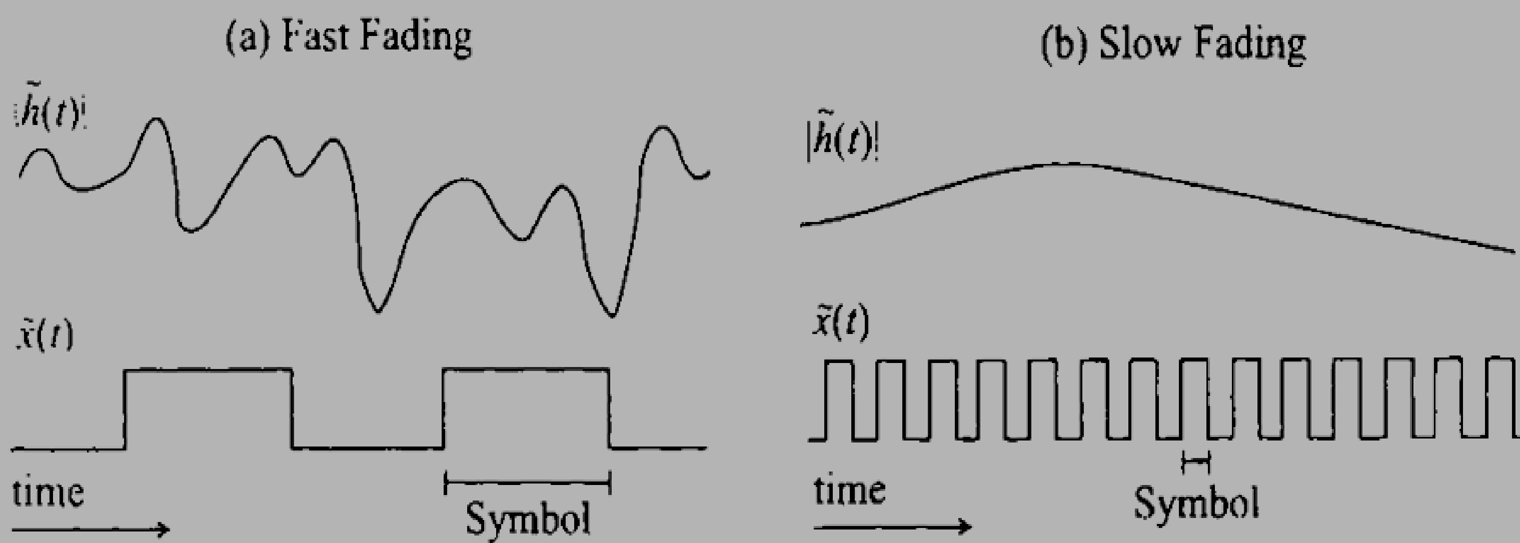
In a fast-fading channel, the attenuation effect is introduced ,the received signal strength is also time varying. The channel referred to as a time-selective channel.

A channel with frequency-flat and time-selective is common in practice, and we refer to it as a flat-fading channel.

- **Frequency-Selective Channel**

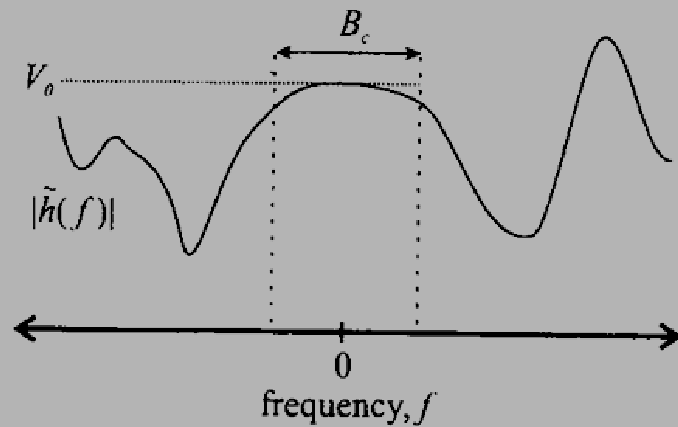
With large-scale effects, the signal may arrive at the receiver via paths with different path length.

This channel is time invariant, but it shows a frequency-dependent response For this reason, the channel is called frequency-selective channel or time flat channel.

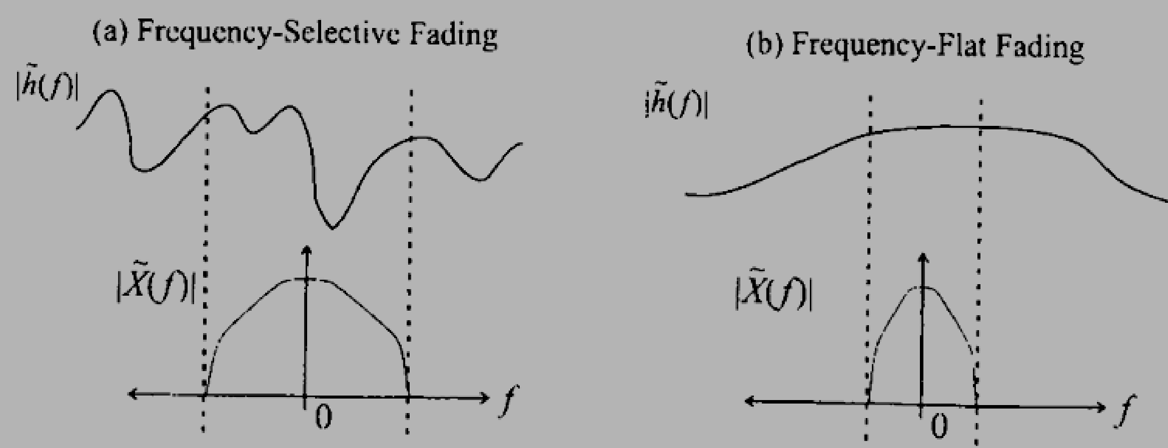


Fast and slow fading for simple square pulse symbols.

Frequency Selectivity



A frequency-varying channel.



Frequency-selective and frequency-flat fading for a sample transmitted signal spectrum, $\tilde{X}(f)$.

3.5.8.1 Wide-Sense Stationary Channels

- A random process is wide-sense stationary (WSS) if it has a mean that is time independent and a correlation function

  $R(t_1, t_2) = R(t_1 - t_2)$ (3.39)

- For a wide-sense stationary channel, the autocorrelation function of the channel impulse response takes the form

$$E[\tilde{h}(t_1, \tau_1)\,\tilde{h}^*(t_2, \tau_2)] = R_h(t_1 - t_2, \tau_1 - \tau_2)$$

(3.40)

That is, the channel autocorrelation function depends only on the time difference $\tau_1 - \tau_2$.

- **In practice, many wireless channels , for example terrestrial mobile channels are usually non-stationary for the following reasons :**
  1. **The propagation path often consists of several discontinuities, such as buildings.**
  2. **The environment itself is physically nonstationary. There may be moving trucks, moving people, etc..**
  3. **The interference caused by other users sharing the same frequency channel will vary dynamically as these other users come onto and leave the system.**
- **Stationary models still have their applications. Even though many communications links are highly nonstationary, the WSSUS model provides a reasonably accurate account of the propagation characteristics for short period of time.**

3.5.8.2 Coherence Time

- Coherence time is defined as the period over which there is a strong correlation of the channel time response .
- For a mobile channel with Doppler spread $2f_D$, where f_D is the maximum Doppler frequency , then the coherence time is given approximately by

$$T_{coh} \doteqdot 1/\ 2f_D \qquad (3.41)$$

- If the coherence time is finite, then the channel is time-selective, that is, time-varying.

If the coherence time is infinite, then the channel is time flat , that is, time invariant.

- Example 2.11 (Haykin p.57)

- **It is also commonly assumed that , in multipath channels, the gain and phase shift at one delay are uncorrelated with the gain and phase shit at another delay. This type of behavior is referred to as uncorrelated scattering (US).**
- **A wide-sense stationary uncorrelated scattering(WSSUS) channel is a channel with wide-sense stationary impulse response with uncorrelated scattering assumption .**

3.5.8.3 Power-Delay Profile

- For a WSSUS channel ,the function $P_h(\tau)$ is known as **power-delay profile** of the channel provides an estimate of the average multipath power as a function of the relative delay τ .
- Consider the situation in which the channel impulse response is given by

$$h(t,\tau) = \Sigma_{k=1}^{L} \alpha_k(t)\, \delta(\tau - \zeta_k) \qquad (3.42)$$

The corresponding autocorrelation of $h(t,\tau)$ is given by

$$R_h(t_1, t_2 ;\tau_1 ,\tau_2) = [\Sigma_{k=1}^{L} P_k\, J_0(2\pi f_D \Delta t)\, \delta(\tau - \zeta_k)] * \delta(\tau - \zeta_k) \qquad (3.43)$$

and the power-delay profile is given by

$$P_h(\tau) = \sum_{k=1}^{L} P_k \, \delta(\tau - \zeta_k) \qquad (3.44)$$

That is , at the delay ζ_k ,, , the power-delay profile is the average power of the *k*-th path.

- Average Delay :

With $P_h(\tau)$ representing the power-delay profile, the average delay is given by

$$T_D = (1/P_m) \int_0^{\infty} \tau \, P_h(\tau) \, d\tau \qquad (3.45)$$

where the average power is

$$P_m = \int_0^{\infty} P_h(\tau) \, d\tau \qquad (3.46)$$

- **The second moment of the average power-delay profile is given by**

$$\mu_2 = (1/P_m) \int_0^{\infty} (\tau - T_D)^2 P_h(\tau)\, d\tau$$
$$= (1/P_m) \int_0^{\infty} \tau^2 P_h(\tau)\, d\tau - T_D^2 \qquad (3.47)$$

- **Delay Spread :**

Delay spread is defined by $S = \sqrt{\mu_2}$, which is simply the root-mean – square (rms) delay

- **Excess Delay**

The maximum excess delay of the channel is given by $N \Delta\tau$

3.5.8.4 Coherence Bandwidth

- The time-varying frequency response of the channel is given by the Fourier transform of the impulse response

$$H(t, f) = F\{\tilde{h}(t, \tau)\} \qquad (3.48)$$

- The coherence bandwidth of a channel is the frequency-domain dual of channel delay spread . The coherence bandwidth gives a rough measure for the maximum separation between frequency f_1 and a frequency f_2

where the channel frequency response is correlated.

$$|f_1 - f_2| \leqq B_c \longrightarrow H(f_1) \doteqdot H(f_2) \qquad (3.49)$$

- The coherence spectrum of the channel is closely related to the coherence bandwidth of the

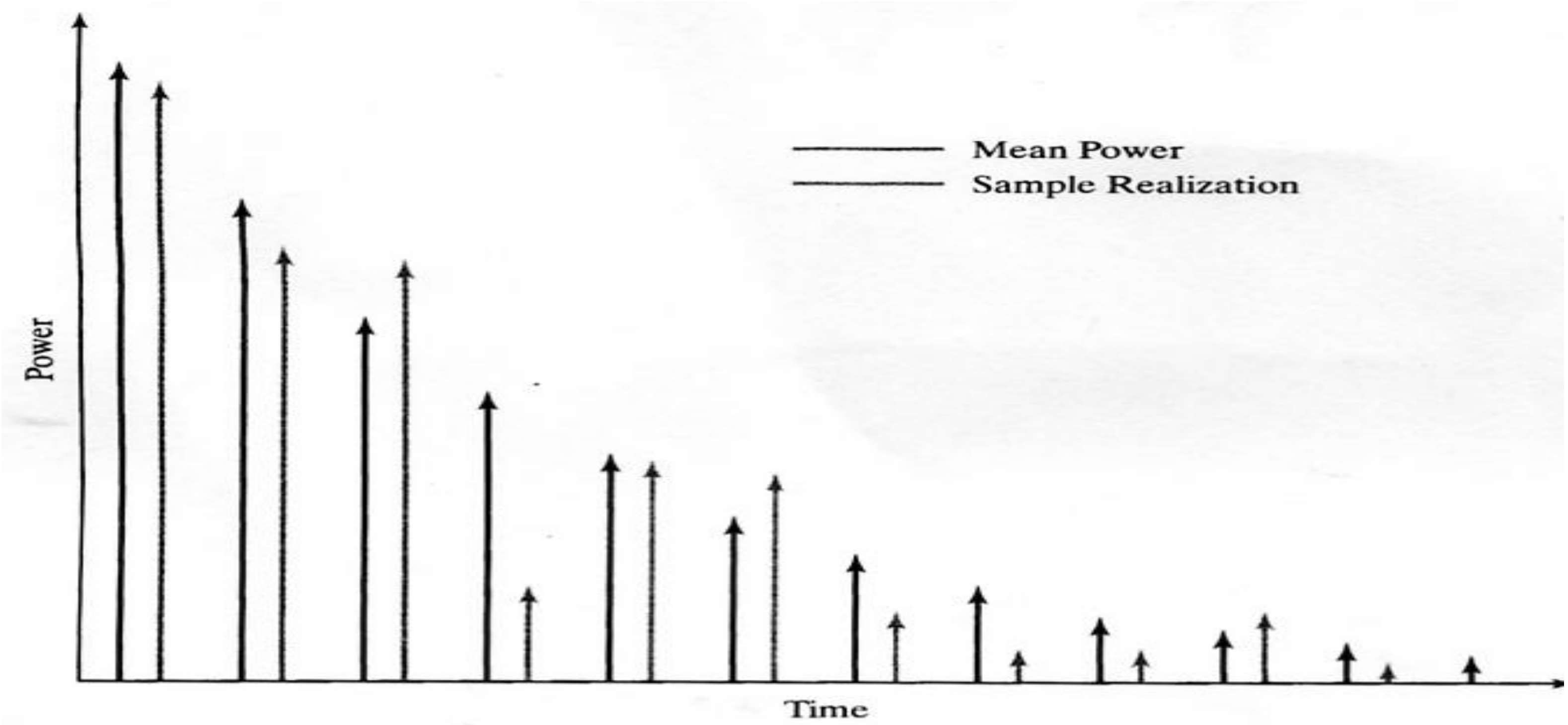
  received signal.

  $$B_{coh} \fallingdotseq 1/T_M \qquad (3.50)$$

  That is, the coherence bandwidth is inversely proportional to the multipath spread of the channel.

Remarks :

The multipath intensity is sometimes modeled with an exponential power-delay profile , as shown in Fig.2.24



Impulse response model for multipath channel.

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