WIELESS COMMUNICATION NETWORKS

IV BTECH II SEM (JNTUH- R15)

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UNIT I
The Cellular Concept-System Design Fundamentals

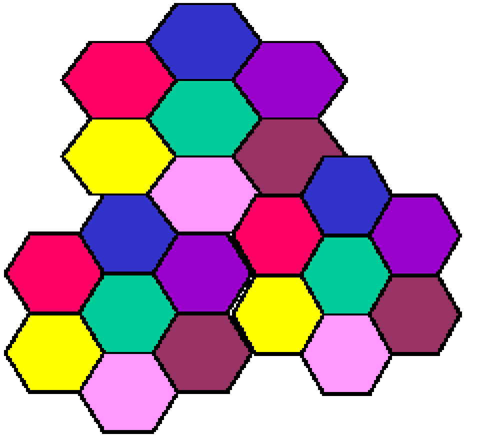
Cellular Concept

- Proposed by Bell Labs 1971
  Geographic Service divided into smaller "cells"

- Neighboring cells do not use same set of frequencies to prevent interference

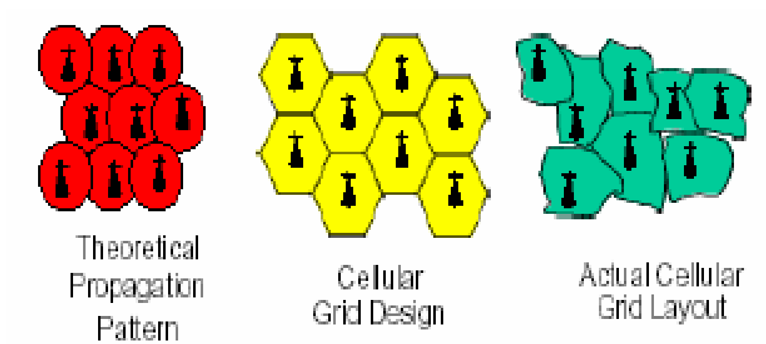
- Often approximate coverage area of a cell by an idealized hexagon

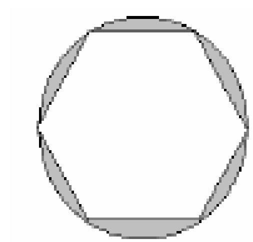
- Increase system capacity by frequency reuse.



Cellular Networks

- Propagation models represent cell as a circular area
- Approximate cell coverage with a hexagon - allows easier analysis
- Frequency assignment of F MHz for the system
- The multiple access techniques translates F to T traffic channels
- Cluster of cells K = group of adjacent cells which use all of the systems frequency
  assignment





Cellular Concept

- Why not a large radio tower and large service area?
  - – Number of simultaneous users would be very limited (to total number of traffic channels T)
  - – Mobile handset would have greater power requirement
- Cellular concept - small cells with frequency reuse

– Advantages

- lower power handsets
- Increases system capacity with frequency reuse

– Drawbacks:

- Cost of cells
- Handoffs between cells must be supported
- Need to track user to route incoming call/message

Cellular Concept (cont)

- Let T = total number of duplex channels

  K cells = size of cell cluster (typically 4, 7,12,

  21) N = T/K = number of channels per cell
- For a specific geographic area, if clusters are replicated M times, then total number of channels

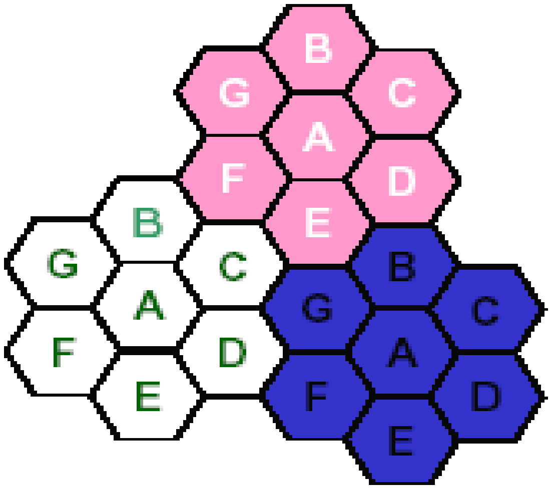
  –system capacity = M *x* T

  –Choice of K determines distance between cells using the same frequencies – termed co-channel cells

  –K depends on how much interference can be tolerated by mobile stations

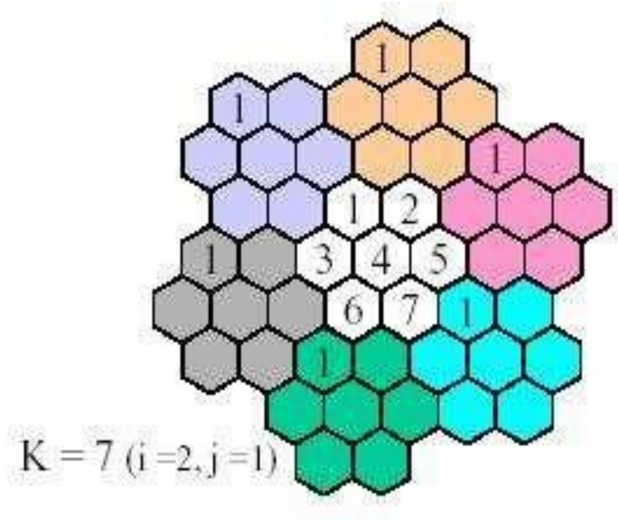
Cellular Design Reuse Pattern

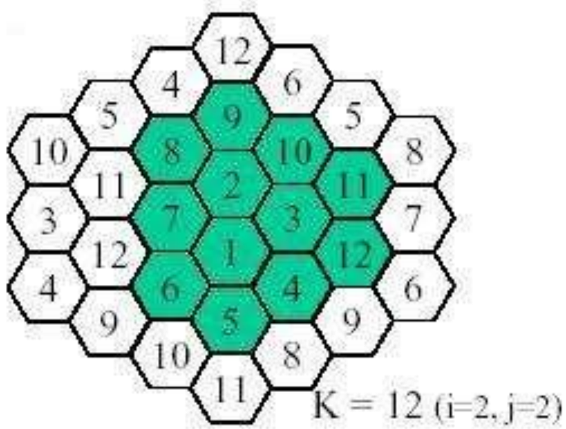
- Example: cell cluster size K = 7, frequency reuse factor = 1/7, assume T = 490 total channels, N = T/K = 70 channels per cell
- Assume T = 490 total channels,
- K = 7, N = 70 channels/cell
- Clusters are replicated M=3 times
- System capacity = 3x490 = 1470 total channels

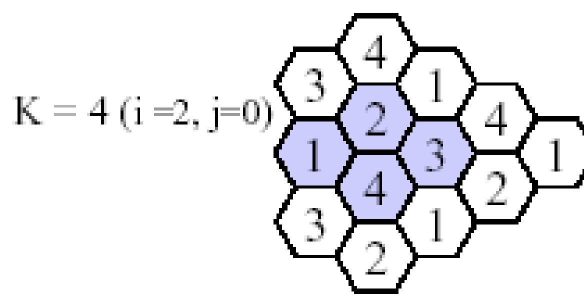


Cluster Size

- From geometry of grid of hexagons only
- certain values of K are possible if replicating cluster without gaps
- $K = i^2 + ij + j^2$ where i and j are non-negative integers







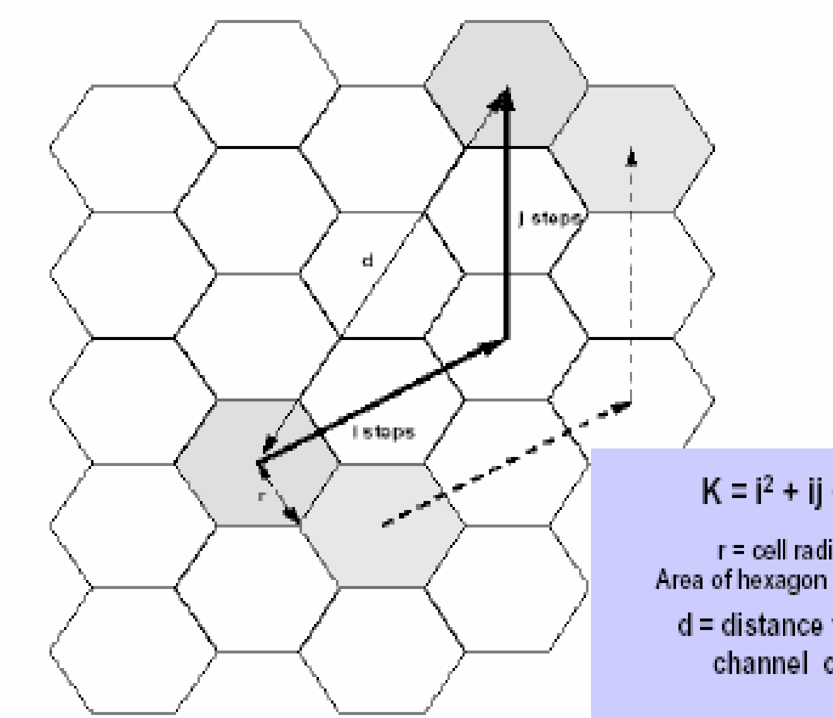
Cellular Concepts

(Co-Channel Cells)

- To find co-channel neighbors of a cell, move i cells perpendicular to the hexagon boundry, turn 60 degrees counterclockwise, and move j cells (example: i=2, j=2, K=12)
- In order to maximize capacity, Co-channel cells are placed as far apart as possible for a given cluster size
- The relationship among the distance between the Co-channel cells, D, the cluster size K and the cell radius R is given as;

$$\mathbf{D/R = \sqrt{3K}}$$

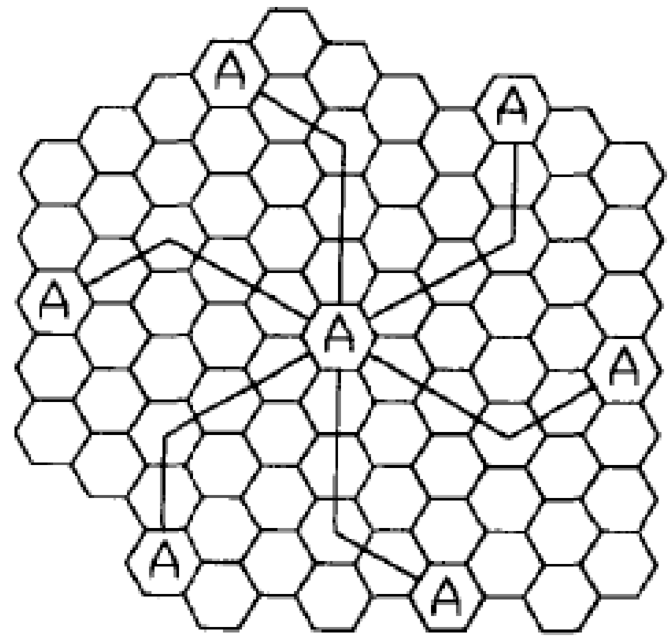
Cellular Concepts



$K = i^2 + ij + j^2$

r = cell radius
Area of hexagon = 2.61 r^2

d = distance to co-channel cell



In this case K=19
(*i=3, j=2*)

Frequency Reuse

- Relate Cluster size K to the Co-channel interference C/I at the edge of the cell
- In general signal-to-noise ratio can be written as;

$$S_r = P_{desired} / \Sigma_i \, P_{interference,i}$$

- $P_{desired}$ is the signal from the desired BS and $P_{interference,i}$ is the signal from the ith undesired BS
- The signal strength falls as some power of α called power-distance gradient or path loss component
- If P_t is the tranmitted power, d is the distance then, received power will be

$$P_r = P_t \; L \, d^{-\alpha}$$

Where, d is in meters

L is the constant depending on frequency

Frequency Assignment

- Aim: To increase the number of available channels without compromising the quality of service e.g.

  1) Efficient Utilization of Spectrum

  2) Increase Capacity

  3) Minimize Interference
- Two Types
  - Fixed Channel Allocation (FCA)
    - The number of traffic channels is fixed. If all channels are busy a new call to or from a mobile will be blocked (rejected by BS)
  - Dynamic Channel Allocation (DCA)
    - The BS requests a channel for the MSC when needed
    - The MSC allocates the channel taking into account

Frequency Assignment (cont)

a) likelihood of future blocking within the cell

b) the frequencies of use of the candidate channel

c) the reuse distance of the channel

- The dynamic channel assignment reduces the probability of blocking (the number of available channels to a cell is increased)
- Increase in the complexity of the MSC which has to collect data on;

a) Channel Occupancy

b) Traffic distribution

c) Radio signal strength of all channels

- *Cell borrowing technique*: a case of FCA in which a cell is allowed to borrow a channel from its neighbour under MSC's supervision

Handoff Strategies

- When a mobile moves from one cell to the next during a call the MSC automatically transfers the call to a new channel belonging to the next cell. This operation is called HANDOFF
- Handoff is similar to an initial call request
- The handoff has the priority over a new call to avoid call cut off in the mid conversation

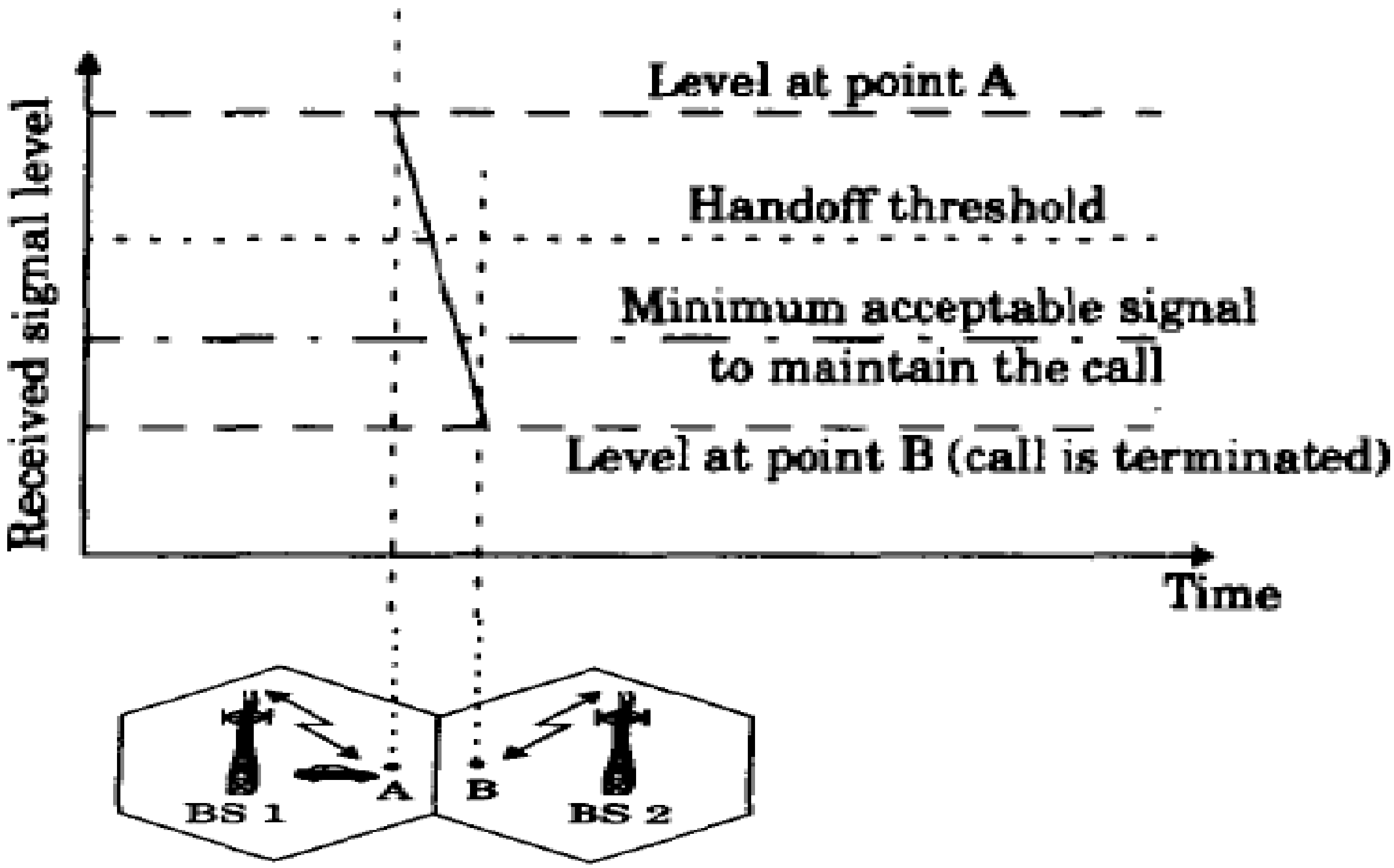
margin is $\Delta = P_{handoff} - P_{min}$

- In reality, a fraction of total channels can be reserved for handoff requests in each cell

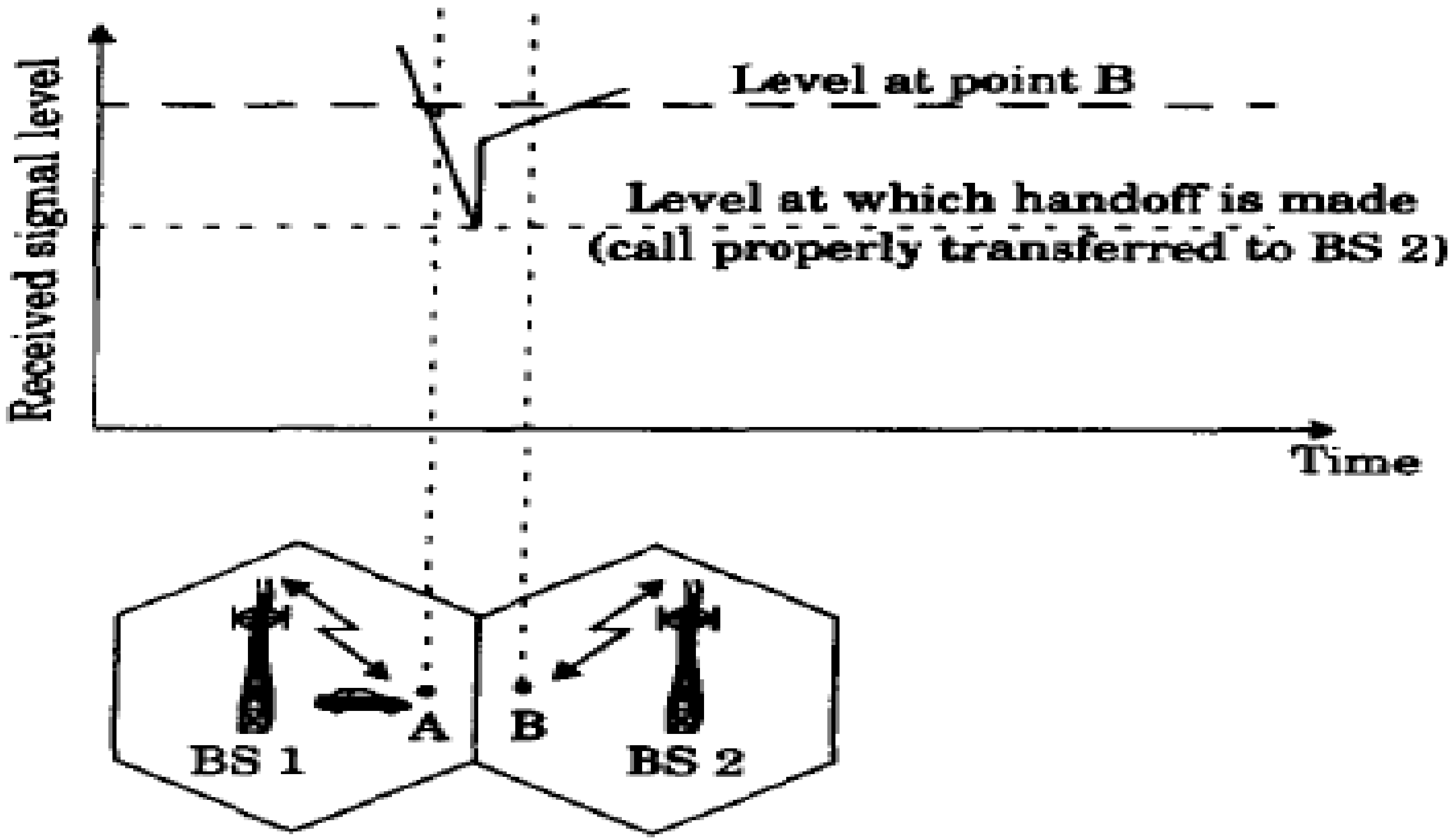
- The handoff must be successful, as infrequent as possible and unnoticeable to the user

- The minimum acceptable level is establised for the received signal to maintain the call. The handoff threshold is slightly above that level. The

Improper Handoff



Proper Handoff



Handoff (cont)

- If the margin is too large there are too frequent and unnecessary handoffs which burden the MSC
- If the margin is too small, there may be not enough time to complete the handoff, particularly when the mobile moves fast
- The time a mobile spends in a cell without handoff is called *dwell time*
- For high speed mobiles, large umbrella cells with wide range are used
- For low speed mobile, microcells with small coverage area are used
- The speed is estimated by the BS or MSC from average signal strength

Interference and System Capacity

- Interference is a limiting factor in the performance of cellular systems
- Co-Channel interference (CCI) is caused by signals at the same frequency
- Adjacent channel interference (ACI) is caused by signals from neighbouring frequencies
- In traffic channels, interference causes crosstalk from undesired users
- In control channels, interference causes errors which result in wrong instructions
- To reduce co-channel interference, co-channel cells must be separated sufficiently

Co-Channel Interference (CCI)

- Let R be the radius of a cell and let D be the distance between the centers of co-channel cells
- The CCI is independent of the transmit power
- By increasing the ratio D/R we reduce CCI
- We define the co-channel frequency reuse ratio as **Q=D/R,** then for hexagonal cells, $\mathbf{Q=\sqrt{3K}}$
- By reducing Q
  - The cluster size K is reduced
  - The systems traffic capacity is increased (the number of channels per cell is increased)
  - CCI is increased

CCI (cont)

- By increasing Q
  - Cluster size K is increased
  - The system capacity is decreased
  - CCI is decreased
- Mathematically, *CCI ratio Calculation*
- Let Ni be the number of co-channel cells
- Signal-to-interference ratio (SIR) is;

$$S/I = S / (\Sigma_{Ni}\, Ii)$$

  Where S is power from desired BS and li is the power from i-th interferer BSi

- Let P_0 be the received power at a distance d_0 from the transmitter.
- The received power of the mobile at the distance d from the transmitter is

$$P_r = P_0\,(d/d_0)^{-n}$$

CCI Ratio (cont)

- Where α is the path loss component and n=2,3,4
- In dBm we have

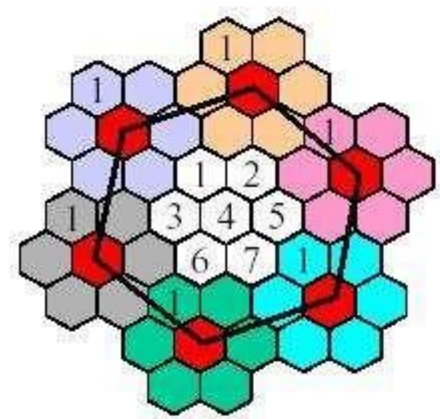
  P_r (dBm) = P_0 (dBm)-10 α log 10 (d/d_0)
- The least value of desired signal S is at the edge of

  the cell, which is R, thus

  $$S= P_0 (R/d_0)^{-n}$$
- For hexagonal cellular systems, most of the CCI results from the first tier
- Let D_i be the distance from the mobile to the i-th BS. Assuming all BSs transmit the same power P_0, we have

  $$Ii= P_0 (D_i/d_0)^{-n}$$
- if we assume that D_i=D and Ni=6, then

  $$S/I = (D/R)^n / N_i = Q^n/ N_i= Q^n/6$$

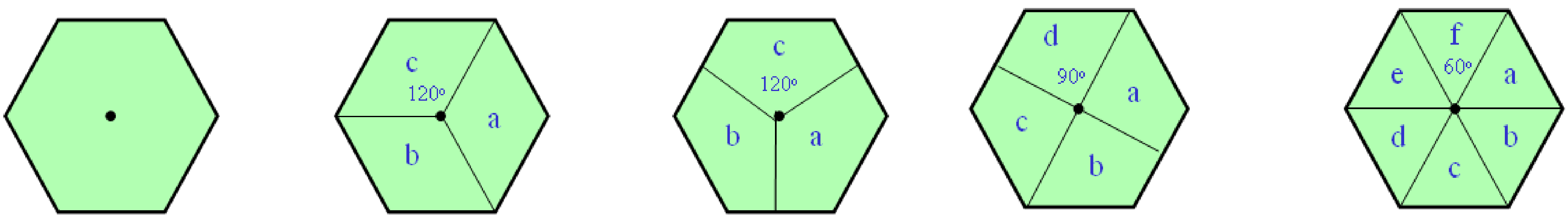


Adjacent Channel Interference

- ACI is caused by signals from neighbouring frequencies
- Particularly severe when the mobile is far away from its BS and very near to an adjacent channel transmitter (near-far effect)
- Also happens when a mobile close to BS uses a channel which is adjacent to a very weak mobile transmitting to the same BS
- ACI can be reduced by careful frequency assignment
- As a cell only has a fraction of channels, these channels do not have to be adjacent in frequency
- ACI is reduced if we maximize the separation between adjacent channels in a cell
- Power control of all mobiles

Improving Capacity in Cellular Systems

- Aim: To provide more channels per unit coverage area
- Techniques: Three techniques are used to improve capacity
- SECTORING:
  - Use directional antennas to further control the interference and frequency reuse of channels.
  - Examples: Omni, 120^{O}, 60^{O} and 90^{O}



(a). Omni (b). 120º sector (c). 120º sector (alternate) (d). 90º sector (e). 60º sector

Sectoring

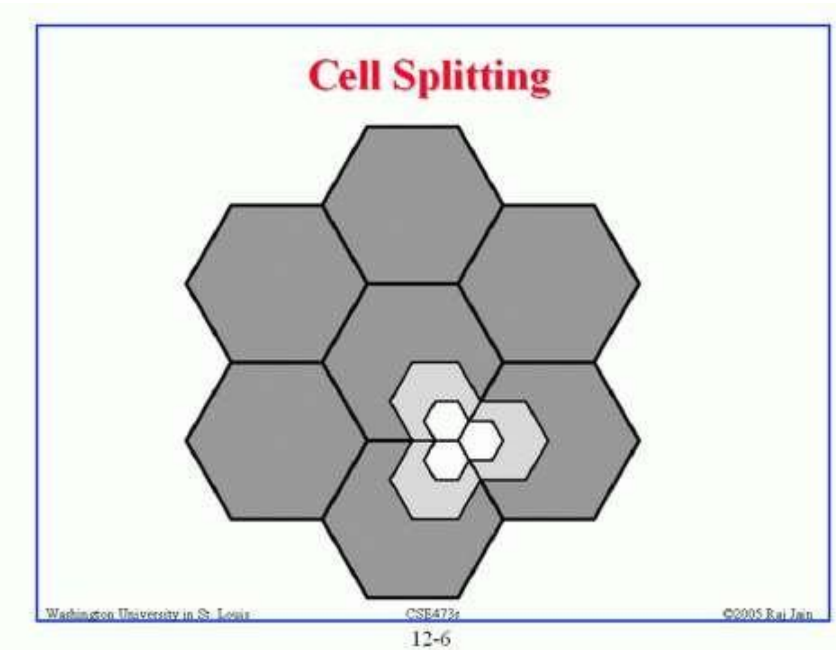
- The sectoring is done by replacing a single omni-directional antenna with 3 directional antennas (120^{O} sectoring) or with 6 directional antennas (60^{O} sectoring)
- In this scheme, each cell is divided into 3 or 6 sectors. Each sector uses a directional antenna at the BS and is assigned a set of channels.
- The number of channels in each sector is the number of channels in a cell divided by the number of sectors. The amount of co-channel interferer is also reduced by the number of sectors.

Drawbacks:

- Increase the number of antennas at each BS
- The number of handoffs increases when the mobile moves from one sector to another.

Cell Splitting

- Cell splitting is the process of splitting a mobile cell into several smaller cells. This is usually done to make more voice channels available to accommodate traffic growth in the area covered by the original cell
- If the radius of a cell is reduced from R to R/2, the area of the cell is reduced from Area to Area/4. The number of available channels is also increased.
- Cell splitting is usually done on demand; when in a certain cell there is too much traffic which causes too much blocking of calls. The cell is split into smaller microcells.


Cell Splitting
Washington University in St. Louis
CSE473s
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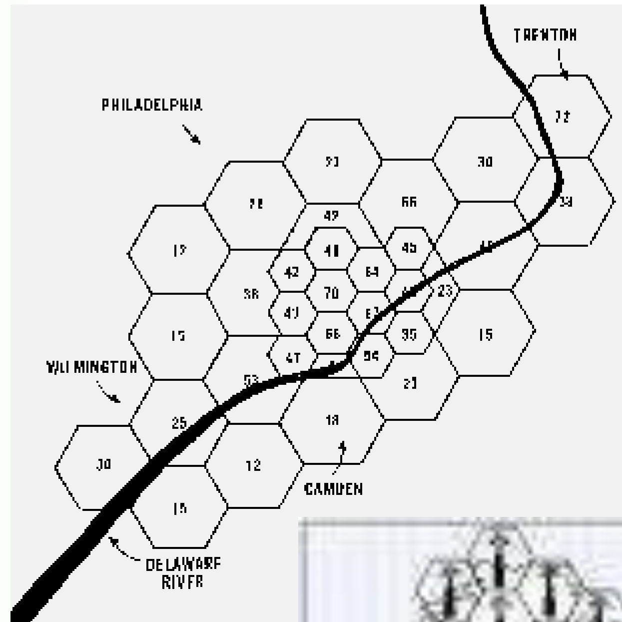
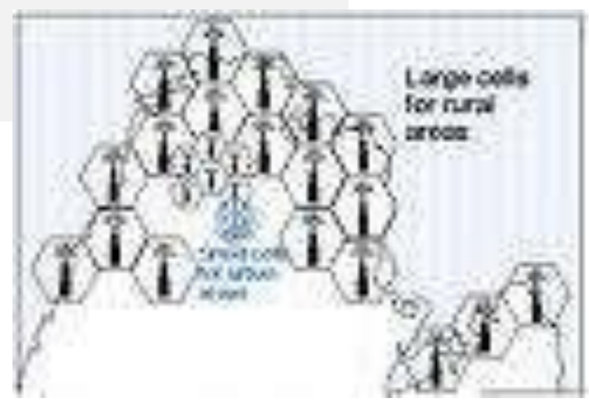

TRENTON
PHILADELPHIA
WILMINGTON
CAMDEN
DELAWARE
RIVER

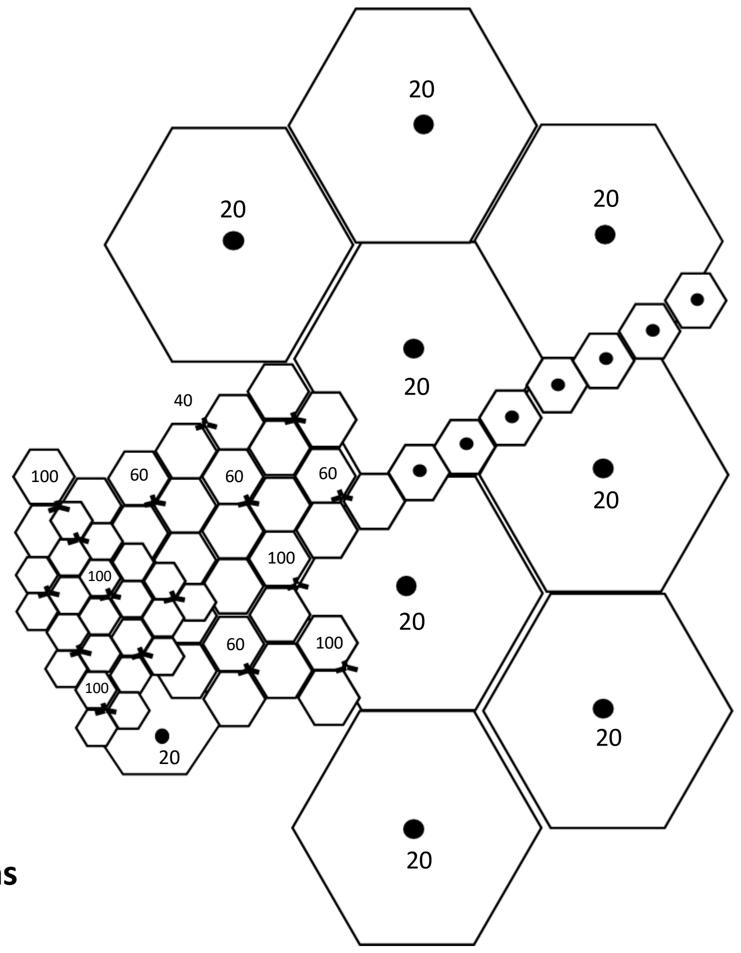

Large cells
for rural
areas

Cell Splitting Drawbacks

- In practice not all cells are split simultaneously, therefore we may have cells of different sizes.
- Also the handoff between the cells and microcells has to be taken care off so that high speed and low speed mobiles are equally served.
- Decreasing cell size results in more handoffs per call and higher processing load per subscriber. Thus, the handoff rate will increase exponentially

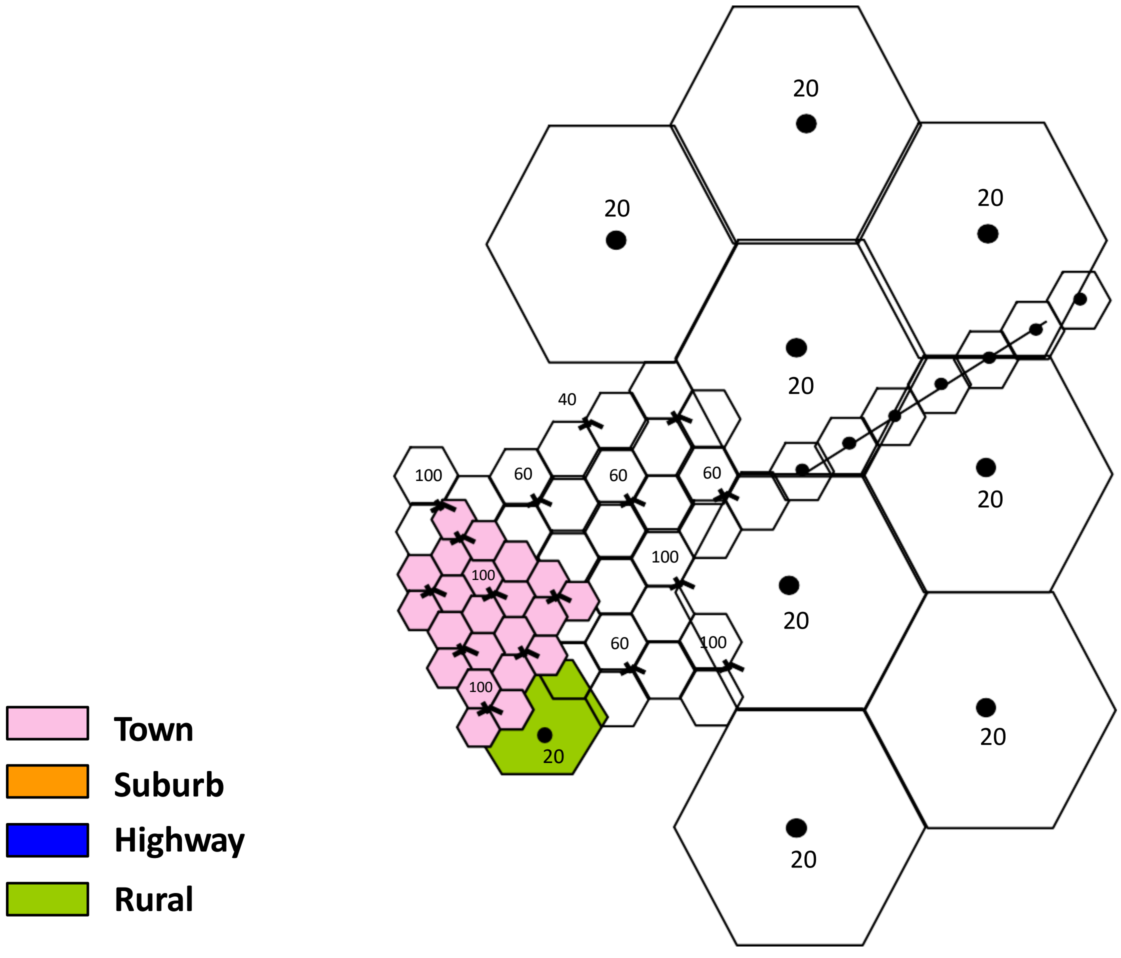
Exercise

Considering this radio coverage, could you identify the topology of the different areas?



Figures indicates Base Stations Erlang capacity

Solution: Topology of Different Areas



Channel Assignment Strategies

Channel Allocation Techniques

- To satisfy the user, a channel needs to be available on request.
- Reasonable probability of call blockage (GOS) is 2%.
- GOS fluctuate with location and time.
- The goal is to keep a uniform GOS across the system.
- Reduction of variations in GOS allow more users – an increase in capacity.
- Three types of algorithms for channel allocation:
  - **Fixed channel allocation (FCA)**
  - **Channel Borrowing**
  - **Dynamic channel allocation (DCA)**

Fixed Channel Allocation Techniques

- Available spectrum is W Hz and each channel is B Hz. Total number of channels:

$$Nc = W/B$$

- For a cluster size N, the number of channels per cell:

$$Cc = Nc/N$$

- To minimize interference, assign adjacent channels to different cells.

Features of Fixed Channel Allocation Techniques

- FCA is the optimum allocation strategy for uniform traffic across the cells.

- A non uniform FCA strategy, when it is possible to evaluate GOS in real time and adjust the FCA accordingly. This requires a more complex algorithm.

Channel Borrowing

- Borrow frequencies from low traffic cells to high traffic cells.
- Temporary channel borrowing: channel is returned after call is completed.
- If all the channels in a cell are occupied, channels are borrowed from neighboring cells.
- The MSC supervises such borrowing procedures and ensures disruption free service.

Dynamic Channel Allocation

- All channels are placed in a pool, and are assigned to new calls according to the reuse pattern. Signal is returned to the pool, when call is completed.

- Issues related to channel allocation are still under research.

Comparison of Channel Allocation Techniques

- **Fixed Channel Allocation**
  - Advantages:
    - Less load on MSC
    - Simple
  - Disadvantages:
    - Blocking may happen
- **Dynamic Channel Allocation**
  - Advantages:
    - Voice channels are not allocated permanently. That is shared on need-basis
  - Disadvantages:
    - Requires MSC for processing---burden on MSC
    - May be very complicated

Hand off

- **HANDOFF:** The process of transferring a call across the cell boundaries.
  - Handoffs are prioritized over new calls.
  - Handoffs need to be performed infrequently.

UNIT II
Mobile Radio Propagation
Large-scale Path loss

Introduction

- The mobile radio channel places fundamental limitations on the performance of a wireless communication system
- The wireless transmission path may be
  - Line of Sight (LOS)
  - Non line of Sight (NLOS)
- Radio channels are random and time varying
- Modeling radio channels have been one of the difficult parts of mobile radio design and is done in statistical manner
- When electrons move, they create EM waves that can propagate through space.
- By using antennas we can transmit and receive these EM wave
- Microwave ,Infrared visible light and radio waves can be used.

Properties of Radio Waves

- Are easy to generate
- Can travel long distances
- Can penetrate buildings
- May be used for both indoor and outdoor coverage
- Are omni-directional-can travel in all directions
- Can be narrowly focused at high frequencies(>100MHz) using parabolic antenna

Properties of Radio Waves

- Frequency dependence

  - Behave more like light at high frequencies
    - Difficulty in passing obstacle
    - Follow direct paths
    - Absorbed by rain

  - Behave more like radio at lower frequencies
    - Can pass obstacles
    - Power falls off sharply with distance from source

- Subject to interference from other radio waves

Propagation Models

- The statistical modeling is usually done based on data measurements made specifically for
  - the intended communication system
  - the intended spectrum

- They are tools used for:
  - Predicting the average signal strength at a given distance from the transmitter

  - Estimating the variability of the signal strength in close spatial proximity to a particular locations

Propagation Models

- Large Scale Propagation Model:
  - Predict the mean signal strength for an arbitrary transmitter-receiver(T-R) separation
  - Estimate radio coverage of a transmitter
  - Characterize signal strength over large T-R separation distances(several 100's to 1000's meters)

Propagation Models

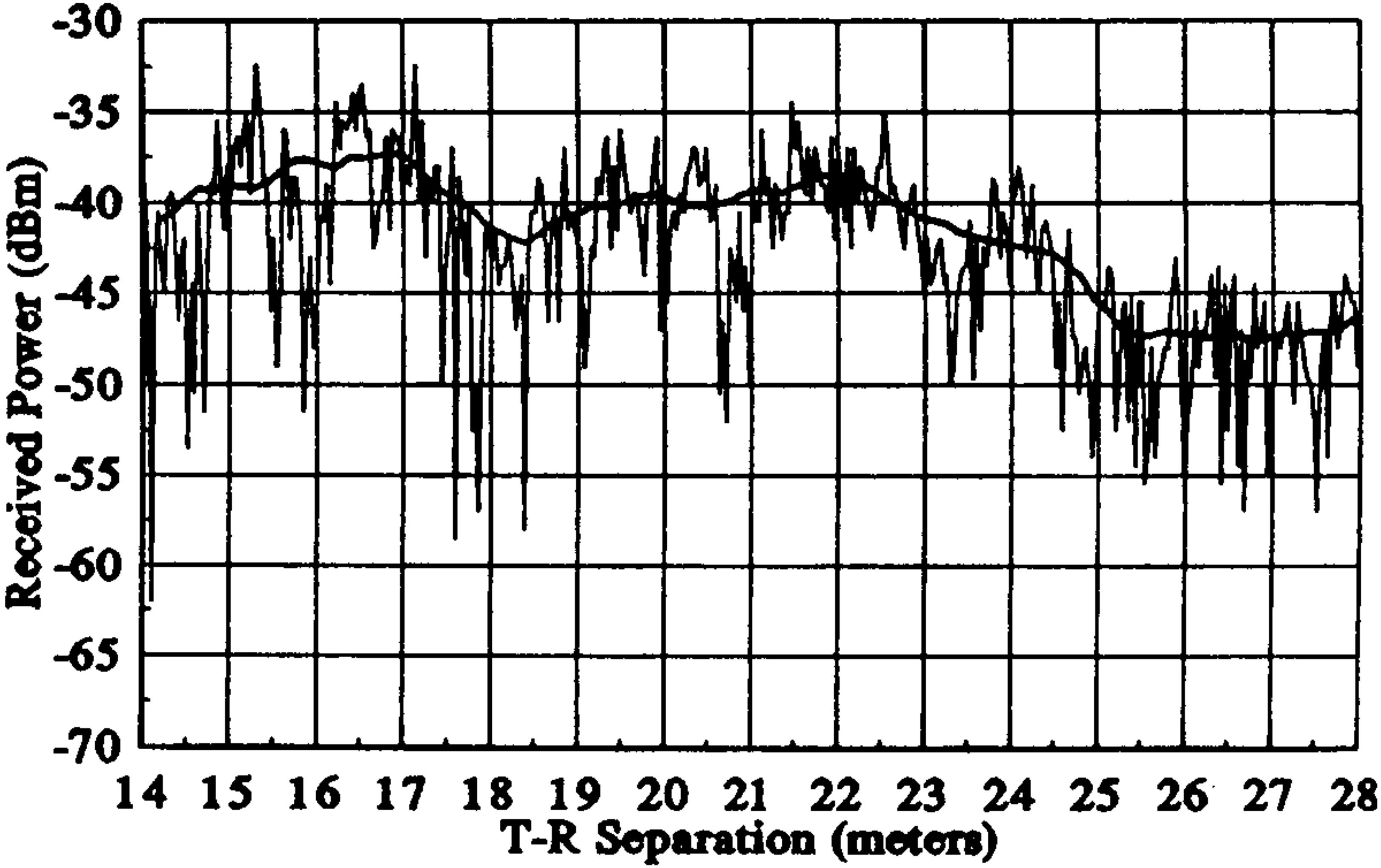
- Small Scale or Fading Models:

  - Characterize rapid fluctuations of received signal strength over

    - Very short travel distances(a few wavelengths)

    - Short time durations(on the order of seconds)

Small-scale and large-scale fading



Free Space Propagation Model

- For clear LOS between T-R
  - Ex: satellite & microwave communications

- Assumes that received power decays as a function of T-R distance separation raised to some power.

- Given by Friis free space eqn:

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

'L' is the system loss factor

L >1 indicates loss due to transmission line attenuation,filter losses & antenna losses

L = 1 indicates no loss in the system hardware

- Gain of antenna is related to its effective aperture A_e by

$$G=4\pi A_e/\lambda^2$$

Free Space Propagation Model

- Effective Aperture A_e is related to physical size of antenna.

$$\lambda = c/f.$$

- c is speed of light,
- P_t and P_r must be in same units
- G_t ad G_r are dimensionless

- An isotropic radiator, an ideal radiator which radiates power with unit gain uniformly in all directions, and is often used as reference

- Effective Isotropic Radiated Power (EIRP) is defined as

$$EIRP = P_t G_t$$

- Represents the max radiated power available from a transmitter in direction of maximum antenna gain, as compared to an isotropic radiator

Free Space Propagation Model

- In practice Effective Radiated Power (ERP) is used instead of (EIRP)

- Effective Radiated Power (ERP) is radiated power compared to half wave dipole antennas

- Since dipole antenna has gain of 1.64(2.15 dB)

$$ERP=EIRP-2.15(dB)$$

- the ERP will be 2.15dB smaller than the EIRP for same Transmission medium

Free Space Propagation Model

- Path Loss (PL) represents signal attenuation and is defined as difference between the effective transmitted power and received power

Path loss PL(dB) = 10 log [Pt/Pr]

= -10 log {GtGr λ^2/(4π)^2d^2}

- Without antenna gains (with unit antenna gains)

PL = - 10 log { λ^2/(4π)^2d^2}

- Friis free space model is valid predictor for P_r for values of d which are in the far-field of transmitting antenna

Free Space Propagation Model

- The far field or Fraunhofer region that is beyond far field distance d_f given as : $d_f = 2D^2/\lambda$
- D is the largest physical linear dimension of the transmitter antenna
- Additionally, $d_f >> D$ and $d_f >> \lambda$
- The Friis free space equation does not hold for d=0
- Large Scale Propagation models use a close-in distance, d_o, as received power reference point, chosen such that $d_o >= d_f$
- Received power in free space at a distance greater then do

$$Pr(d) = Pr(do)(do/d)^2 \qquad d > d_o > d_f$$

Pr with reference to 1 mW is represented as

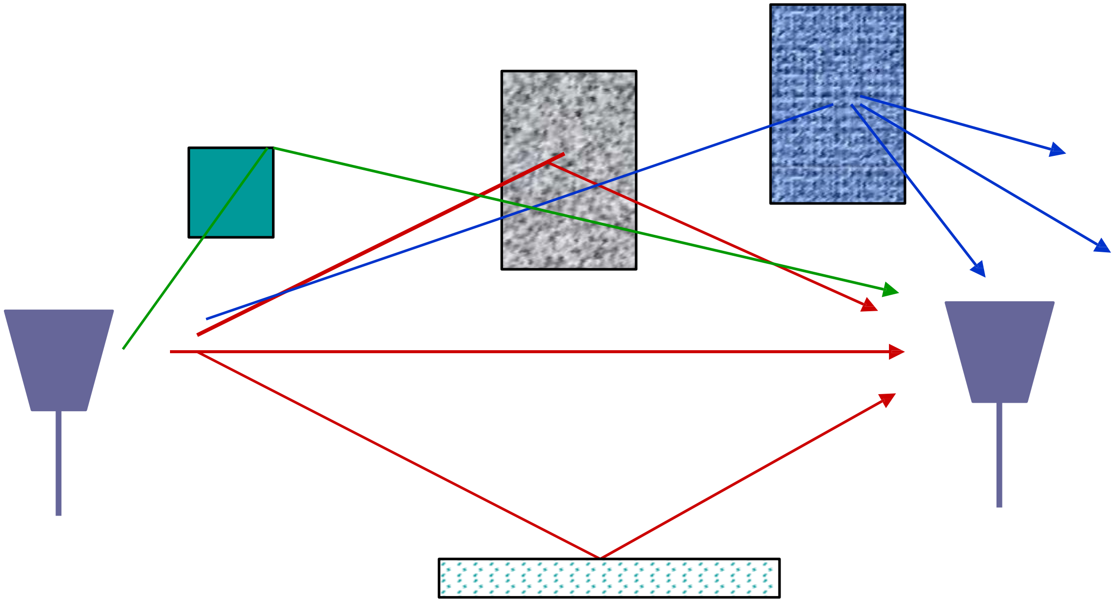
$$Pr(d) = 10\log(Pr(do)/0.001W) + 20\log(do/d)$$

Electrostatic,inductive and radiated fields are launched, due to flow of current from anntena.

Regions far away from transmitter electrostatic and inductive fields become negligible and only radiated field components are considered.

Propagation Mechanisms

- Three basic propagation mechanism which impact propagation in mobile radio communication system are:
  - Reflection
  - Diffraction
  - Scattering



Propagation Mechanisms

- Reflection occurs when a propagating electromagnetic wave impinges on an object which has very large dimensions as compared to wavelength e.g. surface of earth , buildings, walls

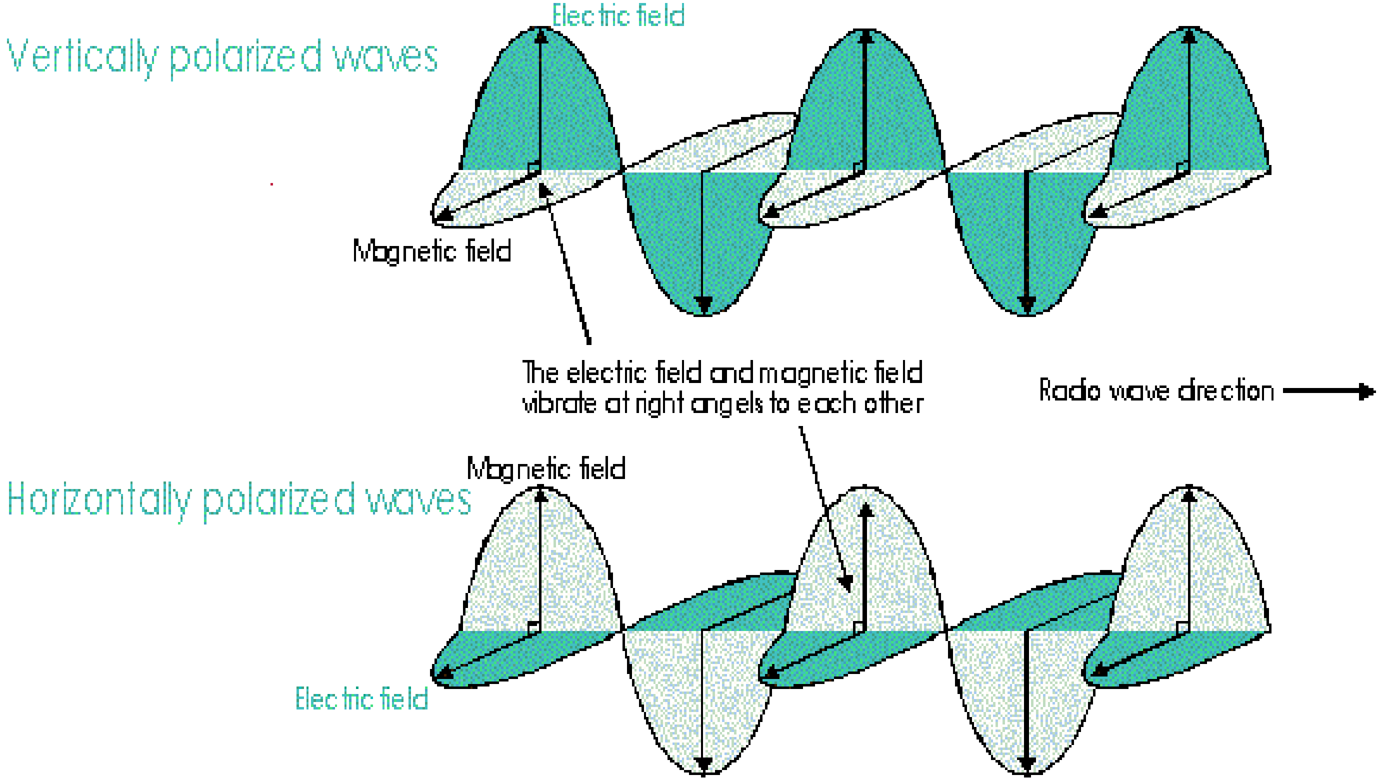
- Diffraction occurs when the radio path between the transmitter and receiver is obstructed by a surface that has sharp irregularities(edges)
  - Explains how radio signals can travel urban and rural environments without a line of sight path

- Scattering occurs when medium has objects that are smaller or comparable to the wavelength (small objects, irregularities on channel, foliage, street signs etc)

Reflection

- Occurs when a radio wave propagating in one medium impinges upon another medium having different electrical properties
- If radio wave is incident on a perfect dielectric
  - Part of energy is reflected back
  - Part of energy is transmitted
- In addition to the change of direction, the interaction between the wave and boundary causes the energy to be split between reflected and transmitted waves
- The amplitudes of the reflected and transmitted waves are given relative to the incident wave amplitude by Fresnel reflection coefficients

Vertical and Horizontal polarization



Reflection- Dielectrics

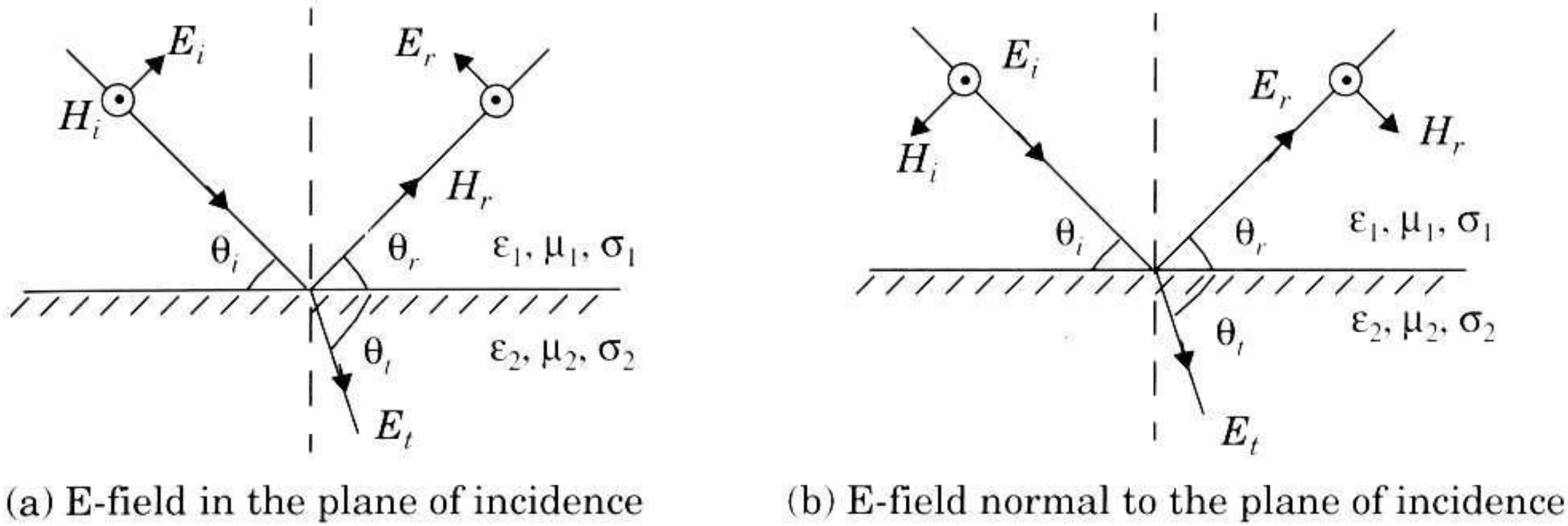


Figure 4.4 Geometry for calculating the reflection coefficients between two dielectrics.

Reflection

- $\Gamma(\parallel) = \frac{E_r}{E_i} = \frac{\eta_2 \sin\theta_t - \eta_1 \sin\theta_i}{\eta_1 \sin\theta_t + \eta_1 \sin\theta_i}$ (Paralell E-field polarization)

- $\Gamma(\perp) = \frac{E_r}{E_i} = \frac{\eta_2 \sin\theta_i - \eta_1 \sin\theta_t}{\eta_1 \sin\theta_i + \eta_1 \sin\theta_t}$ (Perpendicular E-field polarization)

- These expressions express ratio of reflected electric fields to the incident electric field and depend on impedance of media and on angles

- η is the intrinsic impedance given by $\sqrt{(\mu/\varepsilon)}$

- μ=permeability,ε=permittivity

Reflection-Perfect Conductor

- If incident on a perfect conductor the entire EM energy is reflected back
- Here we have $\theta_r = \theta_i$
- $E_i = E_r$ (E-field in plane of incidence)
- $E_i = -E_r$ (E field normal to plane of incidence)
- Γ(parallel)= 1
- Γ(perpendicular)= -1

Reflection - Brewster Angle

- It is the angle at which no reflection occur in the medium of origin. It occurs when the incident angle θ_B is such that the reflection coefficient Γ(parallel) is equal to zero.
- It is given in terms of θ_B as given below

$$Sin(\theta_B) = \sqrt{\frac{\varepsilon_1}{\varepsilon_1 + \varepsilon_2}}$$

- When first medium is a free space and second medium has an relative permittivity of ε_r *then*

$$Sin(\theta_B) = \frac{\sqrt{\varepsilon_{r-1}}}{\sqrt{e_r^2 - 1}}$$

- Brewster angle only occur for parallel polarization

Ground Reflection(Two Ray) Model

- In mobile radio channel, single direct path between base station and mobile and is seldom only physical means for propagation
- Free space model as a stand alone is inaccurate
- Two ray ground reflection model is useful
  - Based on geometric optics
  - Considers both direct and ground reflected path
- Reasonably accurate for predicting large scale signal strength over several kms that use tall tower height
- Assumption: The height of Transmitter >50 meters

Ground Reflection(Two Ray) Model

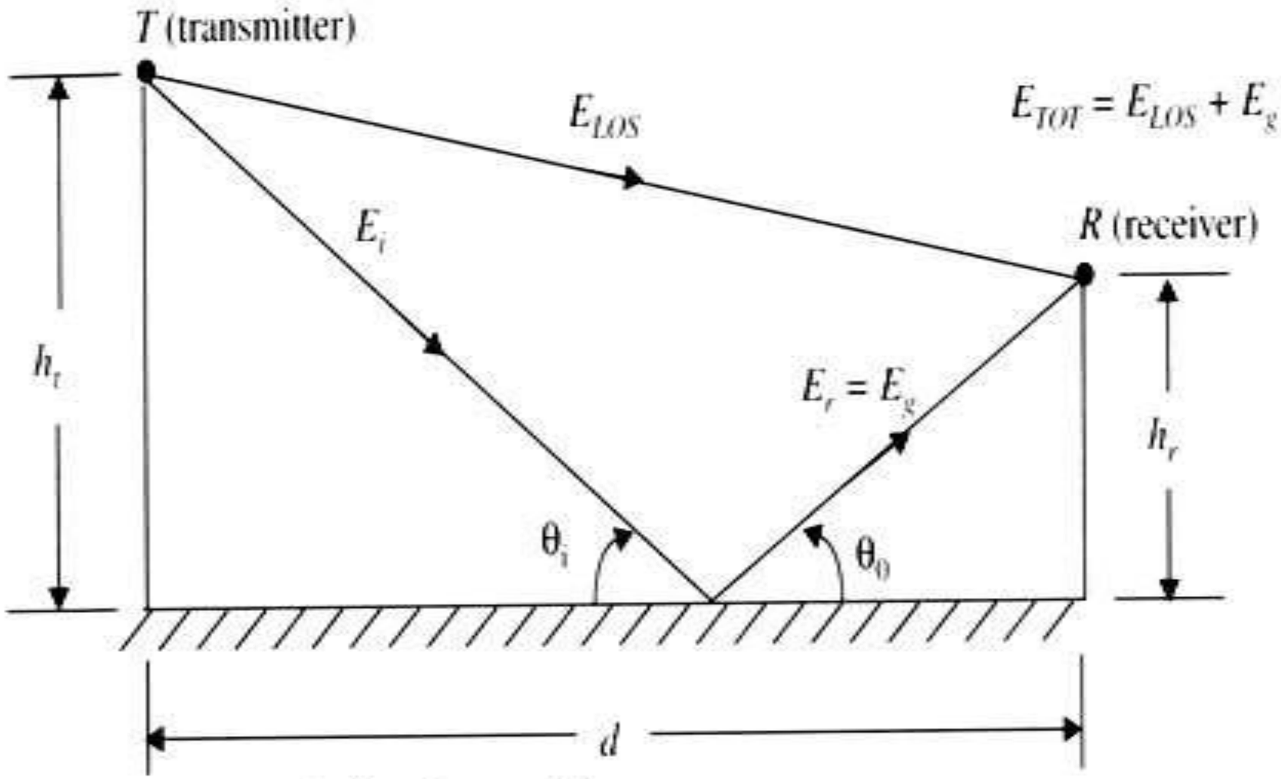


Figure 4.7 Two-ray ground reflection model.

Ground Reflection(Two Ray) Model

$$\vec{E}_{TOT} = \vec{E}_{LOS} + \vec{E}_g$$

let E_o be $|\ \vec{E}\ |$ at reference point d_o then

$$\vec{E}(d,t) = \left(\frac{E_0 d_0}{d}\right)\cos\left(\omega_c\left(t - \frac{d}{c}\right)\right) \quad d > d_0$$

$$E_{LOS}(d',t) = \frac{E_0 d_0}{d'}\cos\left(\omega_c\left(t - \frac{d'}{c}\right)\right) \qquad E_g(d'',t) = \Gamma\frac{E_0 d_0}{d''}\cos\left(\omega_c\left(t - \frac{d''}{c}\right)\right)$$

$$\vec{E}_{TOT}(d,t) = \left(\frac{E_0 d_0}{d'}\right)\cos\left(\omega_c\left(t - \frac{d'}{c}\right)\right) + \Gamma\left(\frac{E_0 d_0}{d''}\right)\cos\left(\omega_c\left(t - \frac{d''}{c}\right)\right)$$

$$E_{TOT}(d,t) = \frac{E_0 d_0}{d'}\cos\left(\omega_c\left(t - \frac{d'}{c}\right)\right) + (-1)\frac{E_0 d_0}{d''}\cos\left(\omega_c\left(t - \frac{d''}{c}\right)\right)$$

Ground Reflection(Two Ray) Model

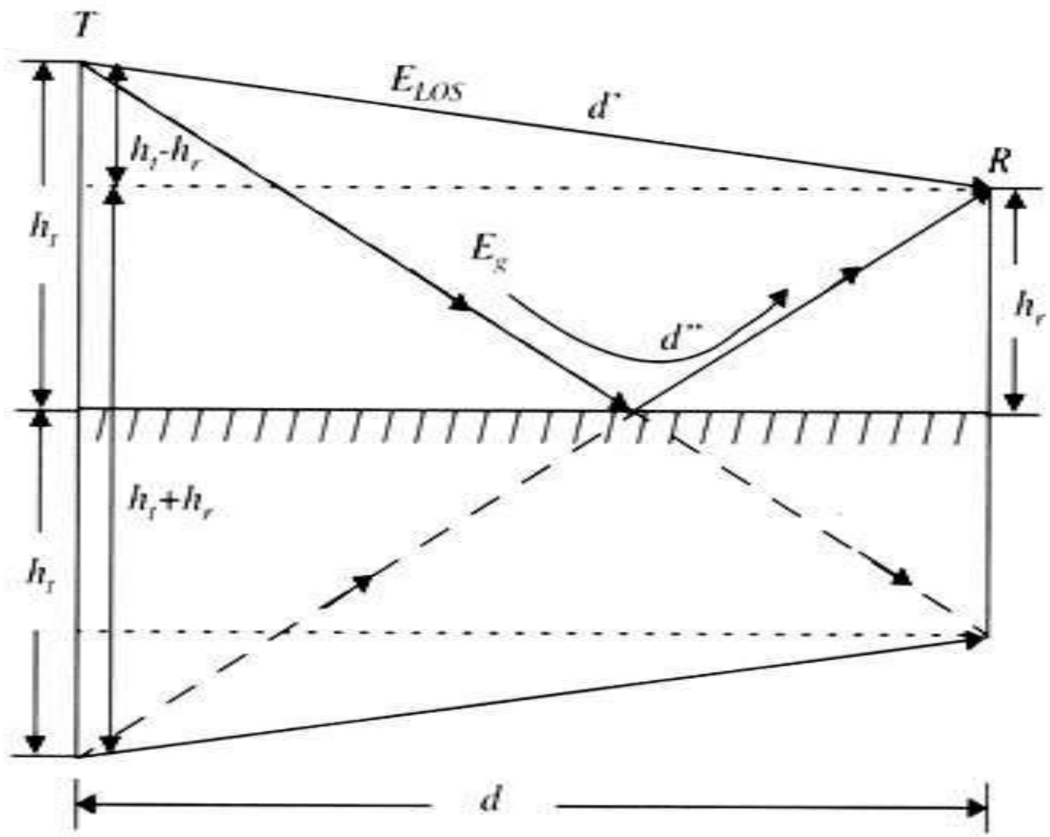


Figure 4.8 The method of images is used to find the path difference between the line-of-sight and the ground reflected paths.

Path Difference

$$\Delta = d'' - d' = \sqrt{(h_t + h_r)^2 + d^2} - \sqrt{(h_t - h_r)^2 + d^2}$$

$$= d\sqrt{\left(\left(\frac{h_t + h_r}{d}\right)^2 + 1\right)} - d\sqrt{\left(\left(\frac{h_t - h_r}{d}\right)^2 + 1\right)}$$

$$\approx d\left(1 + \frac{1}{2}\left(\frac{h_t + h_r}{d}\right)^2\right) - d\left(1 + \frac{1}{2}\left(\frac{h_t - h_r}{d}\right)^2\right)$$

$$\approx \frac{1}{2d}\left((h_t + h_r)^2 - (h_t - h_r)^2\right)$$

$$\approx \frac{1}{2d}\left(\left(h_t{}^2 + 2h_t h_r + h_r{}^2\right) - \left(h_t{}^2 - 2h_t h_r + h_r{}^2\right)\right)$$

$$\approx \frac{2h_t h_r}{d}$$

Phase difference

$$\theta_\Delta \text{ radians } = \frac{2\pi\Delta}{\lambda} = \frac{2\pi\Delta}{\left(c/f_c\right)} = \frac{\omega_c\Delta}{c}$$

$$\left|E_{TOT}(t)\right| = 2\frac{E_0 d_0}{d}\sin\left(\frac{\theta_\Delta}{2}\right)$$

$$\frac{\theta_\Delta}{2} \approx \frac{2\pi h_r h_t}{\lambda d} < 0.3\,\text{rad}$$

$$E_{TOT}(t) \approx 2\frac{E_0 d_0}{d}\frac{2\pi h_r h_t}{\lambda d} \approx \frac{k}{d^2}\ \text{V/m}$$

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

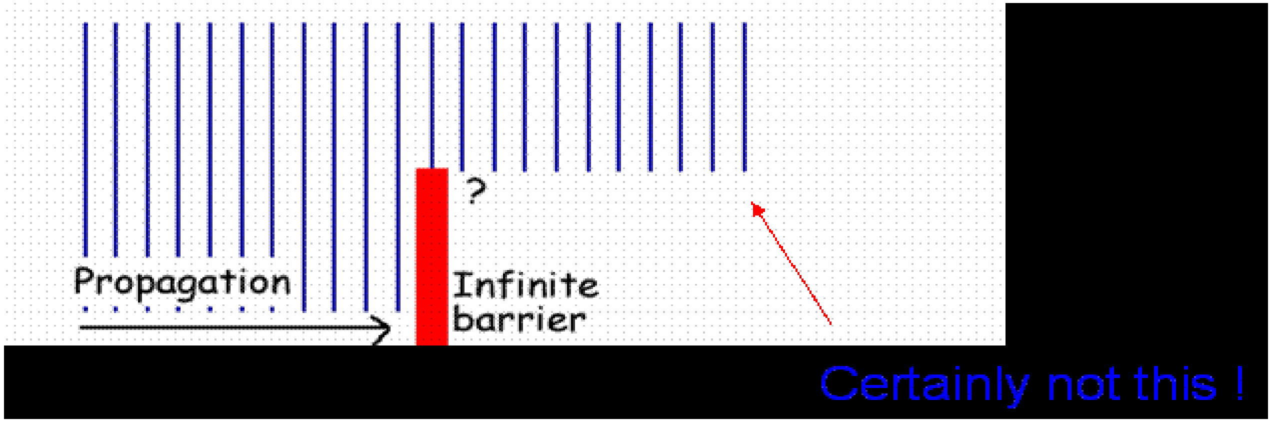
Diffraction

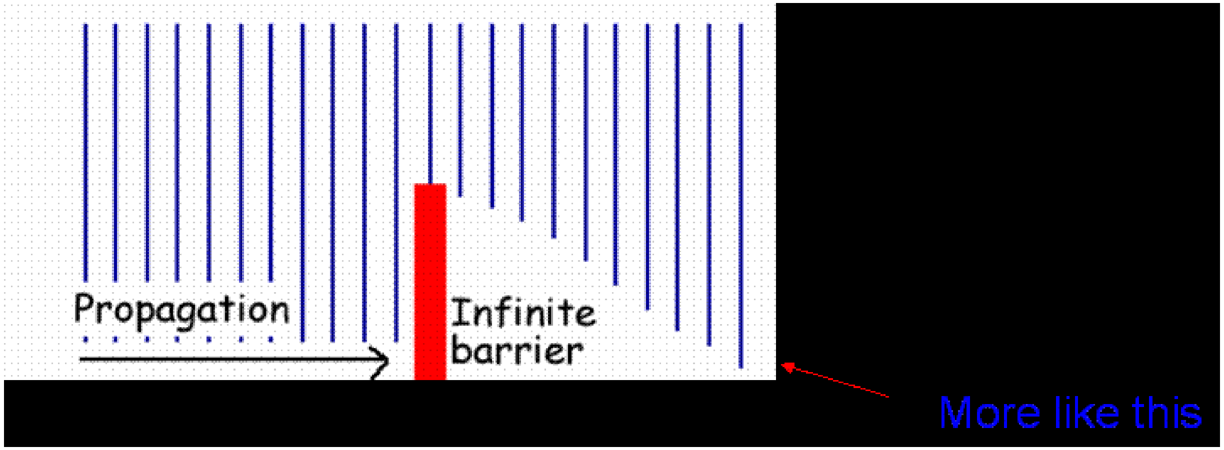
- Diffraction is the bending of wave fronts around obstacles.

- Diffraction allows radio signals to propagate behind obstructions and is thus one of the factors why we receive signals at locations where there is no line-of-sight from base stations

- Although the received field strength decreases rapidly as a receiver moves deeper into an obstructed (shadowed) region, the diffraction field still exists and often has sufficient signal strength to produce a useful signal.

Diffraction





Knife-edge Diffraction Model

- Estimating the signal attenuation caused by diffraction of radio waves over hills and buildings is essential in predicting the field strength in a given service area.

- As a starting point, the limiting case of propagation over a knife edge gives good in sight into the order of magnitude diffraction loss.

- When shadowing is caused by a single object such as a building, the attenuation caused by diffraction can be estimated by treating the obstruction as a diffracting knife edge

Knife-edge Diffraction Model

Consider a receiver at point R located in the shadowed region. The field strength at point R is a vector sum of the fields due to all of the secondary Huygens sources in the plane above the knife edge.

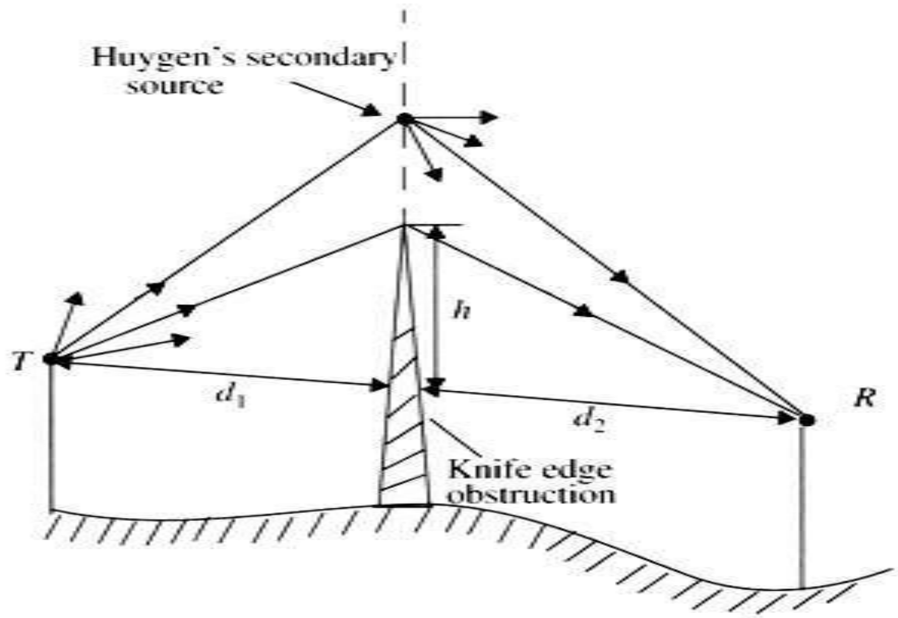


Figure 4.13 Illustration of knife-edge diffraction geometry. The receiver *R* is located in the shadow region.

Knife-edge Diffraction Model

- The difference between the direct path and diffracted path, call *excess path length*

$$\Delta \approx \frac{h^2}{2}\frac{(d_1+d_2)}{d_1 d_2}$$

- The corresponding phase difference

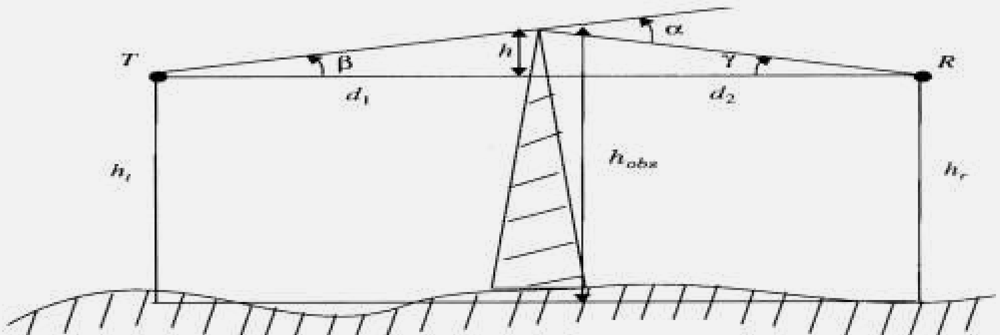
$$\phi = \frac{2\pi\Delta}{\lambda} \approx \frac{2\pi}{\lambda}\frac{h^2}{2}\frac{(d_1+d_2)}{d_1 d_2}$$

- *Fresnel-Kirchoff* diffraction parameter is used to normalize the phased term and given as

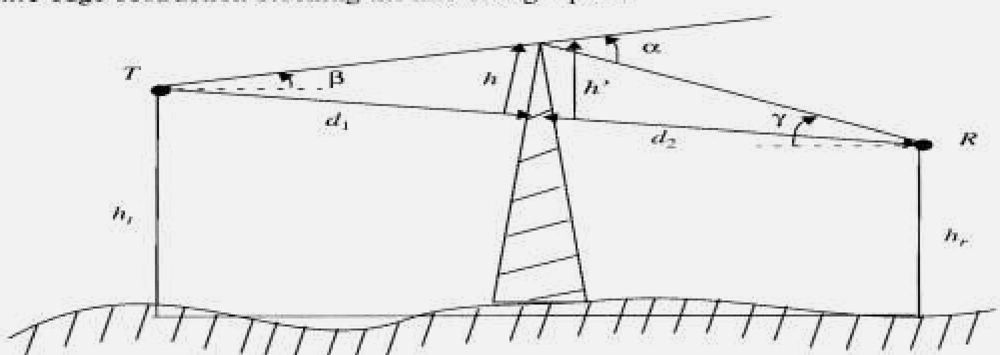
$$v = h\sqrt{\frac{2(d_1+d_2)}{\lambda d_1 d_2}} = \alpha\sqrt{\frac{2d_1 d_2}{\lambda(d_1+d_2)}}$$ Which gives $$\phi = \frac{\pi}{2}v^2$$

- where $\alpha = h\left(\frac{d_1+d_2}{d_1 d_2}\right)$

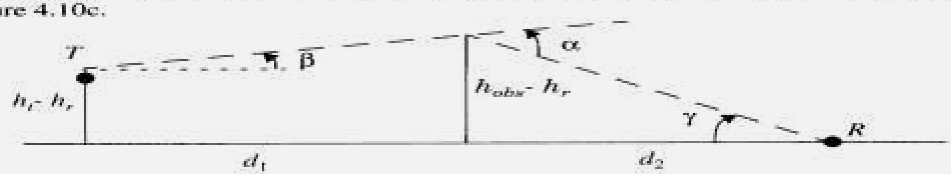
Knife-edge Diffraction Model



(a) Knife-edge diffraction geometry. The point T denotes the transmitter and R denotes the receiver, with an infinite knife-edge obstruction blocking the line-of-sight path.



(b) Knife-edge diffraction geometry when the transmitter and receiver are not at the same height. Note that if α and β are small and $h << d_1$ and d_2, then h and h' are virtually identical and the geometry may be redrawn as shown in Figure 4.10c.



(c) Equivalent knife-edge geometry where the smallest height (in this case h_r) is subtracted from all other heights.

Figure 4.10 Diagrams of knife-edge geometry.

Fresnel zones

- Fresnel zones represent successive regions where secondary waves have a path length from the TX to the RX which are nλ/2 greater in path length than of the LOS path. The plane below illustrates successive Fresnel zones.

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

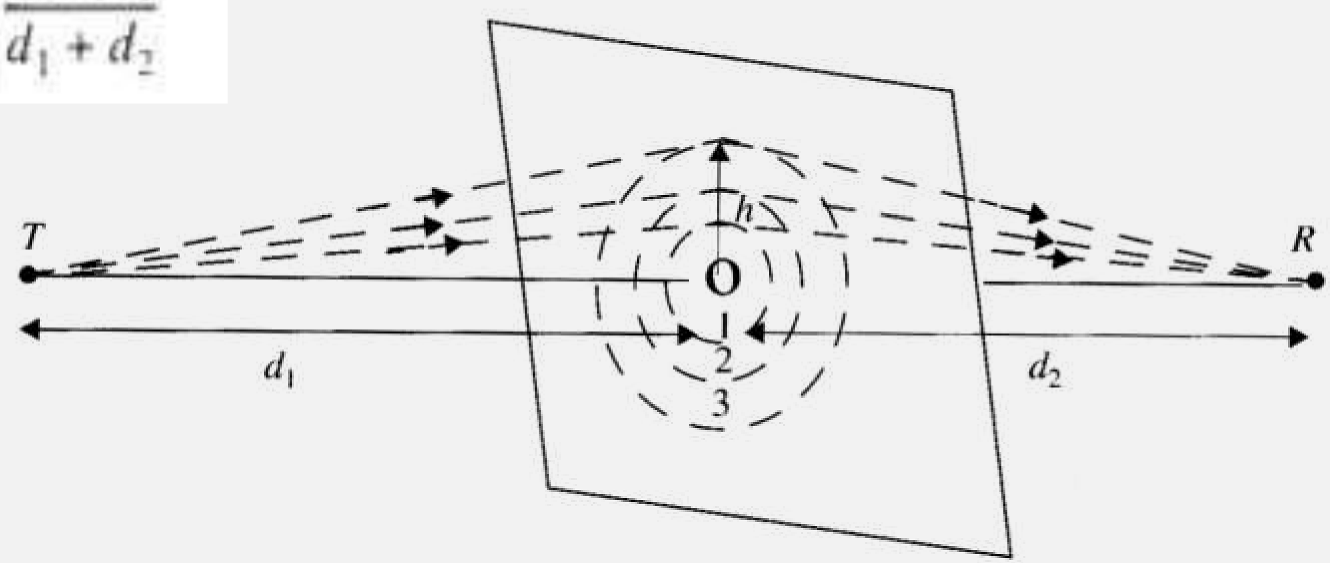
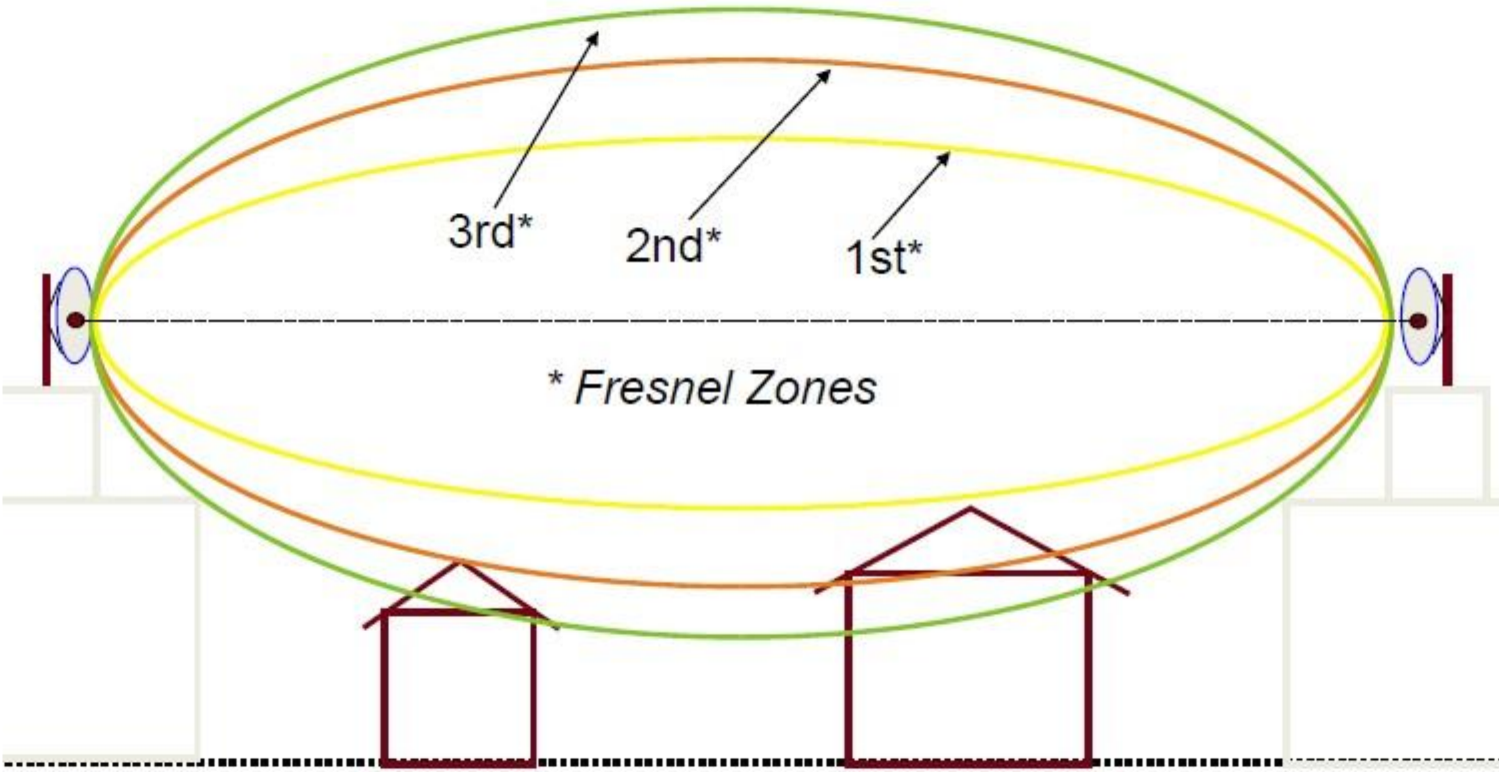


Figure 4.11 Concentric circles which define the boundaries of successive Fresnel zones.

Fresnel zones



Diffraction gain

- The diffraction gain due to the presence of a knife edge, as compared to the free space E-field

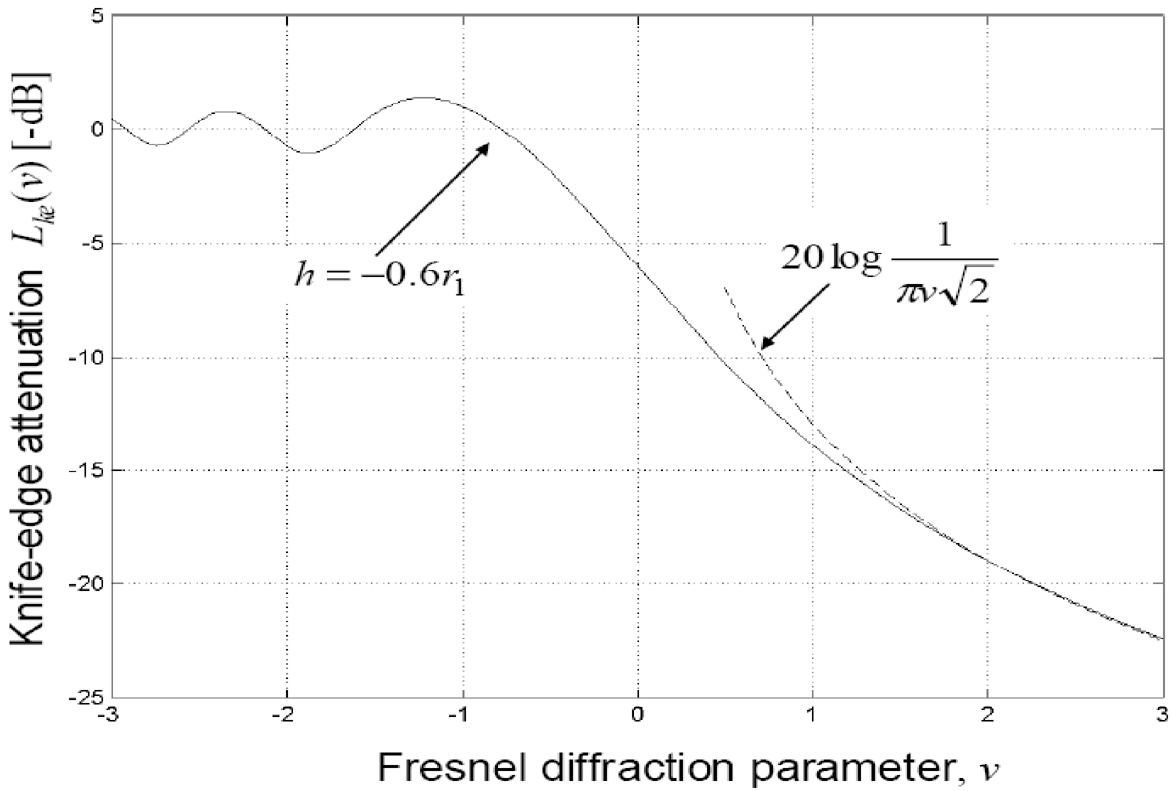
$$G_d(\mathrm{dB}) = 20\log|F(v)|$$

- The electric field strength, *Ed, of a knife edge diffracted wave is given by*

$$\frac{E_d}{E_o} = F(v) = \frac{(1+j)}{2}\int_v^{\infty}\exp((-j\pi t^2)/2)dt$$

- *Eo : is the free space field strength in the absence of both the ground and the knife edge.*
- *F(v): is the complex fresnel integral.*
- *v: is the Fresnel-Kirchoff diffraction parameter*

Graphical Calculation of diffraction attenuation



Multiple Knife Edge Diffraction

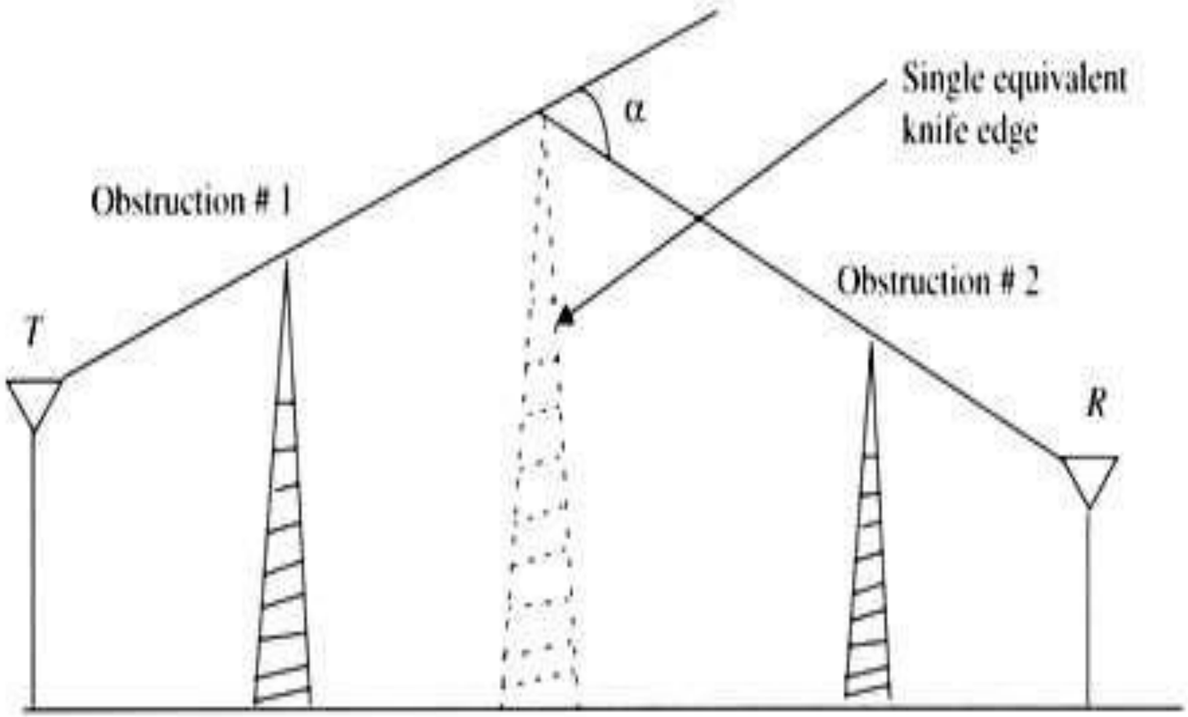


Figure 4.15 Bullington's construction of an equivalent knife edge [from [Bul47] © IEEE].

Scattering

- Scattering occurs when the medium through which the wave travels consists of objects with dimensions that are small compared to the wavelength, and where the number of obstacles per unit volume is large.
- Scattered waves are produced by
  - rough surfaces,
  - small objects,
  - or by other irregularities in the channel.
- Scattering is caused by trees, lamp posts, towers, etc.

Scattering

- Received signal strength is often stronger than that predicted by reflection/diffraction models alone

- The EM wave incident upon a rough or complex surface is **scattered** in **many** directions and provides more energy at a receiver
  - energy that would have been absorbed is instead reflected to the Rx.

- flat surface → EM reflection (one direction)
- rough surface → EM scattering (many directions)

Scattering

- Rayleigh criterion: used for testing surface roughness
- A surface is considered smooth if its min to max protuberance (bumps) h is less than critical height hc

$$h_c = \lambda / 8 \sin\Theta_i$$

- Scattering path loss factor ρ_s is given by

$$\rho_s = \exp[-8[(\pi * \sigma_h * \sin\Theta_i) / \lambda]^2]$$

Where h is surface height and σ_h is standard deviation of surface height about mean surface height.

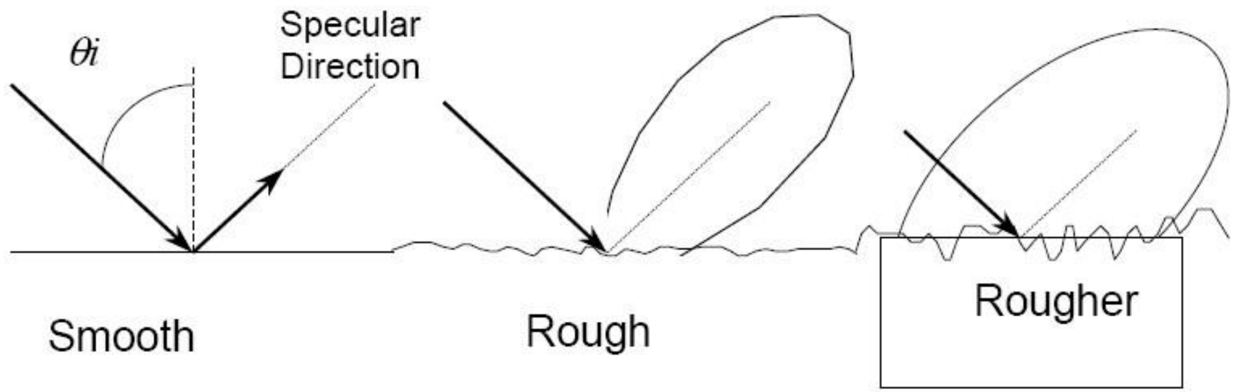
- For rough surface, the flat surface reflection coefficient is multiplied by scattering loss factor ρ_s to account for diminished electric field

- Reflected E-fields for h> h_c for rough surface can be calculated as

$$\Gamma_{rough} = \rho_s \Gamma$$

Scattering

Rough Surface Scattering



Roughness depends on :
- Surface height range
- Angle of incidence
- Wavelength

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Outdoor propagation Environment

- Based on the coverage area, the Outdoor propagation environment may be divided into three categories

1. Propagation in Macro cells
2. Propagation in Micro cells
3. Propagation in street Micro cells

Outdoor propagation Environment

Macrocells versus Microcells

	Macrocell	Microcell
Cell Radius	1 to 20 km	0.1 to 1 km
Tx Power	1 to 10 W	0.1 to 1 W
Fading	Rayleigh	Nakgami-Rice
RMS Delay Spread	0.1 to 10 μs	10 to 100ns
Max. Bit Rate	0.3 Mbps	1 Mbps

Outdoor propagation Models

- Outdoor radio transmission takes place over an irregular terrain.
- The terrain profile must be taken into consideration for estimating the path loss

  e.g. trees buildings and hills must be taken into consideration

- Some common models used are

- Longley Rice Model
- Okumura Model
- Hatta model

Longley Rice Model

- Longley Rice Model is applicable to point to point communication.
- It covers 40MHz to 300 GHz
- It can be used in wide range of terrain
- Path geometry of terrain and the refractivity of troposphere is used for transmission path loss calculations
- Geometrical optics is also used along with the two ray model for the calculation of signal strength.
- Two modes
  - Point to point mode prediction
  - Area mode prediction

Longley Rice Model

- Longley Rice Model is normally available as a computer program which takes inputs as
  - Transmission frequency
  - Path length
  - Polarization
  - Antenna heights
  - Surface reflectivity
  - Ground conductivity and dialectic constants
  - Climate factors
  - A problem with Longley rice is that It doesn't take into account the buildings and multipath.

Okumura Model

- In 1968 Okumura did a lot of measurements and produce a new model.
- The new model was used for signal prediction in Urban areas.
- Okumura introduced a graphical method to predict the median attenuation relative to free-space for a quasi-smooth terrain
- The model consists of a set of curves developed from measurements and is valid for a particular set of system parameters in terms of carrier frequency, antenna height, etc.

Okumura Model

- First of all the model determined the free space path loss of link.
- After the free-space path loss has been computed, the median attenuation, as given by Okumura's curves has to be taken to account
- The model was designed for use in the frequency range 200 up to 1920 MHz and mostly in an urban propagation environment.
- Okumura's model assumes that the path loss between the TX and RX in the terrestrial propagation environment can be expressed as:

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

Okumura Model

- **Estimating path loss using Okumura Model**

1. Determine free space loss and $A_{mu}(f,d)$, between points of interest
2. Add $Amu(f,d)$ and correction factors to account for terrain

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

L_{50} = 50% value of propagation path loss (median)

L_F = free space propagation loss

$A_{mu}(f,d)$ = median attenuation relative to free space

$G(h_{te})$ = base station antenna height gain factor

$G(h_{re})$ = mobile antenna height gain factor

G_{AREA} = gain due to environment

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Okumura Model

- $A_{mu}(f,d)$ & G_{AREA} have been plotted for wide range of frequencies
- Antenna gain varies at rate of 20dB or 10dB per decade

$$G(h_{te}) = 20\log\frac{h_{te}}{200} \qquad 10\text{m} < h_{te} < 1000\text{m}$$

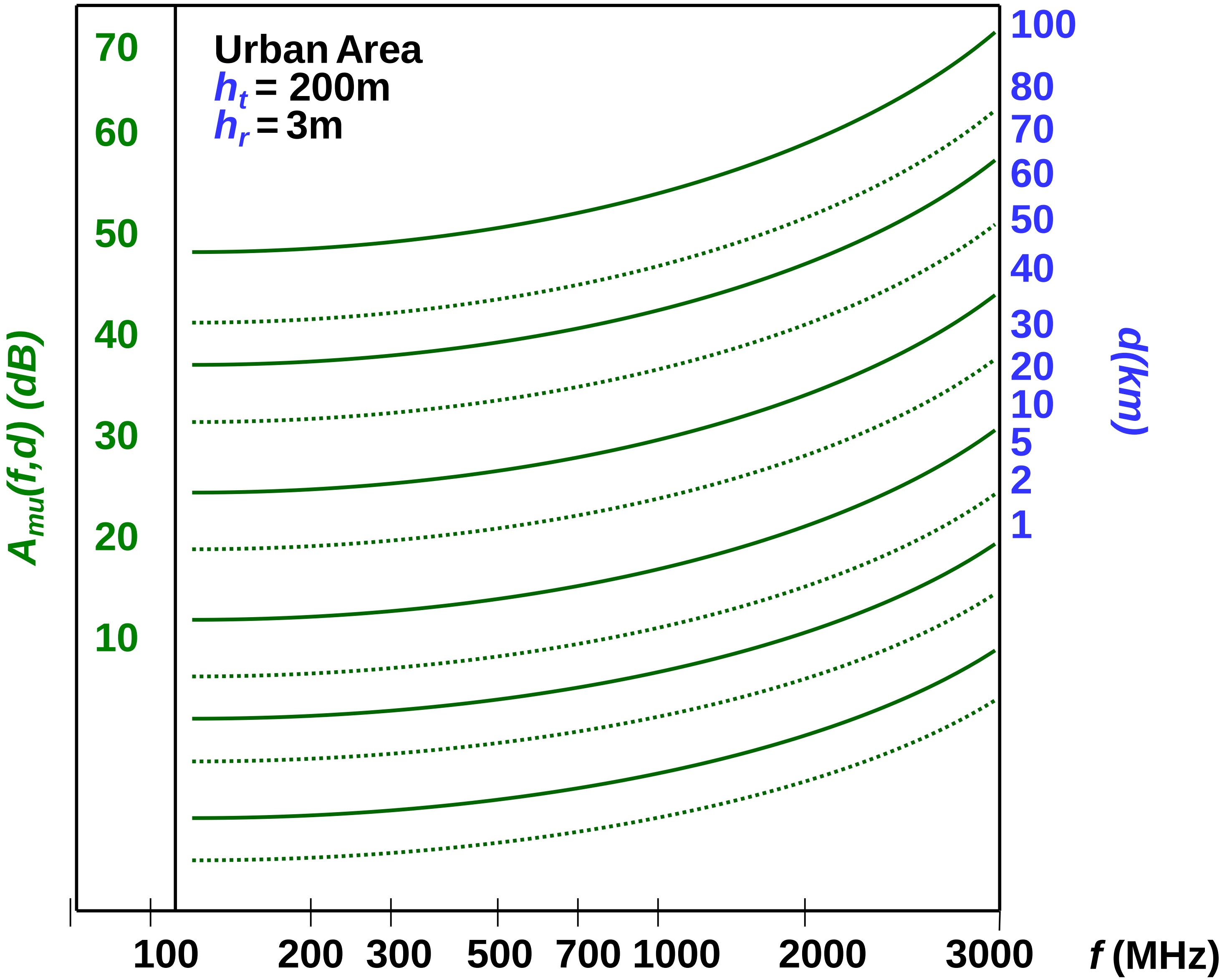
$$G(h_{re}) = 10\log\frac{h_{re}}{3} \qquad h_{re} \square 3\text{m}$$

$$G(h_{re}) = 20\log\frac{h_{re}}{3} \qquad 3\text{m} < h_{re} < 10\text{m}$$

- **model corrected** for

□h = terrain undulation height, isolated ridge height average terrain slope and mixed land/sea parameter

Median Attenuation Relative to Free Space = $A_{mu}(f,d)$ (dB)



Correction Factor G_{AREA}

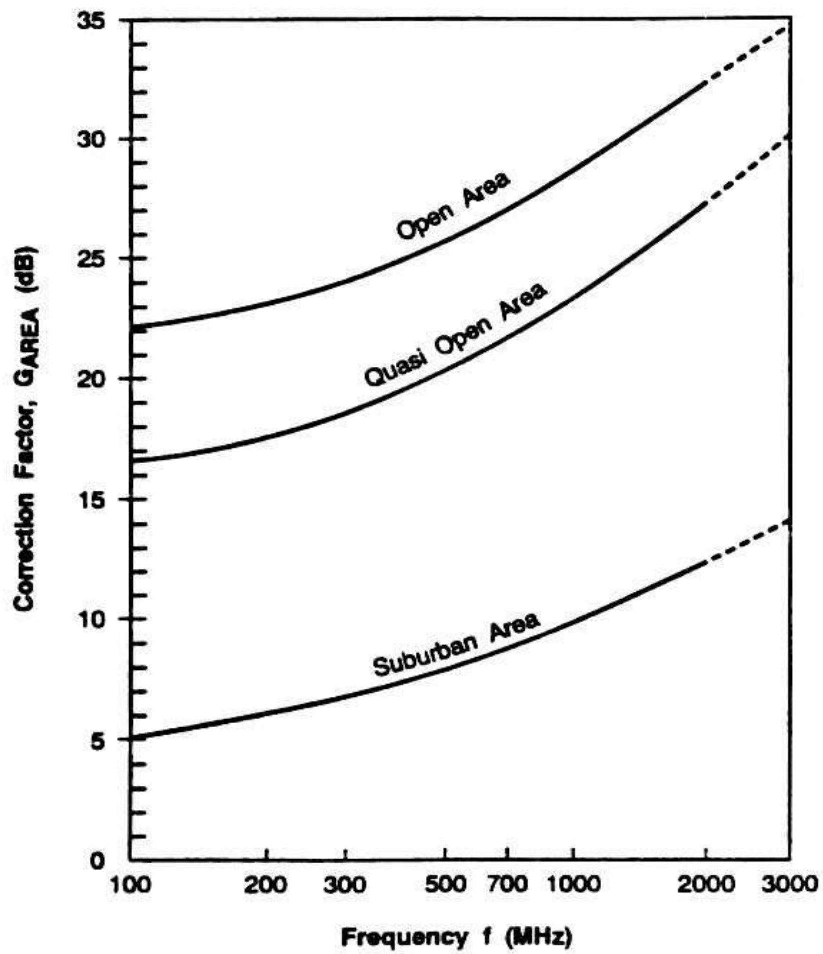


Figure 4.24 Correction factor, G_{AREA}, for different types of terrain [from [Oku68] © IEEE].

Indoor Models

- Indoor Channels are different from traditional channels in two ways

  1. The distances covered are much smaller
  2. The variability of environment is much greater for a much small range of Tx and Rx separation.

- Propagation inside a building is influenced by:

  - Layout of the building
  - Construction materials
  - Building Type: office , Home or factory

Indoor Models

- Indoor models are dominated by the same mechanism as out door models:

  - Reflection, Diffraction and scattering

- Conditions are much more variable

  - Doors/Windows open or not

  - Antenna mounting : desk ceiling etc

  - The levels of floor

- Indoor models are classifies as

  - Line of sight (LOS)

  - Obstructed (OBS) with varying degree of clutter

Indoor Models

- Portable receiver usually experience

  - Rayleigh fading for OBS propagation paths

  - Ricean fading for LOS propagation path

- Indoors models are effected by type of building e.g. Residential buildings, offices, stores and sports area etc.

- Multipath delay spread

  - Building with small amount of metal and hard partition have small delay spread 30 to 60ns

  - Building with large amount of metal and open isles have delay spread up to 300ns

Partition losses (same floor)

- Two types of partitions
  1. hard partitions: Walls of room
  2. Soft partitions : Moveable partitions that donot span to ceiling

- Partitions vary widely in their Physical and electrical properties.

- Path loss depend upon the types of partitions

Partition losses (same floor)

Partition Losses (Same Floor)

Material Type	Loss (dB)	Frequency
All metal partition	26	815 MHz
Concrete Block wall	13	1300 MHz
Empty Cardboard boxes	3 – 6 dB	1300 MHz
Dry Plywood (0.75 inches)	1 dB	9.6 GHz
Dry Plywood (0.75 inches)	4 dB	28.8 GHz

Partitions losses (between floors)

- Partition losses between the two floors depend on

1. External dimension and material used for buildings
2. Types of construction used to create floors
3. External surroundings
4. No of windows used
5. Tinting on the windows

- Floor Attenuation Factor (FAF) increases as we increase the no of floors

Log distance path loss model

- Path loss can be given as

$$PL(\mathrm{dB}) = PL(d_0) + 10n\log\left(\frac{d}{d_0}\right) + X_\sigma$$

where n is path loss exponent and σ is standard deviation

- n and σ depend on the building type.
- Smaller value of σ indicates better accuracy of path loss model

Ericsson Multiple Break Point Model

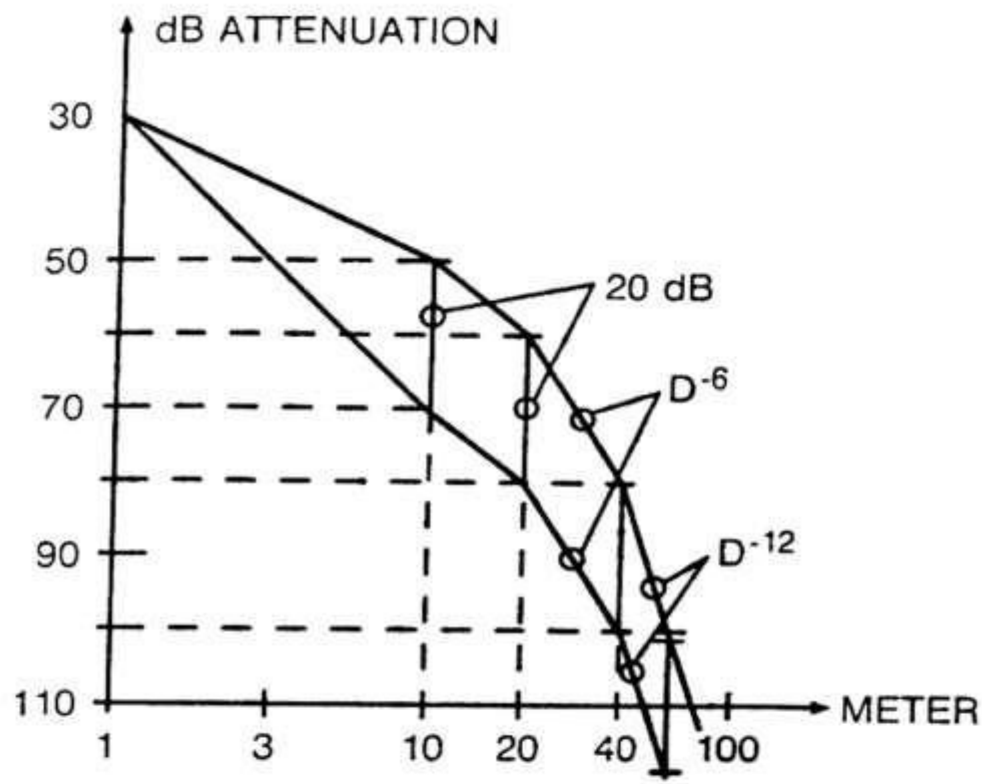


Figure 4.27 Ericsson in-building path loss model [from [Ake88] © IEEE].

Attenuation factor model

- Obtained by measurement in multiple floors building

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

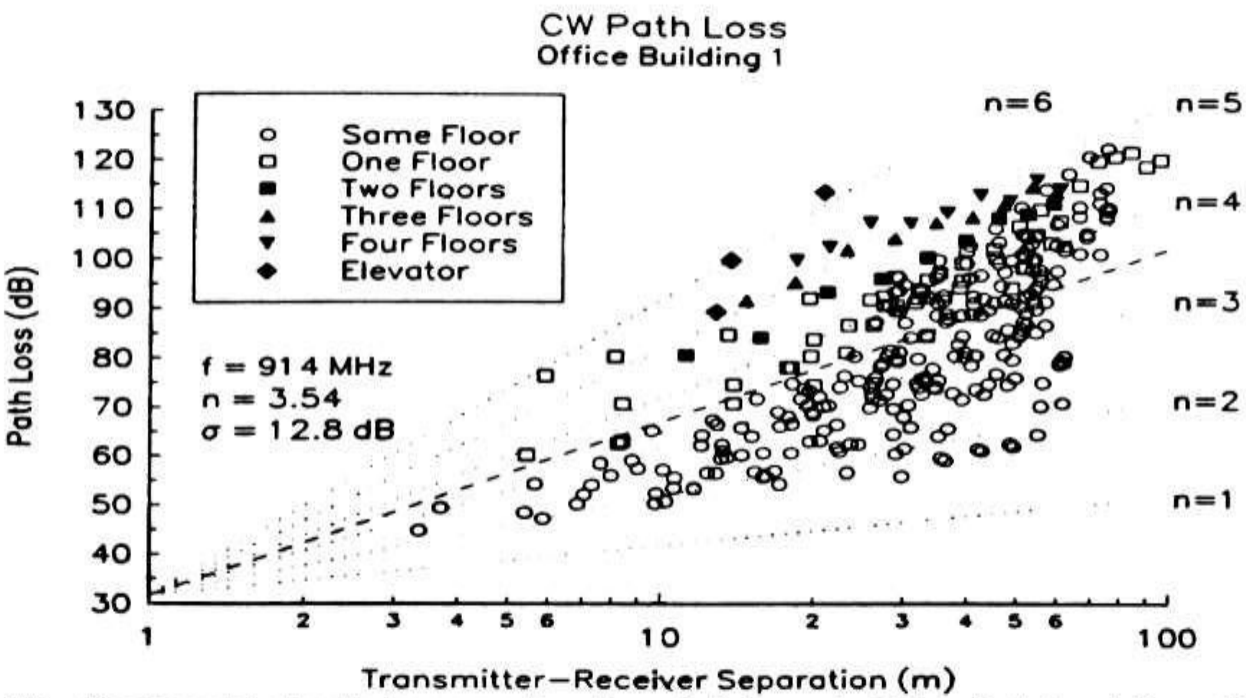


Figure 4.28 Scatter plot of path loss as a function of distance in Office Building 1 [from [Sei92b] © IEEE].

Attenuation factor model

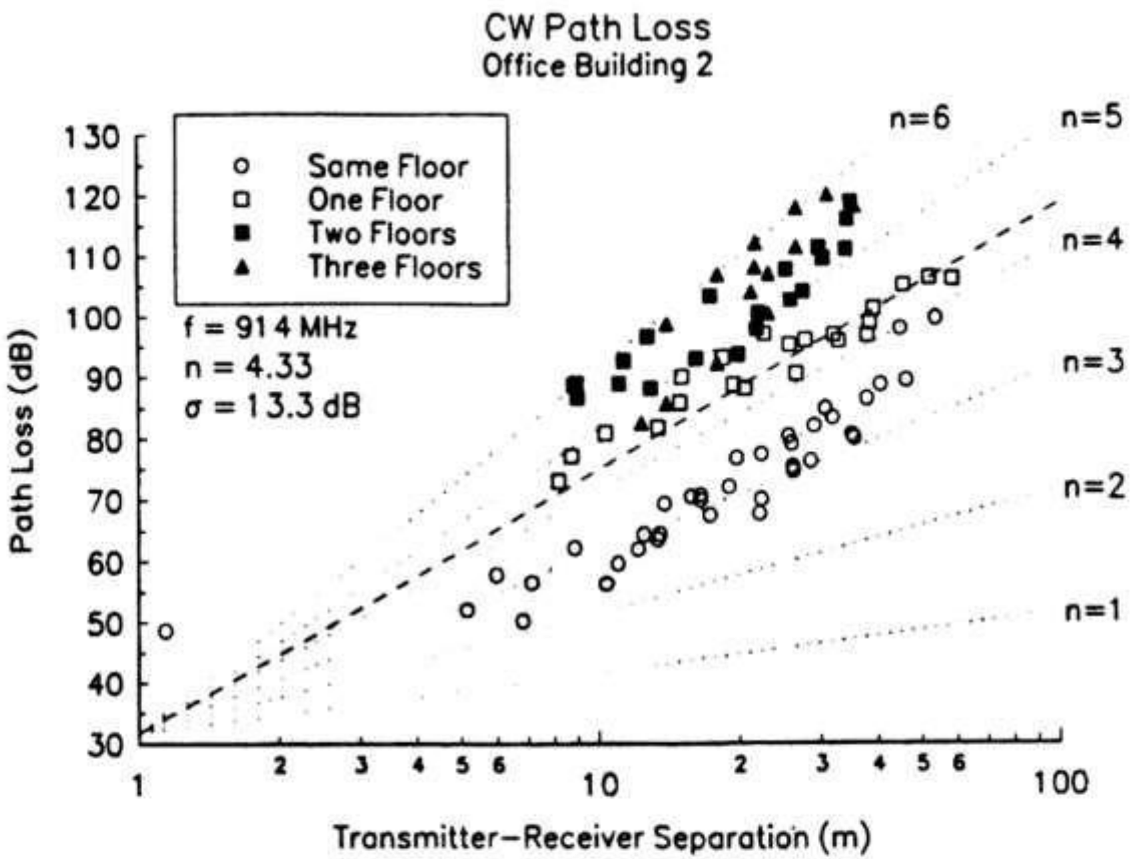


Figure 4.29 Scatter plot of path loss as a function of distance in Office Building 2 [from [Sei92b] © IEEE].

Signal penetration intobuilding

- Effect of frequency

 - Penetration loss decreases with increasing frequency

- Effect of Height

- Penetration loss decreases with the height of building up to some certain height.

 - At lower heights the Urban clutter induces greater attenuation

 - Up to some height attenuation decreases but then again increase after a few floors

 - Increase in attenuation at higher floors is due to the Shadowing effects of adjacent buildings

UNIT III
Mobile Radio Propagation
Small —Scale Fading
and Multipath

Small-Scale Fading and Multipath

- The term fading is used to describe rapid fluctuation of the amplitude of a radio signal over a short period of time or travel distance

- Fading is caused by destructive interference between two or more versions of the transmitted signal being slightly out of phase due to the different propagation time

- This is also called multipath propagation

- The different components are due to reflection and scattering form trees buildings and hills etc.

Small-Scale Fading and Multipath

- At a receiver the radio waves generated by same transmitted signal may come

  From Different direction

  With Different propagation delays,

  With Different amplitudes

  With Different phases

- Each of the factor given above is random

- The multipath components combine vectorially at the receiver and produce a fade or distortion.

Effects of Fading/Multipath

- Multipath propagation creates small-scale fading effects.

  The three most important effects are:
  - Rapid changes in signal strength over a small travel distance or time interval;
  - Random frequency modulation due to varying Doppler shifts on different multipath signals; and
  - Time dispersion (echoes) caused by multipath propagation delays.
- Even when a mobile receiver is stationary, the received signal may fade due to a non-stationary nature of the channel (reflecting objects can be moving)

Factors influencing small-scale fading

- **Multipath propagation**
  - **The presence of reflecting** objects and scatterers in the space between transmitter and receiver creates a constantly changing channel environment
  - Causes the signal at receiver to fade or distort

- **Speed of mobile receiver**
  - **The relative motion** between the transmitter and receiver results in a random frequency modulation due to different Doppler shifts on each of the multipath signals
  - Doppler shift may be positive or negative depending on direction of movement of mobile

Factors influencing small-scale fading

- **Speed of surrounding objects:**
  - If the speed of surrounding objects is greater than mobile, the fading is dominated by those objects
  - If the surrounding objects are slower than the mobile, then their effect can be ignored
- **The transmission bandwidth:**
  - Depending on the relation between the signal bandwidth and the coherence bandwidth of the channel, the signal is either distorted or faded
  - If the signal bandwidth is greater than coherence bandwidth it creates distortion
  - If the signal bandwidth is smaller than coherence bandwidth it create small scale fading

Some Terminologies

- Level Crossing Rate

  Average number of times per sec that the signal crosses a certain level going in positive going direction

- Fading Rate

  Number of times the signal envelop crosses middle value in positive going direction per unit time

- Depth of Fading

  Ratio of mean square value and minimum value of fading

- Fading Duration

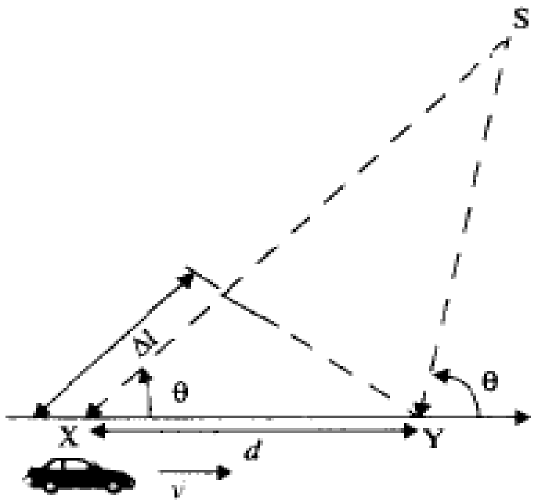
  Time for which signal remain below a certain threshold

Doppler shift

- Change in the apparent frequency of a signal as Tx and Rx move toward or away from each other
- If mobile is moving towards the direction of arrival of the signal, the Doppler shift is positive(apparent received frequency is increased i.e. fc+fd) and vice versa
- Mathematically

$$\Delta\phi = \frac{2\pi\Delta l}{\lambda} = \frac{2\pi v\Delta t}{\lambda}\cos\theta$$

$$f_d = \frac{1}{2\pi}\cdot\frac{\Delta\phi}{\Delta t} = \frac{v}{\lambda}\cdot\cos\theta$$



Impulse response of Multipath channel

- The small scale variations of a mobile radio signal can be directly related to the impulse response of mobile radio channel.
- Impulse response contains information to Simulate and Analyze the channel
- The mobile radio channel can be modeled as

  Linear filter with time varying impulse response
- In case of mobile reception, the length and attenuation of various paths will change with time i.e. Channel is time varying.
- The time variation is strictly due to receiver movement (t=d/v).

Impulse response of Multipath channel

- At any distance d=vt, the received signal is the combination of different signals coming with different propagation delays depending on the distance between transmitter and receiver.

- So the impulse response is a function of d, which is the separation between the transmitter and receiver.

Impulse response Model of Multipath channel

$$x(t) \longrightarrow \boxed{\begin{array}{c}\text{Wireless Multipath Channel}\\ h(d,t)\end{array}} \longrightarrow y(d,t)$$

$$y(d,t) = x(t) \otimes h(d,t) = \int_{-\infty}^{\infty} x(\tau)h(d,t-\tau)d\tau$$

For a causal system, $h(d,t) = 0$ for $t < 0$; hence

$$y(d,t) = \int_{-\infty}^{t} x(\tau)h(d,t-\tau)d\tau$$

Impulse Response Model of Multipath channel

$d = vt$ (Assuming v is constant over short time)

$$y(vt,t) = \int_{-\infty}^{t} x(\tau)h(vt,t-\tau)d\tau$$

$$y(t) = \int_{-\infty}^{t} x(\tau)h(vt,t-\tau)d\tau = x(t)\otimes h(vt,t) = x(t)\otimes h(d,t)$$

$$y(t) = \int_{-\infty}^{\infty} x(\tau)h(t,\tau)d\tau = x(t)\otimes h(t,\tau)$$

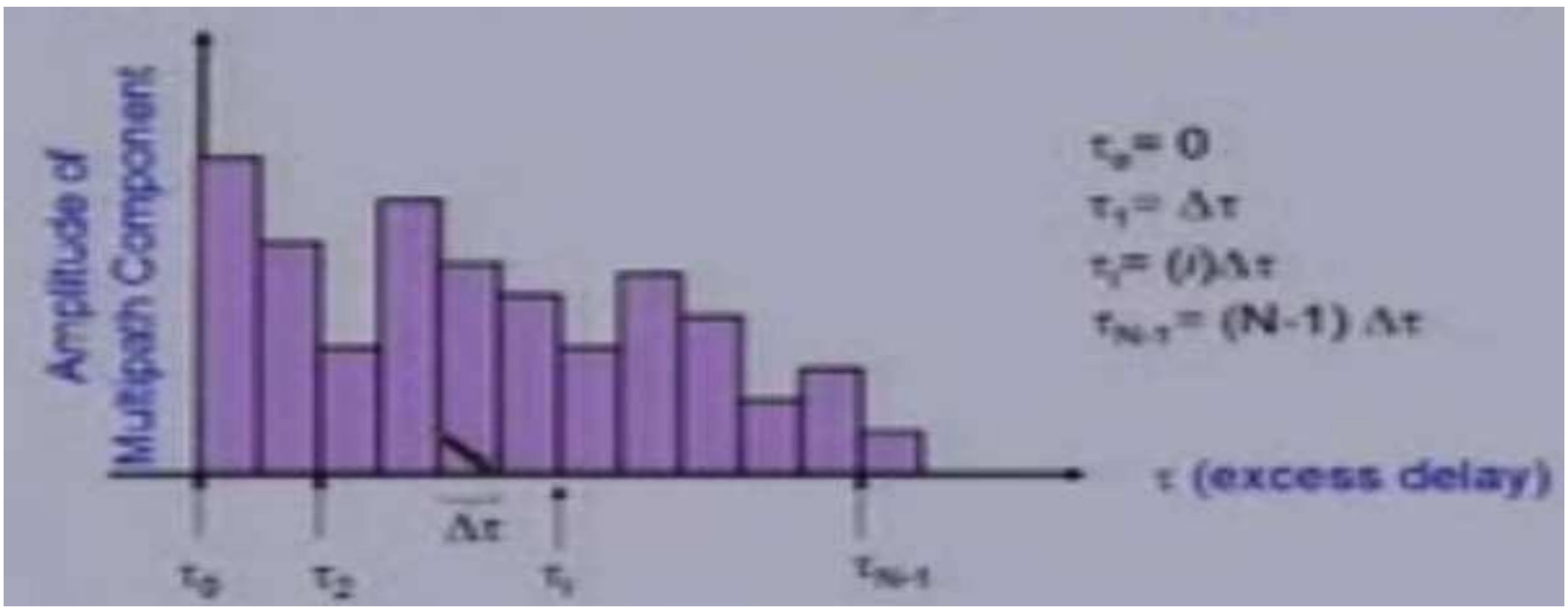
The ***impulse response*** is both a function of t and τ

t represents the variations due to motion

τ represents the channel multipath delay for a fixed value of t.

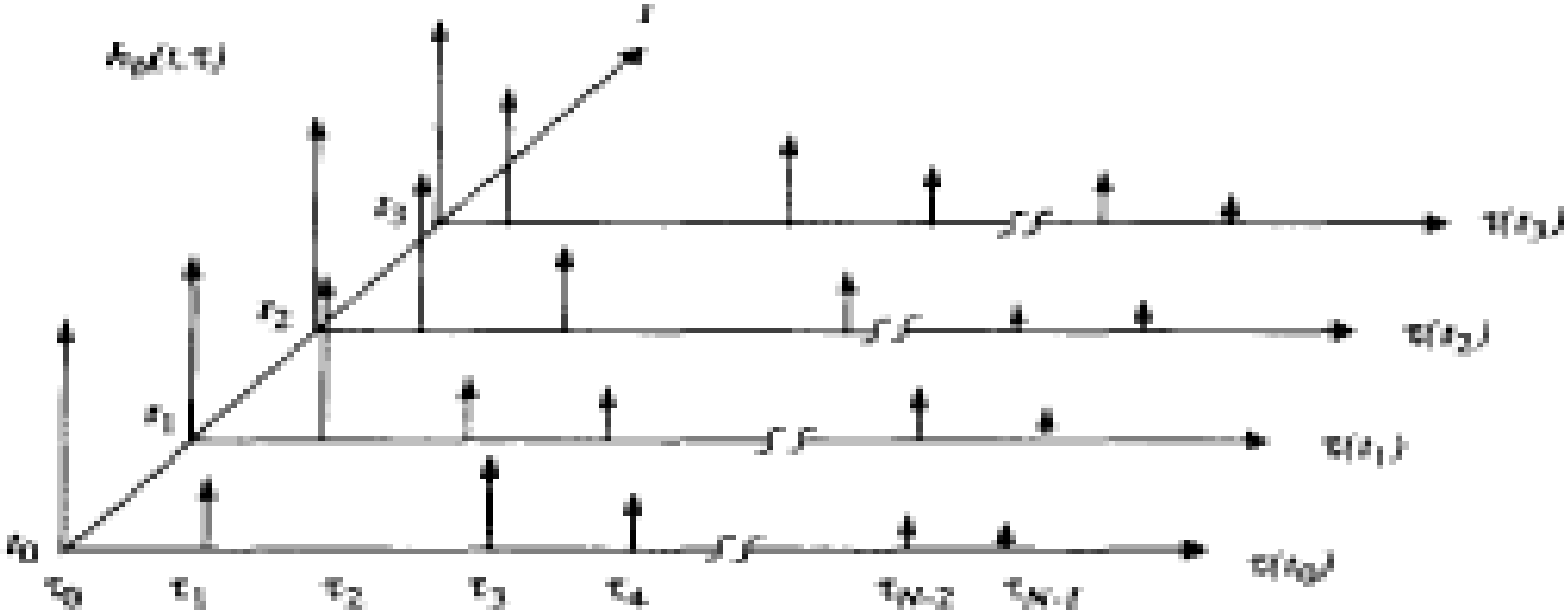
Discrete time Impulse Response Model of Multipath channel

- Discretize the multipath delay axis τ into equal time delay segments called Excess Delay Bins
- For N such multipath components (0…N-1)



Discrete time Impulse Response Model of Multipath channel

$$h_b(t,\tau) = \sum_{i=0}^{N-1} a_i(t,\tau)\exp[j(2\pi f_c \tau_i(t) + \phi_i(t,\tau))]\delta(\tau - \tau_i(t))$$



Discrete time Impulse Response Model of Multipath channel

- If the channel impulse response is assumed to be time invariant over small scale time or distance, then it may be simplified as

$$h_b(\tau) = \sum_{i=0}^{N-1} a_i \exp(-j\theta_i)\,\delta(\tau - \tau_i)$$

- When measuring or predicting $h_b(t)$, a probing pulse P(t) which approximates a unit impulse function is used as signal at the transmitter.

$$p(t) \approx \delta(t - \tau)$$

Power Delay Profile

- For small scale fading, the power delay profile of channel can be found using the spatial average of ov $|h_b(t;\tau)|^2$ ocal area.
- It P(t) has time duration much smaller than the impulse response of multipath channel, the received power delay profile in local area can be

$$P(t;\tau) \approx k|h_b(t;\tau)|^2$$

- Where the gain k relates the power of input pulse to the received power.

Measuring PDPs

- Power Delay Profiles
  - Are measured by channel sounding techniques
  - Plots of relative received power as a function of excess delay
  - They are found by averaging *intantenous* power delay measurements over a local area
    - Local area: no greater than 6m outdoor
    - Local area: no greater than 2m indoor
      - Samples taken at □/4 meters approximately
      - For 450MHz – 6 GHz frequency range.

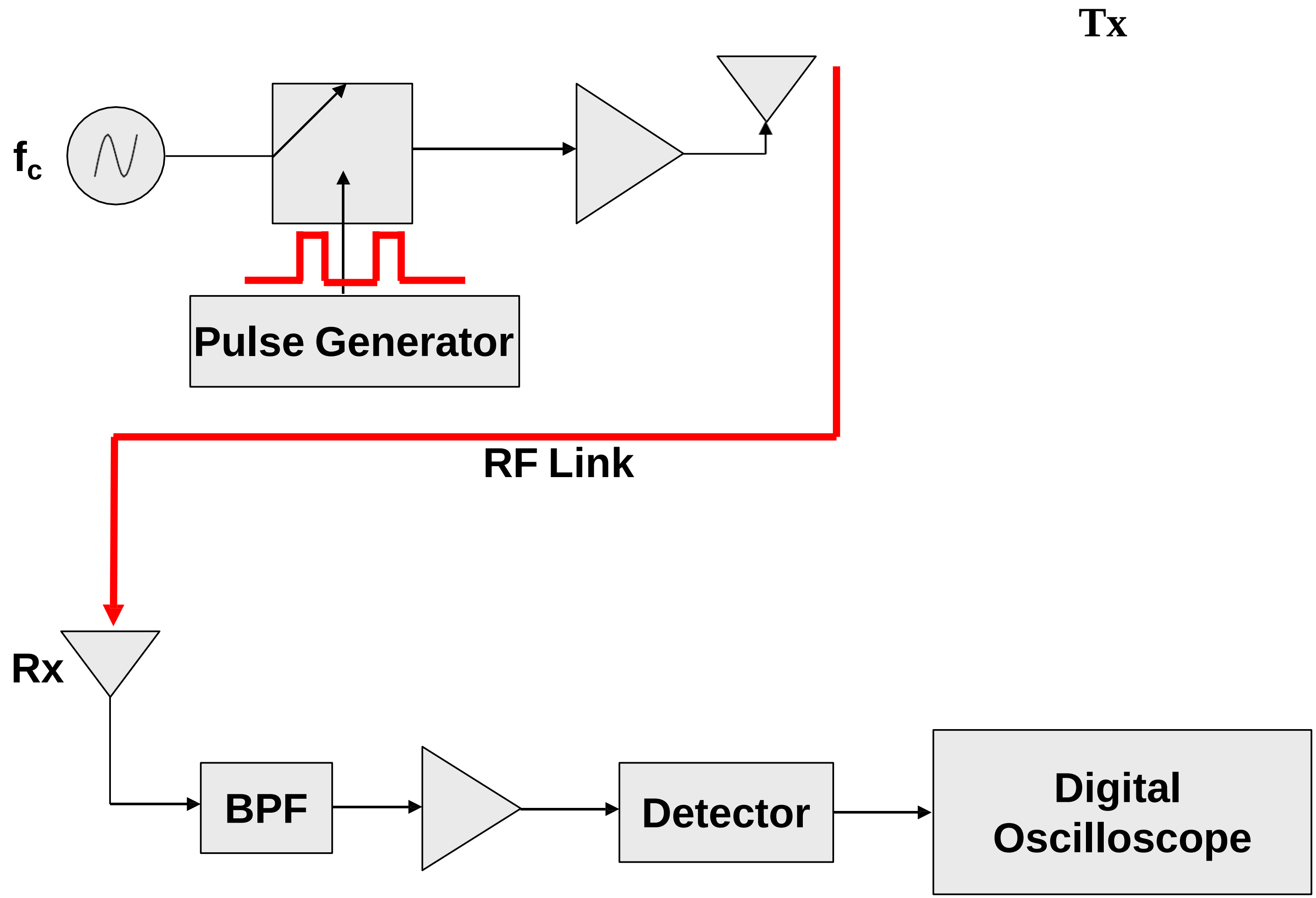
Small-Scale Multipath Measurements

- Multipath structure is very important for small scale fading.
- Several Methods
  - Direct RF Pulse System
  - Spread Spectrum Sliding Correlator Channel Sounding
  - Frequency Domain Channel Sounding
- These techniques are also called channel sounding techniques

Direct RF Pulse System

- This method help us to determine the power delay profile directly
- Objective is to find impulse response
- A narrow pulse is used for channel sounding.
- At the receiver the signal is amplified and detected using an envelop detector.
- It is then stored on a high speed digital oscilloscope.
- If the receiver is set on averaging mode, the local average power delay profile is obtained

Direct RF Pulse System



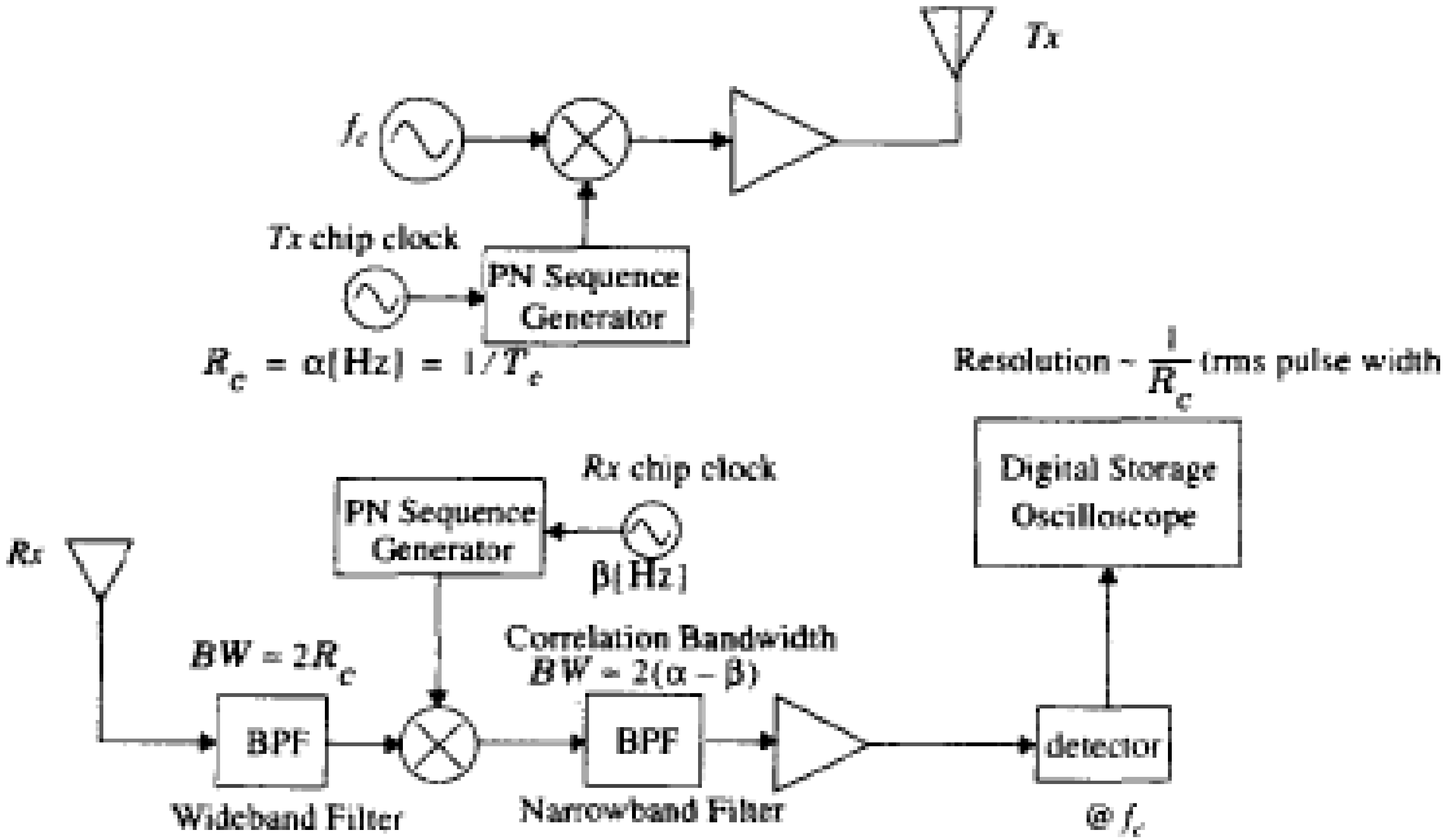
Direct RF Pulse System

- **Problems:**
- Subject to interference
- Subject to noise due to wideband pass band filter required for multipath resolution
- The phases of individual multi path components are not received due to the use of envelop detector

Spread Spectrum Sliding Correlator Channel Sounding

- The probing signal is wide band but the receiver is narrow band
- The carrier signal is spread over large bandwidth by mixing it with Pseudorandom- noise(PN) sequence having chip rate T_c.
- At receiver signal is despread using same PN
- The transmitter chip clock rate is a little faster then the receiver chip clock rate
- The result is sliding correlator.
- If the sequences are not maximally correlated then the mixer will further despread the signal

Spread Spectrum Sliding Correlator Channel Sounding



Spread Spectrum Sliding Correlator Channel Sounding

- The chip rate $R_c=1/T_c$.
- RF bandwidth = $2R_c$
- Processing gain: $$PG = \frac{2R_c}{R_{bb}} = \frac{2\tau_{bb}}{T_c} = \frac{(S/N)_{out}}{(S/N)_{in}}$$
- Time resolution $\Delta\tau=2T_c = 2/R_c$
- Sliding factor (gamma)$\gamma=\alpha/\alpha-\beta$
- Alpha= transmitter chip rate
- Beta=receiver chip rate

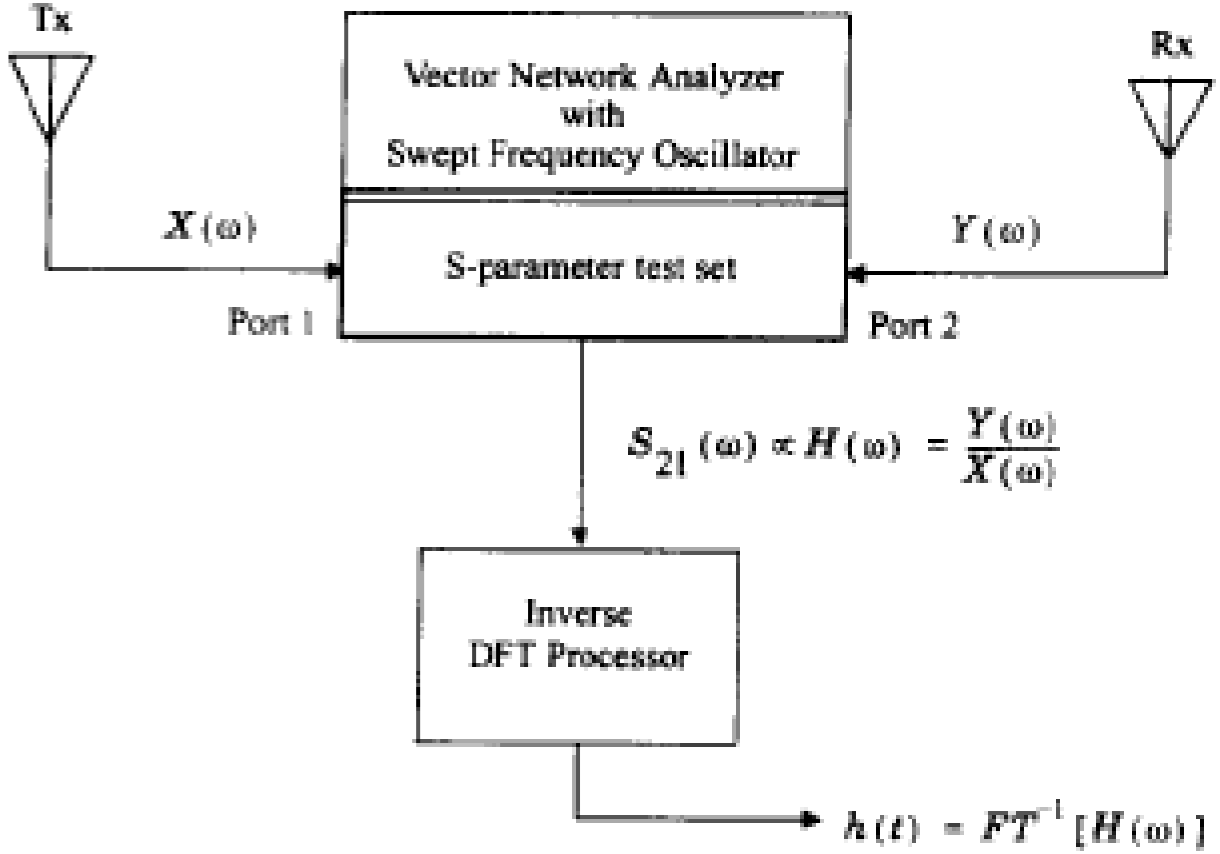
Spread Spectrum Sliding Correlator Channel Sounding

- **Advantages**:
- Improves coverage range using same transmitter power.
- Transmitter receiver synchronization is eliminated using sliding correlator.
- **Disadvantages:**
- Measurement are not made real time
- The associated time required is more
- Phase information is lost.

Frequency Domain Channel Sounding

- Because of the dual relationship between time and frequency it is possible to measure channel impulse response in frequency domain
- A vector network analyzer is used.
- The S-parameter test set is used to monitor the frequency response of the channel.
- The frequency sweeper scans a particular frequency band by stepping through the discrete frequencies.

Frequency Domain Channel Sounding



Frequency Domain Channel Sounding

- The number and spacing of frequency steps impact the time resolution of impulse response measurements.
- The response is converted to time domain by using Inverse Discrete time Fourier Transform(IDFT)

Frequency Domain Channel Sounding

- Disadvantages:
- System requires careful calibration
- System required hardwired synchronization between transmitter and receiver.
- Practical only for indoor channel measurements
- Non real time nature of measurements
- For time varying channels the channel impulse response may change giving erroneous measurements

Parameters of Mobile Multipath Channels

- Time Dispersion Parameters
  - Grossly quantifies the multipath channel
  - Determined from Power Delay Profile
  - Parameters include
    - Mean Access Delay
    - RMS Delay Spread
    - Excess Delay Spread (X dB)
- Coherence Bandwidth
- Doppler Spread and Coherence Time

Timer Dispersion Parameters

- Determined from a power delay profile

Mean excess delay($\bar{\tau}$):

$$\bar{\tau} = \frac{\sum_k a_k^2 \tau_k}{\sum_k a_k^2} = \frac{\sum_k P(\tau_k)(\tau_k)}{\sum_k P(\tau_k)}$$

Rms delay spread (σ_τ):

$$\sigma_\tau = \sqrt{\overline{\tau^2} - (\bar{\tau})^2}$$

$$\overline{\tau^2} = \frac{\sum_k a_k^2 \tau_k^2}{\sum_k a_k^2} = \frac{\sum_k P(\tau_k)(\tau_k^2)}{\sum_k P(\tau_k)}$$

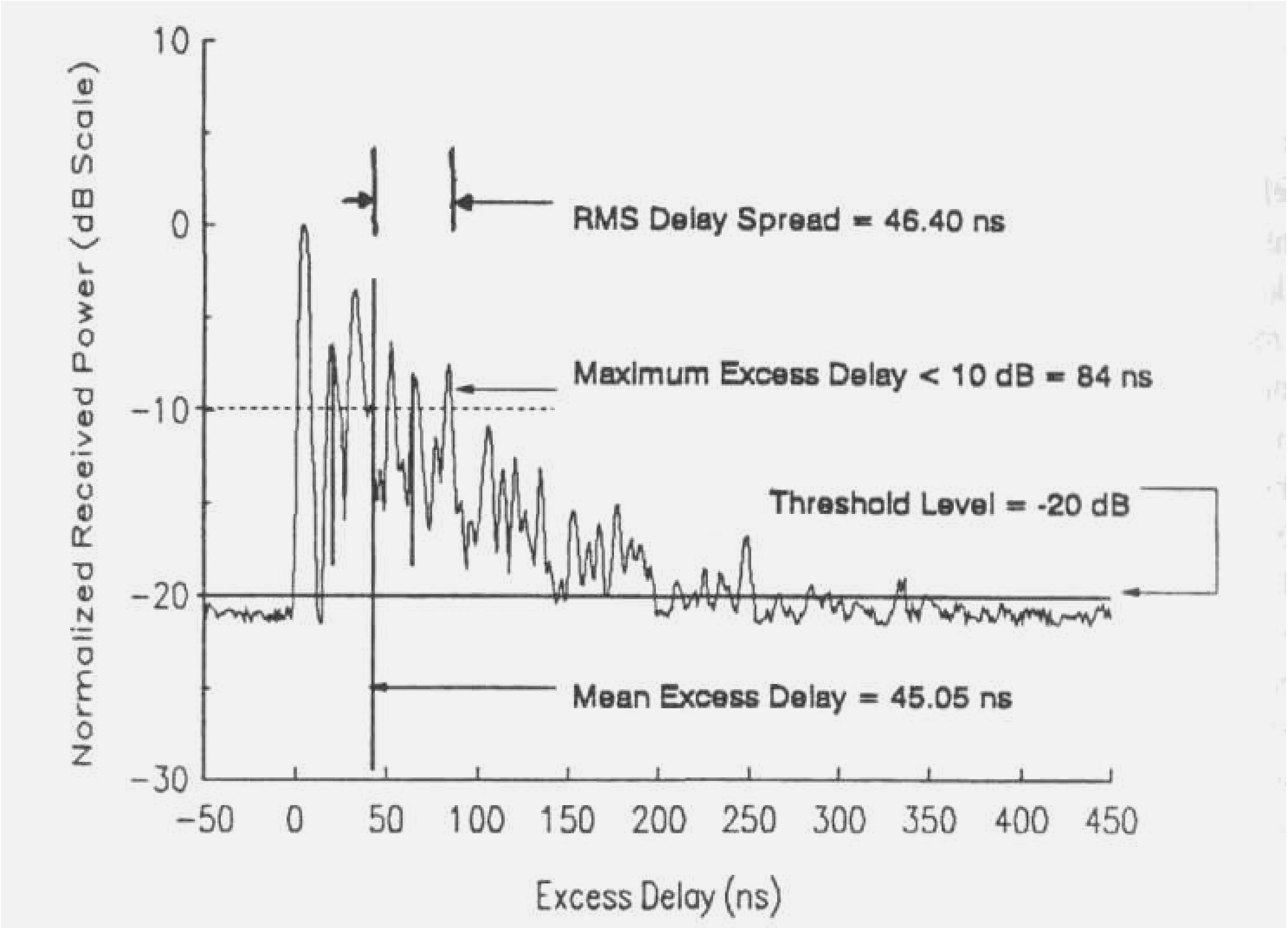
Timer Dispersion Parameters

Maximum Excess Delay (X dB):

- Defined as the time delay value after which the multipath energy falls to X dB below the maximum multipath energy (not necessarily belonging to the first arriving component).

It is also called *excess delay spread*.

RMS Delay Spread



Noise Threshold

- The values of time dispersion parameters also depend on the noise threshold (the level of power below which the signal is considered as noise).

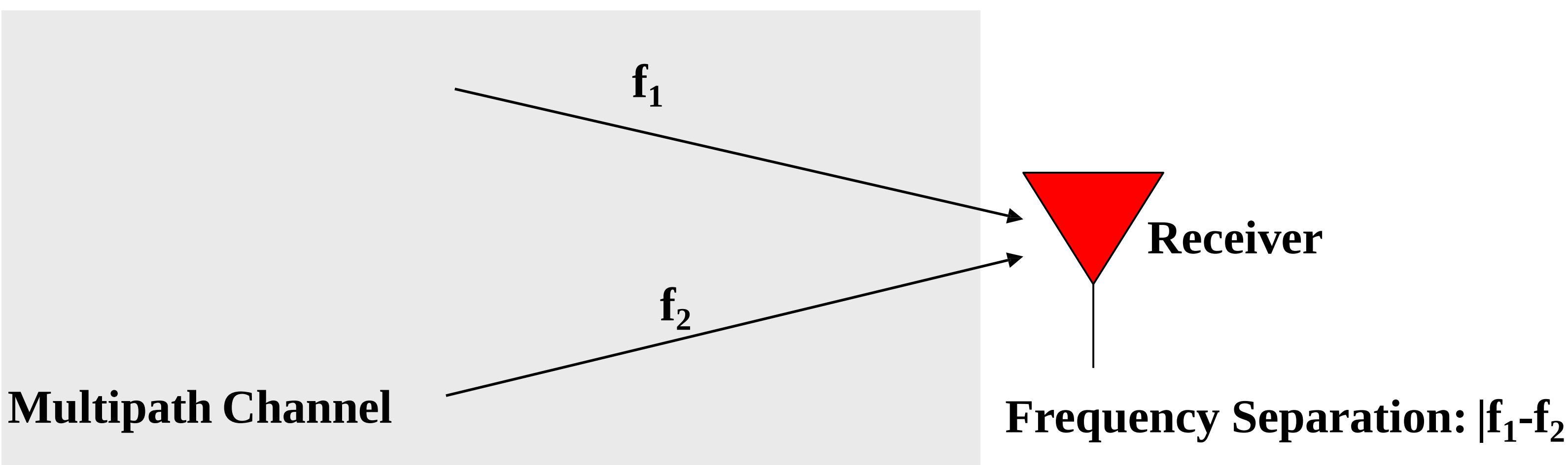
- If noise threshold is set too low, then the noise will be processed as multipath and thus causing the parameters to be higher.

Delay Spread, Coherence BW

- Describes the time dispersive nature of a channel in a local area
- A received signal suffers spreading in time compared to the transmitted signal
- Delay spread can range from a few hundred nanoseconds for indoor scenario up to some microseconds in urban areas
- The coherence bandwidth B_c translates time dispersion into the language of the frequency domain.
- It specifies the frequency range over which a channel affects the signal spectrum nearly in the same way, causing an approximately constant attenuation and linear change in phase
- The rms delay spread and coherence bandwidth are inversely proportional to each other.

Coherence Bandwidth (B_C)

- Range of frequencies over which the channel can be considered flat (i.e. channel passes all spectral components with equal gain and linear phase).
  - It is a definition that depends on RMS Delay Spread.
- Two sinusoids with frequency separation greater than B_c are affected quite differently by the channel.



Coherence Bandwidth

Frequency correlation between two sinusoids: $0 \le C_{r1,\, r2} \le 1$.

If we define Coherence Bandwidth (B_C) as the range of frequencies over which the frequency correlation is above 0.9, then

$$B_C \approx \frac{1}{50\sigma}$$

σ is rms delay spread

If we define Coherence Bandwidth as the range of frequencies over which the frequency correlation is above 0.5, then

$$B_C \approx \frac{1}{5\sigma}$$

This is called 50% coherence bandwidth.

Doppler Spread and Coherence time

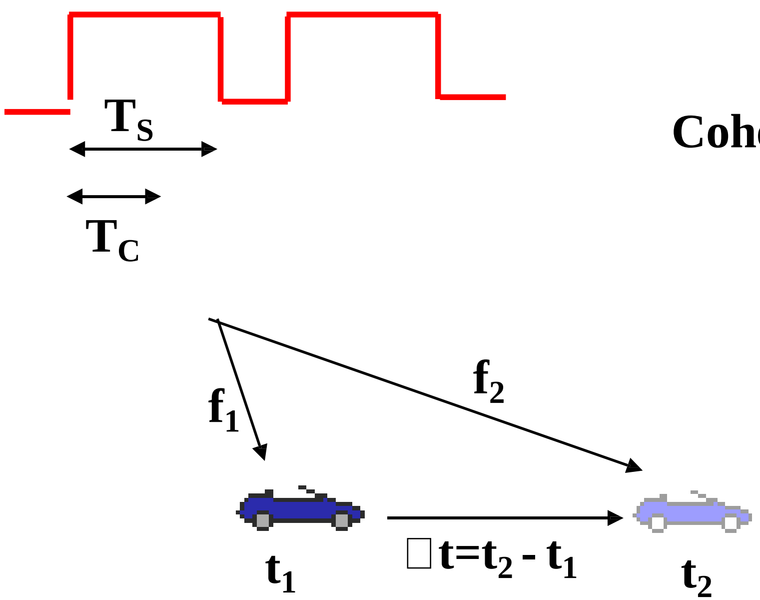
- Delay spread and Coherence bandwidth describe the time dispersive nature of the channel in a local area. They don't offer information about the time varying nature of the channel caused by relative motion of transmitter and receiver.
- Doppler Spread and Coherence time are parameters which describe the time varying nature of the channel in a small-scale region.
- Time varying nature of channel caused either by relative motion between BS and mobile or by motions of objects in channel are categorized by B_D and T_c

Doppler Spread

- Measure of spectral broadening caused by motion
- We know how to compute Doppler shift: f_d
- Doppler spread, B_D, is defined as the maximum Doppler shift: $f_m = v/$□
- if Tx signal bandwidth (B_s) is large such that $B_s >> B_D$ then effects of Doppler spread are **NOT** important so Doppler spread is only important for low bps (data rate) applications (e.g. paging), slow fading channel

Coherence Time

- Coherence time is the time duration over which the channel impulse response is essentially invariant.
- If the symbol period of the baseband signal (reciprocal of the baseband signal bandwidth) is greater the coherence time, than the signal will distort, since channel will change during the transmission of the signal .



Coherence time (T_C) is defined as:

$$T_C \approx \frac{1}{f_m}$$

Coherence Time

- Coherence time is also defined as:

$$T_C \approx \sqrt{\frac{9}{16\pi f_m^2}} = \frac{0.423}{f_m}$$

- Coherence time definition implies that two signals arriving with a time separation greater than T_C are affected differently by the channel.

Small-Scale Fading
(Based on multipath time delay spread)

Flat Fading

1. BW of signal < BW of channel
2. Delay spread < Symbol period

Frequency Selective Fading

1. BW of signal > BW of channel
2. Delay spread > Symbol period

Small-Scale Fading
(Based on Doppler spread)

Fast Fading

1. High Doppler spread
2. Coherence time < Symbol period
3. Channel variations faster than baseband signal variations

Slow Fading

1. Low Doppler spread
2. Coherence time > Symbol period
3. Channel variations slower than baseband signal variations

Figure 5.11 Types of small-scale fading.

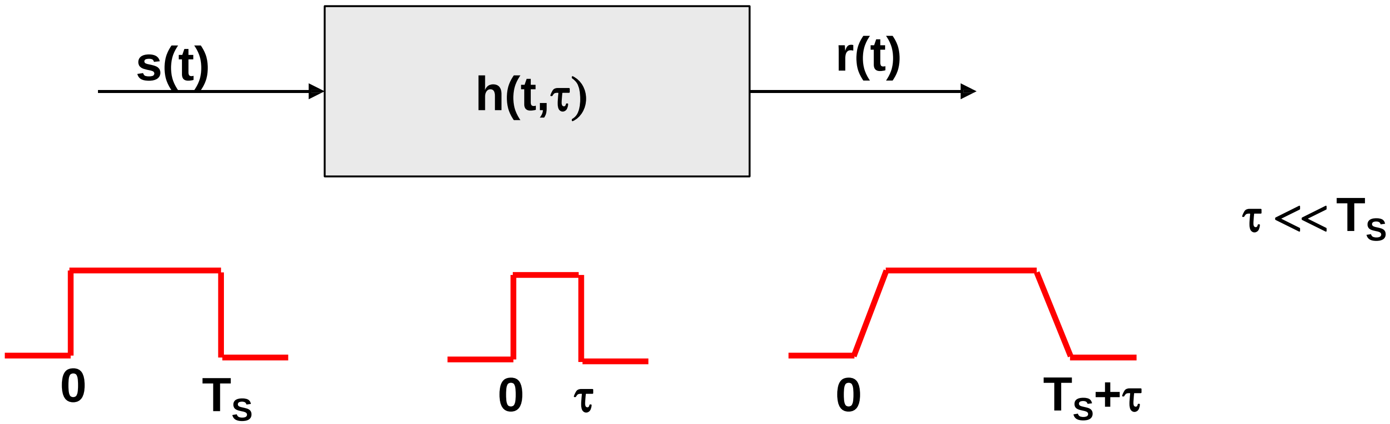
Classification of Multipath Channels

- Depending on the relation between signal parameters (bandwidth and symbol period) and channel parameters (delay spread and Doppler spread) different signals undergo different types of fading
- Based on delay spread the types of small scale fading are
  - Flat fading
  - Frequency selective fading
- Based on Doppler spread the types of small scale fading are
  - Fast fading
  - Slow fading

Flat fading

- Occurs when the amplitude of the received signal changes with time
- Occurs when symbol period of the transmitted signal is much larger than the Delay Spread of the channel
  - Bandwidth of the applied signal is narrow.
- The channel has a flat transfer function with almost linear phase, thus affecting all spectral components of the signal in the same way
- May cause deep fades.
  - Increase the transmit power to combat this situation.

Flat Fading



Occurs when:
$B_S << B_C$
and
$T_S >> \sigma_\tau$

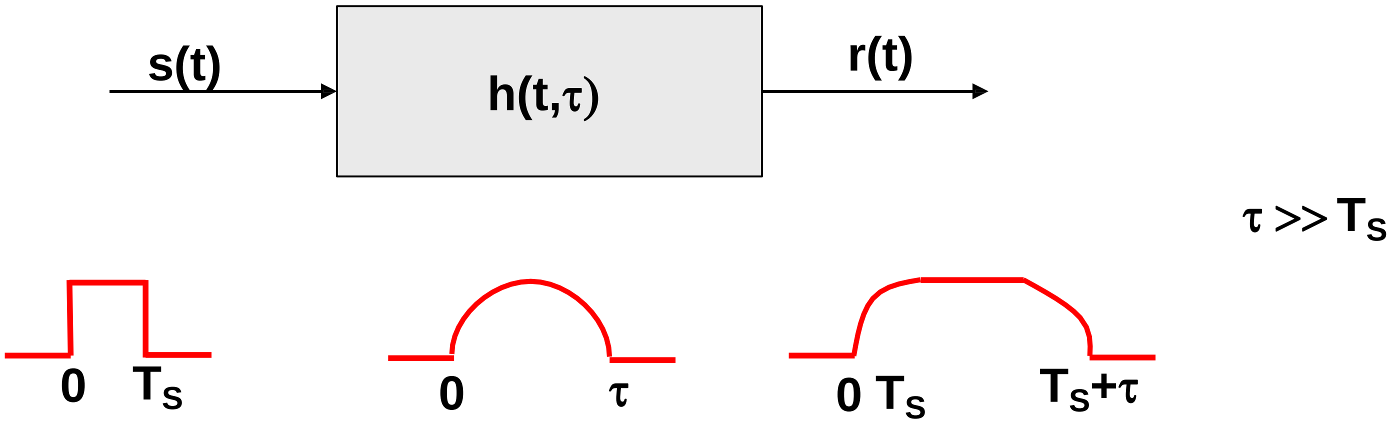
B_C: Coherence bandwidth
B_S: Signal bandwidth
T_S: Symbol period
σ_τ: Delay Spread

Frequency selective fading:

A channel that is not a flat fading channel is called *frequency selective fading* because different frequencies within a signal are attenuated differently by the MRC.

- Occurs when channel multipath delay spread is greater than the symbol period.
  - Symbols face time dispersion
  - Channel induces Intersymbol Interference (ISI)
- Bandwidth of the signal s(t) is wider than the channel impulse response.

Frequency Selective Fading



Causes distortion of the received baseband signal

Causes Inter-Symbol Interference (ISI)

Occurs when:
$B_S > B_C$
and
$T_S < \sigma_\tau$

As a rule of thumb $T_S < \sigma_\tau$

Fast Fading

- Rate of change of the channel characteristics is **larger** than the Rate of change of the transmitted signal
- The channel changes during a symbol period.
- The channel changes because of receiver motion.
- Coherence time of the channel is smaller than the symbol period of the transmitter signal

Occurs when: $B_S < B_D$ **and** $T_S > T_C$	**B_S: Bandwidth of the signal B_D: Doppler Spread** **T_S: Symbol Period** **T_C: Coherence Bandwidth**

Slow Fading

- Rate of change of the <u>channel characteristics</u>
  is **much smaller** than the
  Rate of change of the <u>transmitted signal</u>

Occurs when:
$B_S >> B_D$
and
$T_S << T_C$

B_S: Bandwidth of the signal
B_D: Doppler Spread T_S: Symbol Period
T_C: Coherence Bandwidth

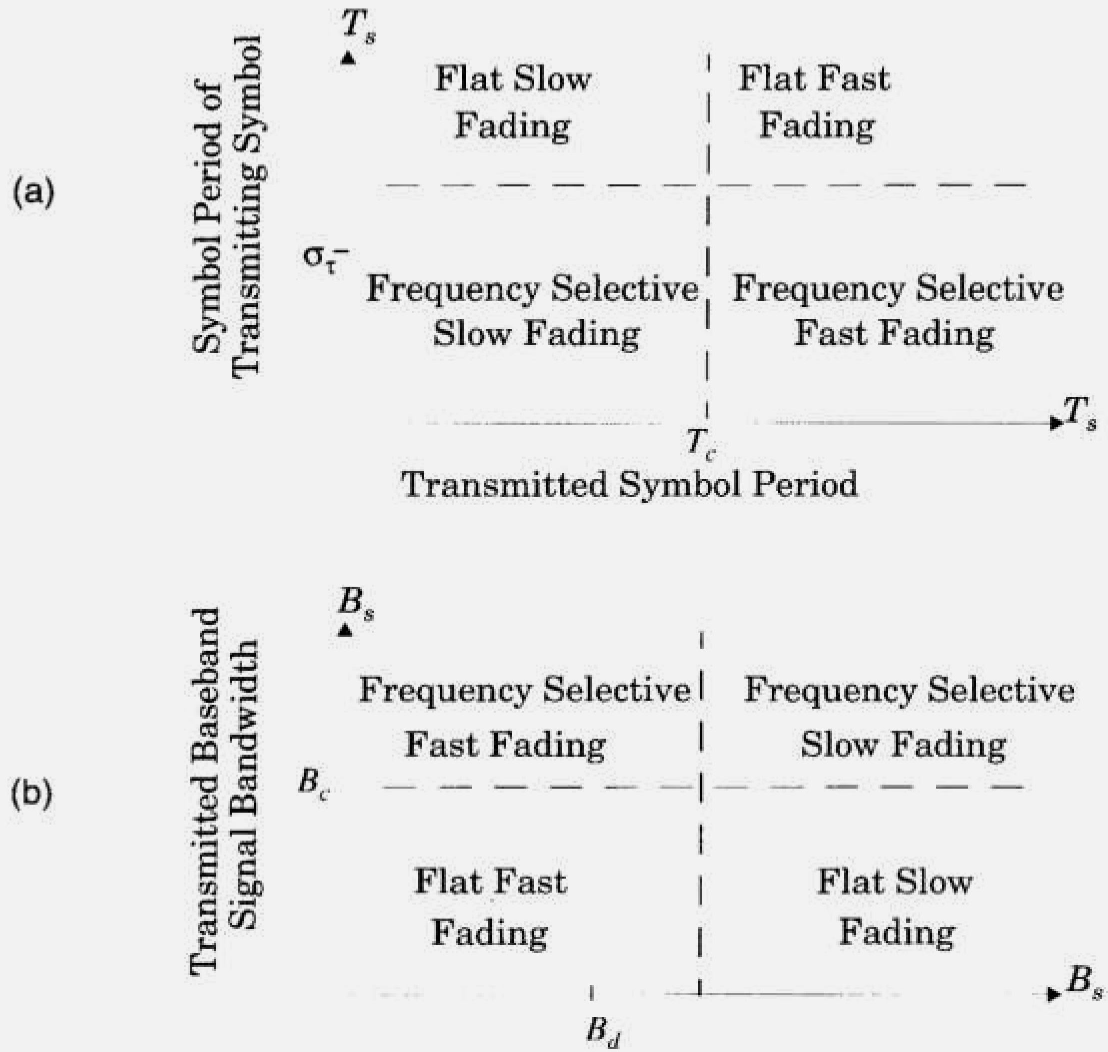


Figure 5.14 Matrix illustrating type of fading experienced by a signal as a function of: (a) symbol period; and (b) baseband signal bandwidth.

Fading Distributions

- Describes how the received signal amplitude changes with time.
  - Remember that the received signal is combination of multiple signals arriving from different directions, phases and amplitudes.
  - With the received signal we mean the baseband signal, namely the envelope of the received signal (i.e. r(t)).

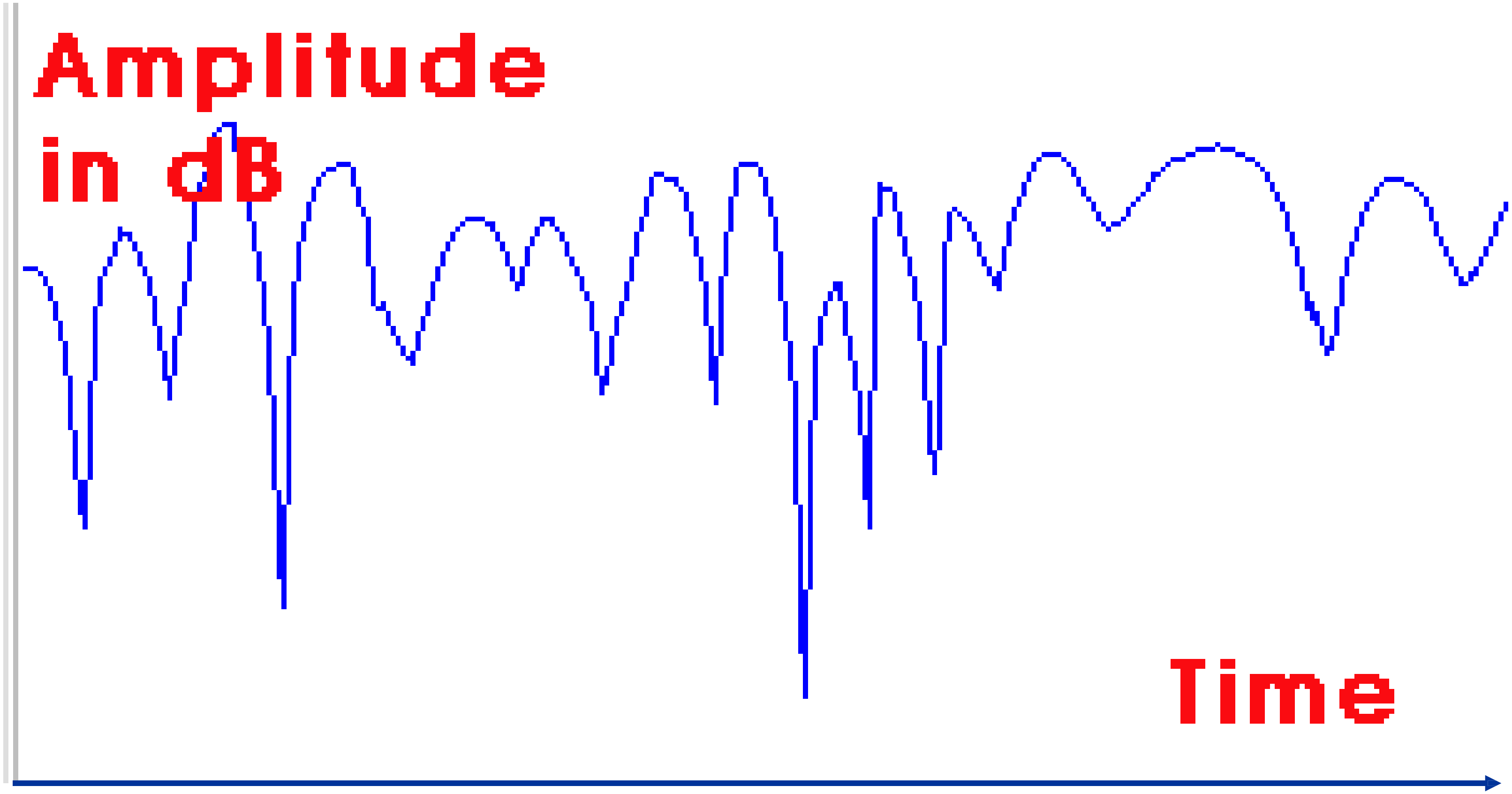
$$r(t) = \sum_{i=0}^{N-1} a_i \exp(j\theta_i(t,\tau))$$

- Its is a statistical characterization of the multipath fading.
- Two distributions
  - Rayleigh Fading
  - Ricean Fading

Rayleigh and Ricean Distributions

- Describes the received signal envelope distribution for channels, where all the components are non-LOS:
  - i.e. there is no line-of–sight (LOS) component.
- Describes the received signal envelope distribution for channels where one of the multipath components is LOS component.
  - i.e. there is one LOS component.

Rayleigh Fading



Rayleigh

- **Rayleigh distribution has the probability density function (PDF) given by:**

$$p(r) = \begin{cases} \dfrac{r}{\sigma^2} e^{\left(-\frac{r^2}{2\sigma^2}\right)} & (0 \le r \le \infty) \\ 0 & (r < 0) \end{cases}$$

- **σ^2 is the time average power of the received signal before envelope detection.**
- **σ is the rms value of the received voltage signal before envelope detection**

Rayleigh

The probability that the envelope of the received signal does not exceed a specified value of R is given by the CDF:

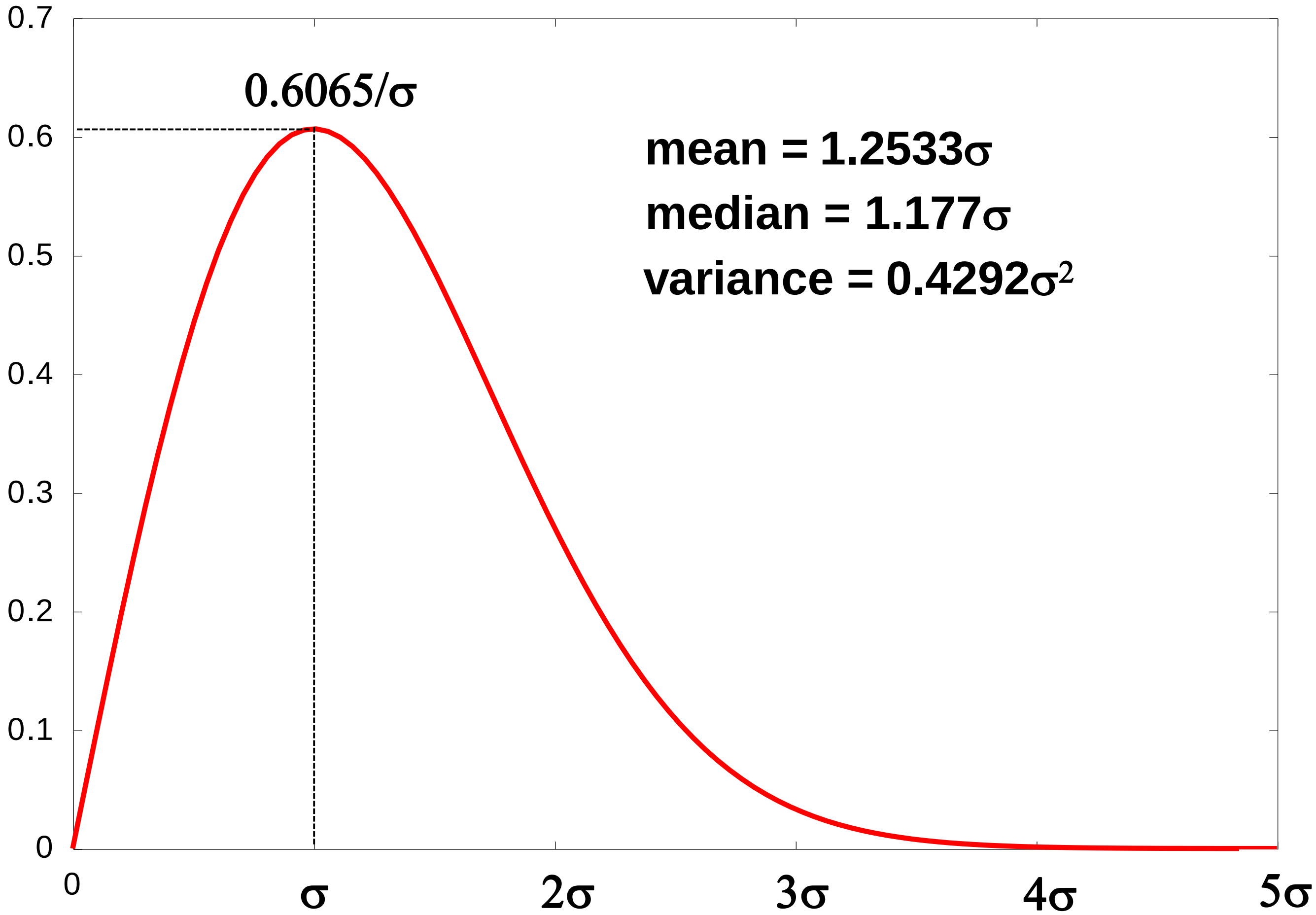
$$P(R) = P_r(r \le R) = \int_0^R p(r)dr = 1 - e^{-\frac{R^2}{2\sigma^2}}$$

$$r_{mean} = E[r] = \int_0^\infty rp(r)dr = \sigma\sqrt{\frac{\pi}{2}} = 1.2533\sigma$$

$r_{median} = 1.177\sigma$ found by solving $\frac{1}{2} = \int_0^{r_{median}} p(r)dr$

$$r_{rms} = \sqrt{2}\sigma$$

Rayleigh PDF

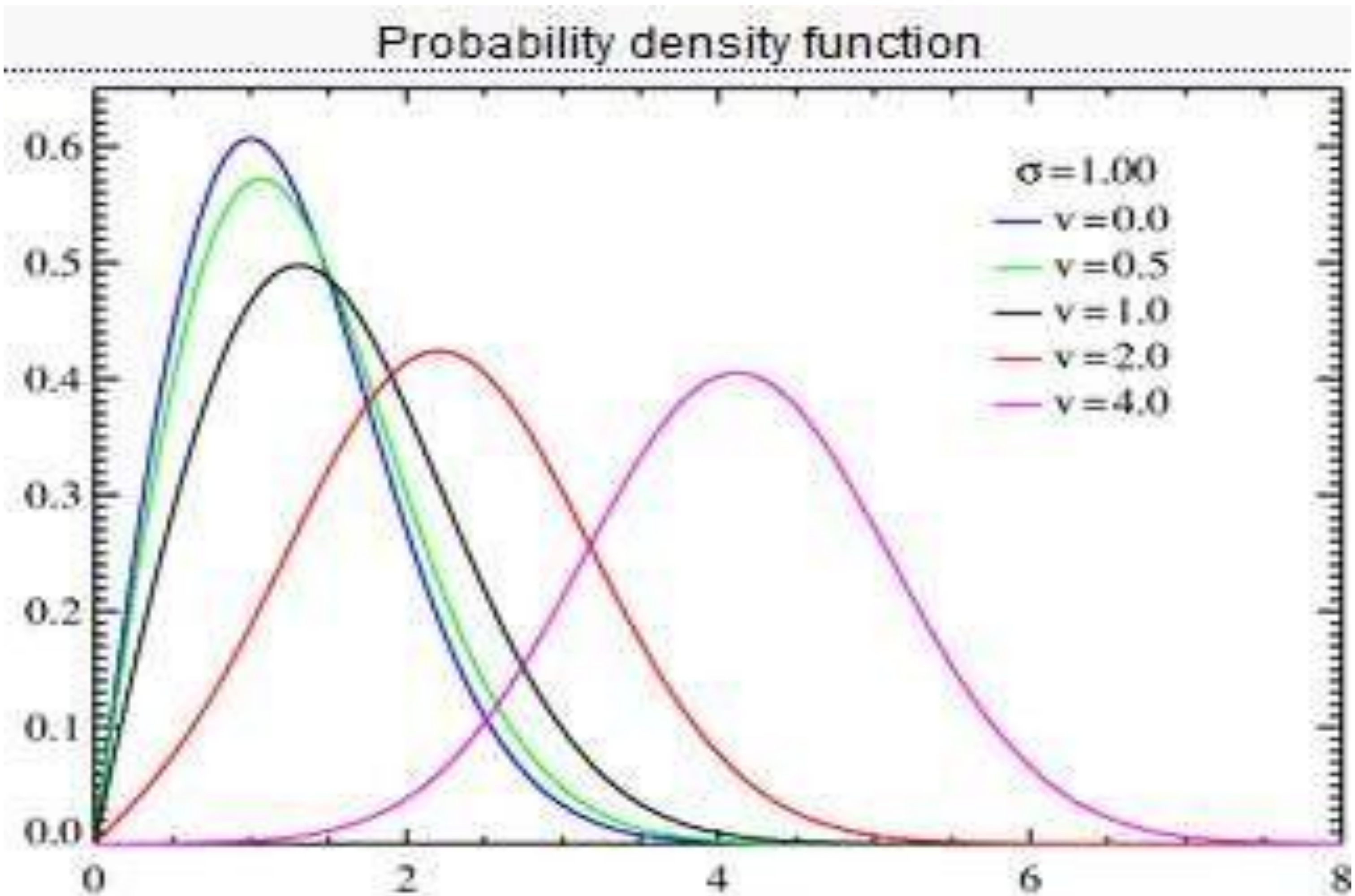


Ricean Distribution

- When there is a stationary (non-fading) LOS signal present, then the envelope distribution is Ricean.
- The Ricean distribution degenerates to Rayleigh when the dominant component fades away.
- The Pdf of Ricean function is given as

$$f(x \mid \nu, \sigma) = \frac{x}{\sigma^2} \exp\left(\frac{-(x^2+\nu^2)}{2\sigma^2}\right) I_0\left(\frac{x\nu}{\sigma^2}\right)$$

Ricean Distribution



Channel Impairments

1) ACI/CCI → system generated interference
   [ACI - Adjacent Channel Inteference,
   CCI - Co-channel Interference]

2) Shadowing → large-scale path loss from LOS obstructions

3) Multipath Fading → rapid small-scale signal variations

4) Doppler Spread → due to motion of mobile unit

Note:All can lead to significant distortion or attenuation of Rx signal
Degrade Bit Error Rate (BER) of digitally modulated signal

UNIT IV
EQUALIZATION AND DIVERSITY

EQUALIZATION AND DIVERSITY

- Three techniques are used to improve Rx signal quality and lower BER:

1) Equalization
2) Diversity
3) Channel Coding

- They can be used independently or combined

Diversity Techniques

Principle of Diversity

- Primary goal is to reduce depth & duration of small-scale fades
- To ensure that the same information reaches the receiver on statistically indeendent channels.

Types of Diversity

Spatial or antenna diversity → most common

- Use multiple Rx antennas in mobile or base station
- Even small antenna separation ($\propto \lambda$) changes phase of signal

→ constructive /destructive nature is changed

Other diversity types → polarization, frequency, & time diversity

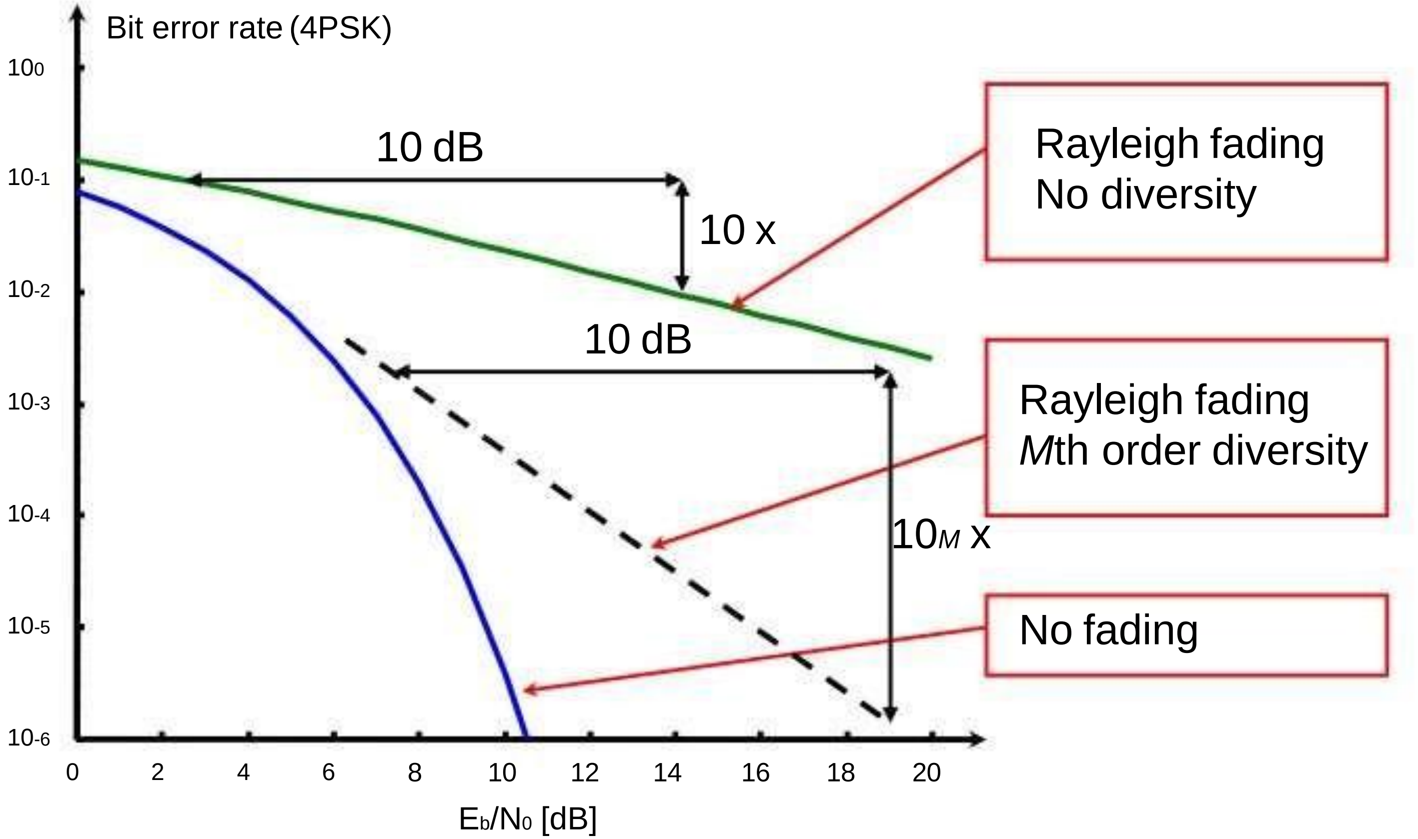
Diversity arrangements
The diversity principle

The principle of diversity is to transmit the same information on M statistically independent channels.

By doing this, we increase the chance that the information will be received properly.

The example given on the previous slide is one such arrangement: antenna diversity.

Diversity arrangements General improvement trend



Microscopic diversity

- Most widely used

- Combat small-scale fading (fading created by interference effects)

- Use multiple antennas separated in space

- At a mobile, signals are independent if separation > λ / 2

- But it is not practical to have a mobile with multiple antennas separated by λ / 2 (7.5cm apart at 2 GHz)

- Can have multiple receiving antennas at base stations, but must be separated on the order of ten wavelengths (1 to 5 meters).

Microscopic diversity

- Since reflections occur near receiver, independent signals spread out a lot before they reach the base station.

- a typical antenna configuration for 120 degree sectoring.

- For each sector, a transmit antenna is in the center, with two diversity receiving antennas on each side.

- If one radio path undergoes a deep fade, another independent path may have a strong signal.

- By having more than one path selection can be made, instantaneous and average SNRs at the receiver may be improved

Microscopic diversity Techniques

- Spatial Diversity (several antenna elemenst separated in space)

- Temporal Diversity (repetition of the transmit signal at different times)

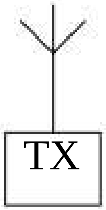
- Frequency Diversity (transmission of the signal on different frequencies)

- Angular Diversity (multiple antennas with different antenna patterns)

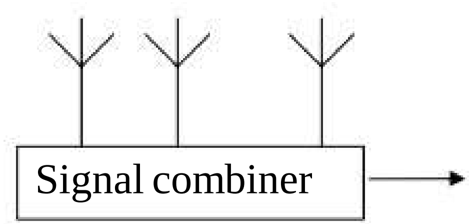
- Polarization Diversity (multiple antennas receiving different polarizations)

Diversity arrangements
Some techniques

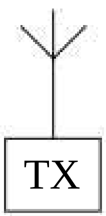
Spatial (antenna) diversity

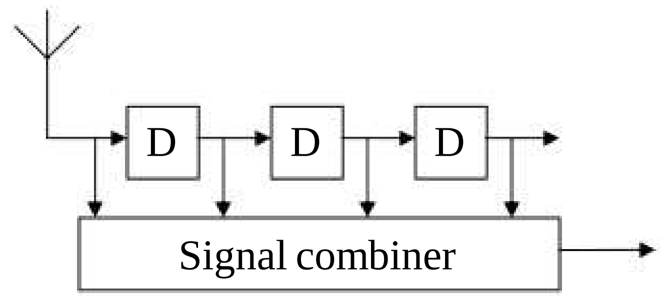


We will focus on this one today!



Frequency diversity

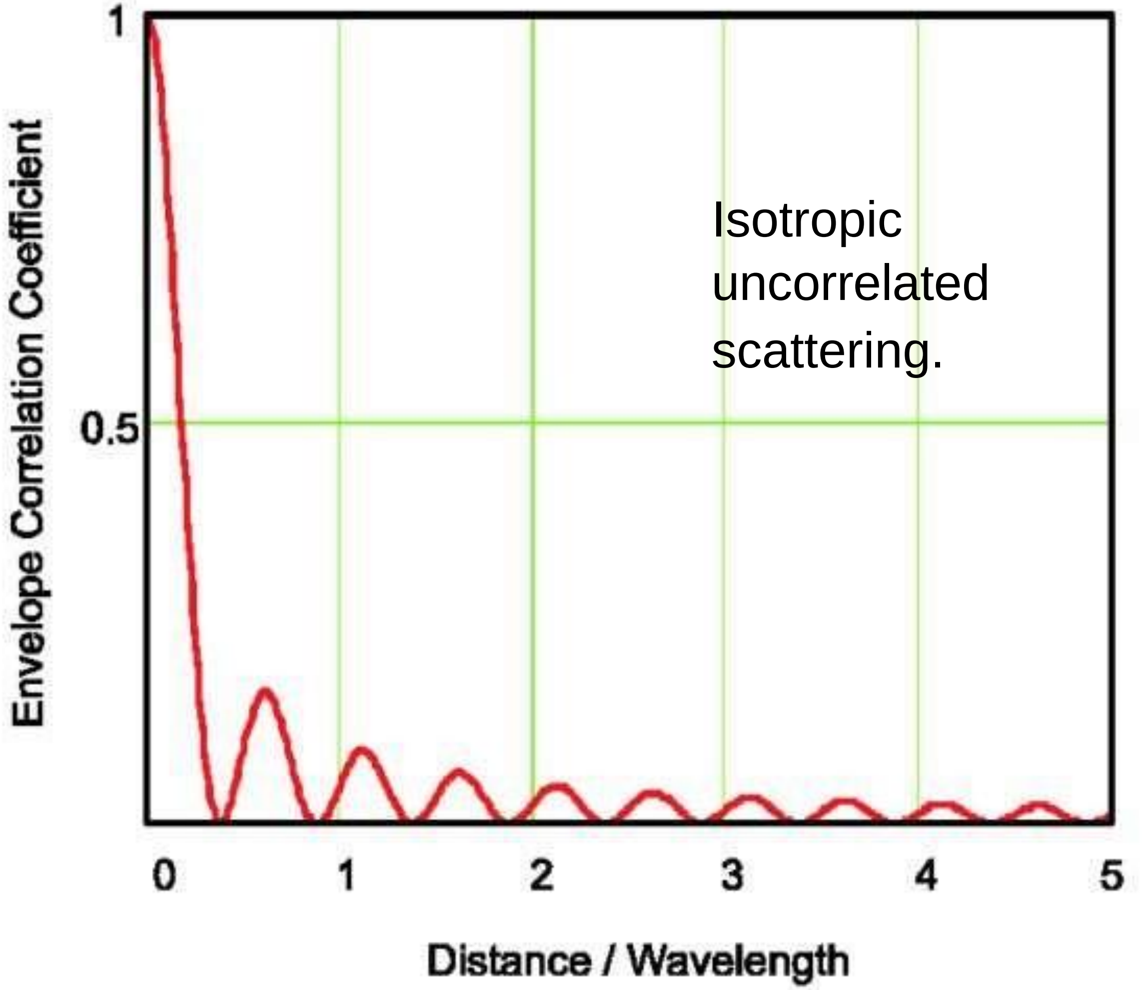




Temporal diversity

(We also have angular and polarization diversity)

Spatial (antenna) diversity
Fading correlation on antennas



Macroscopic diversity

- Combat large-scale fading (fading created by shadowing effects)

- Frequency diversity/Polarization Diversity/Spatial Diversity/ Temporal Diversity are not suitable here.

- If there is a hill in between Tx and Rx antennas on either the BS or MS does not help.

Macroscopic diversity (contd.)

-To solve the problem use a separate BS

- Large distance between BS1 and BS2 gives rise to macrodiversity.

-Use on-frequency repeaters (receive the signal and retransmit the amplified version). It is simpler as synchronization is not necessary but delay and dispersion are larger.

- Simulcast (same signal transmitted simultaneously from different BSs.)

- Simulcast widely used for broadcast applications like digital TV.

-Disadvantage of simulcast is the large amount of signaling information that has to be carried on landlines, synchronization information and transmit data have to be transported on landlines to BSs.

Signal Combining

- **Select** path with best *SNR* or **combine** multiple paths

→ improve overall *SNR* performance

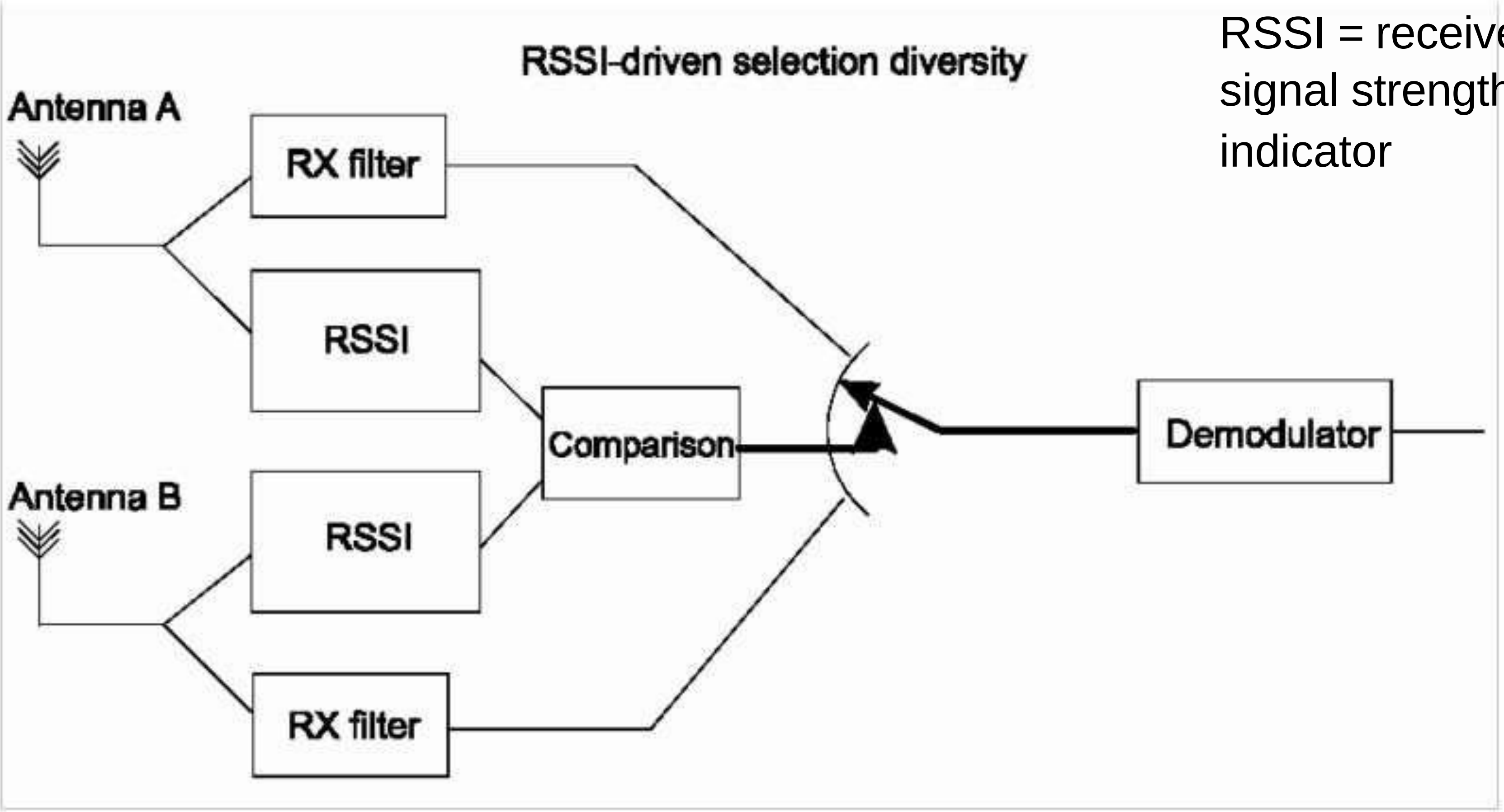
Selection diversity - 'Best' signal copy is selected and processed (demodulated and decoded) and all other copies are discarded

Combining Diversity - All signal copies are combined and combined signal decoded

Note: Combining diversity leads to better performance but Rx complexity higher than Selection Diversity.

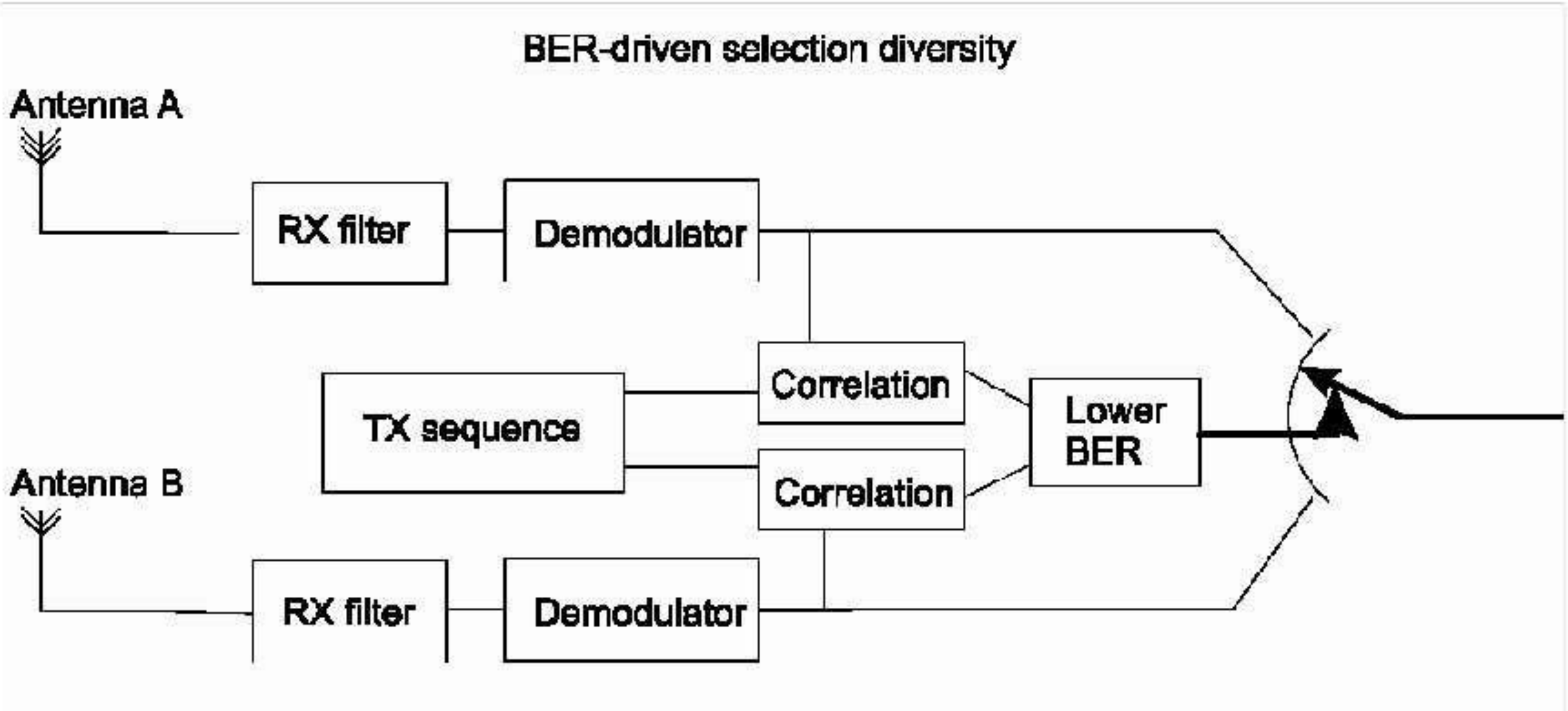
Gain of Multiple Antennas - Diversity Gain and Beamforming Gain.

Spatial (antenna) diversity
Selection diversity



RSSI = received signal strength indicator

Spatial (antenna) diversity
Selection diversity, cont.



Disadvantages of Selection Diversity

- Selection criteria (Power/BER) of all diversity branches monitored to select the best.

Alternately to reduce hardware cost and spectral inefficiency, switched diversity done.

Switched Diversity - Active branch monitored if signal strength falls below threshold Rx switches to a different antenna

Demerits

Works well if sufficient signal quality in one of the branches

If all branches signal strength < threshold then repeated switching

Free Parameters of Switched Diversity - switching threshold neither too low nor too high), hysteresis time (not too long or short)

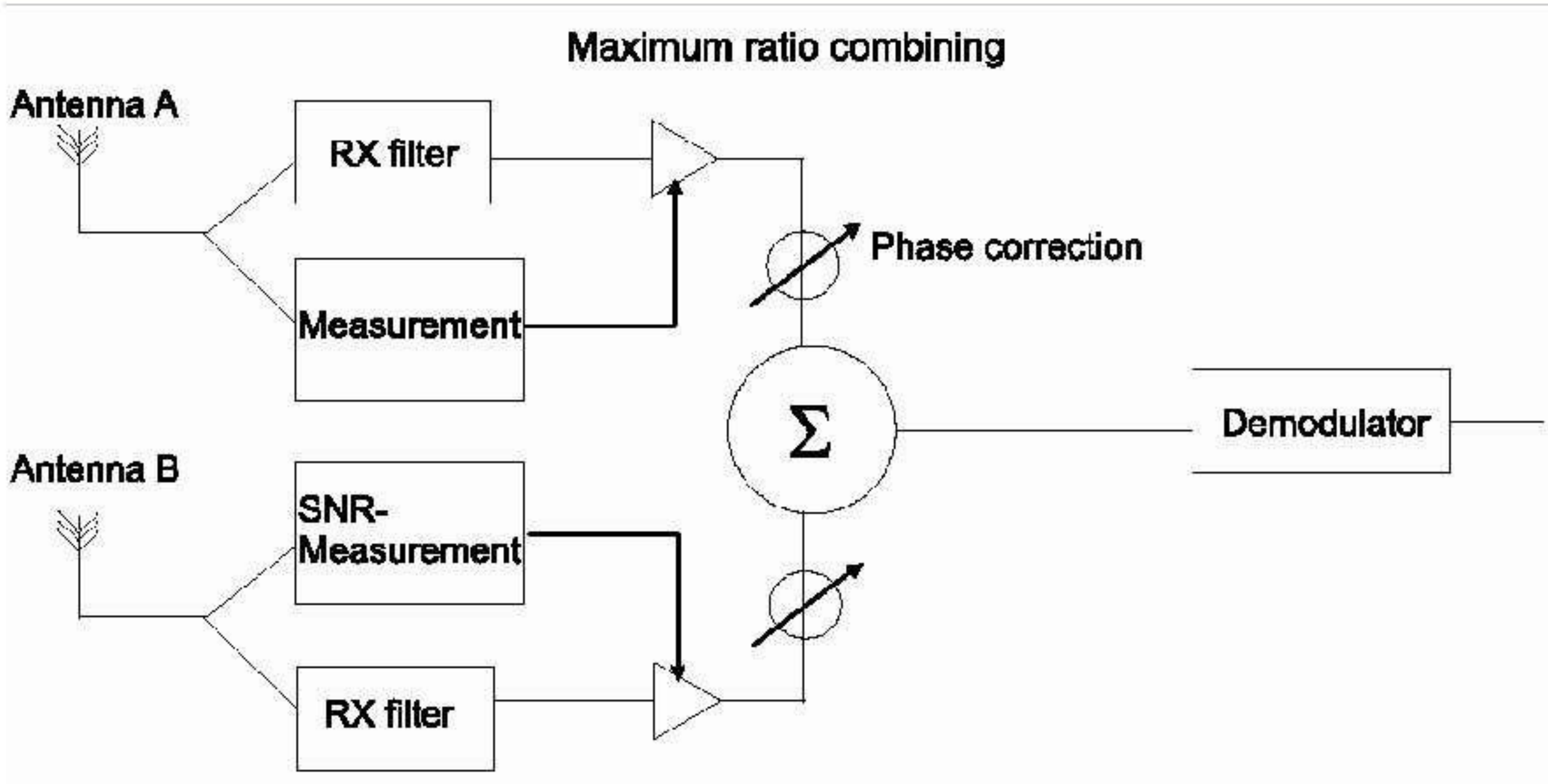
Disadvantages of Selection Diversity

Selection Diversity wastes signal energy by discarding M-1 copies of Rxd signal

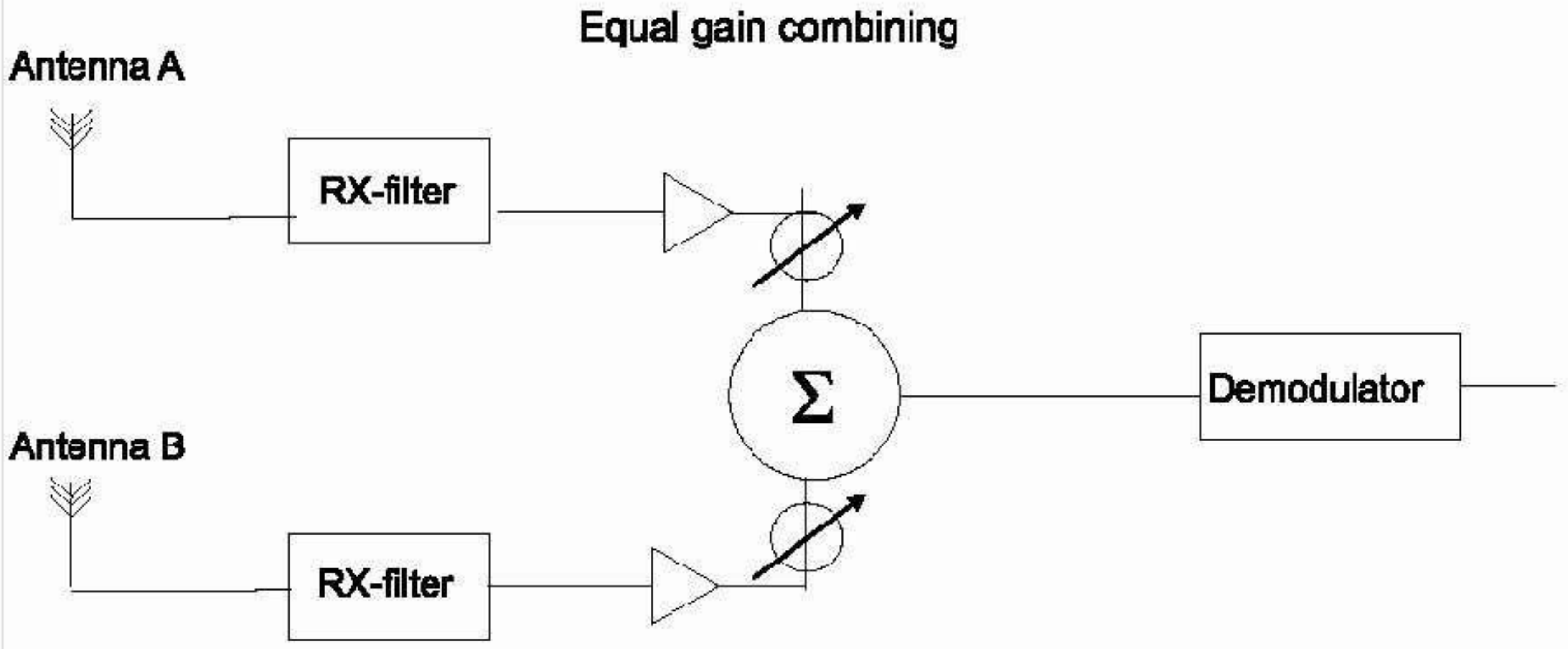
Combining Diversity - All branches are considered

Combining Diversity Types - Maximal Ratio Combining, Equal Gain Combining

Spatial (antenna) diversity
Maximum ratio combining



Spatial (antenna) diversity

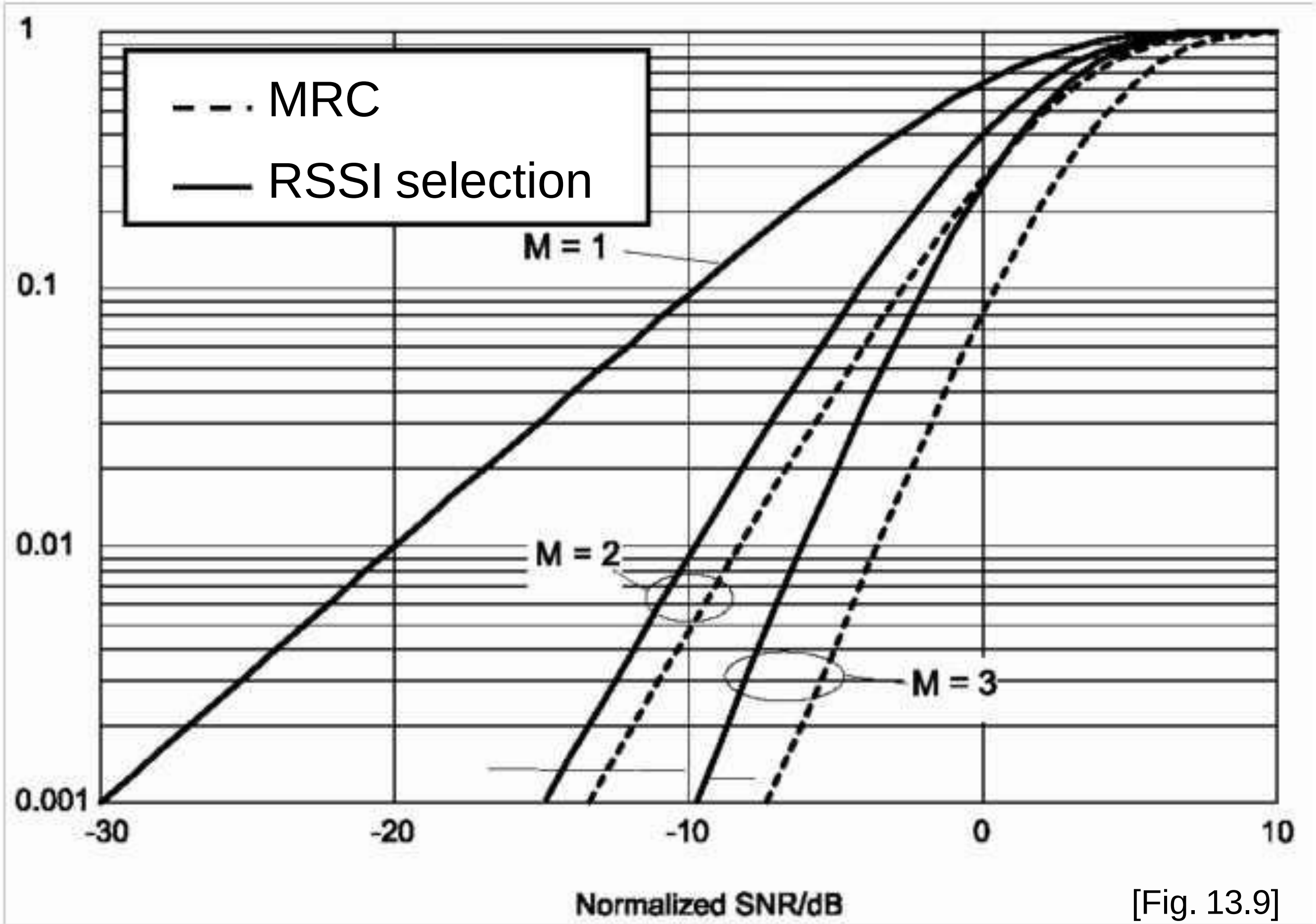


Spatial (antenna) diversity
Performance comparison

Cumulative distribution of SNR

Comparison of SNR distribution

for different number of antennas M and two different diversity techniques.



[Fig. 13.9]

Spatial (Antenna) Diversity

- Spatial or Antenna Diversity
  - *M* independent branches
  - Variable gain & phase at each branch → *G*∠ θ
  - Each branch has same average *SNR*:

$$SNR = \Gamma = \frac{E_b}{N_0}$$

  - Instantaneous $SNR = \gamma_i$ γ_i
  - the pdf of γ_i

$$\Pr[\gamma_i \le \gamma] = \int_0^{\gamma} p(\gamma_i)\,d\gamma_i = \int_0^{\gamma} \frac{1}{\Gamma} e^{\frac{-\gamma_i}{\Gamma}}\,d\gamma_i = 1 - e^{\frac{-\gamma}{\Gamma}}$$

Spatial (Antenna) Diversity

- The probability that all M independent diversity branches Rx signal which are simultaneously less than some specific SNR threshold γ

$$\Pr[\gamma_1, \ldots \gamma_M \le \gamma] = (1 - e^{-\gamma/\Gamma})^M = P_M(\gamma)$$

$$\Pr[\gamma_i > \gamma] = 1 - P_M(\gamma) = 1 - (1 - e^{-\gamma/\Gamma})^M$$

- The pdf of γ : $$p_M(\gamma) = \frac{d}{d\gamma} P_M(\gamma) = \frac{M}{\Gamma}\left(1 - e^{-\gamma/\Gamma}\right)^{M-1} e^{-\gamma/\Gamma}$$
- Average SNR improvement offered by selection diversity

$$\bar{\gamma} = \int_0^\infty \gamma p_M(\gamma) d\gamma = \Gamma \int_0^\infty Mx\left(1 - e^{-x}\right)^{M-1} e^{-x} dx, \quad x = \gamma/\Gamma$$

$$\frac{\bar{\gamma}}{\Gamma} = \sum_{k=1}^{M} \frac{1}{k}$$

Spatial (antenna) diversity
Performance comparison

Comparison of SNR distribution for different number of antennas M

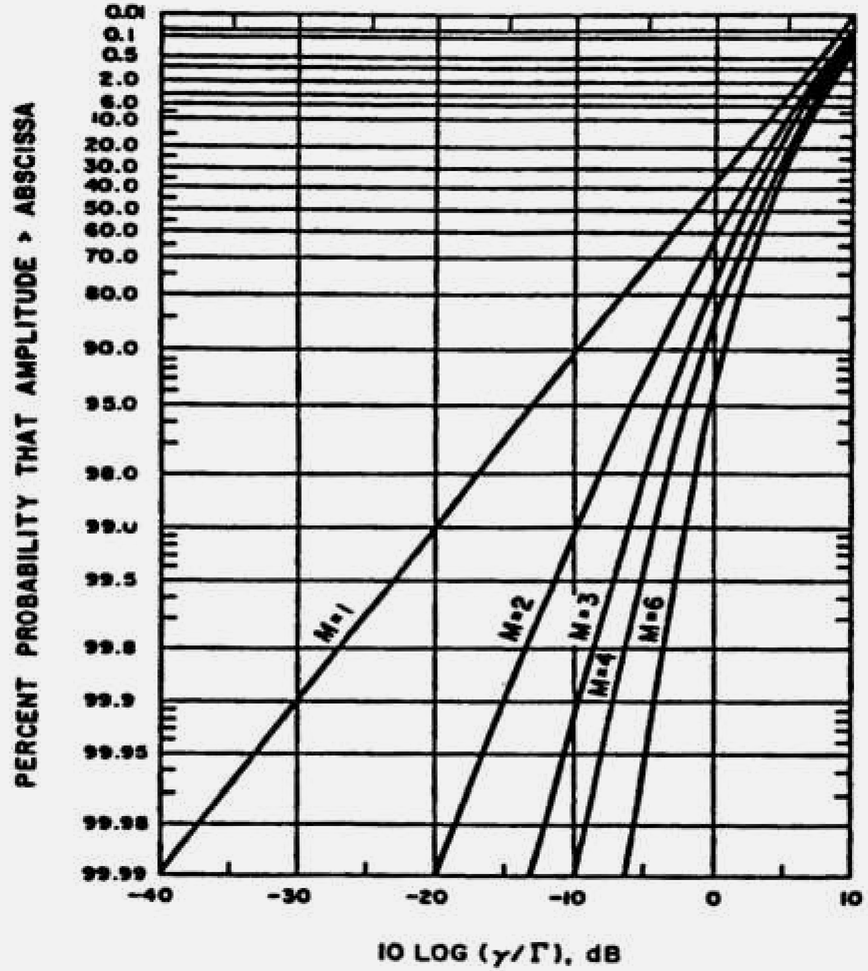
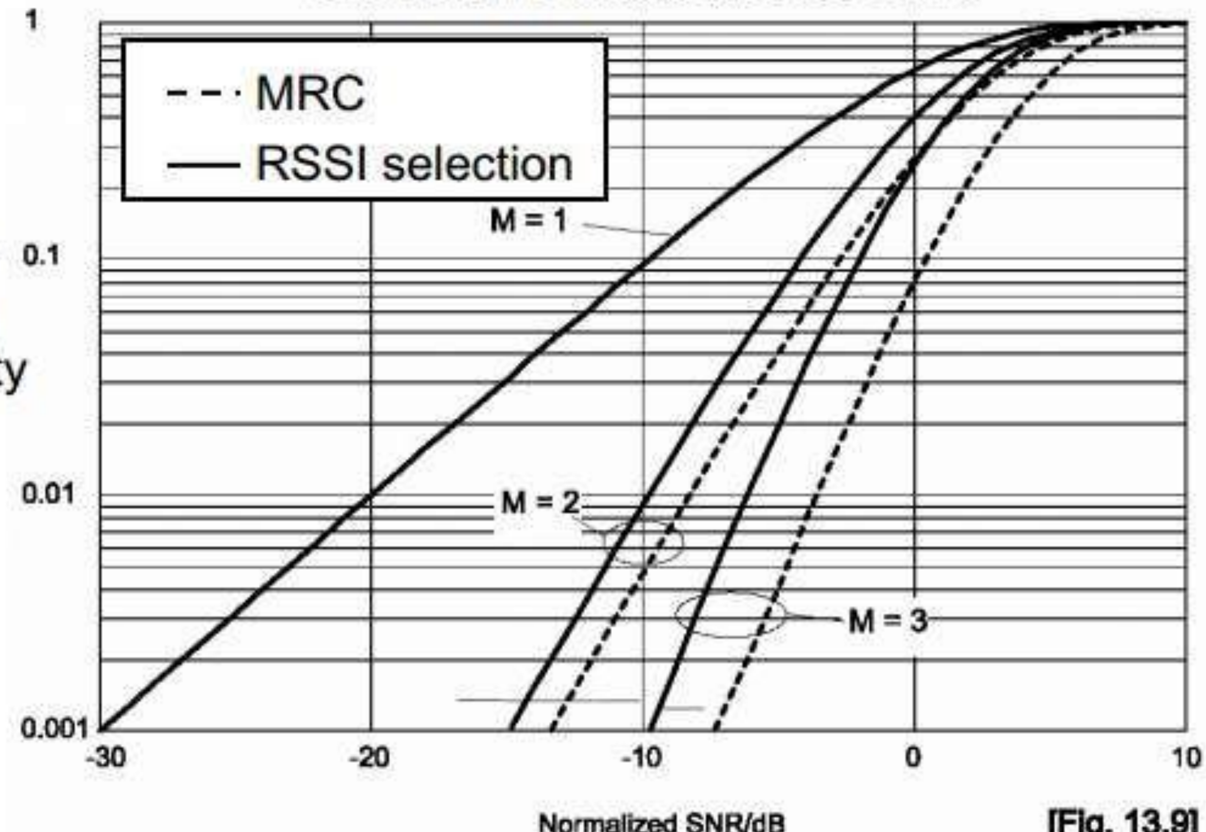


Figure 7.11 Graph of probability distributions of *SNR* = γ threshold for *M* branch selection diversity. The term Γ represents the mean *SNR* on each branch [from [Jak71] © IEEE].

Spatial (antenna) diversity
Performance comparison

Comparison of SNR distribution for different number of antennas *M* and two different diversity techniques.

Cumulative distribution of SNR



[Fig. 13.9]

Space diversity types/methods:

1) Selection diversity

2) Feedback diversity

3) Maximal radio combining

4) Equal gain diversity

Selection diversity Technique

Selection Diversity → simple & cheap

– Rx selects branch with highest **instantaneous** *SNR*

- new selection made at a time that is the reciprocal of the fading rate
- this will cause the system to stay with the current signal until it is likely the signal has faded

– *SNR* improvement :

- γ is new avg. *SNR*
- Γ : avg. *SNR* in each branch

$$\bar{\gamma} = \Gamma \sum_{k=1}^{m} \frac{1}{k} = \Gamma\left(1 + \frac{1}{2} + \frac{1}{3} + \frac{1}{4} + \cdots + \frac{1}{m}\right) > \Gamma$$

Selection Diversity Technique (Contd.):

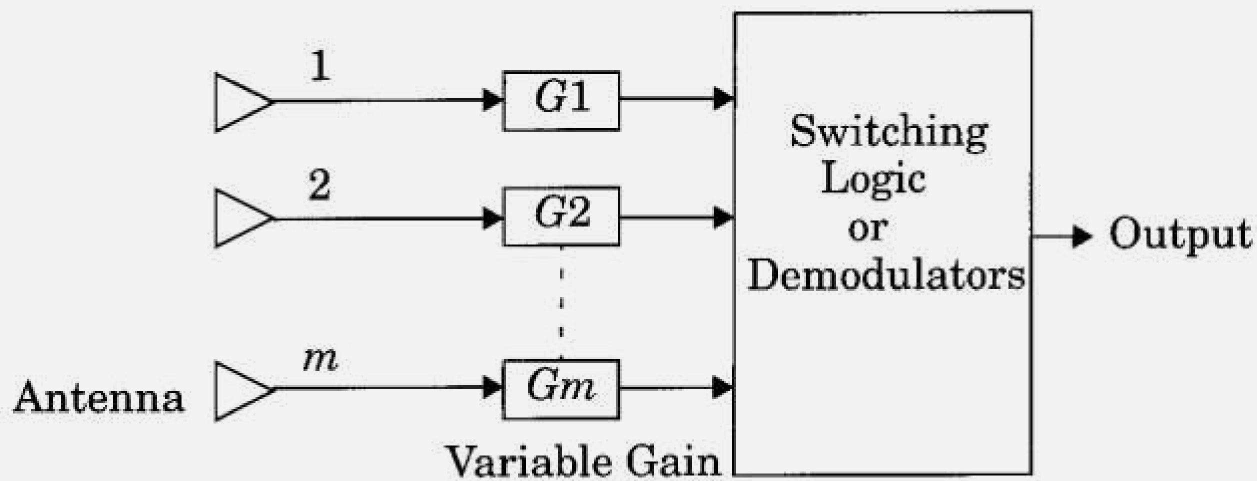


Figure 7.12 Generalized block diagram for space diversity.

Scanning/Feedback Diversity

Scanning/Feedback Diversity

- scan each antenna until a signal is found that is above predetermined threshold
- if signal drops below threshold → rescan
- only one Rx is required (since only receiving one signal at a time), so less costly → still need multiple antennas

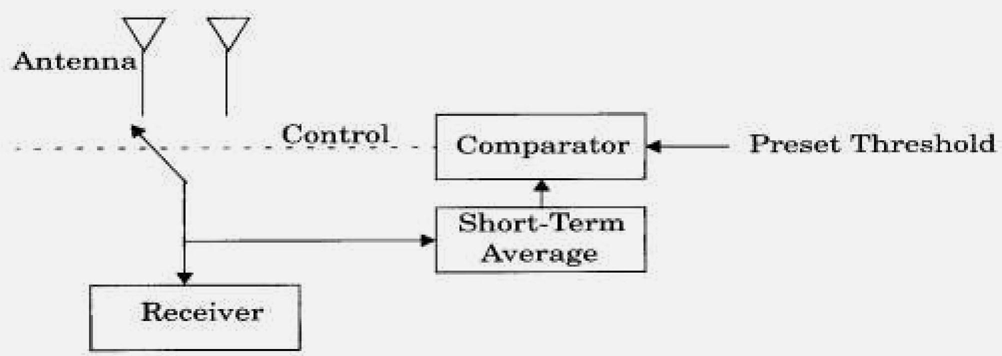


Figure 7.13 Basic form of scanning diversity.

Maximal Ratio Combiner Diversity

- signal amplitudes are weighted according to each *SNR*
- summed **in-phase**
- most complex of all types
- a complicated mechanism, but modern DSP makes this more practical → especially in the base station Rx where battery power to perform computations is not an issue

Maximal Ratio Combiner Diversity

The resulting signal envelop applied to detector:

$$r_M = \sum_{i=1}^{M} G_i r_i$$

Total noise power:

$$N_T = N \sum_{i=1}^{M} G_i^2$$

SNR applied to detector:

$$\gamma_M = \frac{r_M^2}{2N_T}$$

Maximal Ratio Combiner Diversity

The voltage signals from each of the M diversity branches are co-phased to provide coherent voltage addition and are individually weighted to provide optimal SNR

$$\gamma_M = \frac{1}{2}\frac{\sum (r_i^2/N)^2}{N\sum (r_i^2/N^2)} = \frac{1}{2}\sum_{i=1}^{M}\frac{r_i^2}{N} = \sum_{i=1}^{M}\gamma_i$$

(r_M is maximized when $G_i \propto r_i / N$)

The SNR out of the diversity combiner is the sum of the SNRs in each branch.

Maximal Ratio Combiner Diversity

The probability that less than some specific SNR threshold γ

$$p(\gamma_M) = \frac{\gamma_M^{M-1} e^{-\gamma_M/\Gamma}}{\Gamma^M (M-1)!} \qquad \text{for } \gamma_M \geq 0$$

$$Pr\{\gamma_M \leq \gamma\} = \int_0^{\gamma} p(\gamma_M)\, d\gamma_M = 1 - e^{-\gamma/\Gamma} \sum_{k=1}^{M} \frac{(\gamma/\Gamma)^{k-1}}{(k-1)!}$$

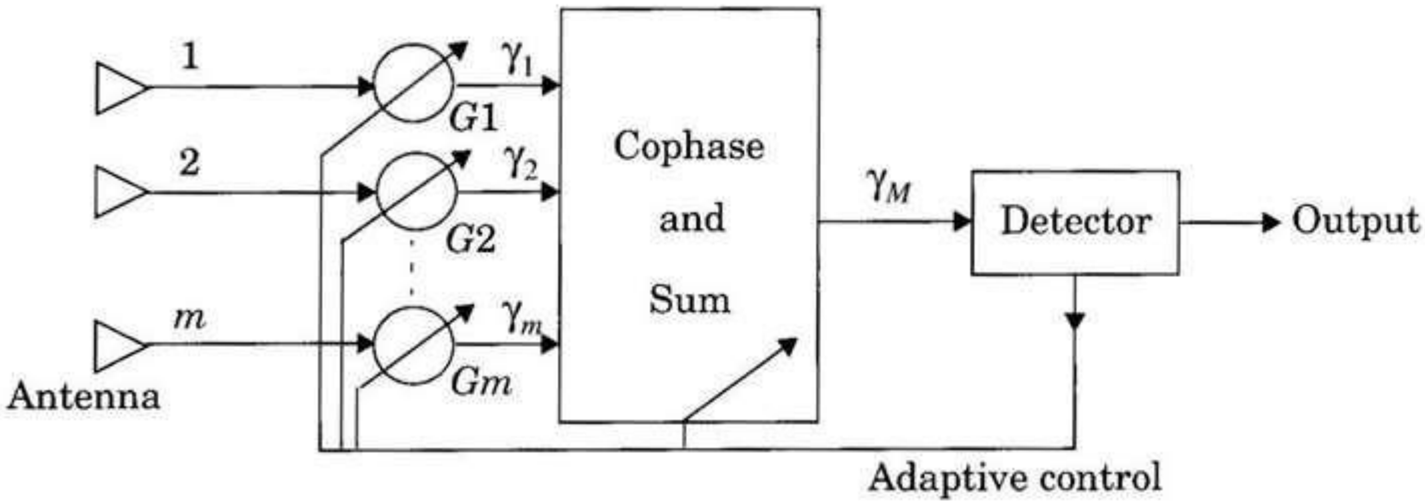
gives **optimal** *SNR* improvement :

Γ$_i$: avg. *SNR* of each individual branch

Γ$_i$ = **Γ** if the avg. *SNR* is the same for each branch

$$\overline{\gamma_M} = \sum_{i=1}^{M} \overline{\gamma_i} = \sum_{i=1}^{M} \Gamma_i = M\Gamma$$

Maximal Ratio Combiner Diversity



Maximal ratio combiner.

Equal Gain Combining Diversity

- Combine multiple signals into one
- G = 1, but the phase is adjusted for each received signal.
- The signal from each branch are co-phased vectors add in-phase.
- Better performance than selection diversity

Transmit Diversity

- Multiple antennas installed at just one link (usually at BS)

- Uplink transmission from MS to BS - multiple antennas act as Rx diversity branches

- For downlink diversity branches originate at Txr.

- Transmit Diversity with channel-state information

- Transmit Diversity without channel-state information

Time Diversity

- Time Diversity → transmit repeatedly the information at different time spacings

- Time spacing > coherence time (coherence time is the time over which a fading signal can be considered to have similar characteristics)

- So signals can be considered independent

- Main disadvantage is that BW efficiency is significantly worsened – signal is transmitted more than once BW must ↑ to obtain the **same** R_d (data rate)

Note: If data stream repeated twice then either BW doubles for the same R_d **or** R_d is reduced by ½ for the same BW

Time Diversity - RAKE Receiver

- Powerful form of time diversity available in spread spectrum (DS) systems → CDMA
- Signal is transmitted only once
- Propagation delays in the MRC provide multiple copies of Tx signals **delayed** in time
- If time delay between multiple signals > chip period of spreading sequence (T_c) → multipath signals can be considered uncorrelated (independent)
- In a basic system, these delayed signals only appear as noise, since they are delayed by more than a chip duration and ignored.
- Multiplying by the chip code results in noise because of the time shift.
- But this can be used to our advantage by shifting the chip sequence to receive that delayed signal separately from the other signals.

Time Diversity - RAKE Receiver

- attempts to collect the time-shifted versions of the original signal by providing a separate correlation receiver for each of the multipath signals.

- Each correlation receiver may be adjusted in time delay, so that a microprocessor controller can cause different correlation receivers to search in different time windows for significant multipath.

- The range of time delays that a particular correlator can search is called a *search window*.

Time Diversity - RAKE Receiver

The RAKE Rx is a time diversity Rx that collects time-shifted versions of the original Tx signal

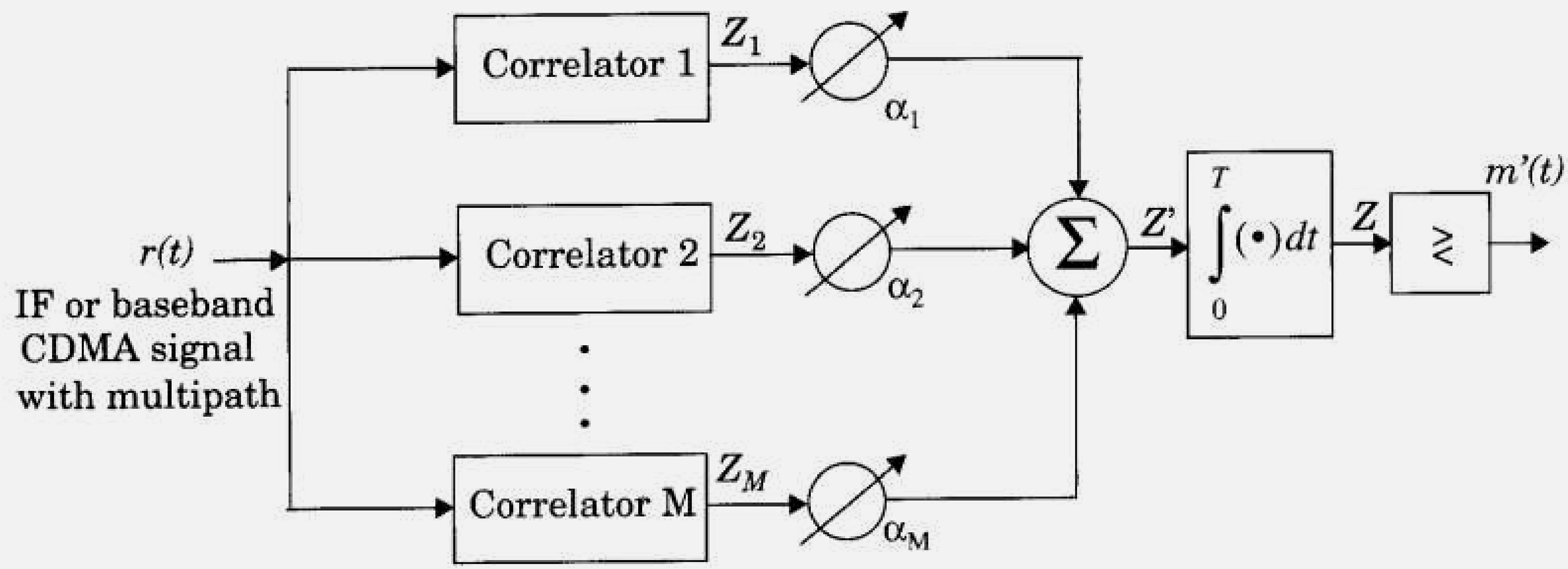


Figure 7.16 An *M*-branch (*M*-finger) RAKE receiver implementation. Each correlator detects a time shifted version of the original CDMA transmission, and each finger of the RAKE correlates to a portion of the signal which is delayed by at least one chip in time from the other fingers.

Time Diversity - RAKE Receiver

The RAKE Rx is a time diversity Rx that collects time-shifted versions of the original Tx signal

M branches or “fingers” of correlation Rx’s

Separately detect the M strongest signals

Weighted sum computed from M branches

faded signal $\rightarrow$ low weight

strong signal $\rightarrow$ high weight

overcomes fading of a signal in a single branch

SNR statistics for diversity receivers

- Selection combining: easiest to compute cdf

$$cdf_\gamma(\gamma) = \left[1 - \exp(-\tfrac{\gamma}{\bar{\gamma}})\right]^{N_r}.$$

- Maximum ratio combining:

$$pdf_\gamma(\gamma) = \frac{1}{(N_r-1)!}\frac{\gamma^{N_r-1}}{\bar{\gamma}^{N_r}}\exp\left(-\frac{\gamma}{\bar{\gamma}}\right).$$

BER of diversity receivers

- Classical computation method: average BER over distribution of SNR output

$$\overline{SER} = \int_0^\infty pdf_\gamma(\gamma) SER(\gamma) d\gamma$$

- Use SNR distribution from previous slides
- For MRC and large SNR

$$\overline{BER} \approx \left(\frac{1}{4\bar{\gamma}}\right)^{N_r} \binom{2N_r - 1}{N_r}$$

Computation via moment-generating function

- BER in AWNG can be written as

$$SER(\gamma) = \int_{\theta_1}^{\theta_2} f_1(\theta) \prod_{i=1}^{N_r} \exp(-\gamma_n f_2(\theta)) d\theta$$

- Averaging over SNR distribution

$$\overline{SER} = \int d\gamma_1 pdf_{\gamma_1}(\gamma_1) \int d\gamma_2 pdf_{\gamma_2}(\gamma_2) \ldots \int d\gamma_{N_r} pdf_{\gamma_{N_r}}(\gamma_{N_r}) \int_{\theta_1}^{\theta_2} d\theta\, f_1(\theta) \prod_{i=1}^{N_r} \exp(-\gamma_n f_2(\theta))$$

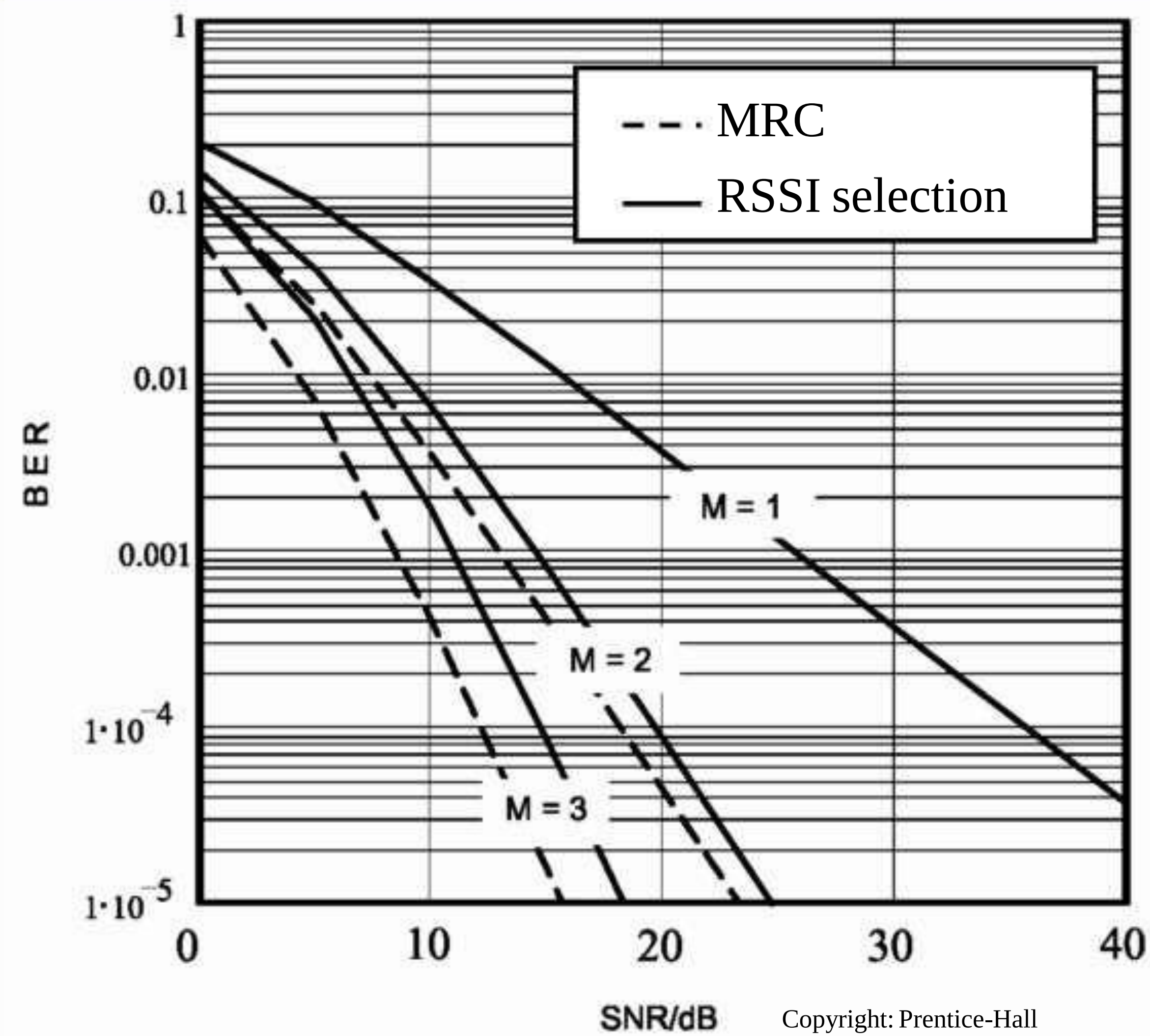
$$= \int_{\theta_1}^{\theta_2} d\theta\, f_1(\theta) \prod_{i=1}^{N_r} \int d\gamma_n pdf_{\gamma_n}(\gamma_n) \exp(-\gamma_n f_2(\theta))$$

$$= \int_{\theta_1}^{\theta_2} d\theta\, f_1(\theta) \prod_{i=1}^{N_r} M_\gamma(-f_2(\theta))$$

$$= \int_{\theta_1}^{\theta_2} d\theta\, f_1(\theta) [M_\gamma(-f_2(\theta))]^{N_r}$$

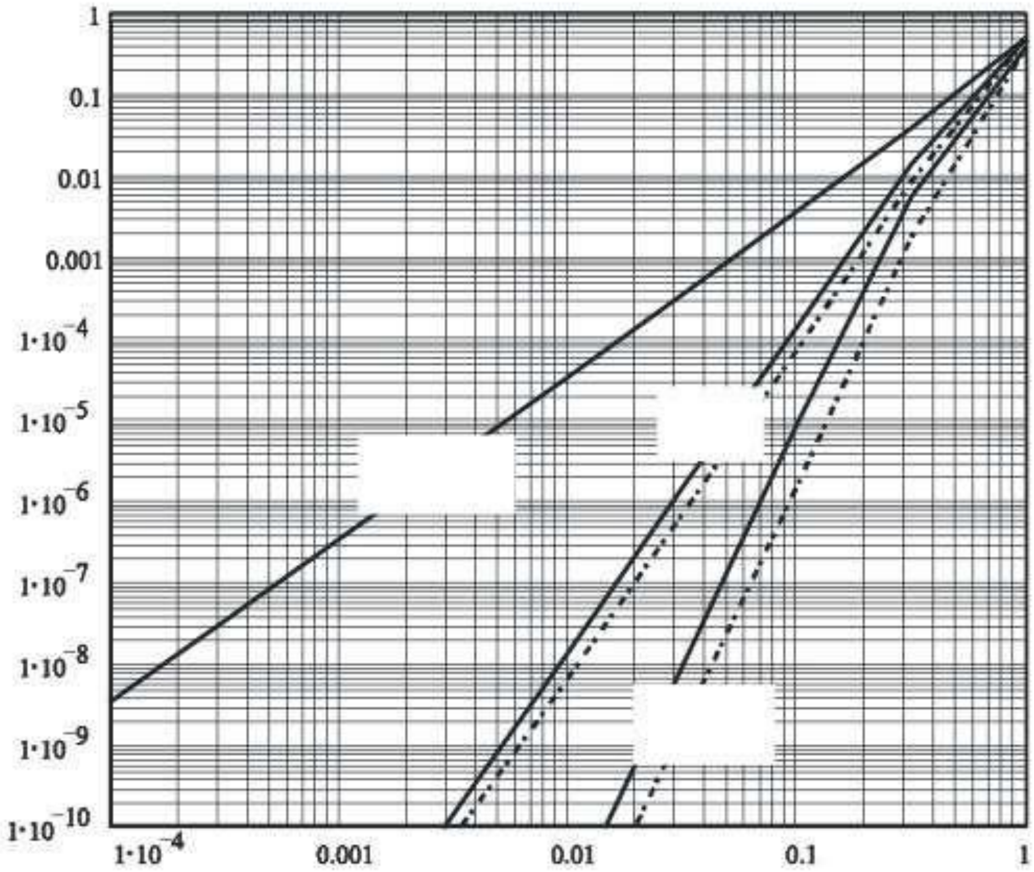
Spatial (antenna) diversity
Performance comparison, cont.

Comparison of 2ASK/2PSK BER for different number of antennas M and two different diversity techniques.



Spatial (antenna) diversity
Errors due to signal distortion

Comparison of 2ASK/2PSK BER for different number of antennas M and two different diversity techniques.



Optimum combining in flat-fading channel

- Most systems interference limited
- OC reduces not only fading but also interference
- Each antenna can eliminate one interferer or give one diversity degree for fading reduction:

 ("zero-forcing").
- MMSE or decision-feedback gives even better results
- Computation of weights for combining

$$\mathbf{w}_{opt} = \mathbf{R}^{-1}\mathbf{h}_d \qquad \mathbf{R} = \sigma^2\mathbf{I} + \sum_{k=1}^{K} E\left(\mathbf{r}\,\mathbf{r}^T\right)$$

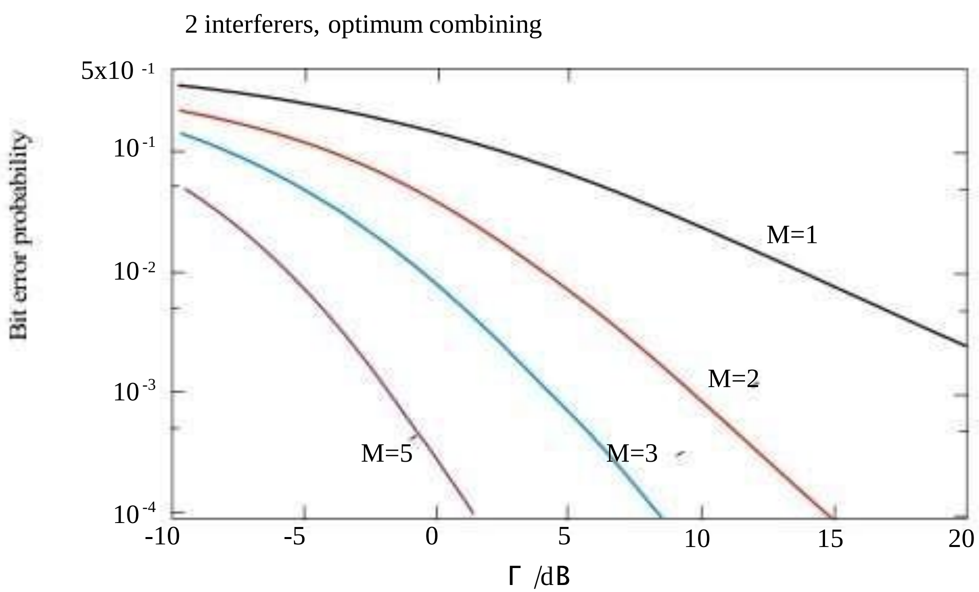
Performance of Optimum Combining

- Define channel matrix H:
  H_{km} is transfer function for
  k-th user to m-th diversity
  antenna
- Error of BPSK, QPSK for one channel constellation bounded as

$$BER_{static} \leq \exp\left[-\boldsymbol{h}_d^H \boldsymbol{R}_{ni}^{-1} \boldsymbol{h}_d\right]$$

- average behavior:

$$BER \leq \left[1+SNR\right]^{-(M-K)}$$



From Winters 1984,

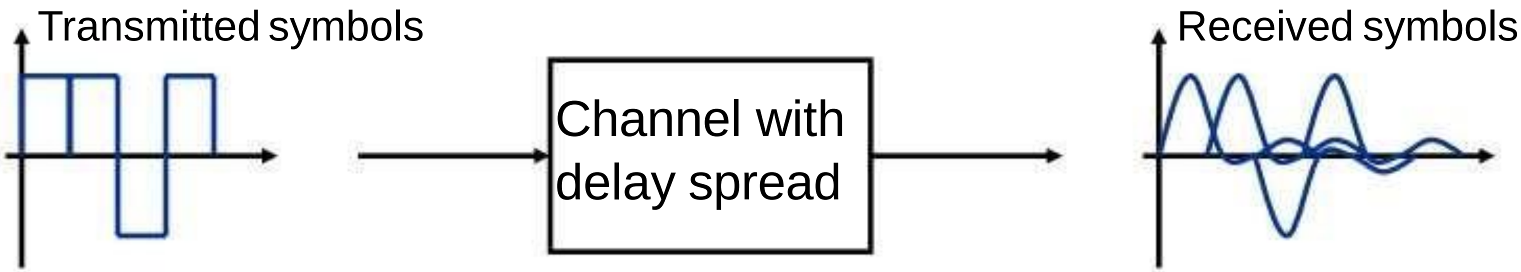
Equalization

Contents

- Inter-symbol interference
- Linear equalizers
- Decision-feedback equalizers
- Maximum-likelihood sequence estimation

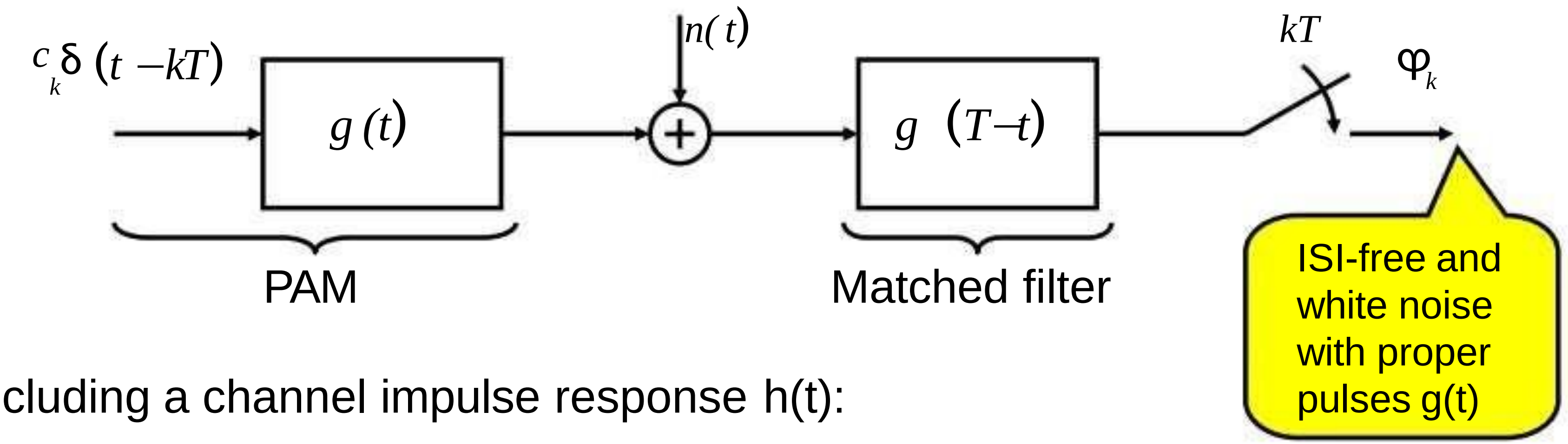
INTER-SYMBOL INTERFERENCE

Inter-symbol interference - Background

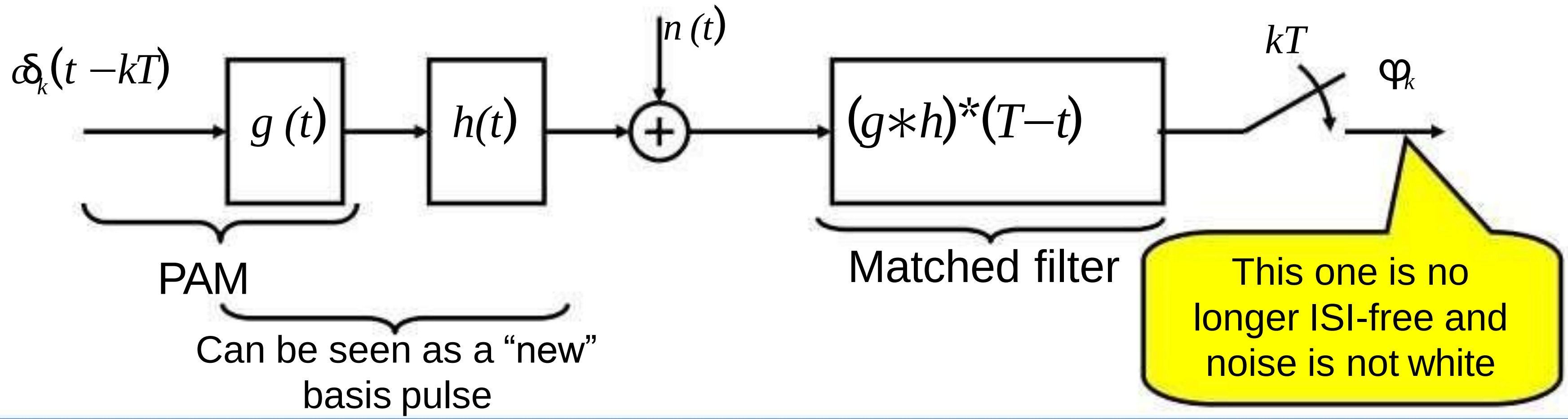


Modeling of channel impulse response

What we have used so far (PAM and optimal receiver):

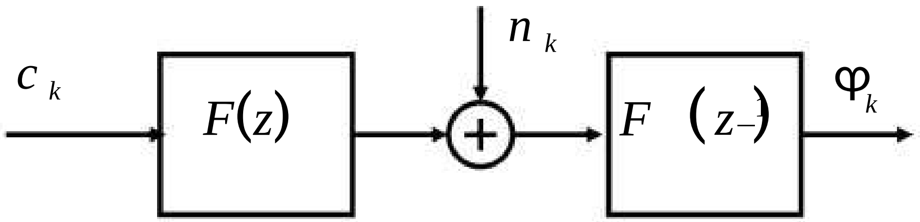


Including a channel impulse response h(t):



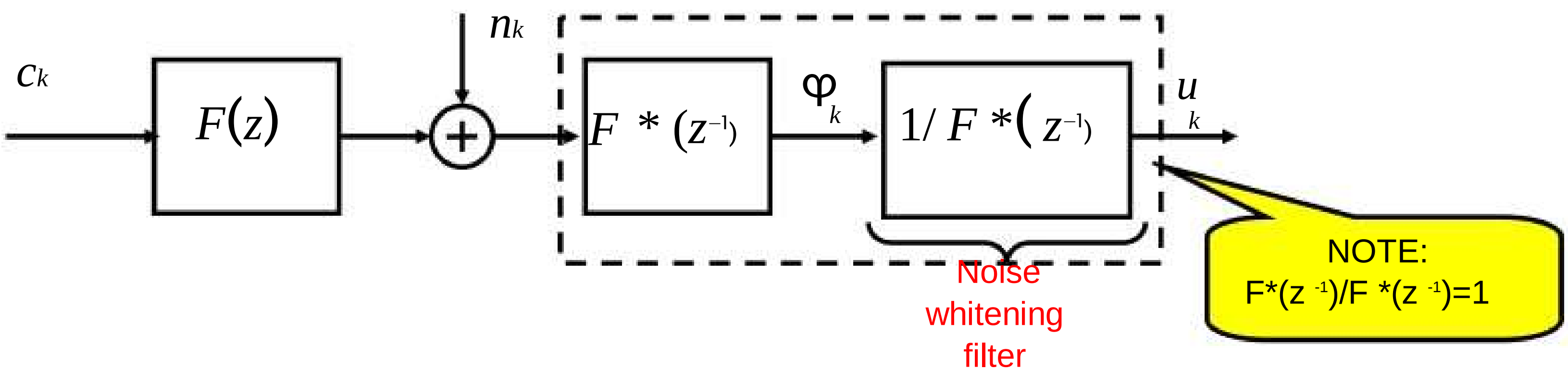
Modeling of channel impulse response

We can create a discrete time equivalent of the “new” system:



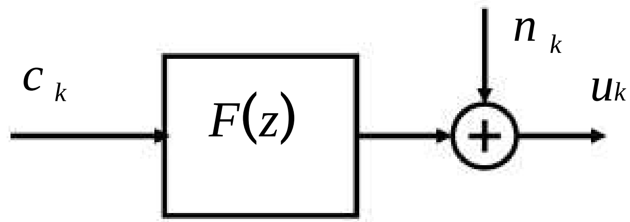
where we can say that F(z) represent the basis pulse and channel, while $F^*(z^{-1})$ represent the matched filter. (This is an abuse of signal theory!)

We can now achieve white noise quite easily, if (the not unique) F(z) is chosen wisely ($F^*(z^{-1})$ has a stable inverse) :



The discrete-time channel model

With the application of a noise-whitening filter, we arrive at a discrete-time model



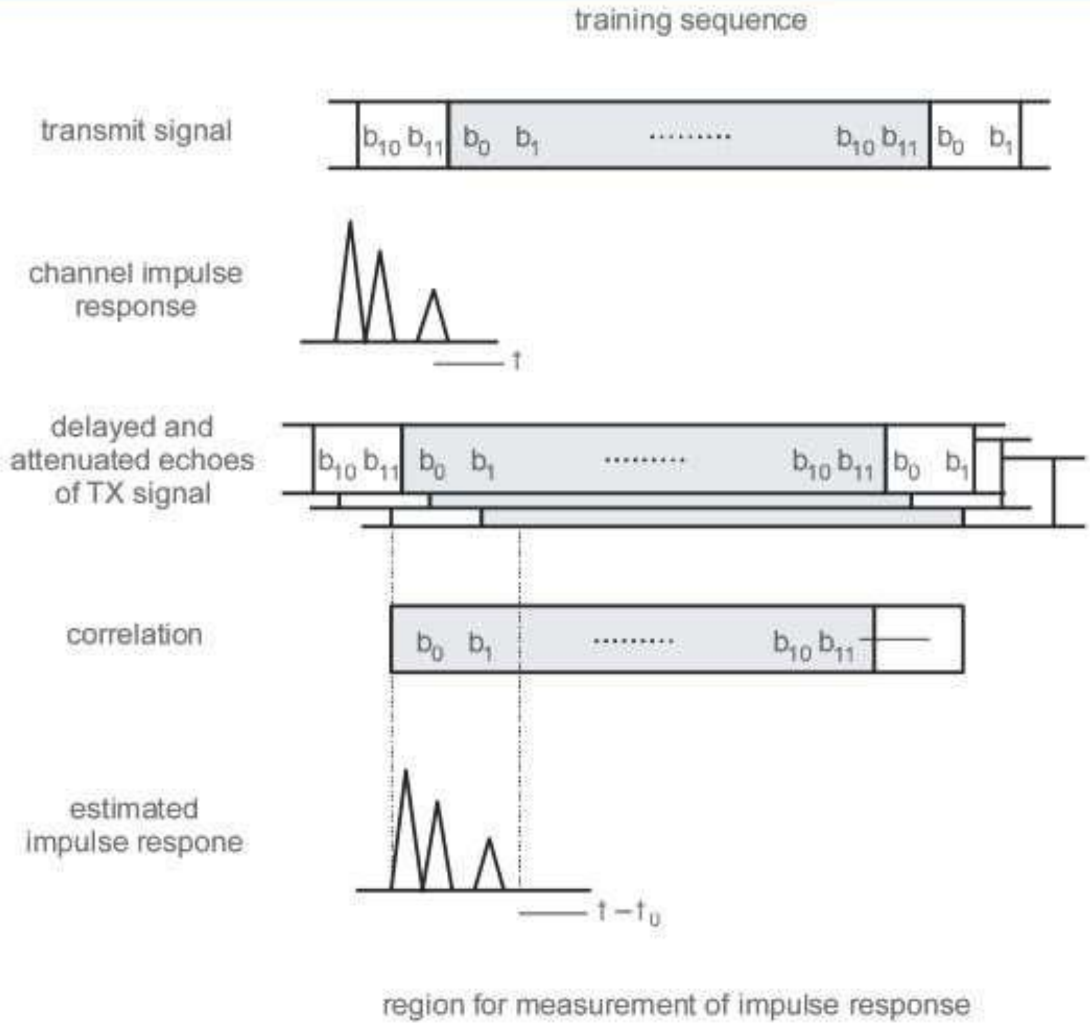
where we have ISI and white additive noise, in the form

$$u_k = \sum_{j=0}^{L} f_j c_{k-j} + n_k$$

This is the model we are going to use when designing equalizers.

The coefficients f_j represent the causal impulse response of the discrete-time equivalent of the channel F(z), with an ISI that extends over L symbols.

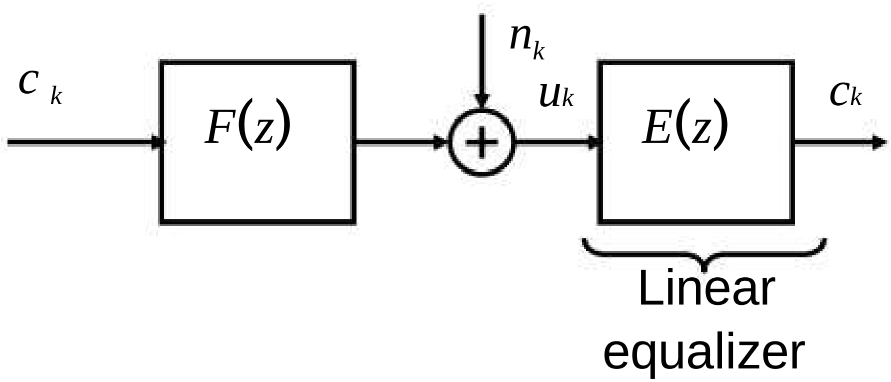
Channel estimation



LINEAR EQUALIZER

Principle

The principle of a linear equalizer is very simple: Apply a filter E(z) at the receiver, mitigating the effect of ISI:

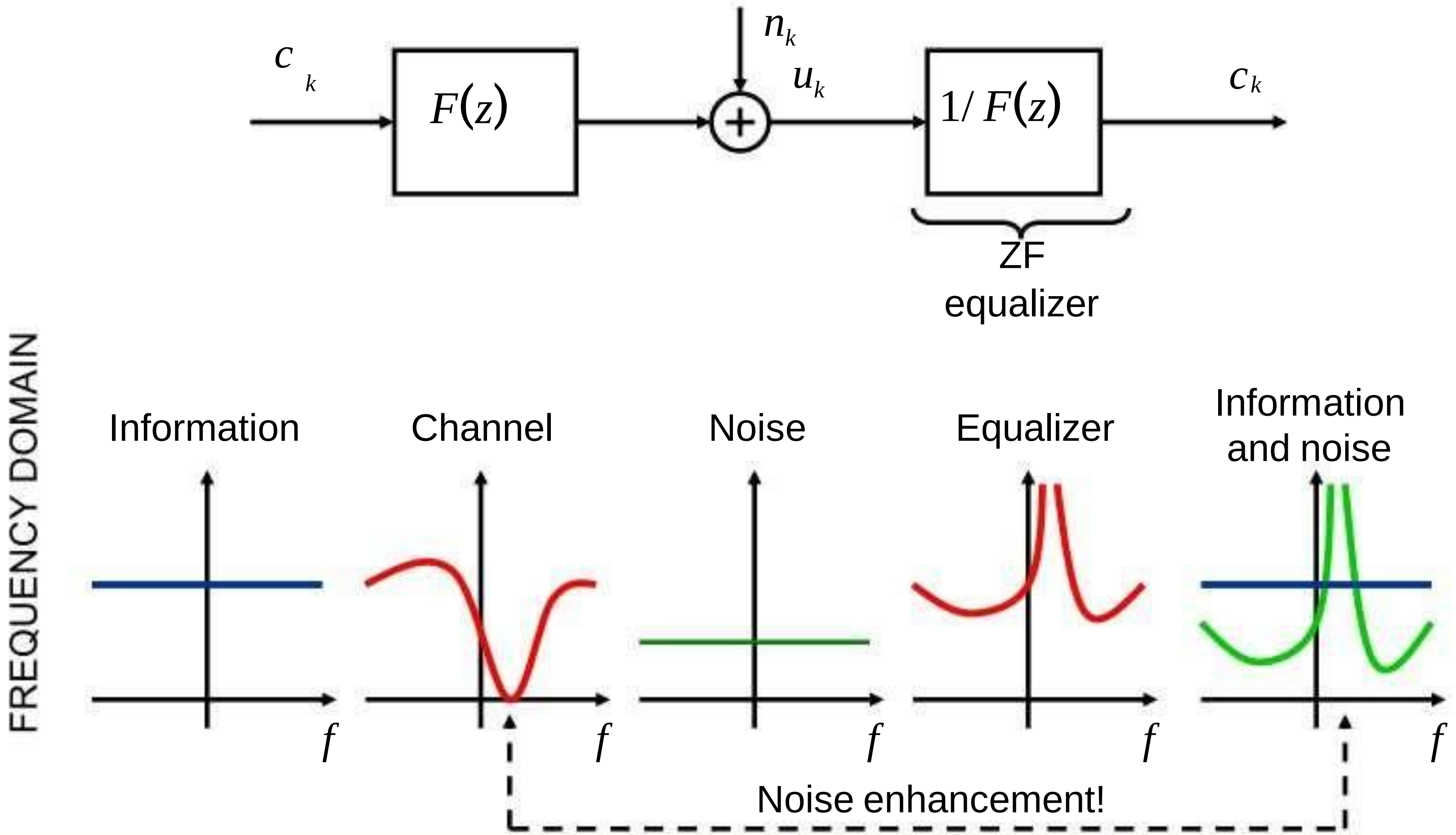


Now we have two different strategies:

1) Design E(z) so that the ISI is totally removed — **Zero-forcing**

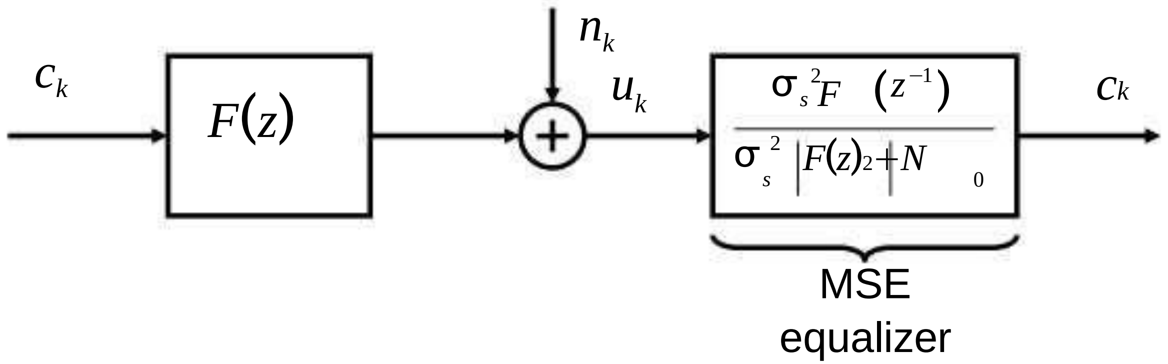
2) Design E(z) so that we minimize the mean squared-error of $\epsilon = c_k - c_k$ — **MSE**

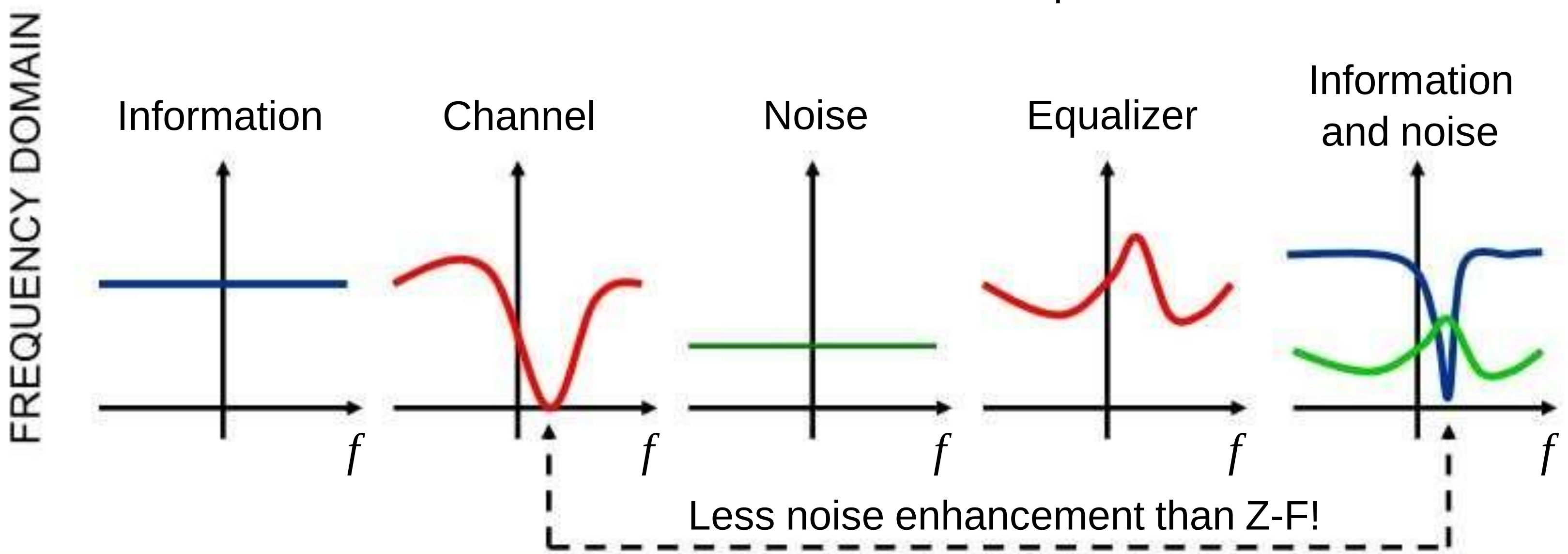
Zero-forcing equalizer



MSE equalizer

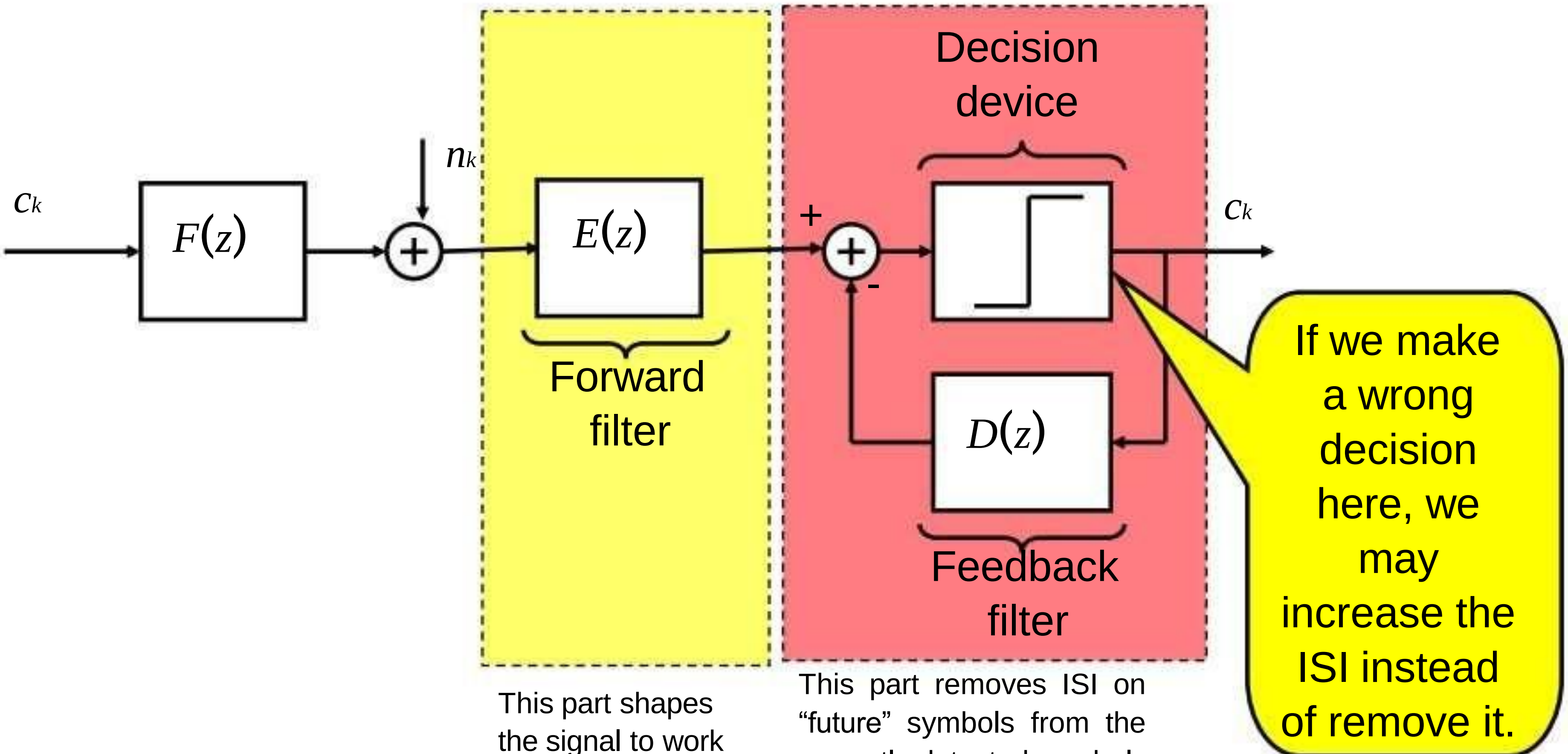
The MSE equalizer is designed to minimize the error variance





DECISION-FEEDBACK EQUALIZER

DFE - Principle

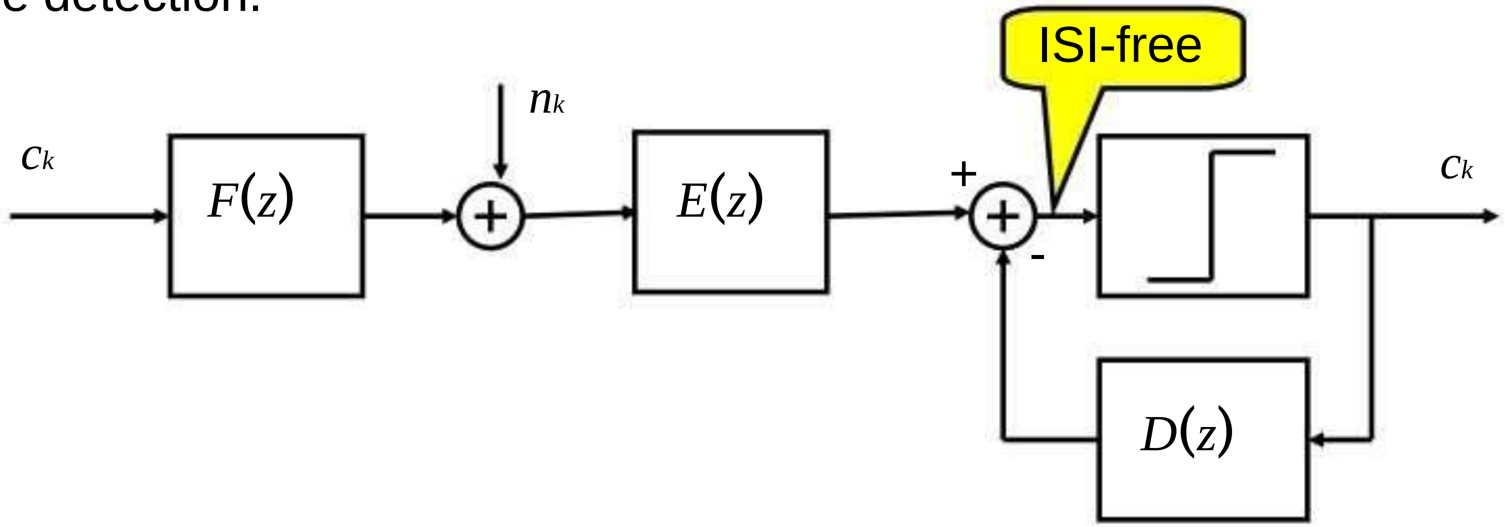


This part shapes the signal to work well with the decision feedback.

This part removes ISI on "future" symbols from the currently detected symbol.

Zero-forcing DFE

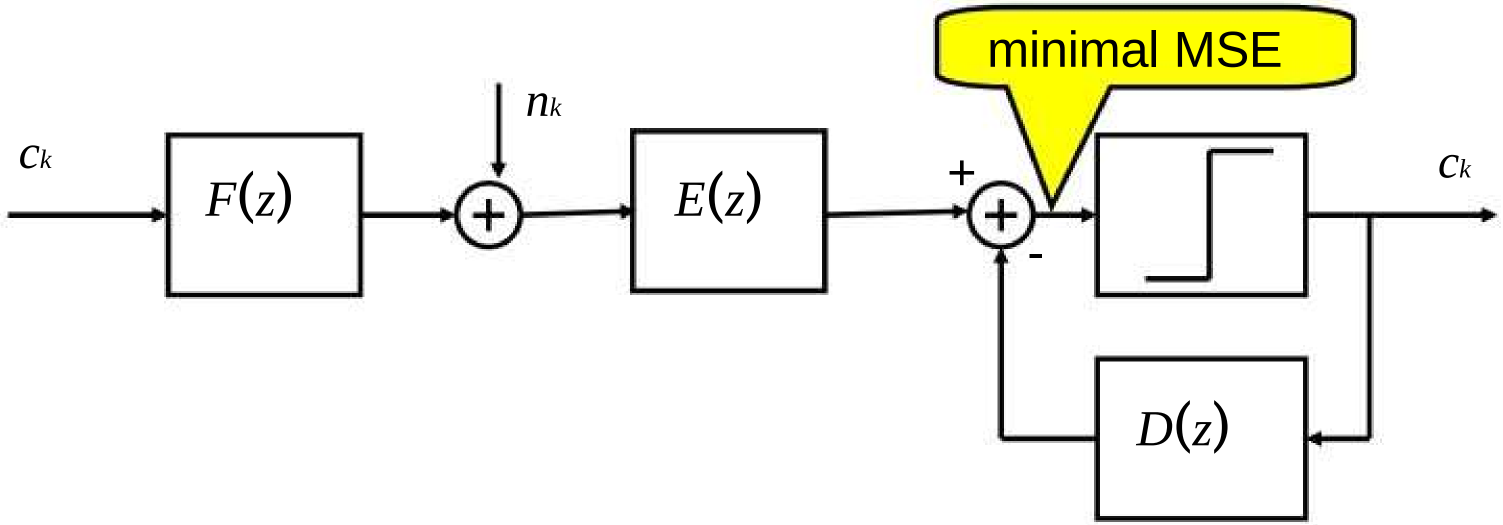
In the design of a ZF-DFE, we want to completely remove all ISI before the detection.



This enforces a relation between the E(z) and D(z), which is (we assume that we make correct decisions!)

$$F(z)E(z) - D(z) = 1$$

MSE-DFE



MAXIMUM-LIKELIHOOD SEQUENCE ESTIMATION

Principle

"noise free signal alternative"

$$u_m^{NF} = \sum_{j=0}^{L} f_j c_{m-j}$$

The squared Euclidean distance (optimal for white Gaussian noise) to the received sequence $\{u_m\}$ is

$$d^2\left(\{u_m\},\{u_m^{NF}\}\right) = \sum_m \left|u_m - u_m^{NF}\right|^2 = \sum_m \left|u_m - \sum_{j=0}^{L} f_j c_{m-j}\right|^2$$

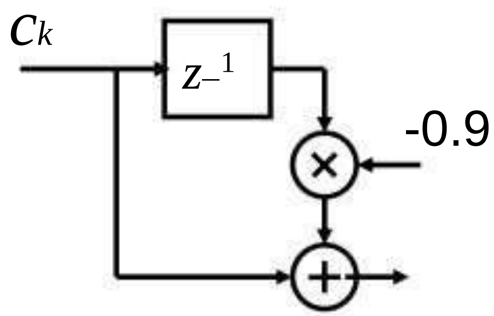
The MLSE decision is then the sequence of symbols $\{c_m\}$ minimizing this distance

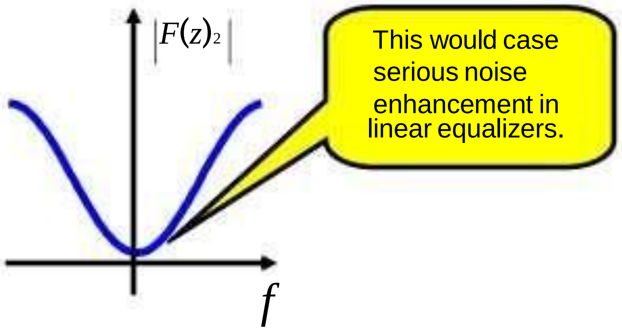
$$c_m = \arg\min_{\{c_m\}} \sum_m \left|u_m - \sum_{j=0}^{L} f_j c_{m-j}\right|^2$$

The Viterbi-equalizer

Let’s use an example to describe the Viterbi-equalizer.

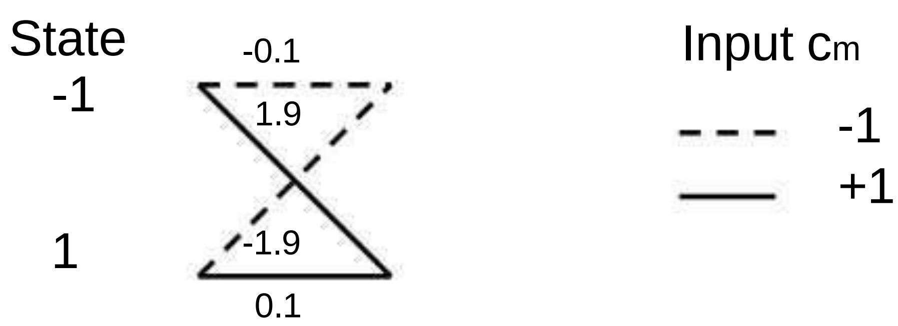
Discrete-time channel:





Further, assume that our symbol alphabet is -1 and +1 (representing the bits 0 and 1, respectively).

The fundamental trellis stage:



The Viterbi-equalizer (2)

Transmitted:

1 1 -1 1 -1

Noise free sequence:

1.9 0.1 -1.9 1.9 -1.9

The filter starts
in state -1.

Noise

$$1 - 0.9z^{-1}$$

Received noisy sequence:

0.72 0.19 -1.70 1.09 -1.06

At this stage,
the path ending
here has the best
metric!

VITERBI
DETECTOR

State
-1

-0.1 0.68 -0.1 0.76 -0.1 3.32 -0.1 2.86 -0.1 3.78

1.9 1.9 1.9 1.9 1.9

5.75 1.44 13.58 2.79

1.39 3.60 13.72 2.09 11.62

1

-1.9 -1.9 -1.9 -1.9

0.1 1.40 0.1 4.64 0.1 5.62 0.1 3.43

Detected sequence:

1 1 -1 1 -1

Correct!

Summary

- Linear equalizers suffer from noise enhancement.
- Decision-feedback equalizers (DFEs) use decisions on data to remove parts of the ISI, allowing the linear equalizer part to be less ”powerful” and thereby suffer less from noise enhancement.
- Incorrect decisions can cause error-propagation in DFEs, since an incorrect decision may add ISI instead of removing it.
- Maximum-likelihood sequence estimation (MLSE) is optimal in the sense of having the lowest probability of detecting the wrong sequence.
- Brut-force MLSE is prohibitively complex.
- The Viterbi-equalizer (detector) implements the MLSE with considerably lower complexity.

UNIT V
WIELESS NETWOKS

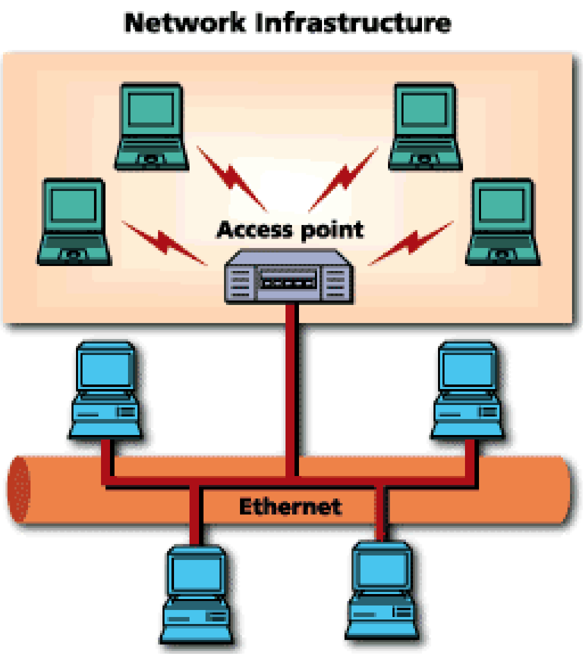
Wireless?

- A wireless LAN or WLAN is a wireless local area network that uses radio waves as its carrier.
- The last link with the users is wireless, to give a network connection to all users in a building or campus.
- The backbone network usually uses cables

Common Topologies

The wireless LAN connects to a wired LAN

- There is a need of an access point that bridges wireless LAN traffic into the wired LAN.
- The access point (AP) can also act as a repeater for wireless nodes, effectively doubling the maximum possible distance between nodes.



Common Topologies

Complete Wireless Networks

- The physical size of the network is determined by the maximum reliable
  propagation range of the radio signals.
- Referred to as **ad hoc** networks
- Are self-organizing networks without any centralized control
- Suited for temporary situations such as meetings and conferences.

How do wireless LANs work?

Wireless LANs operate in almost the same way as wired LANs, using the same networking protocols and supporting the most of the same applications.

How are WLANs Different?

- They use specialized **physical and data link** protocols
- They integrate into existing networks through **access points** which provide a bridging function
- They let you stay connected as you **roam** from one coverage area to another
- They have unique **security** considerations
- They have specific **interoperability** requirements
- They require **different hardware**
- They offer **performance** that differs from wired LANs.

Physical and Data Link Layers

Physical Layer:

- The wireless **NIC** takes **frames** of data from the link layer, scrambles the data in a predetermined way, then uses the modified data stream to modulate a **radio carrier signal**.

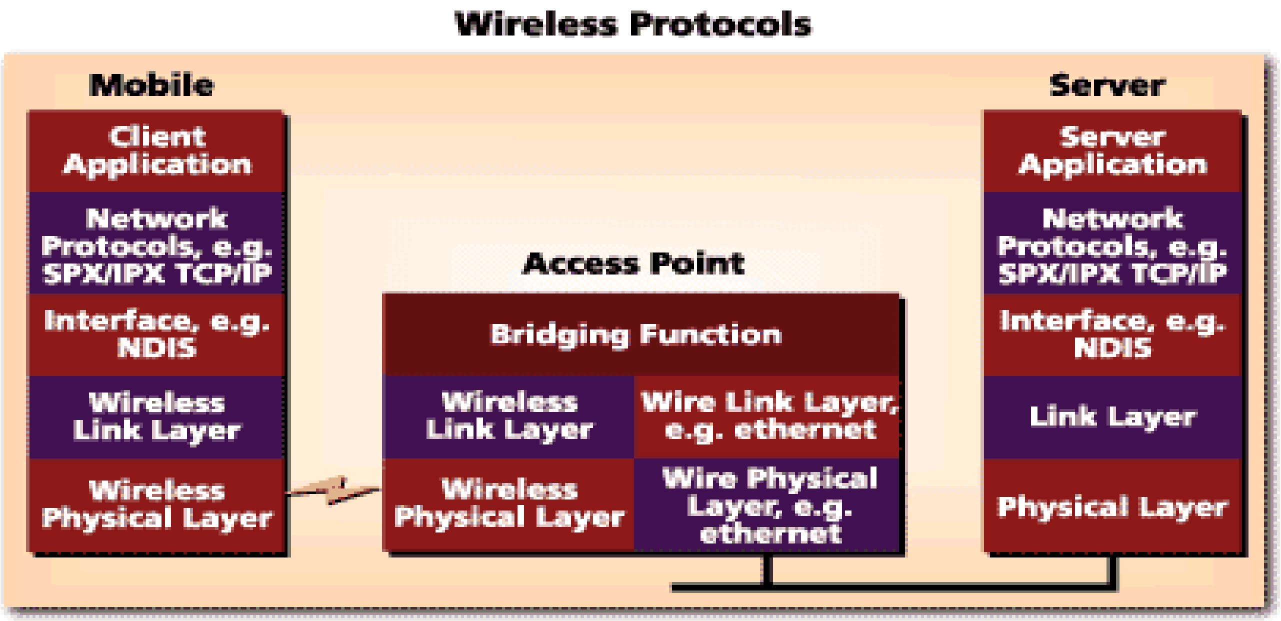
Data Link Layer:

- Uses **C**arriers-**S**ense-**M**ultiple-**A**ccess with **C**ollision **A**voidance (CSMA/CA).

Integration With Existing Networks

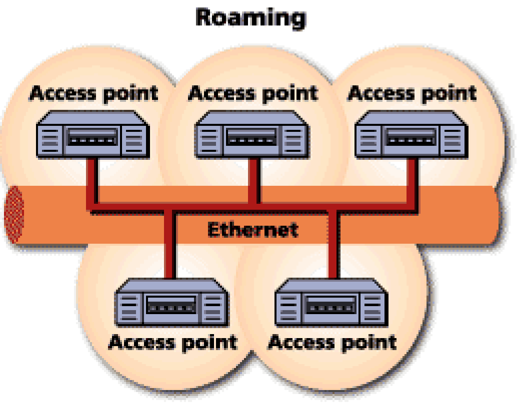
- Wireless Access Points (APs) - a small device that bridges wireless traffic to your network.
- Most access points bridge wireless LANs into Ethernet networks, but Token-Ring options are available as well.

Integration With Existing Networks



Roaming

- Users maintain a continuous connection as they roam from one physical area to another
- Mobile nodes automatically register with the new access point.
- Methods: DHCP, Mobile IP
- IEEE 802.11 standard does not address roaming, you may need to purchase equipment from one vendor if your users need to roam from one access point to another.



Security

- In theory, spread spectrum radio signals are inherently difficult to decipher without knowing the exact hopping sequences or direct sequence codes used
- The IEEE 802.11 standard specifies optional security called "**W**ired **E**quivalent **P**rivacy" whose goal is that a wireless LAN offer privacy equivalent to that offered by a wired LAN. The standard also specifies optional authentication measures.

Interoperability

- Before the IEEE 802.11 interoperability was based on cooperation between vendors.
- IEEE 802.11 only standardizes the physical and medium access control layers.
- Vendors must still work with each other to ensure their IEEE 802.11 implementations interoperate
- Wireless Ethernet Compatibility Alliance (WECA) introduces the Wi-Fi Certification to ensure cross-vendor interoperability of 802.11b solutions

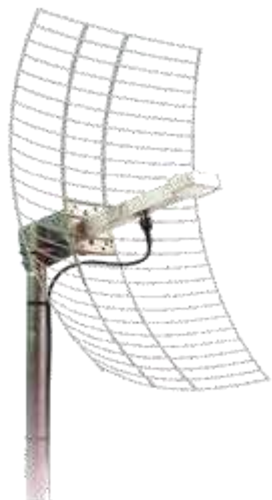
Hardware

- PC Card, either with integral antenna or with external antenna/RF module.
- ISA Card with external antenna connected by cable.
- Handheld terminals
- Access points

Hardware

CISCO Aironet 350 series

Wireless Handheld Terminal



Semi Parabolic Antenna

BreezeCOM AP

Performance

- **802.11a** offers speeds with a theoretically maximum rate of 54Mbps in the 5 GHz band
- **802.11b** offers speeds with a theoretically maximum rate of 11Mbps at in the 2.4 GHz spectrum band
- **802.11g** is a new standard for data rates of up to a theoretical maximum of 54 Mbps at 2.4 GHz.

What is 802.11?

- A family of wireless LAN (WLAN) specifications developed by a working group at the Institute of Electrical and Electronic Engineers (IEEE)
- Defines standard for WLANs using the following four technologies
  - Frequency Hopping Spread Spectrum (FHSS)
  - Direct Sequence Spread Spectrum (DSSS)
  - Infrared (IR)
  - Orthogonal Frequency Division Multiplexing (OFDM)
- Versions: 802.11a, 802.11b, 802.11g, 802.11e, 802.11f, 802.11i

802.11 - Transmission

- Most wireless LAN products operate in unlicensed radio bands
  - 2.4 GHz is most popular
  - Available in most parts of the world
  - No need for user licensing
- Most wireless LANs use spread-spectrum radio
  - Resistant to interference, secure
  - Two popular methods
    - Frequency Hopping (FH)
    - Direct Sequence (DS)

Frequency Hopping Vs. Direct Sequence

- FH systems use a radio carrier that “hops” from frequency to frequency in a pattern known to both transmitter and receiver
  - Easy to implement
  - Resistance to noise
  - Limited throughput (2-3 Mbps @ 2.4 GHz)
- DS systems use a carrier that remains fixed to a specific frequency band. The data signal is spread onto a much larger range of frequencies (at a much lower power level) using a specific encoding scheme.
  - Much higher throughput than FH (11 Mbps)
  - Better range
  - Less resistant to noise (made up for by redundancy – it transmits at least 10 fully redundant copies of the original signal at the same time)

802.11a

- Employs Orthogonal Frequency Division Multiplexing (OFDM)
  - Offers higher bandwidth than that of 802.11b, DSSS (Direct Sequence Spread Spectrum)
  - 802.11a MAC (Media Access Control) is same as 802.11b
- Operates in the 5 GHz range

802.11a Advantages

- Ultra-high spectrum efficiency
  - 5 GHz band is 300 MHz (vs. 83.5 MHz @ 2.4 GHz)
  - More data can travel over a smaller amount of bandwidth
- High speed
  - Up to 54 Mbps
- Less interference
  - Fewer products using the frequency
    - 2.4 GHz band shared by cordless phones, microwave ovens, Bluetooth, and WLANs

802.11a Disadvantages

- Standards and Interoperability
  - Standard not accepted worldwide
  - No interoperability certification available for 802.11a products
  - Not compatible or interoperable with 802.11b
- Legal issues
  - License-free spectrum in 5 GHz band not available worldwide
- Market
  - Beyond LAN-LAN bridging, there is limited interest for 5 GHz adoption

802.11a Disadvantages

- Cost
  - 2.4 GHz will still has >40% cost advantage
- Range
  - At equivalent power, 5 GHz range will be ~50% of 2.4 GHz
- Power consumption
  - Higher data rates and increased signal require more power
    - OFDM is less power-efficient then DSSS

802.11a Applications

- Building-to-building connections
- Video, audio conferencing/streaming video, and audio
- Large file transfers, such as engineering CAD drawings
- Faster Web access and browsing
- High worker density or high throughput scenarios
  - Numerous PCs running graphics-intensive applications

802.11a Vs. 802.11b

802.11a vs. 802.11b	802.11a	802.11b
Raw data rates	Up to 54 Mbps (54, 48, 36, 24,18, 12 and 6 Mbps)	Up to 11 Mbps (11, 5.5, 2, and 1 Mbps)
Range	50 Meters	100 Meters
Bandwidth	UNII and ISM (5 GHz range)	ISM (2.4000—2.4835 GHz range)
Modulation	OFDM technology	DSSS technology

802.11g

- 802.11g is a high-speed extension to 802.11b
  - Compatible with 802.11b
  - High speed up to 54 Mbps
  - 2.4 GHz (vs. 802.11a, 5 GHz)
  - Using ODFM for backward compatibility
  - Adaptive Rate Shifting

802.11g Advantages

- Provides higher speeds and higher capacity requirements for applications
  - Wireless Public Access
- Compatible with existing 802.11b standard
- Leverages Worldwide spectrum availability in 2.4 GHz
- Likely to be less costly than 5 GHz alternatives
- Provides easy migration for current users of 802.11b WLANs
  - Delivers backward support for existing 802.11b products
- Provides path to even higher speeds in the future

802.11e Introduces Quality of Service

- Also know as P802.11 TGe
- Purpose:
  - To enhance the 802.11 Medium Access Control (MAC) to improve and manage Quality of Service (QoS)
- Cannot be supported in current chip design
- Requires new radio chips
  - Can do basic QoS in MAC layer

802.11f – Inter Access Point Protocol

- Also know as P802.11 TGf
- Purpose:
  - To develop a set of requirements for Inter-Access Point Protocol (IAPP), including operational and management aspects

802.11b Security Features

- Wired Equivalent Privacy (**WEP**) – A protocol to protect link-level data during wireless transmission between clients and access points.
- Services:
  - **Authentication**: provides access control to the network by denying access to client stations that fail to authenticate properly.
  - **Confidentiality**: intends to prevent information compromise from casual eavesdropping
  - **Integrity**: prevents messages from being modified while in transit between the wireless client and the access point.

END