17BEEC6E02 **WIRELESS NETWORKS** **L T P C**
3 0 0 3

OBJECTIVES:

- To study about Wireless networks, protocol stack and standards.
- To study about fundamentals of 3G Services, its protocols and applications.
- To study about evolution of 4G Networks, its architecture and applications.

INTENDED OUTCOMES:

Upon completion of the course, the students will be able to
- Conversant with the latest 3G/4G and WiMAX networks and its architecture.
- Design and implement wireless network environment for any application using latest wireless
- protocols and standards.
- Implement different type of applications for smart phones and mobile devices with latest network
- strategies.

UNIT I WIRELESS LAN 9
Introduction-WLAN technologies: Infrared, UHF narrowband, spread spectrum - IEEE802.11: System architecture, protocol architecture, physical layer, MAC layer, 802.11b, 802.11a – Hiper LAN: WATM, BRAN, HiperLAN2 – Bluetooth: Architecture, Radio Layer, Baseband layer, Link manager Protocol, security - IEEE802.16-WIMAX: Physical layer, MAC, Spectrum allocation for WIMAX.

UNIT II MOBILE NETWORK LAYER 9
Introduction - Mobile IP: IP packet delivery, Agent discovery, tunneling and encapsulation, IPV6-Network layer in the internet- Mobile IP session initiation protocol - mobile ad-hoc network: Routing, Destination Sequence distance vector, Dynamic source routing.

UNIT III MOBILE TRANSPORT LAYER 9
TCP enhancements for wireless protocols - Traditional TCP: Congestion control, fast retransmit /fast recovery, Implications of mobility - Classical TCP improvements: Indirect TCP, Snooping TCP, Mobile TCP, Time out freezing, Selective retransmission, Transaction oriented TCP - TCP over 3G wireless networks.

UNIT IV WIRELESS WIDE AREA NETWORK 9
Overview of UTMS Terrestrial Radio access network-UMTS Core network Architecture: 3G-MSC, 3GSGSN,3G-GGSN, SMS-GMSC/SMS-IWMSC, Firewall, DNS/DHCP-High speed Downlink packet access (HSDPA)- LTE network architecture and protocol.

UNIT V 4G NETWORKS 9
Introduction – 4G vision – 4G features and challenges - Applications of 4G – 4G Technologies:
Multicarrier Modulation, Smart antenna techniques, OFDM-MIMO systems, Adaptive Modulation and coding with time slot scheduler, Cognitive Radio.

Total Hours: 45

TEXTBOOKS:

S.NO.	Author(s) Name	Title of the book	Publisher	Year of Publication
1	Jochen Schiller	Mobile Communications 2^{nd} Edition	Pearson Education	2012
2	Vijay Garg	Wireless Communications and networking	Elsevier	2007

REFERENCES:

S.NO.	Author(s) Name	Title of the book	Publisher	Year of Publication
1	Erik Dahlman, Stefan Parkvall, Johan Skold and Per Beming.	3G Evolution HSPA and LTE for Mobile Broadband. 2^{nd} Edition.	Academic Press.	2008
2	Anurag Kumar, D. Manjunath, Joy kuri.	Wireless Networking 1^{st} Edition.	Elsevier	2011
3	Simon Haykin, Michael Moher, David Koilpillai.	Modern Wireless Communications 1^{st} Edition	Pearson Education .	2013

UNIT-I
CELLULAR CONCEPT AND SYSTEM DESIGN FUNDAMENTALS

Introduction to wireless Communications Systems

- In 1897, Guglielmo Marconi first demonstrated radio's ability to provide continuous contact with ships sailing the English channel.
- During the past 10 years, fueled by
  - Digital and RF circuit fabrication improvements
  - New VLSI technologies
  - Other miniaturization technologies

    (e.g., passive components)

  The mobile communications industry has grown by orders of magnitude.
- The trends will continue at an even greater pace during the next decade.

Evolution of Mobile Radio Communications

- Major Mobile Radio Systems
  - 1934 - Police Radio uses conventional AM mobile communication system.
  - 1935 - Edwin Armstrong demonstrate FM
  - 1946 - First public mobile telephone service - push-to-talk
  - 1960 - Improved Mobile Telephone Service, IMTS - full duplex
  - 1960 - Bell Lab introduce the concept of Cellular mobile system
  - 1968 - AT&T propose the concept of Cellular mobile system to FCC.
  - 1976 - Bell Mobile Phone service, poor service due to call blocking
  - 1983 - Advanced Mobile Phone System (AMPS), FDMA, FM
  - 1991 - Global System for Mobile (GSM), TDMA, GMSK
  - 1991 - U.S. Digital Cellular (USDC) IS-54, TDMA, DQPSK
  - 1993 - IS-95, CDMA, QPSK, BPSK

Mobile Radiotelephone in the U.S.

- In 1934, AM mobile communication systems for municipal police radio systems.
  - vehicle ignition noise was a major problem.
- In 1946, FM mobile communications for the first public mobile telephone service
  - Each system used a single, high-powered transmitter and large tower to cover distances of over 50 km.
  - Used 120 kHz of RF bandwidth in a half-duplex mode. (push-to-talk release-to-listen systems.)
  - Large RF bandwidth was largely due to the technology difficulty (in mass-producing tight RF filter and low-noise, front-end receiver amplifiers.)
- In 1950, the channel bandwidth was cut in half to 60kHZ due to improved technology.

- By the mid 1960s, the channel bandwidth again was cut to 30 kHZ.
- Thus, from WWII to the mid 1960s, the spectrum efficiency was improved only a factor of 4 due to the technology advancements.
- Also in 1950s and 1960s, automatic channel truncking was introduced in IMTS(Improved Mobile Telephone Service.)
  - offering full duplex, auto-dial, auto-trunking
  - became saturated quickly
  - By 1976, has only twelve channels and could only serve 543 customers in New York City of 10 millions populations.

- Cellular radiotelephone
  - Developed in 1960s by Bell Lab and others
  - The basic idea is to reuse the channel frequency at a sufficient distance to increase the spectrum efficiency.
  - But the technology was not available to implement until the late 1970s. (mainly the microprocessor and DSP technologies.)

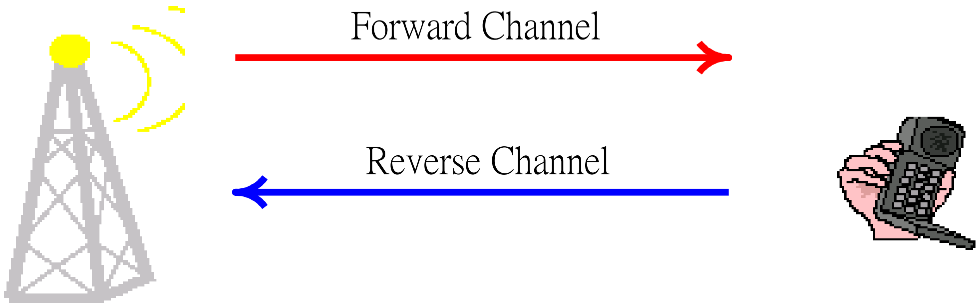
- In 1983, AMPS (Advanced Mobile Phone System, IS-41) deployed by Ameritech in Chicago.
  - 40 MHz spectrum in 800 MHz band
  - 666 channels (+ 166 channels), per Fig 1.2.
  - Each duplex channel occupies > 60 kHz (30+30) FDMA to maximize capacity.
  - Two cellular providers in each market.

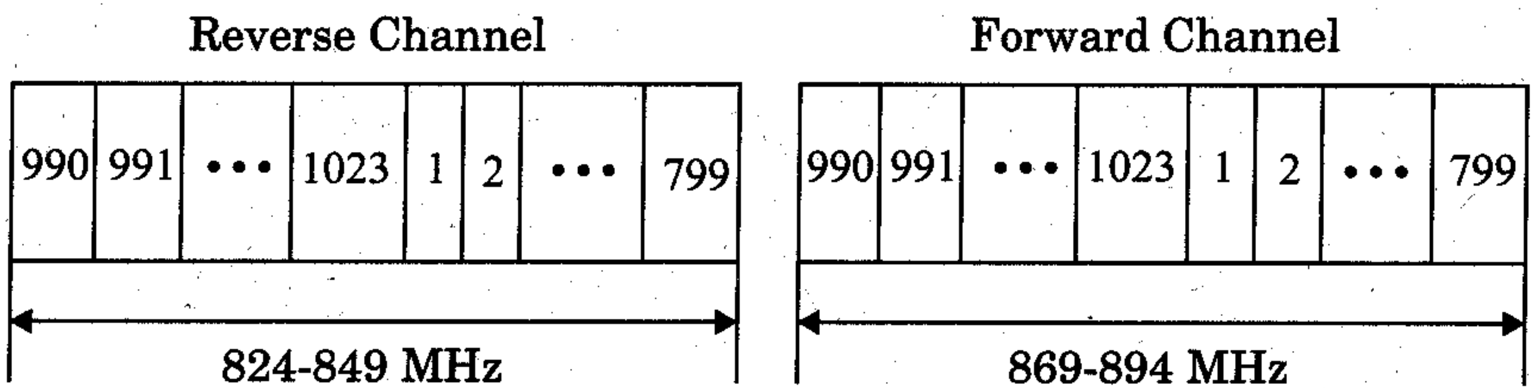
- In late 1991, U.S. Digital Cellular (USDC, IS-54) was introduced.
  - to replace AMPS analog channels
  - 3 times of capacity due to the use of digital modulation ($\frac{\pi}{4}$ DQPSK), speech coding, and TDMA technologies.
  - could further increase up to 6 times of capacity given the advancements of DSP and speech coding technologies.
- In mid 1990s, Code Division Multiple Access (CDMA, IS-95) was introduced by Qualcomm.
  - based on spread spectrum technology.
  - supports 6-20 times of users in 1.25 MHz shared by all the channels.
  - each associated with a unique code sequence.
  - operate at much smaller SNR.(FdB)

Example of Mobile Radio Systems

- Examples
  - Cordless phone
  - Remote controller
  - Hand-held walkie-talkies
  - Pagers
  - Cellular telephone
  - Wireless LAN
- Mobile - any radio terminal that could be moves during operation
- Portable - hand-held and used at walking speed
- Subscriber - mobile or portable user

- Classification of mobile radio transmission system
  - Simplex: communication in only one direction
  - Half-duplex: same radio channel for both transmission and reception (push-to-talk)
  - Full-duplex: simultaneous radio transmission and reception (FDD, TDD)
- Frequency division duplexing uses two radio channel
  - Forward channel: base station to mobile user
  - Reverse channel: mobile user to base station
- Time division duplexing shares a single radio channel in time.



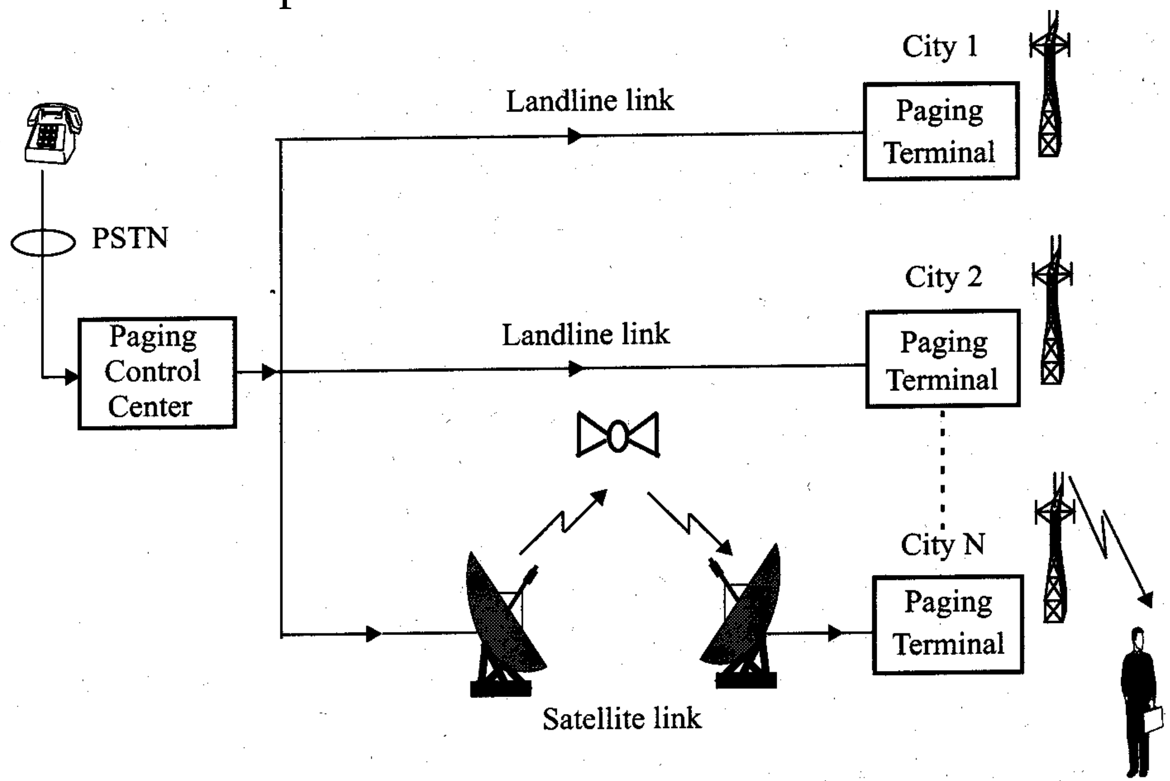


	Channel Number	Center Frequency (MHz)
Reverse Channel	$1 \le N \le 799$	$0.030N + 825.0$
	$990 \le N \le 1023$	$0.030\,(N - 1023) + 825.0$
Forward Channel	$1 \le N \le 799$	$0.030N + 870.0$
	$990 \le N \le 1023$	$0.030\,(N - 1023) + 870.0$

(Channels 800 - 989 are unused)

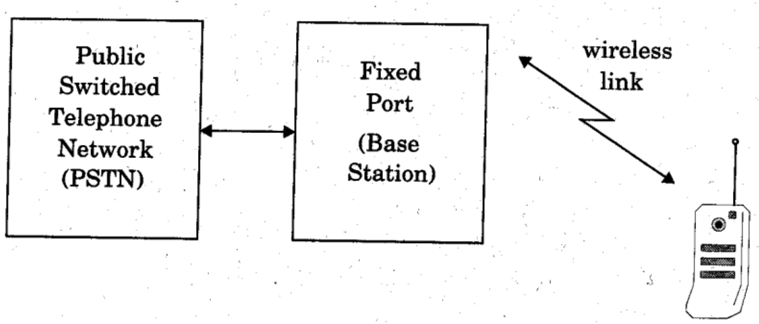
Paging Systems

- Conventional paging system send brief messages to a subscriber
- Modern paging system: news headline, stock quotations, faxes, etc.
- Simultaneously broadcast paging message from each base station (simulcasting)
- Large transmission power to cover wide area.



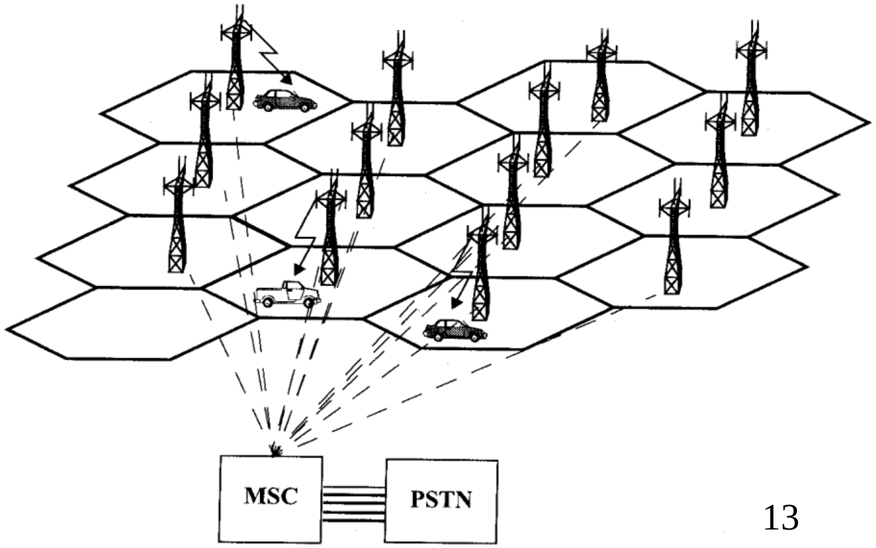
Cordless Telephone System

- Cordless telephone systems are full duplex communication systems.
- First generation cordless phone
  - in-home use
  - communication to dedicated base unit
  - few tens of meters
- Second generation cordless phone
  - outdoor
  - combine with paging system
  - few hundred meters per station



Cellular Telephone Systems

- Provide connection to the PSTN for any user location within the radio range of the system.
- Characteristic
  - Large number of users
  - Large Geographic area
  - Limited frequency spectrum
  - Reuse of the radio frequency by the concept of "cell".
- Basic cellular system: mobile stations, base stations, and mobile switching center.



- Communication between the base station and mobiles is defined by the standard common air interface (CAI)
  - forward voice channel (FVC): voice transmission from base station to mobile
  - reverse voice channel (RVC): voice transmission from mobile to base station
  - forward control channels (FCC): initiating mobile call from base station to mobile
  - reverse control channel (RCC): initiating mobile call from mobile to base station

Trends in Cellular Radio and Personal Communication

- Personal Communication Services (PCS) or PCN.
  - voice+data (PDA)
  - wireless internet services
- Low earth orbit (LEO) satellite communication

- Indoor Wireless Networking
  - WLAN
  - HyperLAN
  - Bluetooth(PAN)
  - BRAN

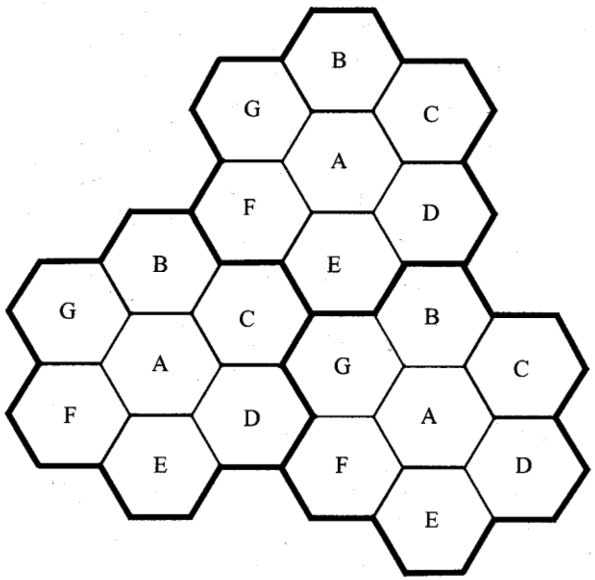
- Future Public Land Mobile Telephone System (FPLMTS)---A worldwide Standard
  - 3G, 4G
  - Software-defined Radio

- Fixed Wireless Access
  - WLL
  - LMDS

Cellular Concept

Introduction to Cellular Systems

- Solves the problem of spectral congestion and user capacity.
- Offer very high capacity in a limited spectrum without major technological changes.
- Reuse of radio channel in different cells.
- Enable a fix number of channels to serve an arbitrarily large number of users by reusing the channel throughout the coverage region.



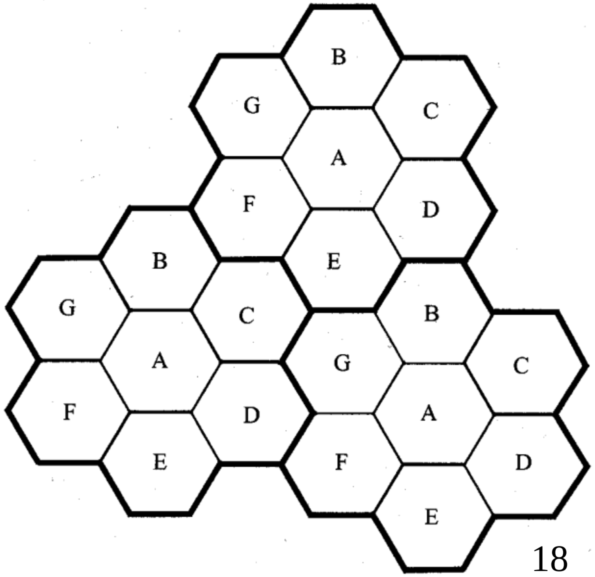
Frequency Reuse

- Each cellular base station is allocated a group of radio channels within a small geographic area called a *cell*.
- Neighboring cells are assigned different channel groups.
- By limiting the coverage area to within the boundary of the cell, the channel groups may be reused to cover different cells.
- Keep interference levels within tolerable limits.
- Frequency reuse or frequency planning

•seven groups of channel from A to G

•footprint of a cell - actual radio coverage

•omni-directional antenna v.s. directional antenna



- Consider a cellular system which has a total of S duplex channels.
- Each cell is allocated a group of k channels, $k < S$.
- The S channels are divided among N cells.
- The total number of available radio channels

$$S = kN$$

- The N cells which use the complete set of channels is called *cluster*.
- The cluster can be repeated M times within the system. The total number of channels, C, is used as a measure of capacity

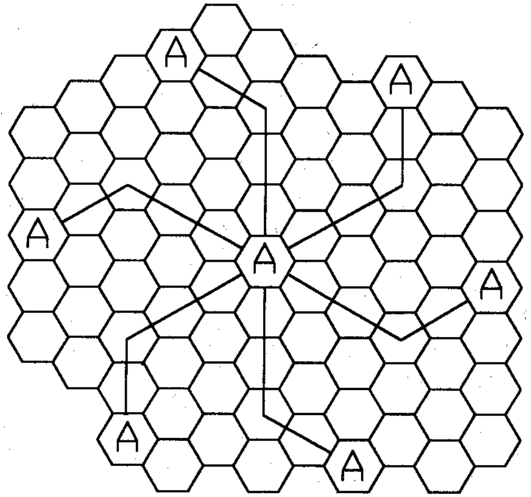
$$C = MkN = MS$$

- The capacity is directly proportional to the number of replication M.
- The cluster size, N, is typically equal to 4, 7, or 12.
- Small N is desirable to maximize capacity.
- The frequency reuse factor is given by $1/N$

- Hexagonal geometry has
  - exactly six equidistance neighbors
  - the lines joining the centers of any cell and each of its neighbors are separated by multiples of 60 degrees.
- Only certain cluster sizes and cell layout are possible.
- The number of cells per cluster, *N*, can only have values which satisfy

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

- Co-channel neighbors of a particular cell, ex, *i=3* and *j=2*.

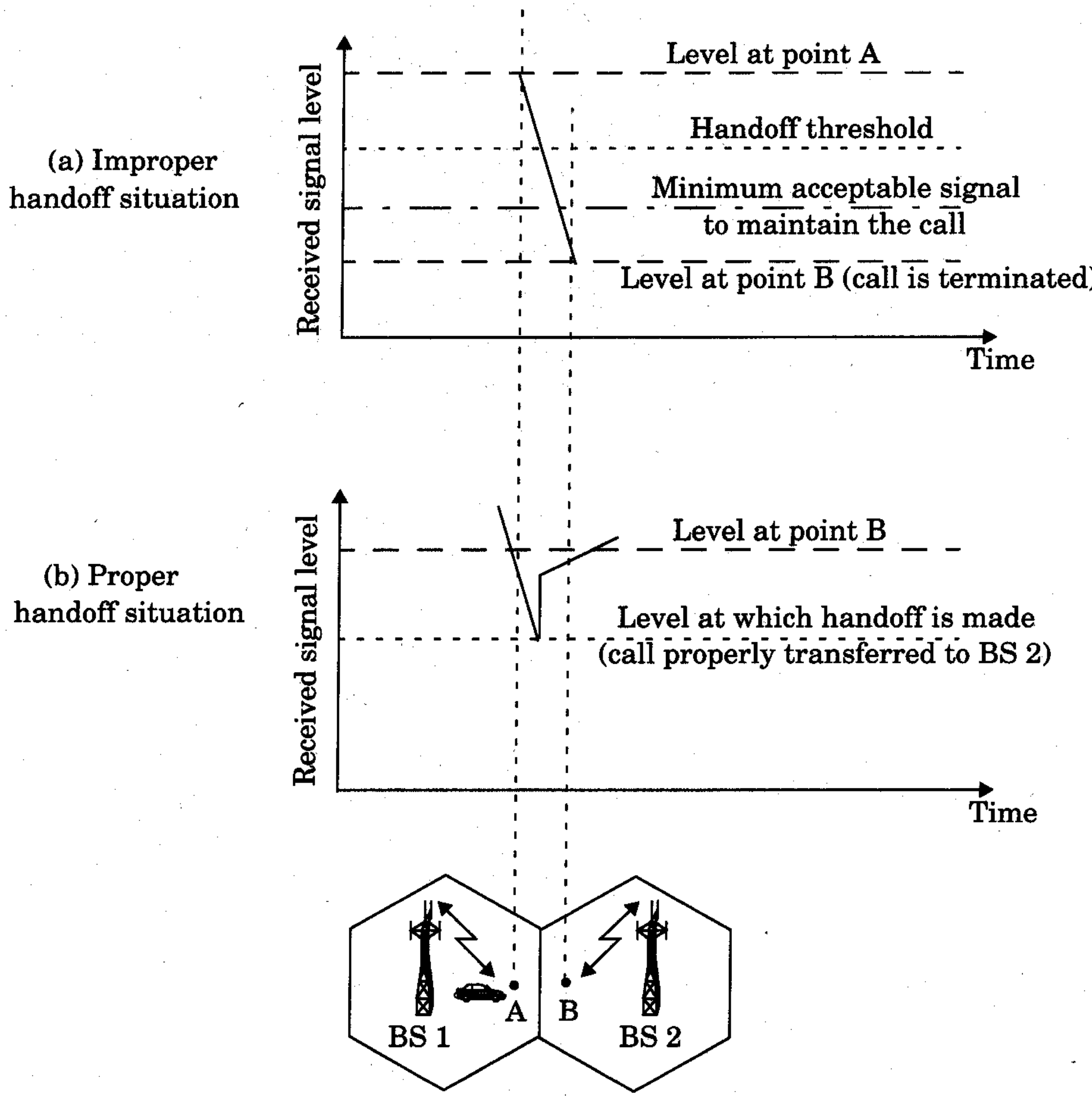


Channel Assignment Strategies

- Frequency reuse scheme
  - increases capacity
  - minimize interference
- Channel assignment strategy
  - fixed channel assignment
  - dynamic channel assignment
- Fixed channel assignment
  - each cell is allocated a predetermined set of voice channel
  - any new call attempt can only be served by the unused channels
  - the call will be *blocked* if all channels in that cell are occupied
- Dynamic channel assignment
  - channels are not allocated to cells permanently.
  - allocate channels based on request.
  - reduce the likelihood of blocking, increase capacity.

Handoff Strategies

- When a mobile moves into a different cell while a conversation is in progress, the MSC automatically transfers the call to a new channel belonging to the new base station.
- Handoff operation
  - identifying a new base station
  - re-allocating the voice and control channels with the new base station.
- Handoff Threshold
  - Minimum usable signal for acceptable voice quality (-90dBm to -100dBm)
  - Handoff margin $\Delta = P_{r,handoff} - P_{r,minimumusable}$ cannot be too large or too small.
  - If Δ is too large, unnecessary handoffs burden the MSC
  - If Δ is too small, there may be insufficient time to complete handoff before a call is lost.

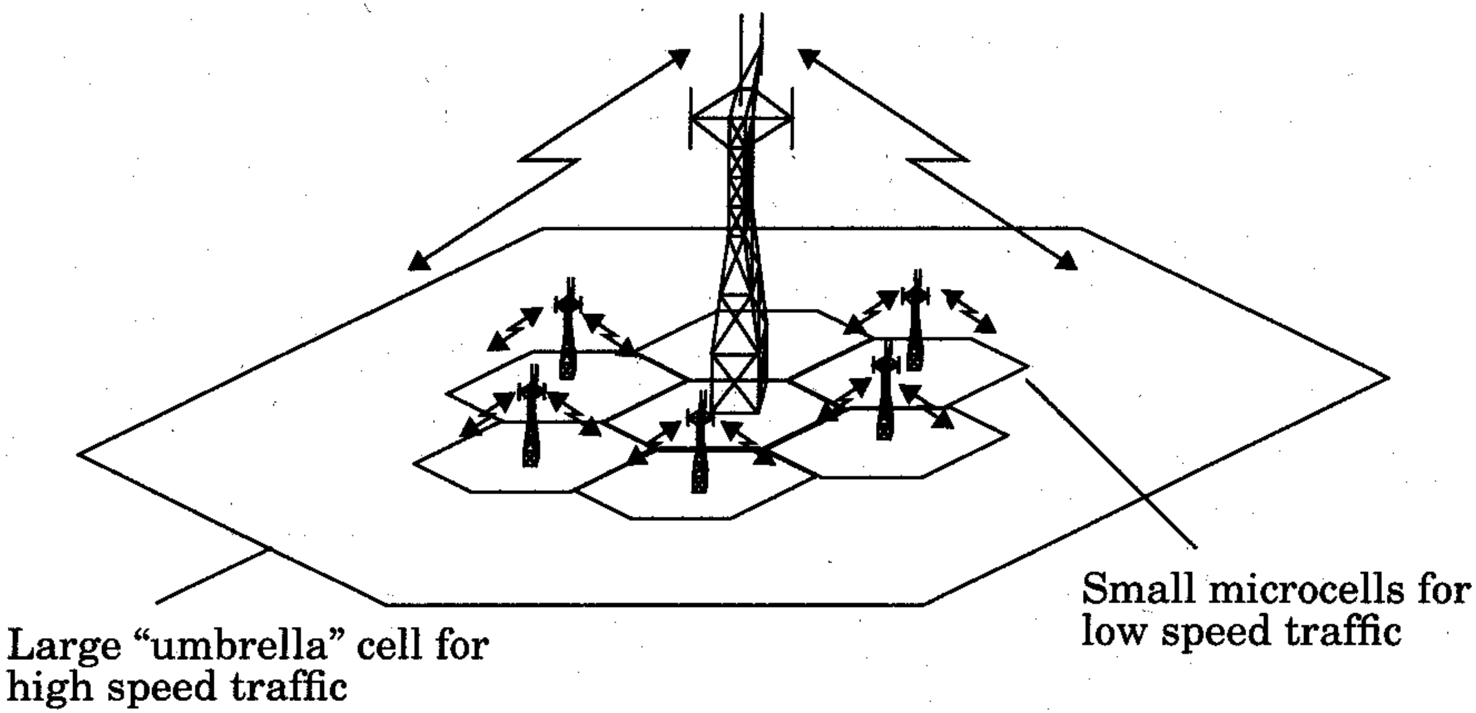

Level at point A
Handoff threshold
(a) Improper handoff situation
Received signal level
Minimum acceptable signal to maintain the call
Level at point B (call is terminated)
Time
Level at point B
(b) Proper handoff situation
Received signal level
Level at which handoff is made (call properly transferred to BS 2)
Time
A
B
BS 1
BS 2

- Handoff must ensure that the drop in the measured signal is not due to momentary fading and that the mobile is actually moving away from the serving base station.
- Running average measurement of signal strength should be optimized so that unnecessary handoffs are avoided.
  - Depends on the speed at which the vehicle is moving.
  - Steep short term average -> the hand off should be made quickly
  - The speed can be estimated from the statistics of the received short-term fading signal at the base station
- Dwell time: the time over which a call may be maintained within a cell without handoff.

- Dwell time depends on
  - propagation
  - interference
  - distance
  - speed
- Handoff measurement
  - In first generation analog cellular systems, signal strength measurements are made by the base station and supervised by the MSC.
  - In second generation systems (TDMA), handoff decisions are mobile assisted, called mobile assisted handoff (MAHO)
- Intersystem handoff: If a mobile moves from one cellular system to a different cellular system controlled by a different MSC.
- Handoff requests is much important than handling a new call.

Practical Handoff Consideration

- Different type of users
  - High speed users need frequent handoff during a call.
  - Low speed users may never need a handoff during a call.
- Microcells to provide capacity, the MSC can become burdened if high speed users are constantly being passed between very small cells.
- Minimize handoff intervention
  - handle the simultaneous traffic of high speed and low speed users.
- Large and small cells can be located at a single location (umbrella cell)
  - different antenna height
  - different power level
- Cell dragging problem: pedestrian users provide a very strong signal to the base station
  - The user may travel deep within a neighboring cell


Large "umbrella" cell for
high speed traffic
Small microcells for
low speed traffic

- Handoff for first generation analog cellular systems
  - 10 secs handoff time
  - Δ is in the order of 6 dB to 12 dB
- Handoff for second generation cellular systems, e.g., GSM
  - 1 to 2 seconds handoff time
  - mobile assists handoff
  - Δ is in the order of 0 dB to 6 dB
  - Handoff decisions based on signal strength, co-channel interference, and adjacent channel interference.
- IS-95 CDMA spread spectrum cellular system
  - Mobiles share the channel in every cell.
  - No physical change of channel during handoff
  - MSC decides the base station with the best receiving signal as the service station

Interference and System Capacity

- Sources of interference
  - another mobile in the same cell
  - a call in progress in the neighboring cell
  - other base stations operating in the same frequency band
  - noncellular system leaks energy into the cellular frequency band
- Two major cellular interference
  - co-channel interference
  - adjacent channel interference

Co-channel Interference and System Capacity

- Frequency reuse - there are several cells that use the same set of frequencies
  - co-channel cells
  - co-channel interference
- To reduce co-channel interference, co-channel cell must be separated by a minimum distance.
- When the size of the cell is approximately the same
  - co-channel interference is independent of the transmitted power
  - co-channel interference is a function of
    - R: Radius of the cell
    - D: distance to the center of the nearest co-channel cell
- Increasing the ratio $Q=D/R$, the interference is reduced.
- Q is called the co-channel reuse ratio

- For a hexagonal geometry

$$Q = \frac{D}{R} = \sqrt{3N}$$

- A small value of Q provides large capacity
- A large value of Q improves the transmission quality - smaller level of co-channel interference
- A tradeoff must be made between these two objectives

Table 2.1 Co-channel Reuse Ratio for Some Values of N

	Cluster Size (N)	Co-channel Reuse Ratio(Q)
$i = 1, j = 1$	3	3
$i = 1, j = 2$	7	4.58
$i = 2, j = 2$	12	6
$i = 1, j = 3$	13	6.24

- Let i_0 be the number of co-channel interfering cells. The signal-to-interference ratio (SIR) for a mobile receiver can be expressed as

$$\frac{S}{I} = \frac{S}{\sum_{i=1}^{i_0} I_i}$$

S: the desired signal power

I_i: interference power caused by the ith interfering co-channel cell base station

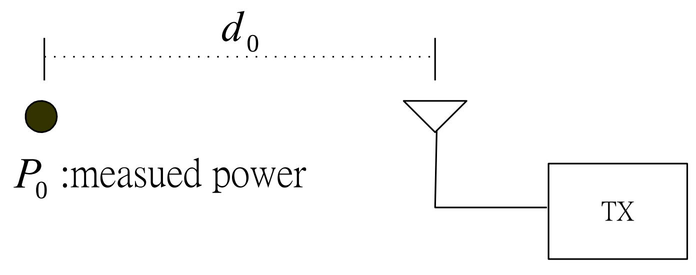
- The average received power at a distance d from the transmitting antenna is approximated by

$$P_r = P_0 \left(\frac{d}{d_0} \right)^{-n}$$

or

$$P_r(\text{dBm}) = P_0(\text{dBm}) - 10n \log\left(\frac{d}{d_0} \right)$$

close-in reference point



n is the path loss exponent which ranges between 2 and 4.

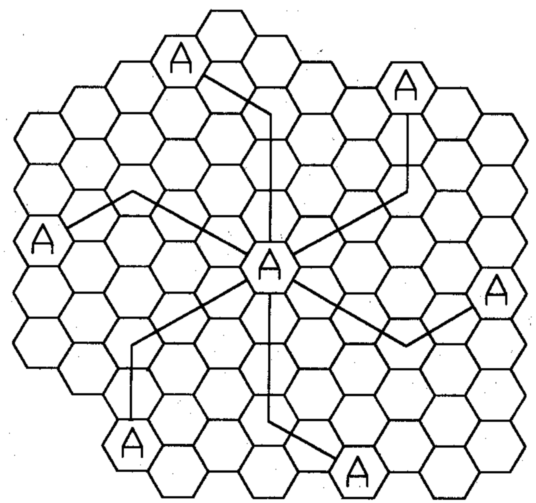
- When the transmission power of each base station is equal, SIR for a mobile can be approximated as

$$\frac{S}{I} = \frac{R^{-n}}{\sum_{i=1}^{i_0} (D_i)^{-n}}$$

- Consider only the first layer of interfering cells

$$\frac{S}{I} = \frac{(D/R)^n}{i_0} = \frac{\left(\sqrt{3N}\right)^n}{i_0}$$

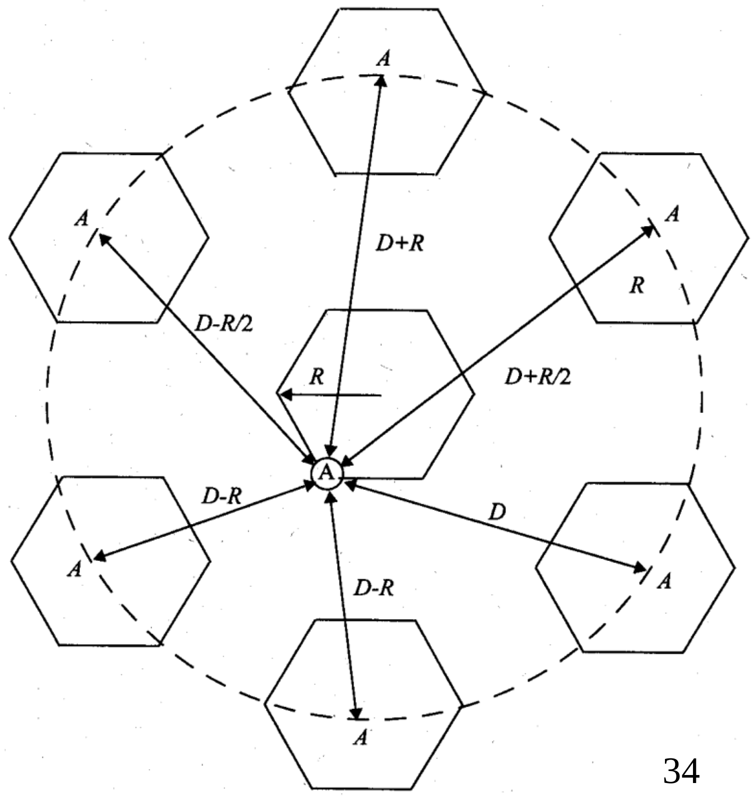
$i_0 = 6$



- Example: AMPS requires that SIR be greater than 18dB
  - N should be at least 6.49 for $n=4$.
  - Minimum cluster size is 7

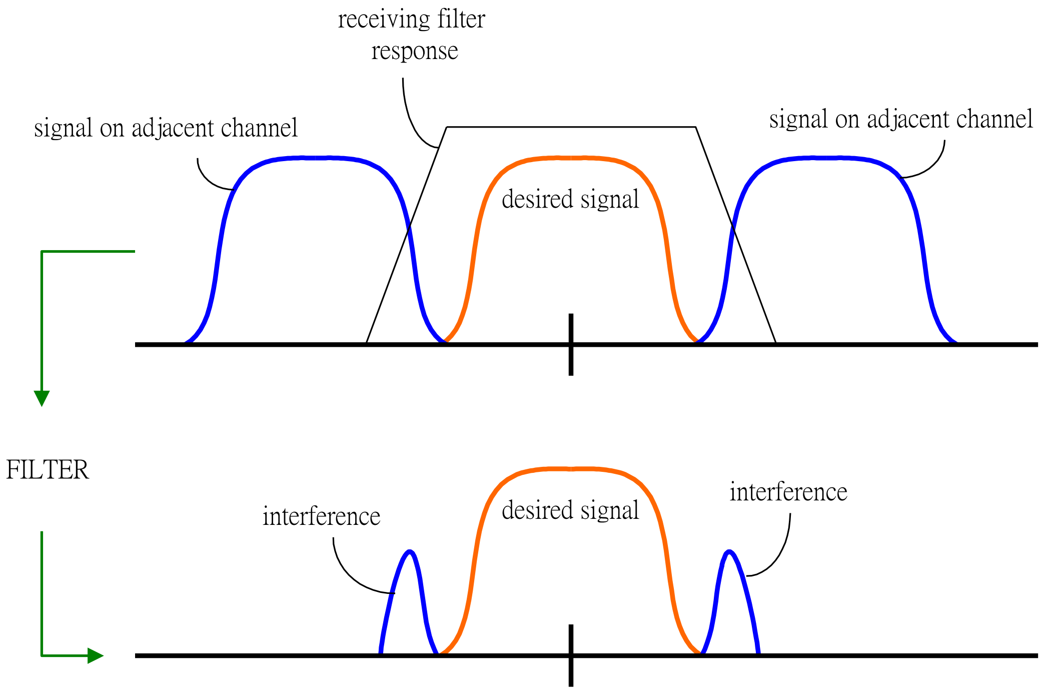
- For hexagonal geometry with 7-cell cluster, with the mobile unit being at the cell boundary, the signal-to-interference ratio for the worst case can be approximated as

$$\frac{S}{I} = \frac{R^{-4}}{2(D-R)^{-4} + (D-R/2)^{-4} + (D+R/2)^{-4} + (D+R)^{-4} + D^{-4}}$$



Adjacent Channel Interference

- Adjacent channel interference: interference from adjacent in frequency to the desired signal.
  - Imperfect receiver filters allow nearby frequencies to leak into the passband
  - Performance degrade seriously due to *near-far* effect.



- Adjacent channel interference can be minimized through careful filtering and *channel assignment*.
- Keep the frequency separation between each channel in a given cell as large as possible
- A channel separation greater than six is needed to bring the adjacent channel interference to an acceptable level.

Power Control for Reducing Interference

- Ensure each mobile transmits the smallest power necessary to maintain a good quality link on the reverse channel
  - long battery life
  - increase SIR
  - solve the near-far problem

Trunking and Grade of Service

- Erlangs: One Erlangs represents the amount of traffic density carried by a channel that is completely occupied.
  - Ex: A radio channel that is occupied for 30 minutes during an hour carries 0.5 Erlangs of traffic.
- Grade of Service (GOS): The likelihood that a call is blocked.
- Each user generates a traffic intensity of A_u Erlangs given by

$$A_u = \mu H$$

H: average duration of a call.

μ : average number of call requests per unit time

- For a system containing U users and an unspecified number of channels, the total offered traffic intensity A, is given by

$$A = UA_u$$

- For C channel trunking system, the traffic intensity, A_c is given as

$$A_c = UA_u / C$$

Improving Capacity in Cellular Systems

- Methods for improving capacity in cellular systems
  - Cell Splitting: subdividing a congested cell into smaller cells.
  - Sectoring: directional antennas to control the interference and frequency reuse.
  - Coverage zone : Distributing the coverage of a cell and extends the cell boundary to hard-to-reach place.

- Transmission power reduction from P_{t1} to P_{t2}
- Examining the receiving power at the new and old cell boundary

$$P_r[\text{at old cell boundary}] \propto P_{t1} R^{-n}$$

$$P_r[\text{at new cell boundary}] \propto P_{t2} (R/2)^{-n}$$

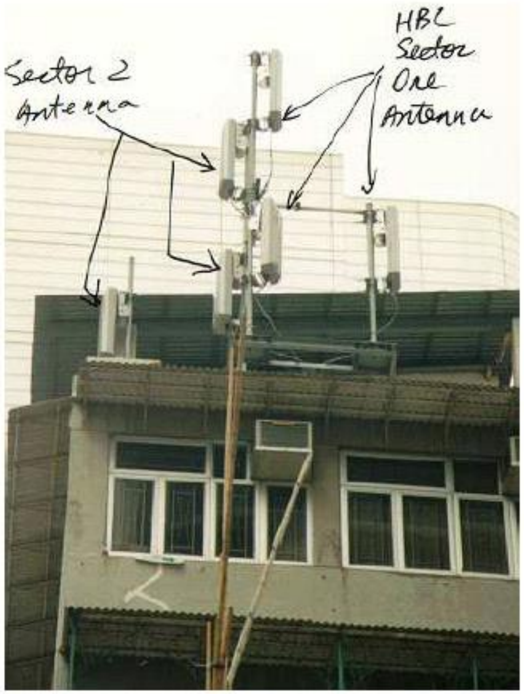
- If we take *n = 4* and set the received power equal to each other

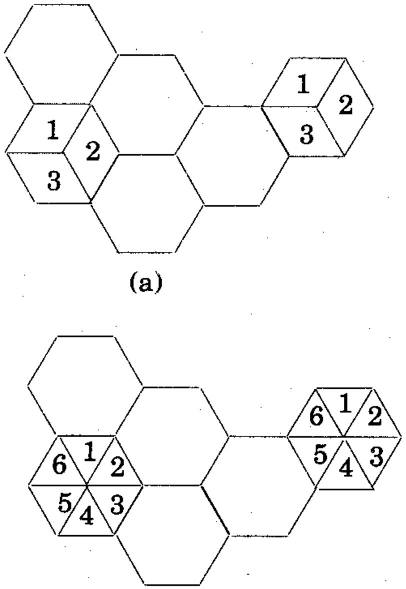
$$P_{t2} = \frac{P_{t1}}{16}$$

- The transmit power must be reduced by 12 dB in order to fill in the original coverage area.
- Problem: if only part of the cells are splited
  - Different cell sizes will exist simultaneously
- Handoff issues - high speed and low speed traffic can be simultaneously accommodated

Sectoring

- Decrease the *co-channel interference* and keep the cell radius *R* unchanged
  - Replacing single omni-directional antenna by several directional antennas
  - Radiating within a specified sector

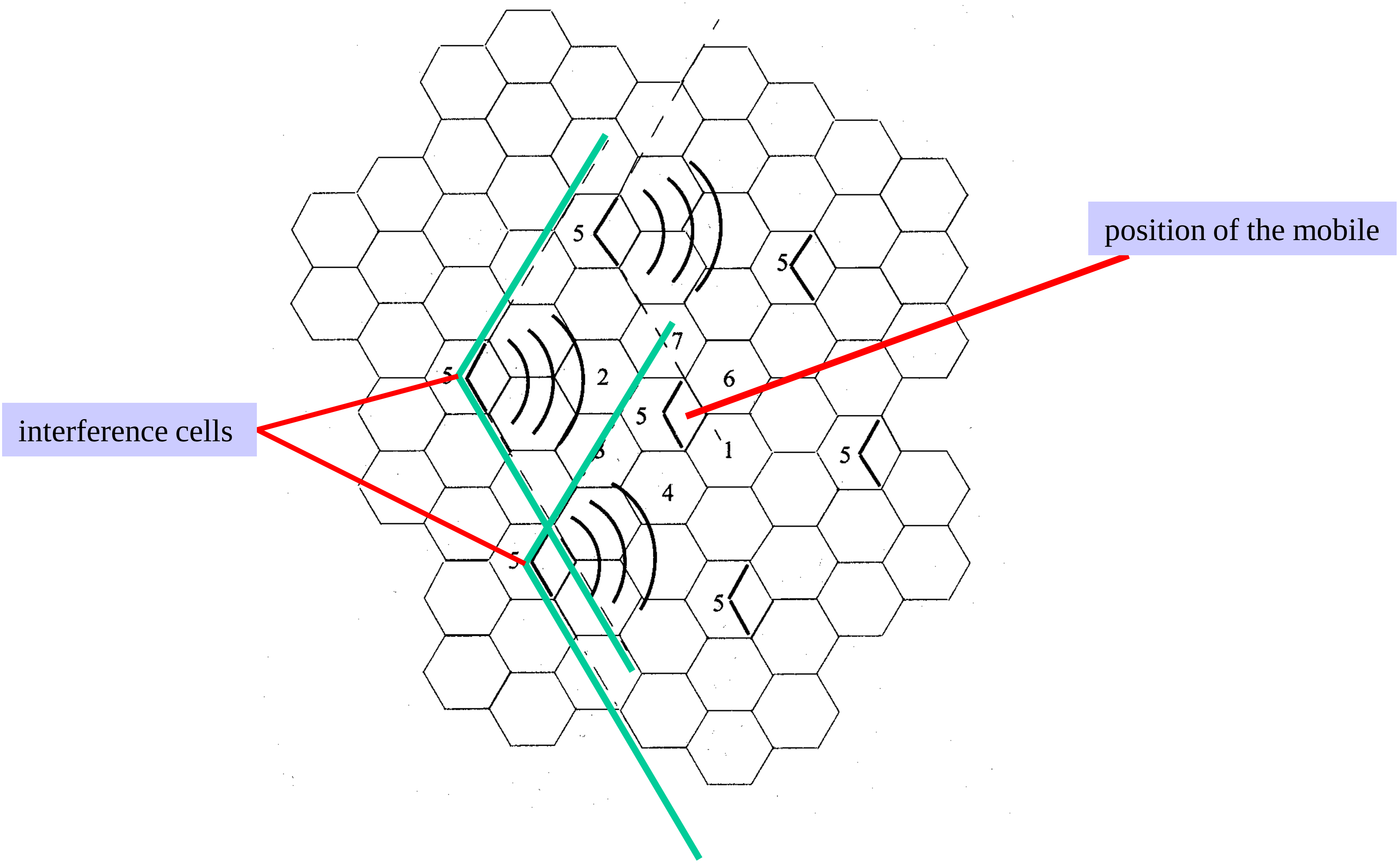




(a)

(b)

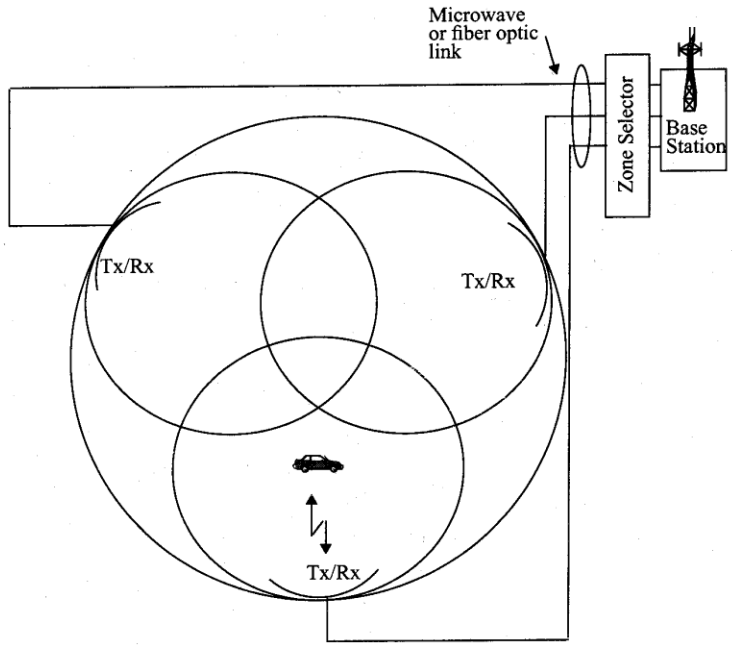
- Interference Reduction



Microcell Zone Concept

- Antennas are placed at the outer edges of the cell
- Any channel may be assigned to any zone by the base station
- Mobile is served by the zone with the strongest signal.

- Handoff within a cell
  - No channel re-assignment
  - Switch the channel to a different zone site
- Reduce interference
  - Low power transmitters are employed

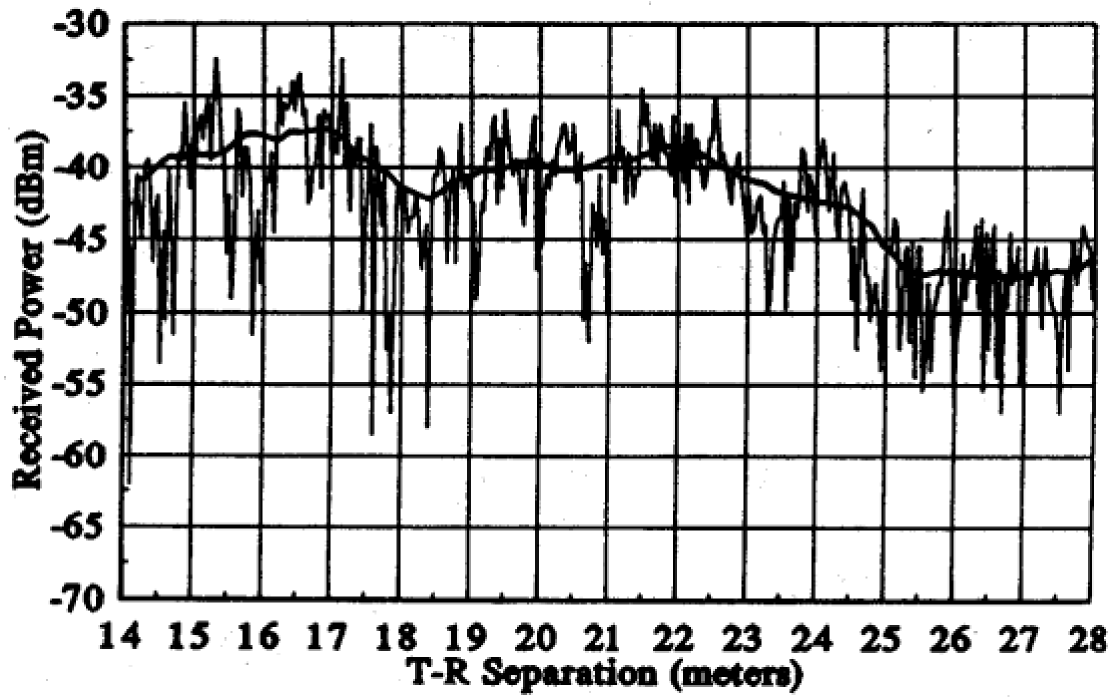


UNIT-II
MOBILE RADIO PROPAGATION

INTRODUCTION TO RADIO WAVE PROPAGATION

- Electromagnetic wave propagation
  - reflection
  - diffraction
  - scattering
- Urban areas
  - No direct line-of-sight
  - high-rise buildings causes severe diffraction loss
  - multipath fading due to different paths of varying lengths
- Large-scale propagation models predict the mean signal strength for an arbitrary T-R separation distance.
- Small-scale (fading) models characterize the rapid fluctuations of the received signal strength over very short travel distance or short time duration.

- Small-scale fading: rapidly fluctuation
  - sum of many contributions from different directions with different phases
  - random phases cause the sum varying widely. (ex: Rayleigh fading distribution)
- Local average received power is predicted by large-scale model (measurement track of 5λ to 40λ)



FREE SPACE PROPAGATION MODEL

- The free space propagation model is used to predict received signal strength when the transmitter and receiver have a clear line-of-sight path between them.
  - satellite communication
  - microwave line-of-sight radio link
- Friis free space equation

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

P_t : transmitted power

$P_r(d)$: received power

G_t : transmitter antenna gain

G_r : receiver antenna gain

d : T-R separation distance (m)

L: system loss

λ : wave length in meters

- The gain of the antenna

$$G = \frac{4\pi A_e}{\lambda^2}$$

A_e: effective aperture is related to the physical size of the antenna

- The wave length λ is related to the carrier frequency by

$$\lambda = \frac{c}{f} = \frac{2\pi c}{\omega_c}$$

f: carrier frequency in Hertz

ω_c: carrier frequency in radians

c: speed of light (meters/s)

- The losses L $(L \geq 1)$ are usually due to transmission line attenuation, filter losses, and antenna losses in the communication system. A value of *L=1* indicates no loss in the system hardware.

- Isotropic radiator is an ideal antenna which radiates power with unit gain.
- Effective isotropic radiated power (EIRP) is defined as

$$EIRP = P_t G_t$$

and represents the maximum radiated power available from transmitter in the direction of maximum antenna gain as compared to an isotropic radiator.

- Path loss for the free space model with antenna gains

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

- When antenna gains are excluded

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

- The Friis free space model is only a valid predictor for P_r for values of *d* which is in the far-field (Fraunhofer region) of the transmission antenna.

- The far-field region of a transmitting antenna is defined as the region beyond the far-field distance

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

where *D* is the largest physical linear dimension of the antenna.

- To be in the far-filed region the following equations must be satisfied

$$d_f >> D \quad \text{and} \quad d_f >> \lambda$$

- Furthermore the following equation does not hold for *d=0*.

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

- Use close-in distance d_0 and a known received power $P_r(d_0)$ at that point

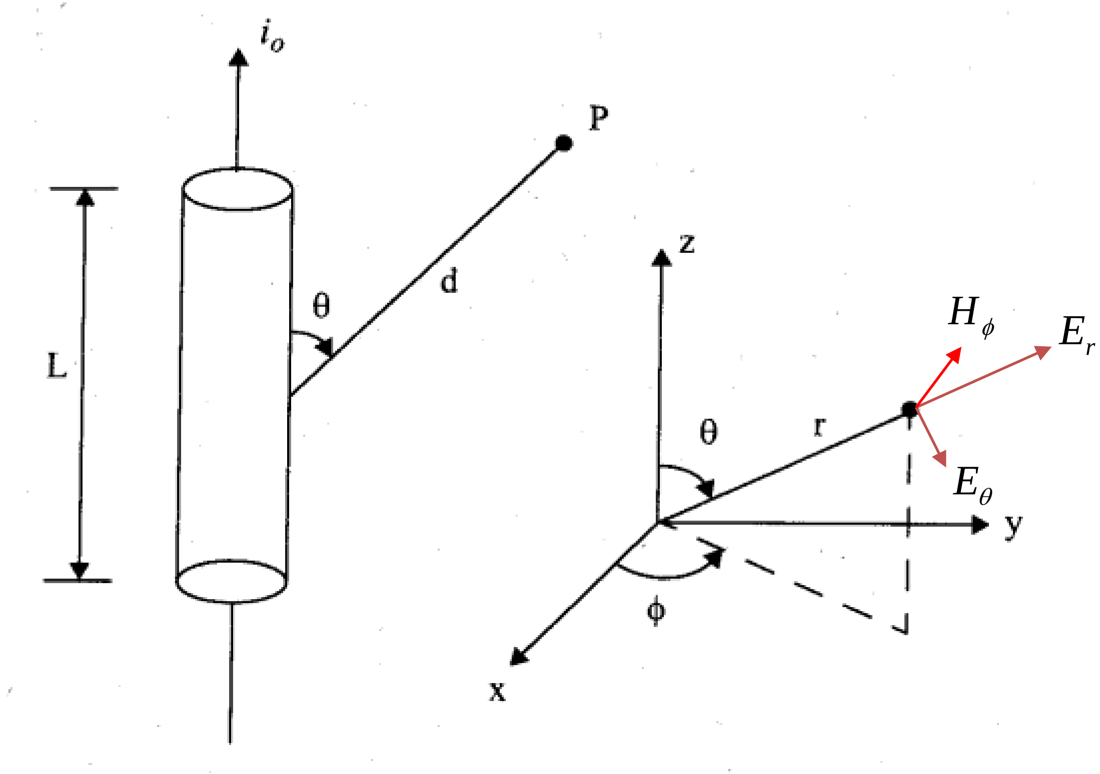
$$P_r(d) = P_r(d_0)\left(\frac{d_0}{d}\right)^2 \qquad d \ge d_0 \ge d_f$$

or

$$P_r(d)\,\text{dBm} = 10\log\left(\frac{P_r(d_0)}{0.001\,\text{W}}\right) + 20\log\left(\frac{d_0}{d}\right) \qquad d \ge d_0 \ge d_f$$

Relating Power to Electric Field

- Consider a small linear radiator of length *L*



- Electric and magnetic fields for a small linear radiator of length *L*

$$E_r = \frac{i_0 L \cos\theta}{2\pi\varepsilon_0 c}\left\{\frac{1}{d^2} + \frac{c}{j\omega_c d^3}\right\}e^{j\omega_c (t-d/c)}$$

$$E_\theta = \frac{i_0 L \sin\theta}{2\pi\varepsilon_0 c}\left\{\frac{j\omega_c}{d} + \frac{c}{d^2} + \frac{c^2}{j\omega_c d^3}\right\}e^{-j\omega_c (t-d/c)}$$

$$H_\phi = \frac{i_0 L \sin\theta}{4\pi c}\left\{\frac{j\omega_c}{d} + \frac{c}{d^2}\right\}e^{j\omega_c (t-d/c)}$$

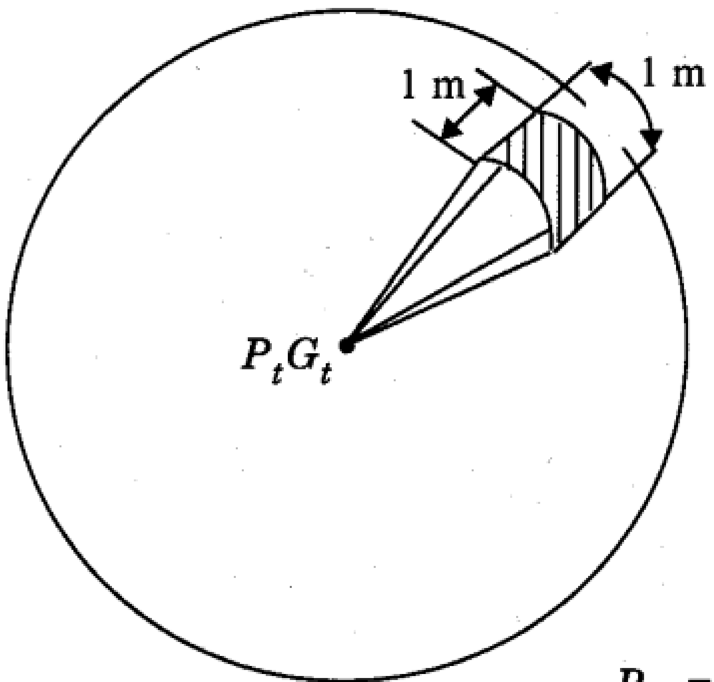
with $E_\phi = H_r = H_\theta = 0$

- At the region far away from the transmitter only E_θ and H_ϕ need to be considered.
- In free space, the power flux density is given by

$$P_d = \frac{EIRP}{4\pi d^2} = \frac{P_t G_t}{4\pi d^2} = \frac{|E|^2}{R_{fs}} = \frac{|E|^2}{\eta} \quad W/m^2$$

- where R_{fs} is the intrinsic impedance of free space given by $\eta = 120\pi \ \Omega$

$$P_d = \frac{|E|^2}{377 \ \Omega} \quad W/m^2$$



(a)

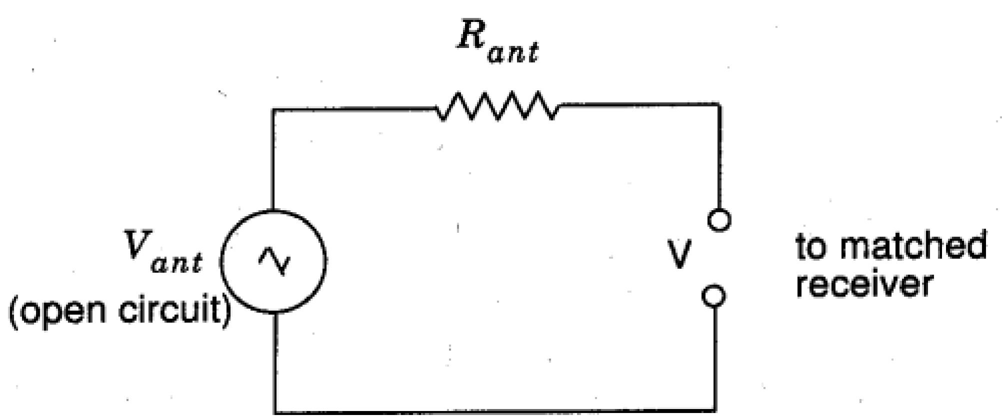
$$P_d = \frac{P_tG_t}{4\pi d^2} = \frac{EIRP}{4\pi d^2} = \frac{|E|^2}{120\pi}\ \text{W/m}^2$$

- The power received at distance   is given by the power flux density times the effective aperture of the receiver antenna

$$P_r(d) = P_d A_e = \frac{|E|^2}{120\pi} A_e = \frac{P_t G_t G_r \lambda^2}{(4\pi)^2 d^2} \quad \text{Watts}$$

- If the receiver antenna is modeled as a matched resistive load to the receiver, the received power is given by

$$P_r(d) = \frac{(V/2)^2}{R_{ant}} = \frac{V^2}{4R_{ant}}$$

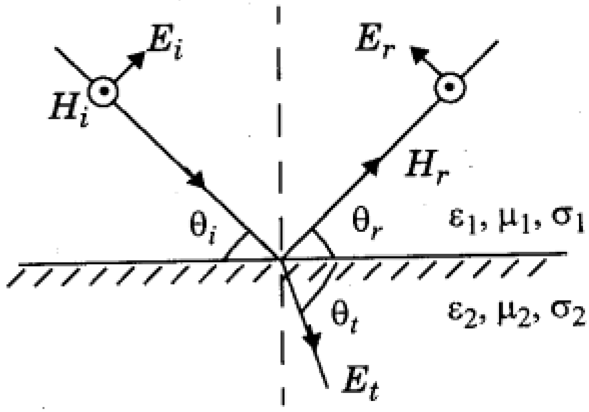


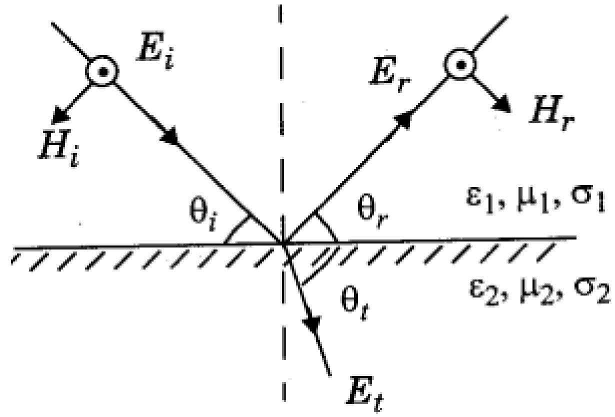
(b)

THE THREE BASIC PROPAGATION MECHANISMS

- Basic propagation mechanisms
  - reflection
  - diffraction
  - scattering
- Reflection occurs when a propagating electromagnetic wave impinges upon an object which has very large dimensions when compared to the wavelength, e.g., buildings, walls.
- Diffraction occurs when the radio path between the transmitter and receiver is obstructed by a surface that has sharp edges.
- Scattering occurs when the medium through which the wave travels consists of objects with dimensions that are small compared to the wavelength.

- Reflection from dielectrics





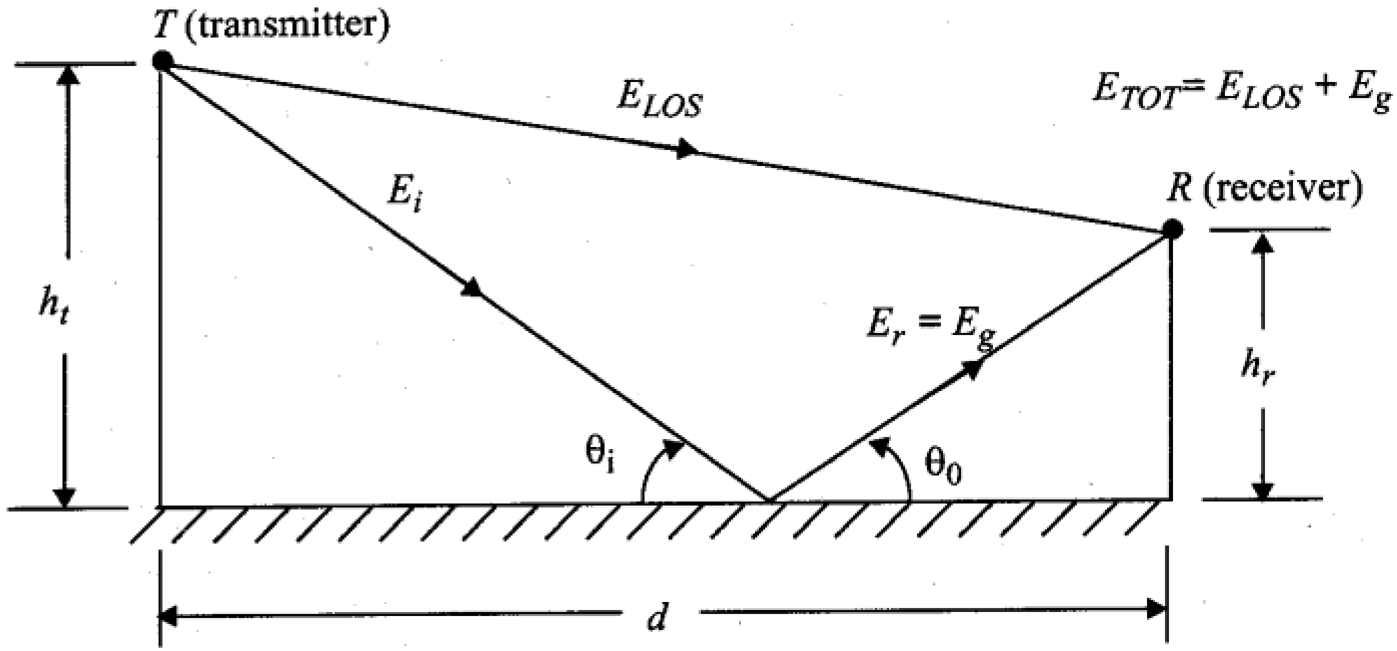
- Reflection from perfect conductors
  - E-field in the plane of incidence

$$\theta_i = \theta_r \qquad \text{and} \qquad E_i = E_r$$

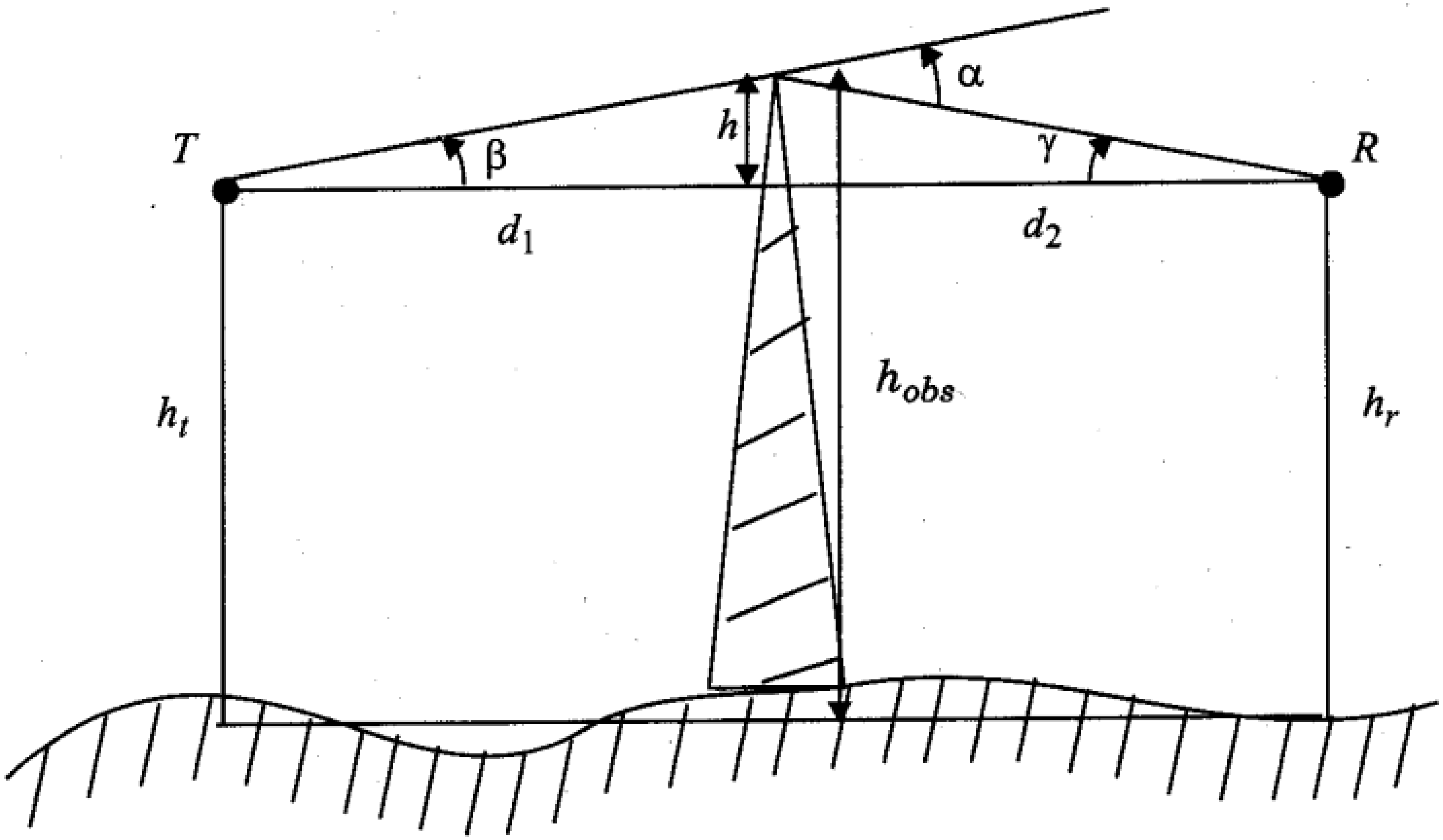
  - E-field normal to the plane of incidence

$$\theta_i = \theta_r \qquad \text{and} \qquad E_i = -E_r$$

- Ground Reflection (2-ray) Model

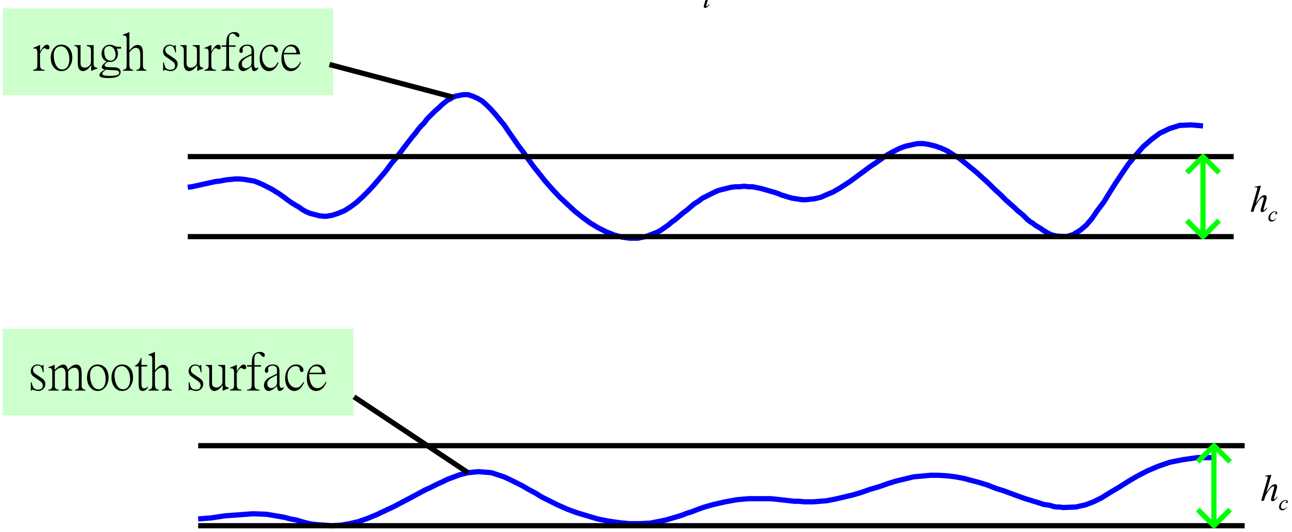


- Diffraction



- The actual received signal is often stronger than what is predicted by reflection and diffraction
- Scattering
  - when a radio wave impinges on a rough surface, the reflected energy is spread out, e.g., trees, lamp posts.
- Surface roughness is test using Rayleigh criterion which defines a critical height h_c for a given angle of incidence θ_i

$$h_c = \frac{\lambda}{8 \sin \theta_i}$$



- For rough surface, the flat surface reflection coefficient needs to be multiplied by a scattering loss factor

$$\rho_s = \exp\left[\left(\frac{\pi\sigma_h \sin\theta_i}{\lambda}\right)^2\right]$$

σ_h is the standard deviation of the surface height.

PRACTICAL LINK BUDGET DESIGN USING PATH LOSS MODELS

- Radio propagation models combine
  - analytical method
  - empirical method
- Log-distance Path Loss Model
  - average received signal power decreases logarithmically with distance
- The average path loss

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

or

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

Table 3.2 Path Loss Exponents for Different Environments

Environment	Path Loss Exponent, n
Free space	2
Urban area cellular radio	2.7 to 3.5
Shadowed urban cellular radio	3 to 5
In building line-of-sight	1.6 to 1.8
Obstructed in building	4 to 6
Obstructed in factories	2 to 3

- Log-normal Shadowing
  - Surrounding environmental clutter may be different at two different locations having the same T-R separation.
- Measurements have shown that at any value *d*, the path loss *PL(d)* at a particular location is random and distributed normally (normal in dB)

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

and

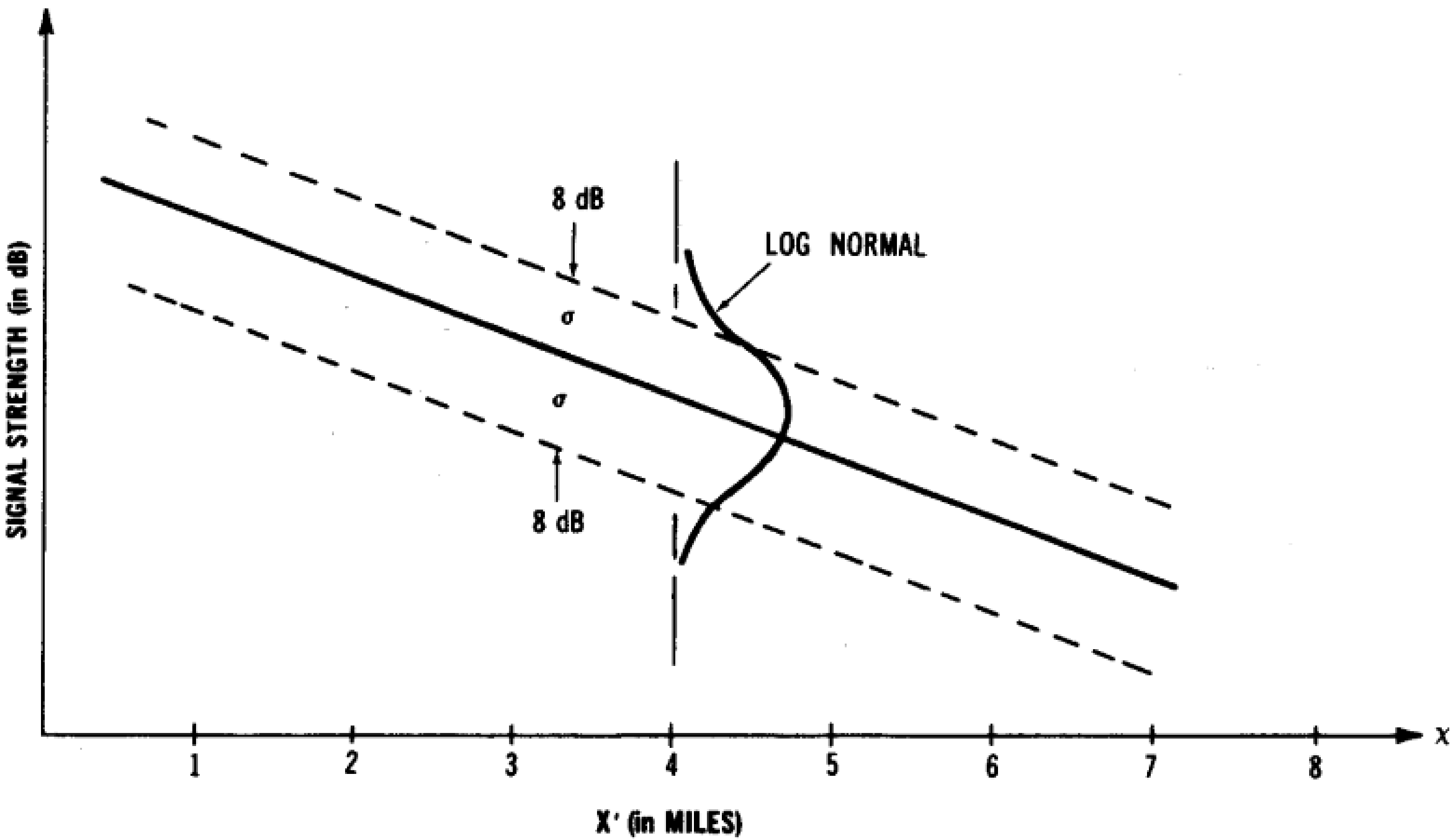
$$P_r(d) = P_t(d) - PL(d)$$

X_σ: zero-mean Gaussian distributed random variable (in dB) with standard deviation σ

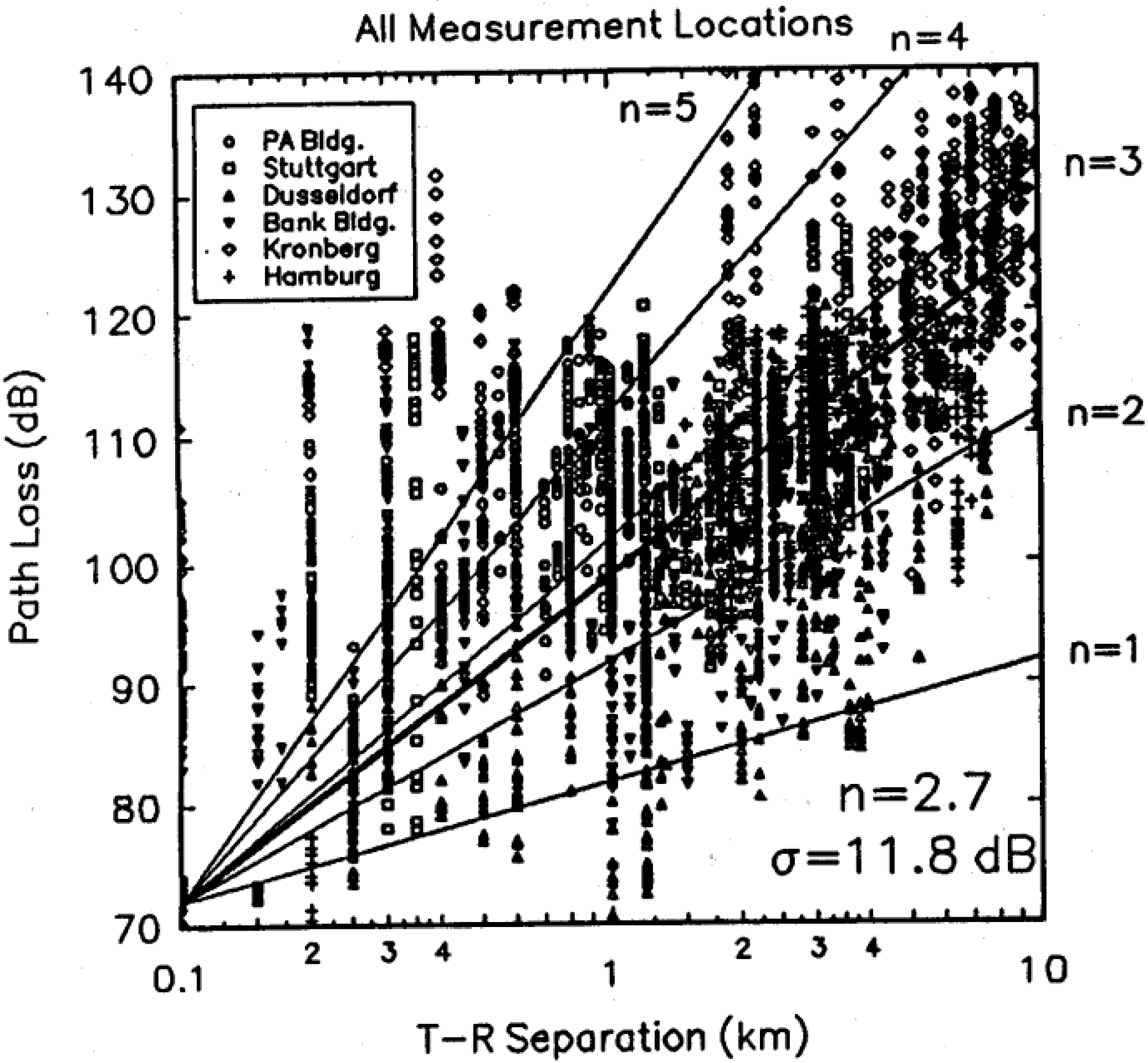
- The probability that the received signal level will exceed a certain value γ can be calculated from

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

where $\overline{P_r(d)} = P_t(d) - \overline{PL}(d)$



SIGNAL STRENGTH (in dB)
8 dB
σ
σ
8 dB
LOG NORMAL
1
2
3
4
5
6
7
8
x′
X′ (in MILES)



All Measurement Locations
PA Bldg.
Stuttgart
Dusseldorf
Bank Bldg.
Kronberg
Hamburg
n=5
n=4
n=3
n=2
n=1
n=2.7
σ=11.8 dB
Path Loss (dB)
140
130
120
110
100
90
80
70
0.1
2
3
4
1
2
3
4
10
T–R Separation (km)

OUTDOOR PROPAGATION MODELS

Okumura Model

- It is one of the most widely used models for signal prediction in urban areas, and it is applicable for frequencies in the range 150 MHz to 1920 MHz
- Based totally on measurements (not analytical calculations)
- Applicable in the range: 150MHz to ~ 2000MHz, 1km to 100km T-R separation, Antenna heights of 30m to 100m

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

Where

L_{50} is the median path loss (50%)

L_F is the free space path loss

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

$G(h_{re}), G(h_{te})$ are antenna height gain factors

G_{AREA} is the gain due to the type of environment

Okumura Model

- The major disadvantage with the model is its low response to rapid changes in terrain, therefore the model is fairly good in urban areas, but not as good in rural areas.
- Common standard deviations between predicted and measured path loss values are around 10 to 14 dB.
- G(hre) :

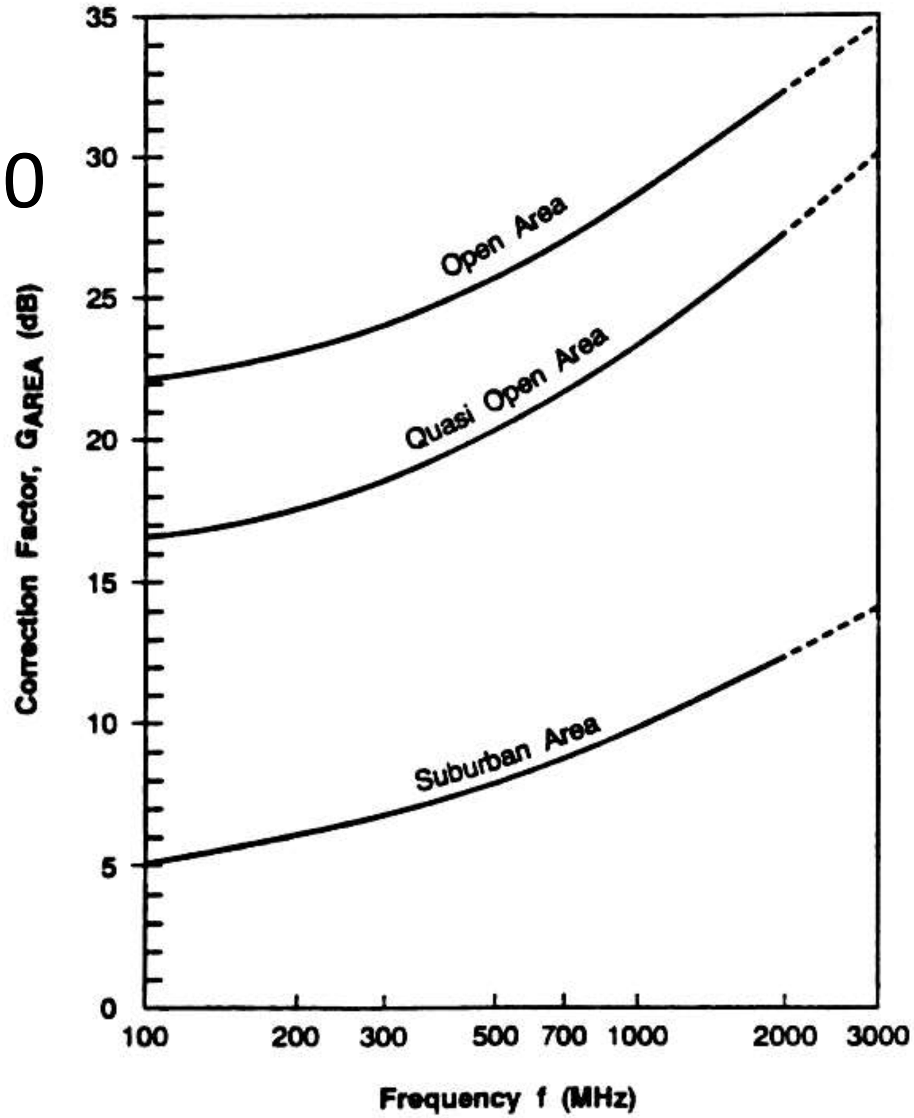
$$G(h_{te}) = 20\log\left(\frac{h_{te}}{200}\right) \qquad 1000\,\text{m} > h_{te} > 30\,\text{m}$$

$$G(h_{re}) = 10\log\left(\frac{h_{re}}{3}\right) \qquad h_{re} \le 3\,\text{m}$$

$$G(h_{re}) = 20\log\left(\frac{h_{re}}{3}\right) \qquad 10\,\text{m} > h_{re} > 3\,\text{m}$$

Okumura and Hata's model

- Example 4.10



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

Hata Model

- Empirical formulation of the graphical data in the Okamura model. Valid 150MHz to 1500MHz, Used for cellular systems
- The following classification was used by Hata:

■Urban area

$$L_{dB} = A + B \log d - E$$

■Suburban area

$$L_{dB} = A + B \log d - C$$

■Open area

$$L_{dB} = A + B \log d - D$$

$$A = 69.55 + 26.16 \log f - 13.82 h_b$$

$$B = 44.9 - 6.55 \log h_b$$

$$C = 2(\log(f/28))^2 + 5.4$$

$$D = 4.78 \log(f/28)^2 + 18.33 \log f + 40.94$$

$$E = 3.2(\log(11.75 h_m))^2 - 4.97 \quad \text{for large cities, } f \geq 300MHz$$

$$E = 8.29(\log(1.54 h_m))^2 - 1.1 \quad \text{for large cities, } f < 300MHz$$

$$E = (1.11 \log f - 0.7) h_m - (1.56 \log f - 0.8) \quad \text{for medium to small cities}$$

PCS Extension of Hata Model

- **COST-231 Hata Model, European standard**
- Higher frequencies: up to 2GHz
- Smaller cell sizes
- Lower antenna heights

$$L_{dB} = F + B\log d - E + G$$

$$F = 46.3 + 33.9\log f - 13.82\log h_b$$ f >1500MHz

$$G = \begin{cases} 3 & \text{Metropolitan centers} \\ 0 & \text{Medium sized city and suburban areas} \end{cases}$$

INDOOR PROPAGATION MODELS

- The distances covered are much smaller
- The variability of the environment is much greater
- Key variables: layout of the building, construction materials, building type, where the antenna mounted, …etc.
- In general, indoor channels may be classified either as LOS or OBS with varying degree of clutter
- The losses between floors of a building are determined by the external dimensions and materials of the building, as well as the type of construction used to create the floors and the external surroundings.
- Floor attenuation factor (FAF)
- Log-distance Path Loss Model

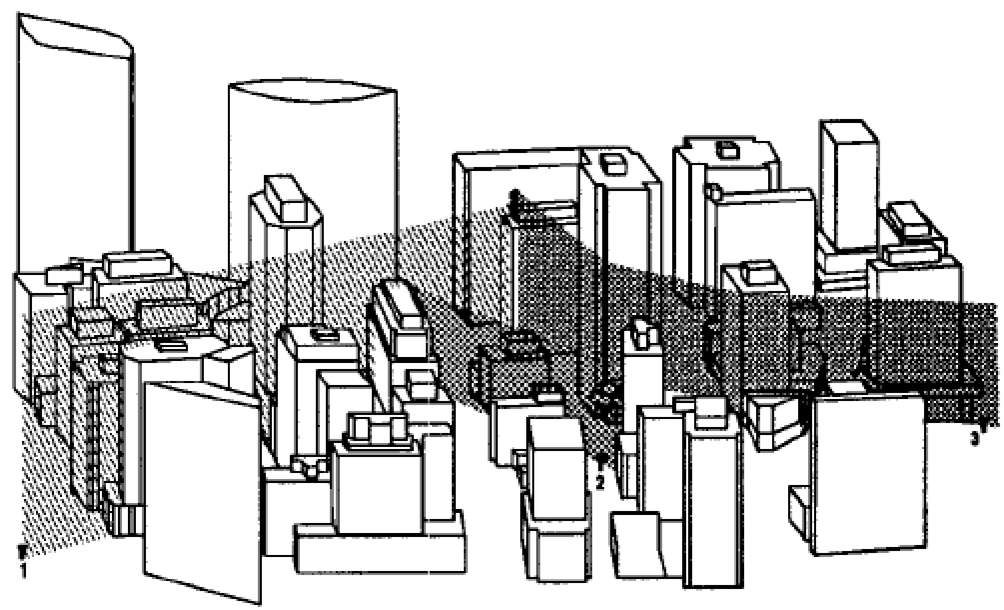
$$PL(\text{dB}) = PL(d_0) + 10n\log\left(\frac{d}{d_0}\right) + X_\sigma$$

Signal Penetration into Buildings

- RF penetration has been found to be a function of frequency as well as height within the building. Signal strength received inside a building increases with height, and penetration loss decreases with increasing frequency.
- Walker's work shows that building penetration loss decrease at a rate of 1.9 dB per floor from the ground level up to the 15th floor and then began increasing above the 15th floor. The increase in penetration loss at higher floors was attributed to shadowing effects of adjacent buildings.
- Some devices to conduct the signals into the buildings

Ray Tracing and Site Specific Modeling

- Site specific propagation model and graphical information system. Ray tracing. Deterministic model.
- Data base for buildings, trees, etc.
- SitePlanner



SMALL-SCALE MULTIPATH PROPAGATION

- The three most important effects
  - 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
  - Time dispersion caused by multipath propagation delays
- Factors influencing small-scale fading
  - Multipath propagation: reflection objects and scatters
  - Speed of the mobile: Doppler shifts
  - Speed of surrounding objects
  - Transmission bandwidth of the signal
    - The received signal will be distorted if the transmission bandwidth is greater than the bandwidth of the multipath channel.
    - Coherent bandwidth: bandwidth of the multipath channel.

- Doppler Shift
  - A mobile moves at a constant velocity *v*, along a path segment having length *d* between points *X* and *Y*.
  - Path length difference

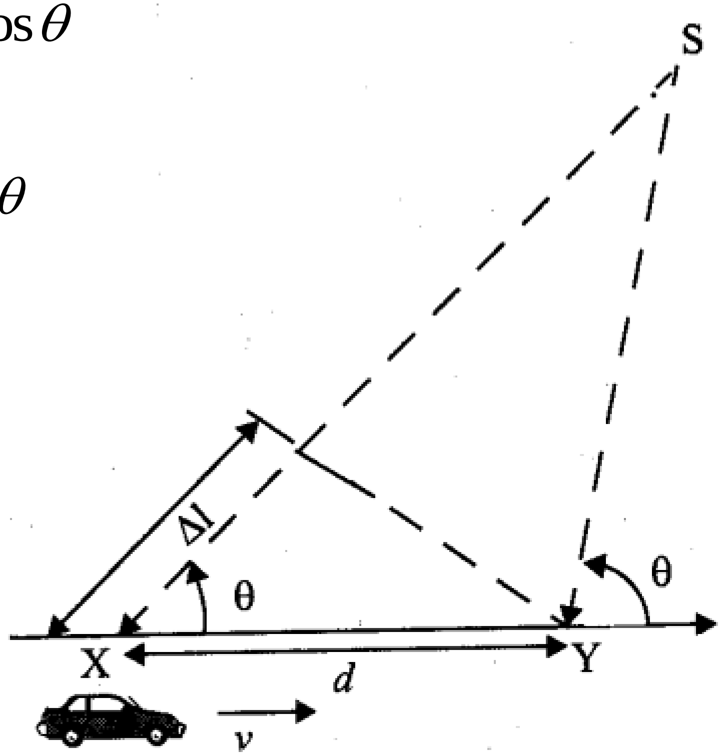
$$\Delta l = d\cos\theta = v\Delta t\cos\theta$$

  - Phase change

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

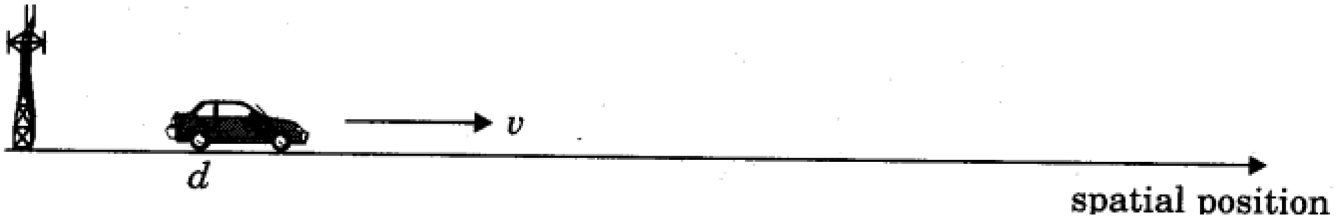
  - Doppler shift

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



IMPULSE RESPONSE MODEL OF A MULTIPATH CHANNEL

- A mobile radio channel may be modeled as a linear filter with a time varying impulse response
  - time variation is due to receiver motion in space
  - filtering is due to multipath



- The channel impulse response can be expressed as *h(d,t).* Let *x(t)* represent the transmitted signal, then the received signal *y(d,t)* at position *d* can be expressed as

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

- For a causal system

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

- The position of the receiver can be expressed as

$$d = vt$$

- We have

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

- Since *v* is a constant, $y(vt,t)$ is just a function of *t*.

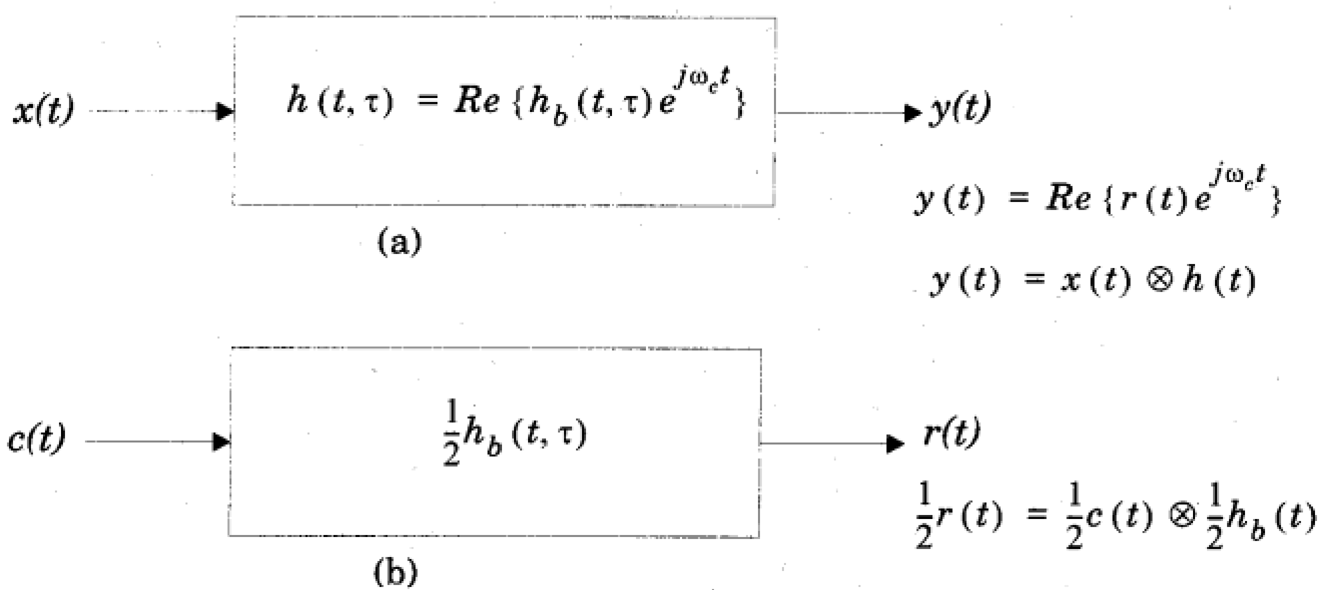
$$y(t) = \int_{-\infty}^{t} x(\tau)h(vt, t-\tau)d\tau$$

- In general, the channel impulse response can be expressed $h(t,\tau)$
  - *t* : time variation due to motion
  - τ: channel multipath delay for a fixed value of *t*.
- With the channel impulse response $h(t,\tau)$, we may have the output

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

- For bandlimited bandpass channel, then $h(t,\tau)$ may be equivalently described by a complex baseband impulse response $h_b(t,\tau)$
  - The equivalent baseband output

$$\frac{1}{2}r(t) = \frac{1}{2}c(t) \otimes \frac{1}{2}h_b(t,\tau) \qquad \text{or} \qquad r(t) = \frac{1}{2}c(t) \otimes h_b(t,\tau)$$



$$x(t) = \mathrm{Re}\{c(t)\exp(j\omega_c t)\} \qquad r(t) = \frac{1}{2}c(t) \otimes h_b(t,\tau)$$

$$y(t) = \mathrm{Re}\{r(t)\exp(j\omega_c t)\}$$

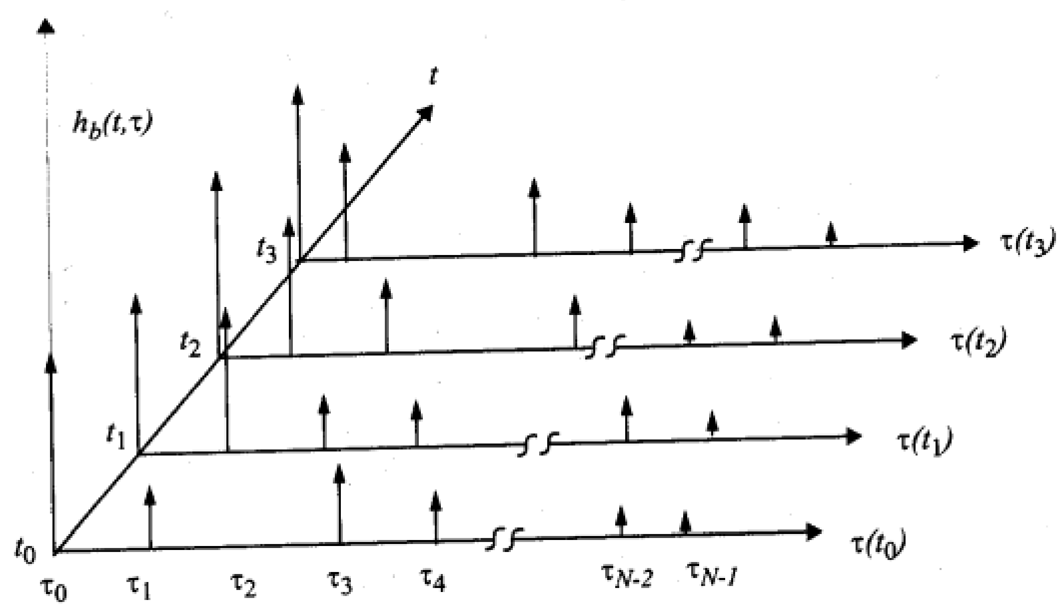
- Discretize the multipath delay axis τ into equal time delay segments called *excess delay bins*.
- The baseband response of a multipath channel can be expressed as

$$h_b(t,\tau) = \sum_{i=0}^{N-1} a_i(t,\tau)\exp\left(j2\pi f_c \tau_i(t) + j\phi(t,\tau)\right)\delta(\tau - \tau_i(t))$$

$a_i(t,\tau)$: amplitude of the *i*th multipath component

$\tau_i(t)$: excess delay of *i*th multipath component

- Define $\theta_i(t,\tau) = 2\pi f_c \tau_i(t) + \phi(t,\tau)$



- If the channel impulse response is assumed to be time invariant, the channel impulse response may be simplified as

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

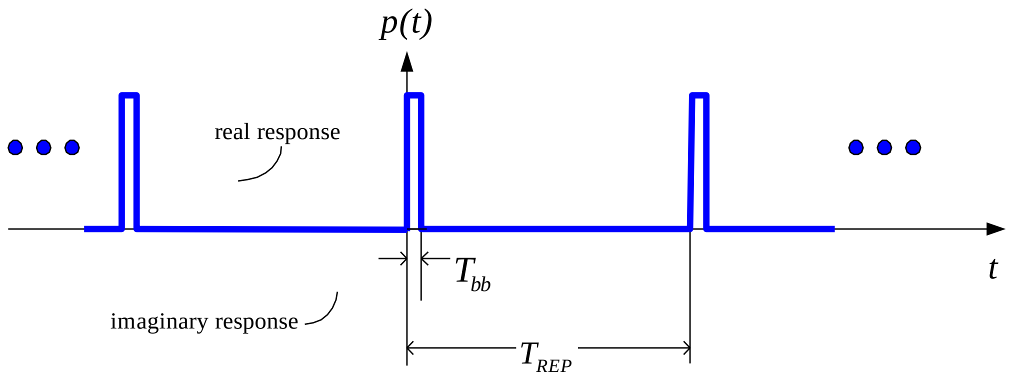
- The impulse response may be measured by using a probing pulse $p(t)$ which approximates a delta function.

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

Relationship Between Bandwidth and Received Power

- Consider a pulsed, transmitted signal of the form

$$x(t) = \mathrm{Re}\left\{p(t)\exp(j2\pi f_c t)\right\}$$



- The signal *p(t)* is a repetitive baseband pulse train with very narrow pulse width T_{bb} and repetition period T_{REP}, with $T_{REP} >> \tau_{\max}$.
- Now, let

$$p(t) = 2\sqrt{\tau_{\max} / T_{bb}} \qquad\qquad 0 \le t \le T_{bb}$$

- The channel output r(t) closely approximates the impulse response and is given by

$$r(t) = \frac{1}{2}\sum_{i=0}^{N-1} a_i \exp(-j\theta_i)\cdot p(t-\tau_i)$$
$$= \sum_{i=0}^{N-1} a_i \exp(-j\theta_i)\cdot \sqrt{\frac{\tau_{\max}}{T_{bb}}} rect\left[t-\frac{T_{bb}}{2}-\tau_i\right]$$

- Instantaneous multipath power delay profile

$$|r(t_0)|^2 = \frac{1}{\tau_{\max}}\int_0^{\tau_{\max}} r(t)r^*(t)dt$$
$$= \frac{1}{\tau_{\max}}\int_0^{\tau_{\max}} \frac{1}{4}\mathrm{Re}\left\{\sum_{j=0}^{N-1}\sum_{i=0}^{N-1} a_j(t_0)a_i(t_0)p(t-\tau_j)p(t-\tau_i)\exp(-j(\theta_j-\theta_i))\right\}dt$$

- If all the multipath components are resolved by the probe *p(t),* then

$$\left|\tau_j - \tau_i\right| > T_{bb} \qquad \forall \quad j \neq i$$

- Then we have

$$\begin{aligned}
\left|r(t_0)\right|^2 &= \frac{1}{\tau_{\max}} \int_0^{\tau_{\max}} \frac{1}{4} \left(\sum_{k=0}^{N-1} a_k^2(t_0) p^2(t-\tau_k) \right) dt \\
&= \frac{1}{\tau_{\max}} \sum_{k=0}^{N-1} a_k^2(t_0) \int_0^{\tau_{\max}} \left(\sqrt{\frac{\tau_{\max}}{T_{bb}}} rect\left[t - \frac{T_{bb}}{2} - \tau_k \right] \right) dt \\
&= \sum_{k=0}^{N-1} a_k^2(t_0)
\end{aligned}$$

- The total receiving power is related to the sum of the powers in the individual multipath components.

- Assuming that the received power from the multipath components forms a random process where each component has a random amplitude and phase at any time *t*, the average small-scale received power is

$$E_{a,\theta}[P_{WB}] = E_{a,\theta}\left[\sum_{i=0}^{N-1} \left|a_i \exp(j\theta_i)\right|^2\right] = \sum_{i=0}^{N-1} \overline{a_i^2}$$

- Now, consider a CW signal which is transmitted into the exact same channel, and let the complex envelope be given by *c(t)=2*. Then the received signal can be expressed as

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

- The instantaneous power is given by

$$\left|r(t)\right|^2 = \left|\sum_{i=0}^{N-1} a_i \exp(j\theta_i(t,\tau))\right|^2$$

- In a local area, a_i varies little, but θ_i will vary greatly due to changes in propagation distance over space, resulting in large fluctuations of *r(t)*.
- The average received power over a local area is given by

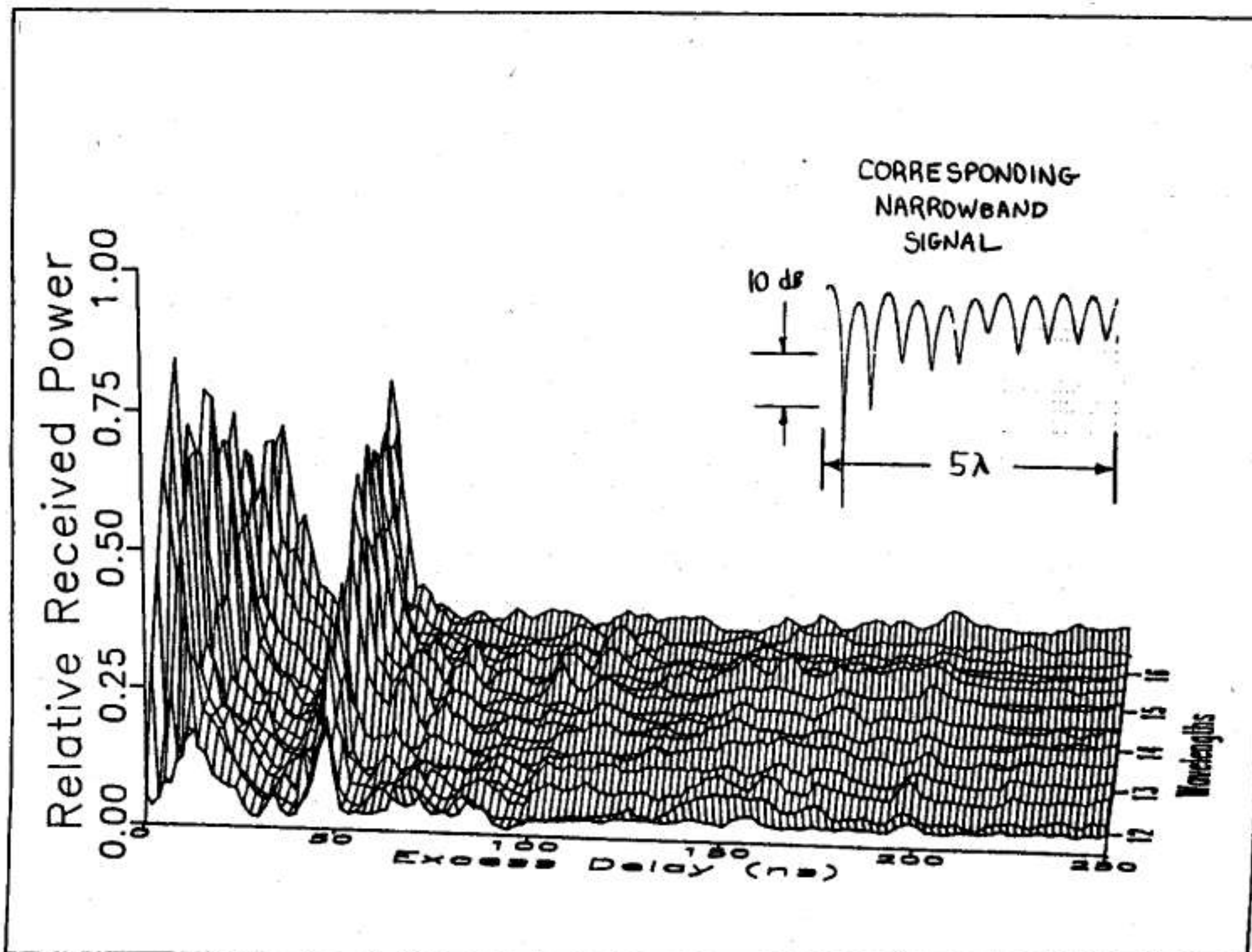
$$E_{a,\theta}\left[P_{CW}\right] = E_{a,\theta}\left[\left|\sum_{i=0}^{N-1} a_i \exp(j\theta_i(t,\tau))\right|^2\right]$$

$$\approx \sum_{i=0}^{N-1} \overline{a_i^2} + 2\sum_{i=0}^{N-1}\sum_{i,j\neq i}^{N} r_{ij}\overline{\cos(\theta_i - \theta_j)}$$

where

$$r_{ij} = E_a[a_i a_j]$$

- The received power for CW wave has large fluctuations than that for WB signal.


CORRESPONDING
NARROWBAND
SIGNAL
10 dB
5λ
Relative Received Power
0.00
0.25
0.50
0.75
1.00
0
50
100
150
200
250
Excess Delay (ns)
12
13
14
15
16
Wavelengths

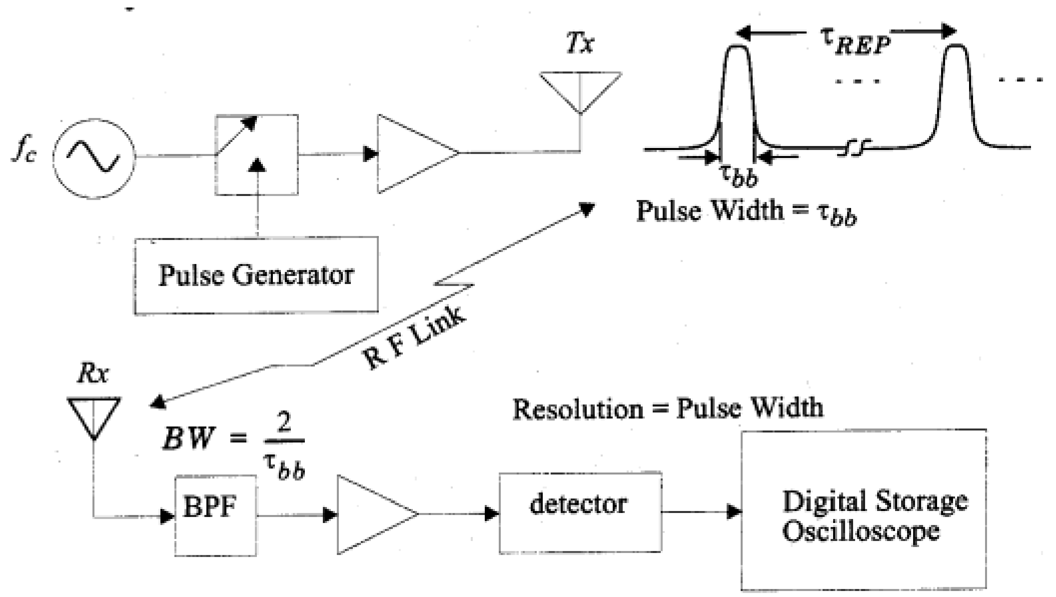
SMALL-SCALE MULTIPATH MEASUREMENT

- Multipath channel measurement techniques
  - Direct pulse measurements
  - Spread spectrum sliding correlator measurements
  - Swept frequency measurements

Direct RF Pulse System

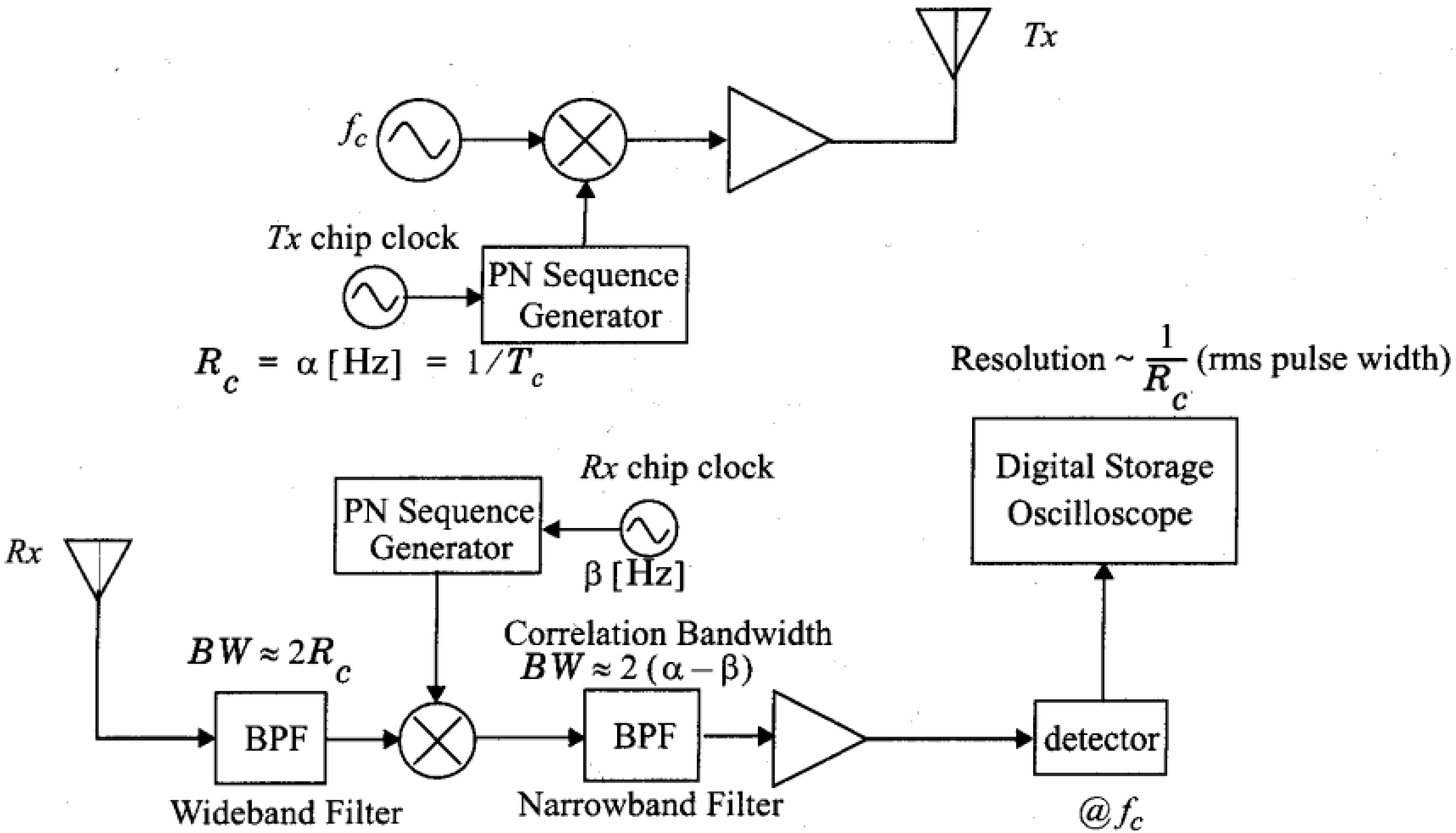
- Direct RF pulse system
  - This system transmits a repetitive pulse of width τ_{bb}, and uses a receiver with a wideband filter with bandwidth $BW = 2/\tau_{bb}$
  - Envelope detector to detect the amplitude response.
- Minimum resolvable delay τ_{bb}

- No phase information can be measured.



Spread Spectrum Sliding Correlator Channel Sounding

- System description
  - A carrier is spread over a large bandwidth by using a pseudo-noise sequence having chip duration T_c and a chip rate R_c .
  - Despread using a PN sequence identical to that used at the transmitter.
- The probing signal is wideband.
- Use a narrowband receiver preceded by a wideband mixer.
- The transmitter chip clock is run at a slightly faster rate than the receiver chip clock – sliding correlator.



Tx
f_c
Tx chip clock
PN Sequence Generator
$R_c = \alpha\,[\mathrm{Hz}] = 1/T_c$
Resolution ~ $\frac{1}{R_c}$ (rms pulse width)
Digital Storage Oscilloscope
Rx chip clock
PN Sequence Generator
β [Hz]
Rx
$BW \approx 2R_c$
Correlation Bandwidth
$BW \approx 2(\alpha - \beta)$
BPF
BPF
detector
Wideband Filter
Narrowband Filter
@ f_c

- The time resolution of multipath components using a spread spectrum system with sliding correlation is

$$\Delta\tau = 2T_c = \frac{1}{R_c}$$

- The time between maximum correlation can be calculated

$$\Delta T = T_c r l = \frac{rl}{R_c}$$

T_c: chip period $\qquad$ r: sliding factor

R_c: chip rate $\qquad$ l: sequence length

- The sliding factor can be expressed as

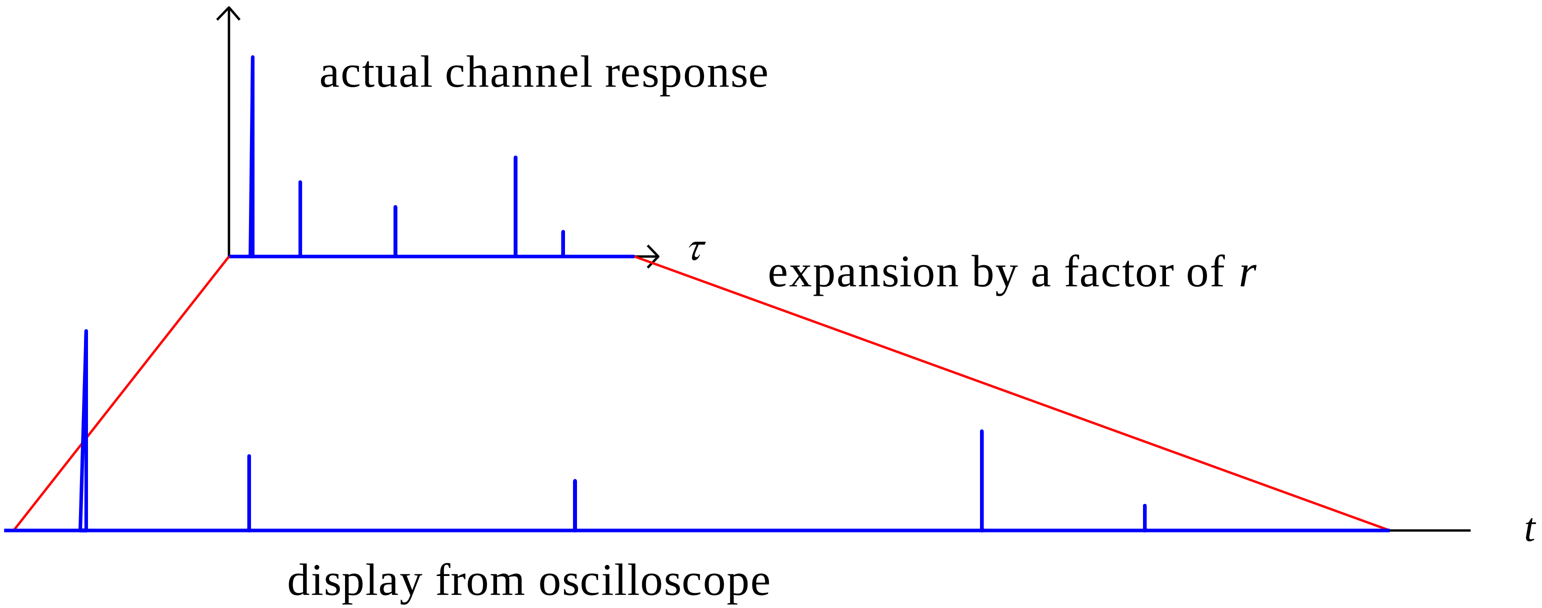
$$r = \frac{\alpha}{\alpha - \beta}$$

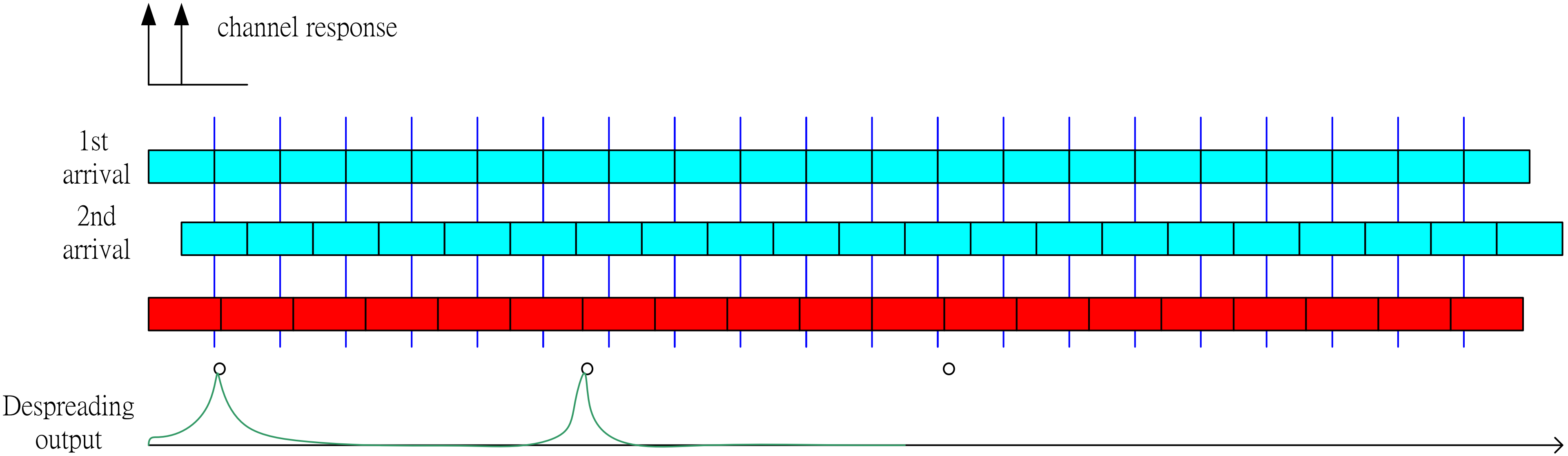
α : transmitter chip clock rate $\qquad$ β: receiver chip clock rate

- The incoming signal is mixed with a PN sequence that is slower than the transmitter sequence. The signal is down converted to a low-frequency narrow band signal.

- The observed time scale on the oscilloscope using a sliding correlator is related to the actual propagation time scale by

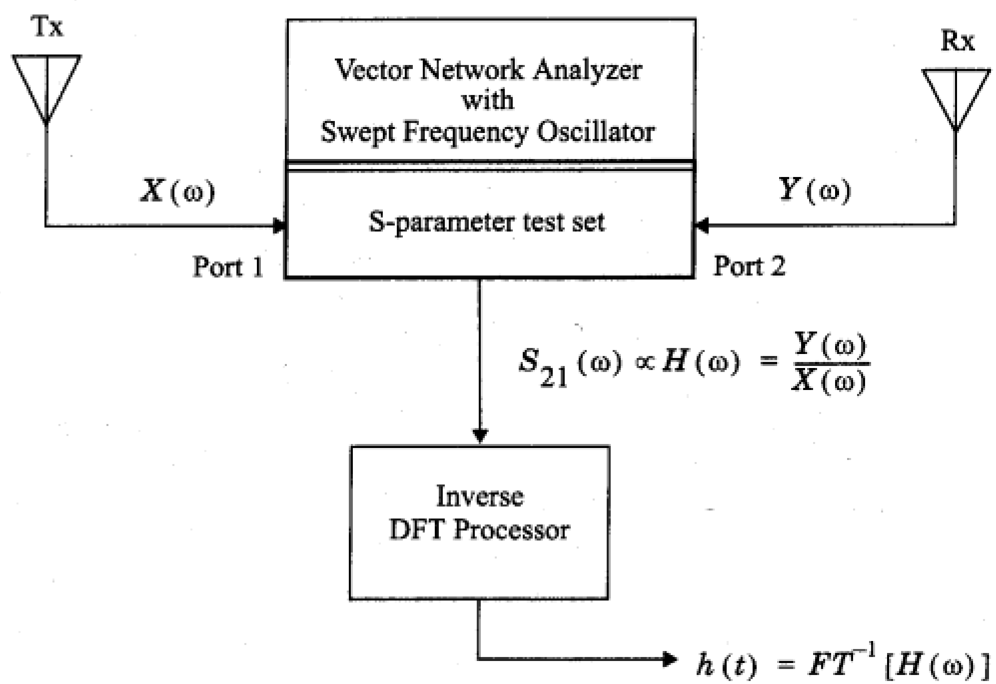
$$\text{Actual Propagation Time} = \frac{\text{Observed Time}}{r}$$




channel response
1st arrival
2nd arrival
Despreading output

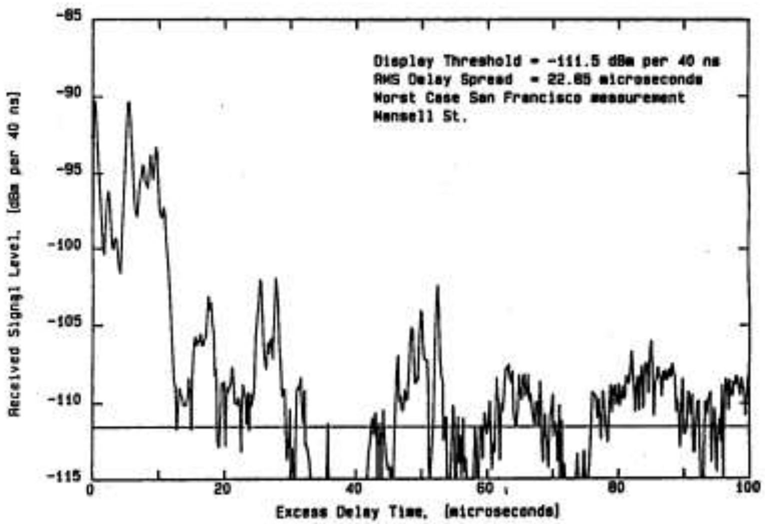
Frequency Domain Channel Sounding

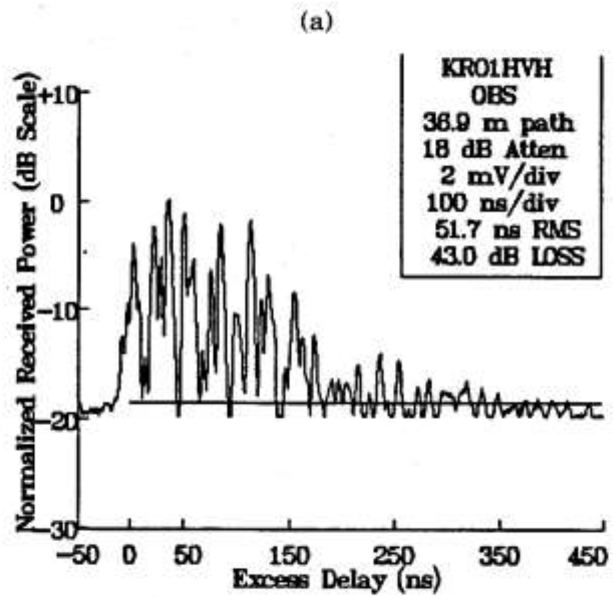
- Dual relationship between time domain and frequency domain.
- It is possible to measure the channel impulse response in the frequency domain.
- Measure the frequency domain response and then converted to the time domain using inverse discrete Fourier transform (IDFT).



PARAMETERS OF MOBILE MULTIPATH CHANNELS

- Power delay profiles for different types of channels are different





Outdoor

Indoor

Time Dispersion Parameters

- Time dispersion parameters
  - mean excess delay
  - RMS delay spread
  - excess delay spread
- Mean excess delay

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

- RMS delay spread

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

where

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

- Depends only on the relative amplitude of the multipath components.
- Typical RMS delay spreads
  - Outdoor: on the order of microseconds
  - Indoor: on the order of nanoseconds
- Maximum excess delay (X dB) is defined to be the time delay during which multipath energy falls to X dB below the maximum.

$$\text{excess delay} = \tau_X - \tau_0$$

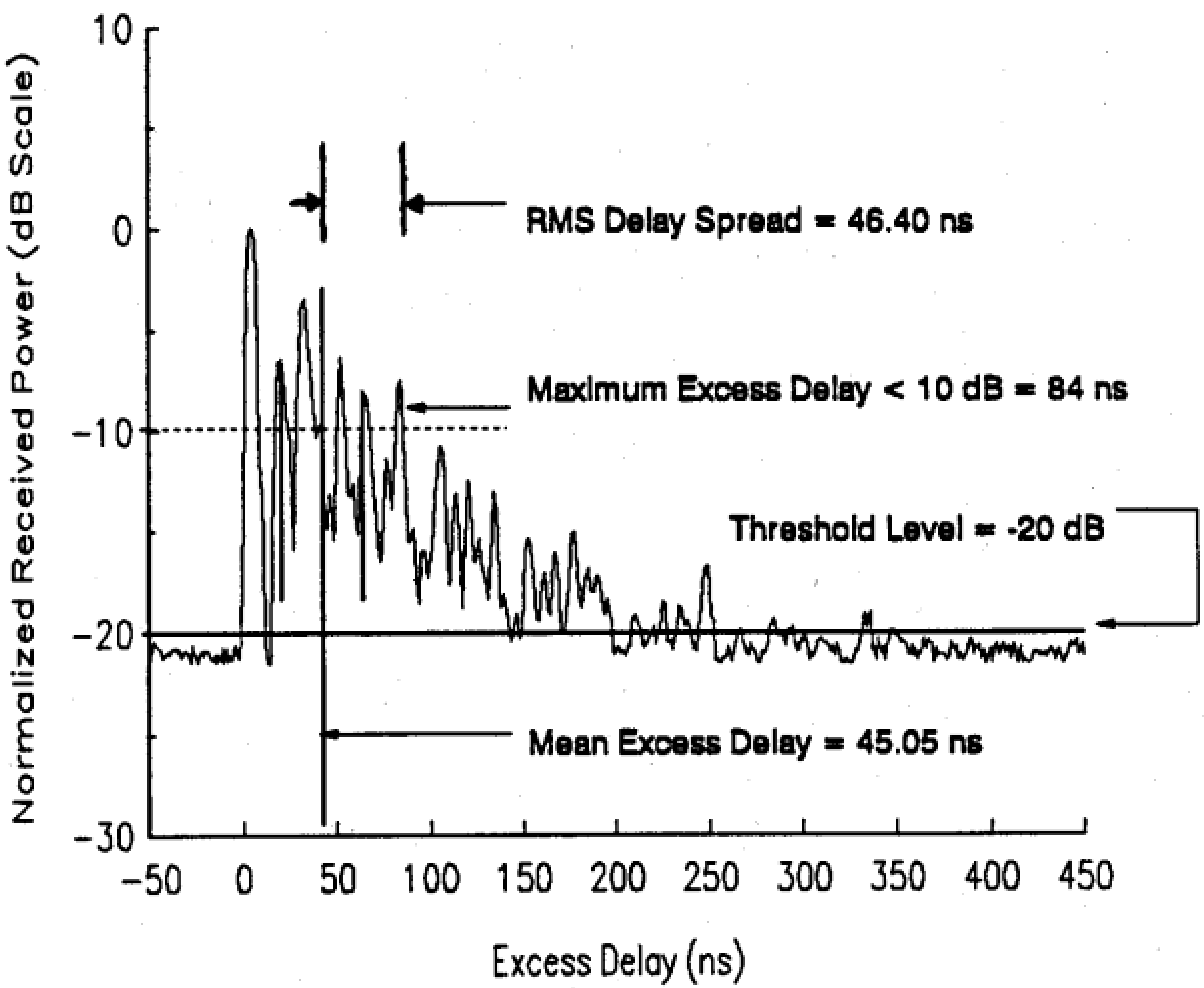
τ_X : maximum delay at which a multipath component is within X dB

τ_0 : delay for the first arriving signal

Table 4.1 Typical Measured Values of RMS Delay Spread

Environment	Frequency (MHz)	RMS Delay Spread (σ_τ)	Notes	Reference
Urban	910	1300 ns avg. 600 ns st. dev. 3500 ns max.	New York City	[Cox75]
Urban	892	10-25 μs	Worst case San Francisco	[Rap90]
Suburban	910	200-310 ns	Averaged typical case	[Cox72]
Suburban	910	1960-2110 ns	Averaged extreme case	[Cox72]
Indoor	1500	10-50 ns 25 ns median	Office building	[Sal87]
Indoor	850	270 ns max.	Office building	[Dev90a]
Indoor	1900	70-94 ns avg. 1470 ns max.	Three San Francisco buildings	[Sei92a]

- Example of an indoor power delay profile; rms delay spread, mean excess delay, maximum excess delay (10dB), and the threshold level are shown



Coherent Bandwidth

- Coherent bandwidth, B_c , is a statistic measure of the range of frequencies over which the channel can be considered to be "flat".
- Two sinusoids with frequency separation greater than B_c are affected quite differently by the channel.
- If the coherent bandwidth is defined as the bandwidth over which the frequency correlation function is above 0.9, then the coherent bandwidth is approximately

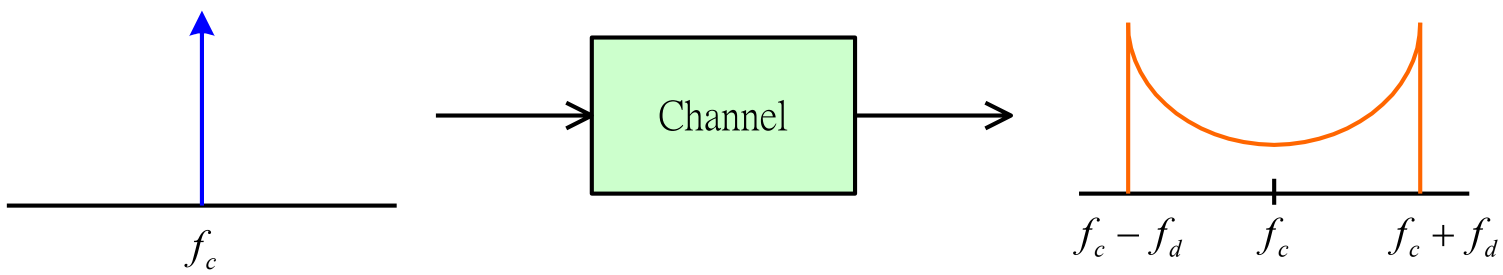
$$B_c \approx \frac{1}{50\sigma_\tau}$$

- If the frequency correlation function is above 0.5

$$B_c \approx \frac{1}{5\sigma_\tau}$$

Doppler Spread and Coherent Time

- Doppler spread and coherent time are parameters which describe the time varying nature of the channel in a small-scale region.
- When a pure sinusoidal tone of f_c is transmitted, the received signal spectrum, called the Doppler spectrum, will have components in the range $f_c - f_d$ and $f_c + f_d$, where f_d is the Doppler shift.



- f_d is a function of the relative velocity of the mobile, and the angle between the direction of motion of the mobile and direction of arrival of the scattered waves

- Coherent time T_C is the time domain dual of Doppler spread.
- Coherent time is used to characterize the time varying nature of the frequency dispersiveness of the channel in the time domain.

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

f_m : maximum Doppler shift given by $f_m = v / \lambda$

v : speed of the mobile λ : speed of the light

- Two signals arriving with a time separation greater than T_C are affected differently by the channel
- A statistic measure of the time duration over which the channel impulse response is essentially invariant.
- If the coherent time is defined as the time over which the time corrleation function is above 0.5, then

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

TYPES OF SMALL-SCALE FADING

- Multipath delay spread leads to *time dispersion* and *frequency selective fading.*
- Doppler spread leads to *frequency dispersion* and *time selective fading*.
- Multipath delay spread and Doppler spread are independent of one another.

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

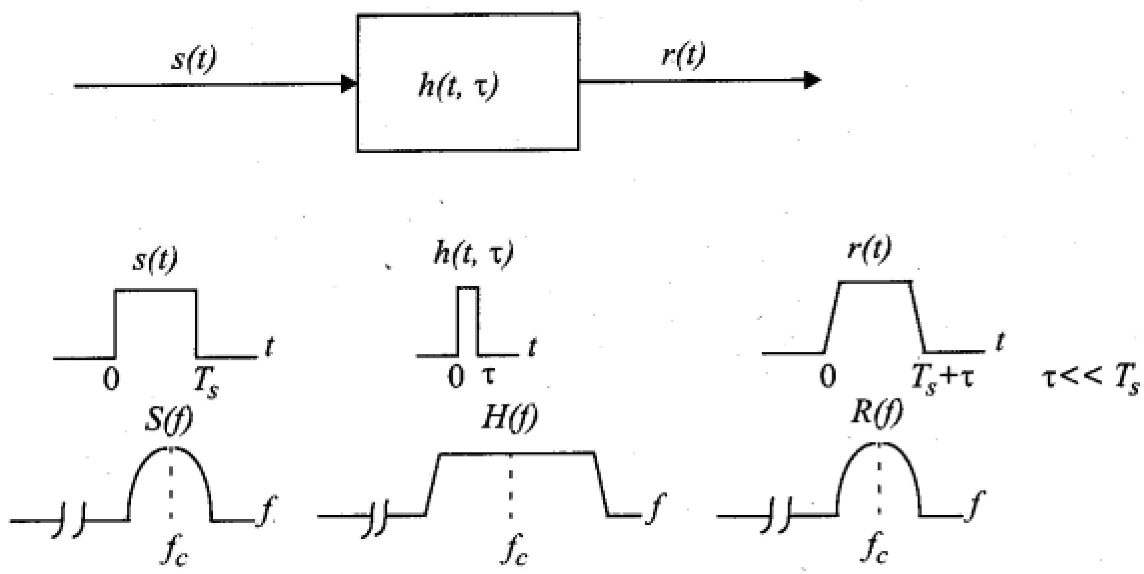
1. High Doppler spread
2. Coherence time < Symbol period
3. Channel variations faster than base-band signal variations

Slow Fading

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

Flat Fading

- If the channel has a constant gain and linear phase response over a bandwidth which is greater than the bandwidth of the transmitted signal, the received signal will undergo flat fading.
- The received signal strength changes with time due to fluctuations in the gain of the channel caused by multipath.
- The received signal varies in gain but the spectrum of the transmission is preserved.



- Flat fading channel is also called amplitude varying channel.
- Also called narrow band channel: bandwidth of the applied signal is *narrow* as compared to the channel bandwidth.
- Time varying statistics: Rayleigh flat fading.
- A signal undergoes flat fading if

$$B_S << B_C$$

and

$$T_S >> \sigma_\tau$$

T_S : reciprocal bandwidth (symbol period)

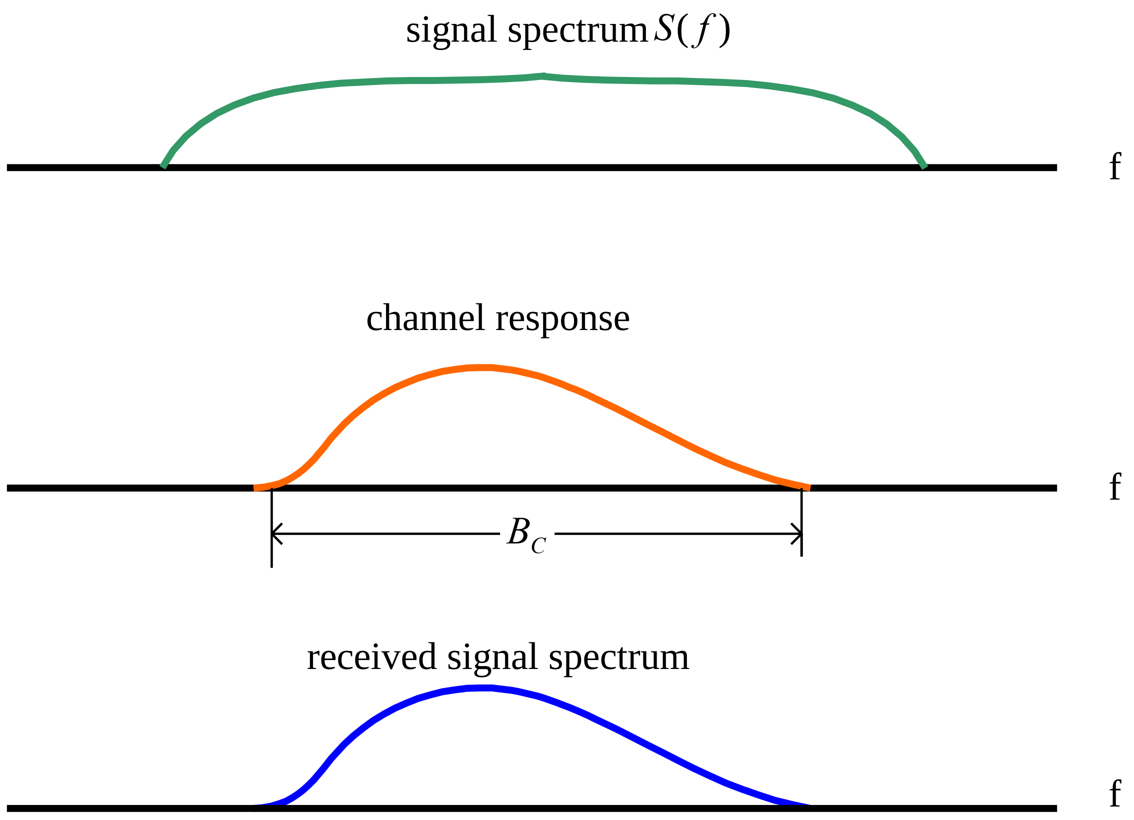
B_S : bandwidth of the transmitt ed signal

B_C : coherent bandwidth

σ_τ : rms delay spread

Frequency Selective Fading

- If the channel possesses a constant-gain and linear phase response over a bandwidth that is smaller than the bandwidth of transmitted signal, then the channel creates frequency selective fading.



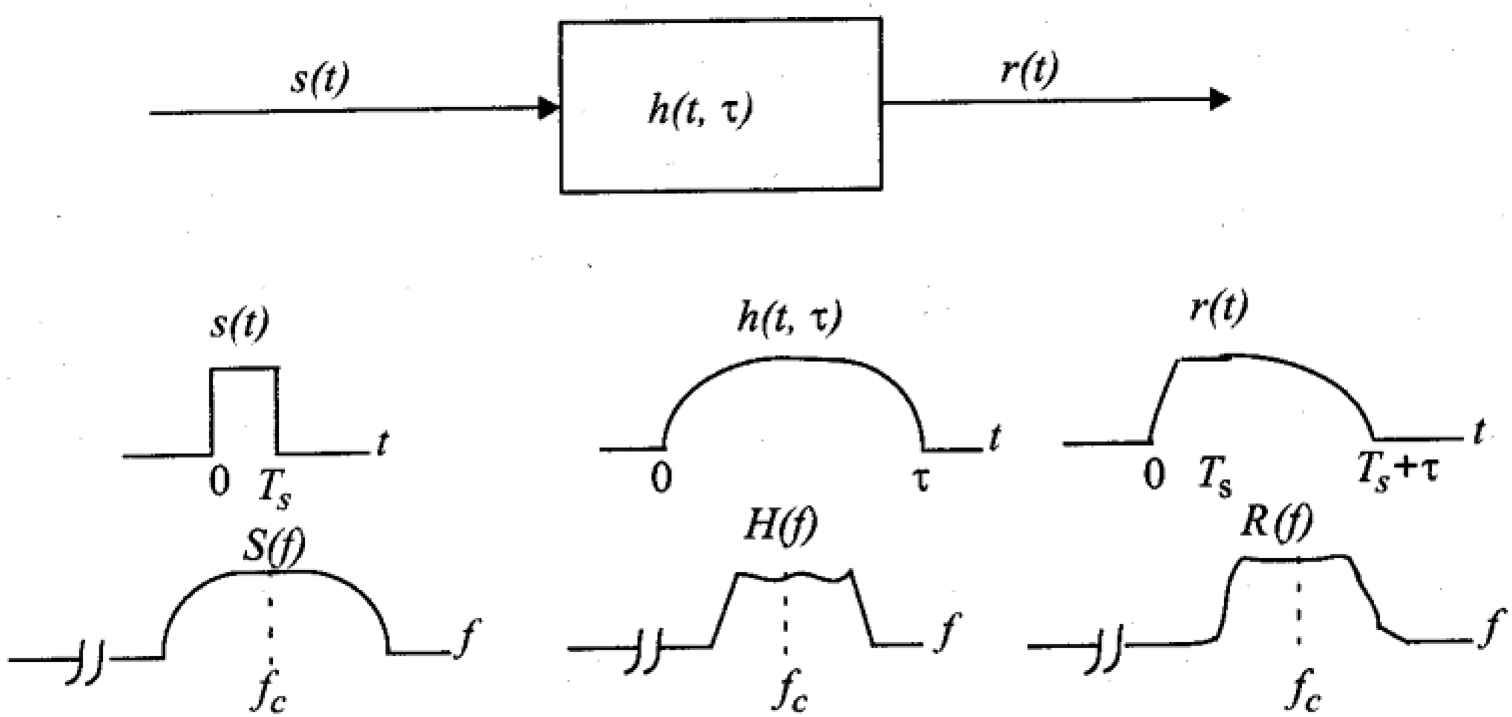
- Frequency selective fading is due to time dispersion of the transmitted symbols within the channel.
  - Induces intersymbol interference
- Frequency selective fading channels are much more difficult to model than flat fading channels.
- Statistic impulse response model
  - 2-ray Rayleigh fading model
  - computer generated
  - measured impulse response
- For frequency selective fading

$$B_S > B_C$$

and

$$T_S > \sigma_\tau$$

- Frequency selective fading channel characteristic



Fading Effects Due to Doppler Spread

- Fast Fading: The channel impulse response changes rapidly within the symbol duration.
  - The coherent time of the channel is smaller then the symbol period of the transmitted signal.
  - Cause frequency dispersion due to Doppler spreading.
- A signal undergoes fast fading if

$$T_S > T_C$$

and

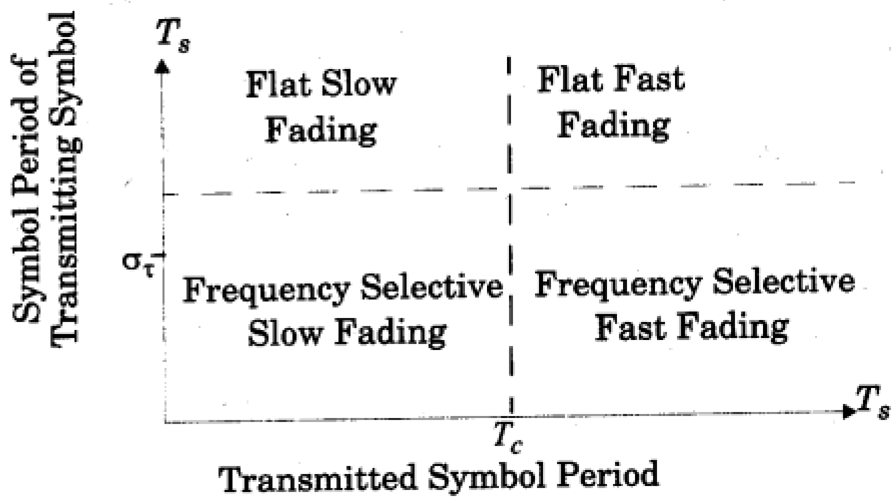
$$B_S < B_D$$

- Slow Fading: The channel impulse response changes at a rate much slower than the transmitted baseband signal s(t).
  - The Doppler spread of the channel is much less then the bandwidth of the baseband signal.
- A signal undergoes slow fading if

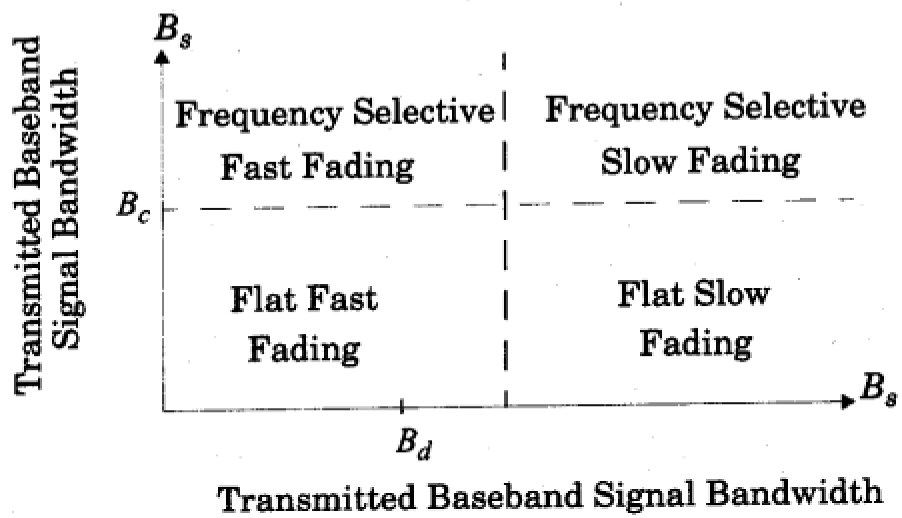
$$T_S << T_C$$

and

$$B_S >> B_D$$


T_s
Symbol Period of Transmitting Symbol
Flat Slow Fading
Flat Fast Fading
σ_τ
Frequency Selective Slow Fading
Frequency Selective Fast Fading
T_c
T_s
Transmitted Symbol Period

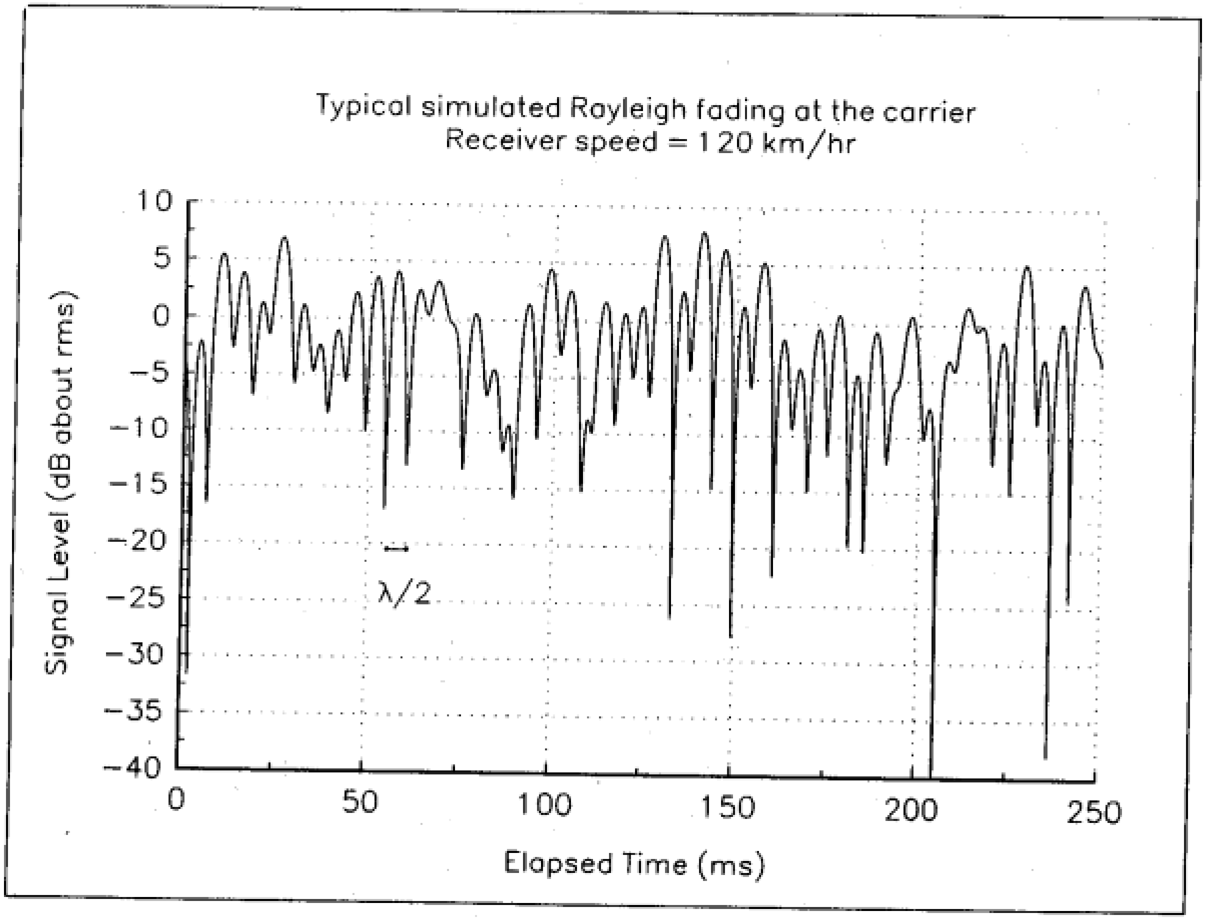
(a)


B_s
Transmitted Baseband Signal Bandwidth
Frequency Selective Fast Fading
Frequency Selective Slow Fading
B_c
Flat Fast Fading
Flat Slow Fading
B_d
B_s
Transmitted Baseband Signal Bandwidth

(b)

Rayleigh and Ricean Distributions

- Rayleigh Fading Distribution
  - The sum of two quadrature Gaussian noise signals



- Consider a carrier signal at frequency ω_0 and with an amplitude a

$$s(t) = a\exp(j\omega_0 t)$$

- The received signal is the sum of *n* waves

$$s_r(t) = \sum_{i=1}^{n} a_i \exp(j\omega_0 t + \theta_i) = r\exp\left[j(\omega_0 t + \theta)\right] = r\exp(j\theta)\exp(j\omega_0 t)$$

where

$$r\exp\left(j\theta\right) = \sum_{i=1}^{n} a_i \exp(\theta_i)$$

define

$$r\exp\left(j\theta\right) = \sum_{i=1}^{n} a_i \cos(\theta_i) + j\sum_{i=1}^{n} a_i \sin(\theta_i) = x + jy$$

We have

$$x \equiv \sum_{i=1}^{n} a_i \cos(\theta_i) = r\cos(\theta) \qquad \text{and} \qquad y \equiv \sum_{i=1}^{n} a_i \sin(\theta_i) = r\sin(\theta)$$

- It can be assumed that *x* and *y* are Gaussian random variables with mean equal to zero due to the following reasons
  - *n* is usually very large.
  - The individual amplitude a_i are random.
  - The phases θ_i have a uniform distribution.
- Because *x* and *y* are independent random variables, the joint distribution *p(x,y)* is

$$p(x,y) = p(x)p(y) = \frac{1}{2\pi\sigma^2}\exp\left(-\frac{x^2+y^2}{2\sigma^2}\right)$$

- The distribution $p(r,\theta)$ can be written as a function of $p(x,y)$

$$p(r,\theta) = |J|\,p(x,y)$$

$$|J| = \begin{vmatrix} \partial x/\partial r & \partial x/\partial\theta \\ \partial y/\partial r & \partial y/\partial\theta \end{vmatrix} = \begin{vmatrix} \cos\theta & -r\sin\theta \\ \sin\theta & r\cos\theta \end{vmatrix} = r$$

- We have

$$p(r,\theta) = \frac{r}{2\pi\sigma^2}\exp\left(-\frac{r^2}{2\sigma^2}\right)$$

- The Rayleigh distribution has a pdf given by

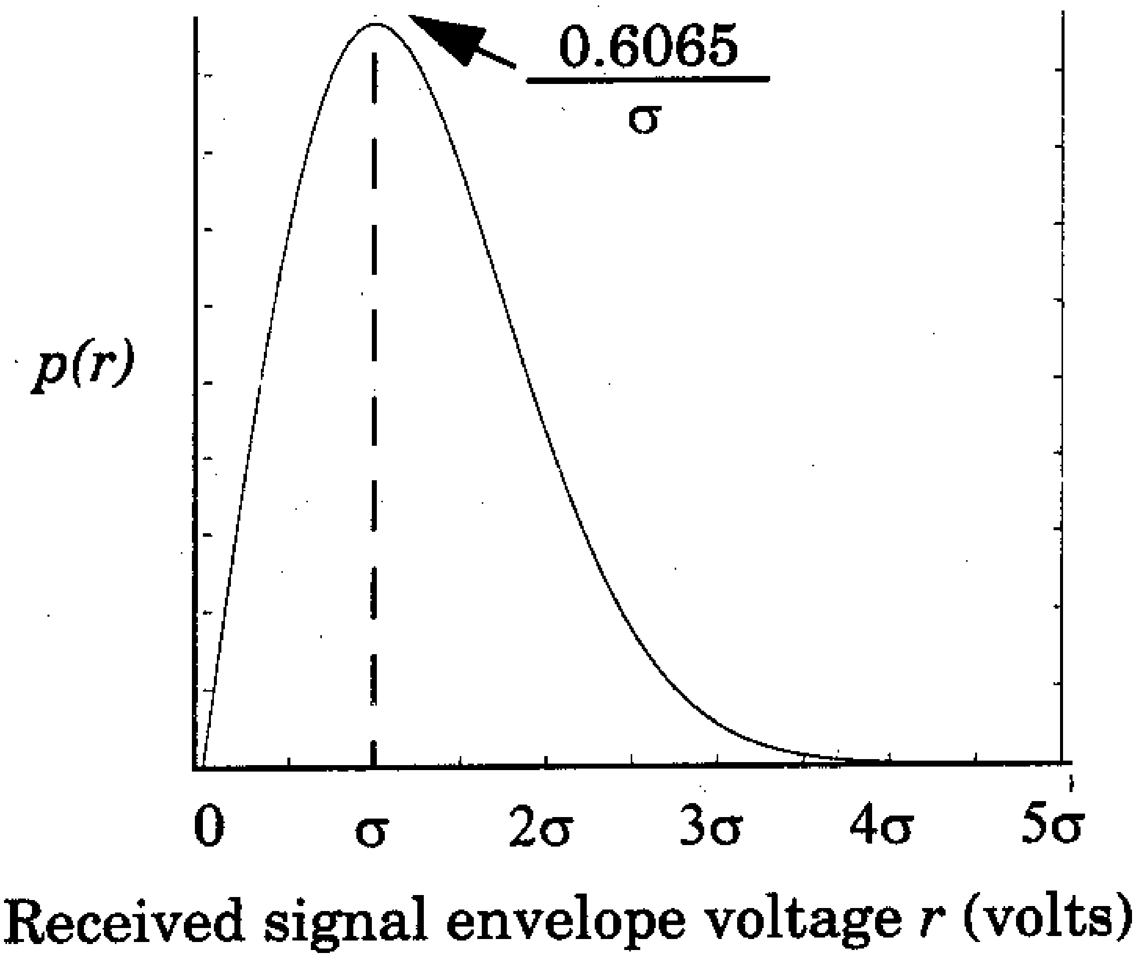
$$p(r) = \int_0^{2\pi} p(r,\theta)d\theta = \begin{cases} \frac{r}{\sigma^2}\exp\left(-\frac{r^2}{2\sigma^2}\right) & r \geq 0 \\ 0 & \text{otherwise} \end{cases}$$

- pdf of Rayleigh distribution

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

σ: rms value of the received signal before envelop detection

σ^2: time - average power of the received signal before envelop detection


0.6065
σ
p(r)
0
σ
2σ
3σ
4σ
5σ
Received signal envelope voltage r (volts)

- Cumulative distribution function (CDF)

$$P(R) = \Pr(r \le R) = \int_0^R p(r)dr = 1 - \exp\left(-\frac{R^2}{2\sigma^2}\right)$$

- The mean value of the Rayleigh distribution is given by

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

- The variance of the Rayleigh distribution is given by

$$\sigma_r^2 = E[r^2] - E^2[r] = \int_0^\infty r^2 p(r)dr - \frac{\sigma^2\pi}{2}$$

$$= \sigma^2\left(2 - \frac{\pi}{2}\right) = 0.4292\sigma^2$$

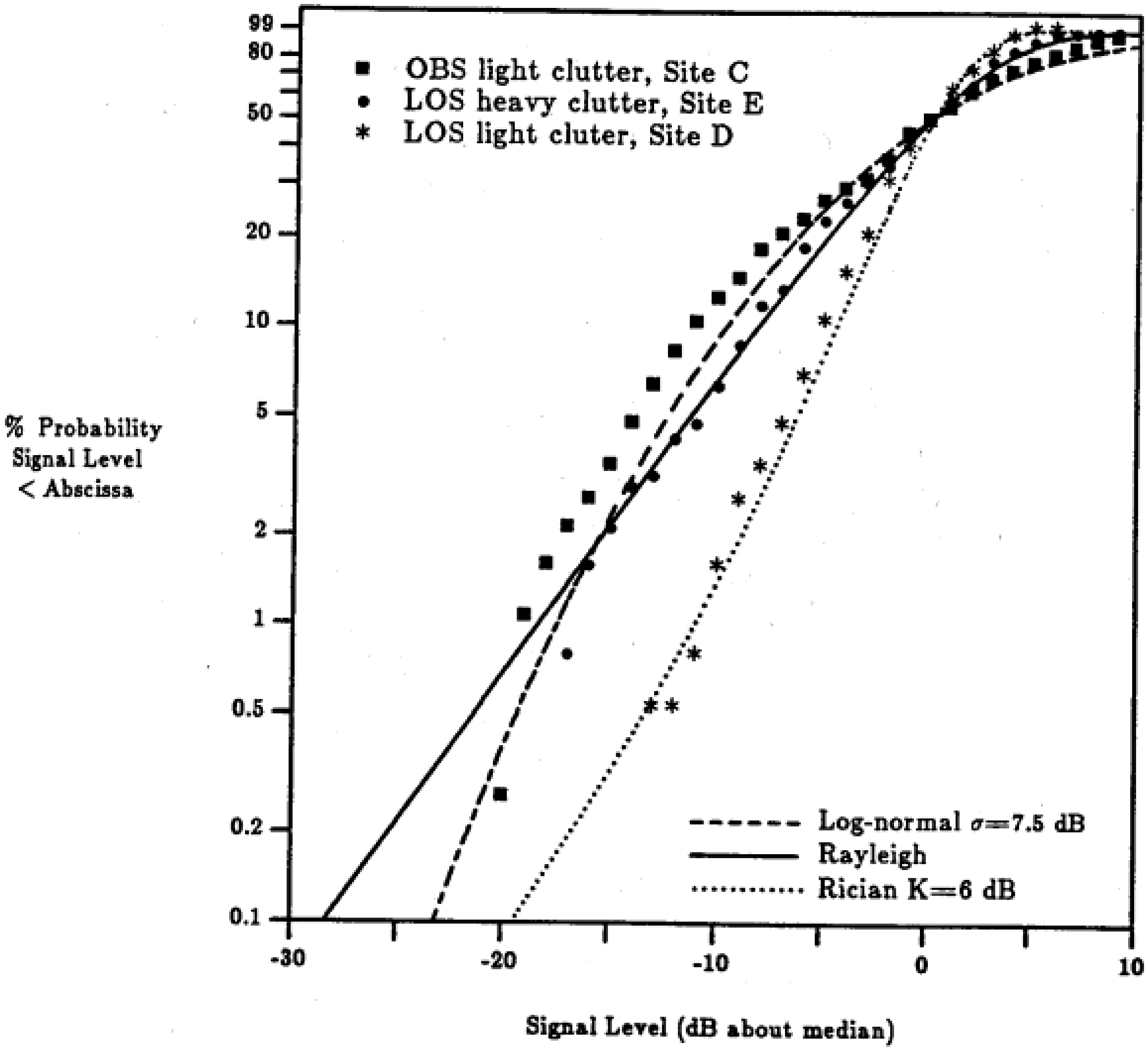


Figure 4.17
Cumulative distribution for three small-scale fading measurements and their fit to Rayleigh, Ricean, and log-normal distributions [From [Rap89] © IEEE].

- Ricean Fading Distribution: When there is a dominant stationary (non-fading) signal component present, such as a line-of-sight propagation path, the small-scale fading envelope distribution is Ricean.

Scattered waves

Direct wave

$$s_r(t) = r\exp\left[j(\omega_0 t + \theta)\right] + A\exp(j\omega_0 t)$$

$$= [(x + A) + jy]\exp(j\omega_0 t)$$

$$r^2 = (x + A)^2 + y^2$$

$$x + A = r\cos\theta$$

$$y = r\sin\theta$$

- By following similar steps described in Rayleigh distribution, we obtain

$$p(r) = \begin{cases} \frac{r}{\sigma^2} \exp\left(-\frac{r^2 + A^2}{2\sigma^2}\right) I_0\left(\frac{Ar}{\sigma^2}\right) & A \geq 0, r \geq 0 \\ 0 & r < 0 \end{cases}$$

where

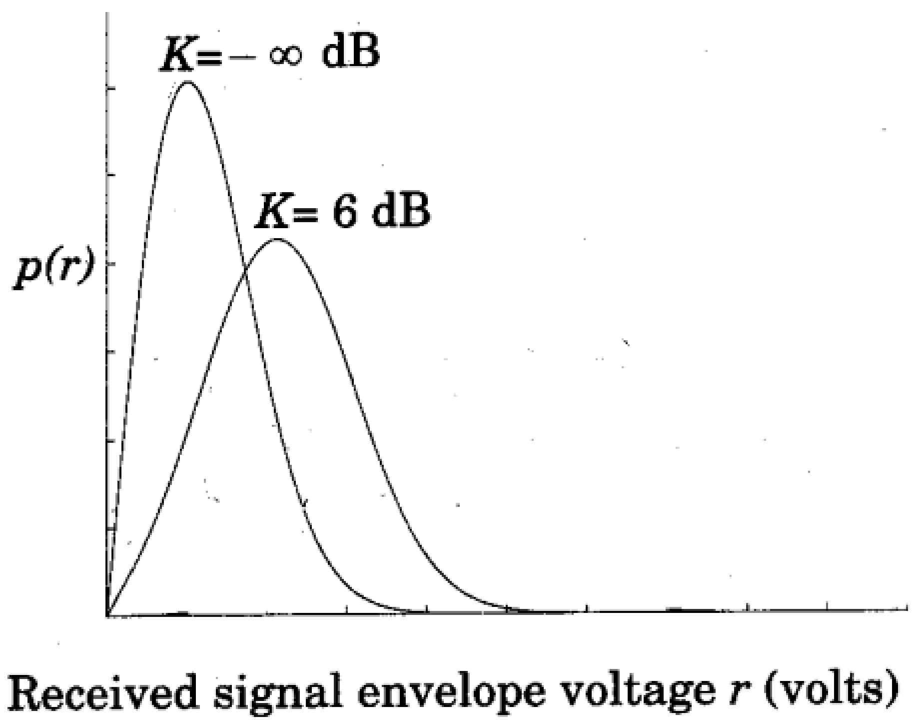
$$I_0\left(\frac{Ar}{\sigma^2}\right) = \frac{1}{2\pi}\int_0^{2\pi} \exp\left(\frac{Ar\cos\theta}{\sigma^2}\right) d\theta$$

is the modified Bessel function of the first kind and zero-order.

- The Ricean distribution is often described in terms of a parameter *K* which is defined as the ratio between the deterministic signal power and the variance of the multipath. It is given by $K = A^2/(2\sigma^2)$ or in terms of dB

$$K(dB) = 10\log\frac{A^2}{2\sigma^2} \quad \text{dB}$$

- The parameter K is known as the Ricean factor and completely specifies the Ricean distribution.
- As $A \to 0$, we have $K \to -\infty$ dB. The dominant path decrease in amplitude, the Ricean distribution degenerates to a Rayleigh distribution.



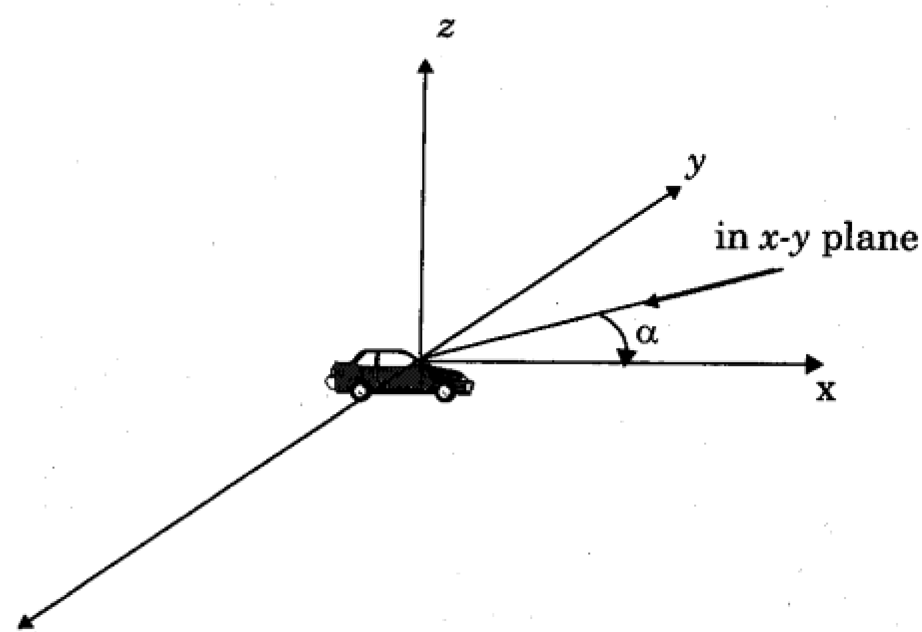
Statistical Models for Multipath Fading Channels

Clarke's Models for Flat Fading

- Clark developed a model where the statistical characteristics of the electromagnetic fields of the received signal are deduced from scattering.
- The model assumes a fixed transmitter with a vertically polarized antenna.
- The received antenna is assumed to comprise of N azimuthal plane waves with arbitrary carrier phase, arbitrary angle of arrival, and each wave having equal average amplitude.
- Equal amplitude assumption is based on the fact that in the absence of a direct line-of-sight path, the scattered components arriving at a receiver will experience similar attenuation over small-scale distance.

- Doppler shift due to the motion of the receiver.
- Assume no excess delay due to multipath.
  - Flat fading assumption.
- For the *n*th wave arriving at an angle α_n to the *x*-axis, the Doppler shift is given by

$$f_n = \frac{v}{\lambda}\cos\alpha_n$$



- The vertically polarized plane waves arriving at the mobile have *E* field components given by (assume a single tone is transmitted)

$$E_z(t) = E_0 \sum_{n=1}^{N} C_n \cos(2\pi f_c t + \theta_n)$$

E_0 : real amplitude of local average E-field (constant)

C_n : real random variable representing the amplitude of *n*th arriving wave.

f_c : carrier frequency.

θ_n : random phase of the *n*th arriving wave.

- The random arriving phase is given by

$$\theta_n = 2\pi f_n t + \phi_n$$

- The amplitude of E-field is normalized such that

$$\sum_{i=1}^{N} \overline{C_n^2} = 1$$

- $E_z(t)$ can be modeled as a Gaussian random process if *N* is sufficient large.
- Since the Doppler shift is very small when compared to the carrier frequency, the three field components may be modeled as narrow band random process.

$$E_z(t) = T_c(t)\cos(2\pi f_c t) + T_s(t)\sin(2\pi f_c t)$$

where

$$T_c(t) = E_0 \sum_{i=1}^{N} C_n \cos(2\pi f_n t + \phi_n)$$
$$T_s(t) = E_0 \sum_{i=1}^{N} C_n \sin(2\pi f_n t + \phi_n)$$

- $T_c(t)$ and $T_s(t)$ are Gaussian random processes which are denoted as T_c and T_s, respectively.

- $T_c(t)$and $T_s(t)$are uncorrelated zero-mean Gaussian random variable with equal variance given by

$$\overline{T_c^2} = \overline{T_c^2} = \overline{|E_z|^2} = E_0^2 / 2$$

- The envelope of the received E-field is given by

$$|E_z(t)| = \sqrt{T_c^2(t) + T_s^2(t)} = r(t)$$

- It can be shown that the random received signal envelope *r* has a Rayleight distribution given by

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

where $\sigma^2 = E_0^2 / 2$

- Let $p(\alpha)d\alpha$ denote the function of the total incoming power within $d\alpha$ of the angle α, and let A denote the average received power with respect to an isotropic antenna.
- As $N \to \infty$ $p(\alpha)d\alpha$ approached a continuous distribution.
- If $G(\alpha)$ is the azimuthal gain pattern of the mobile antenna as a function of the angle of arrival, the total received power can be expressed as

$$P_r = \int_0^{2\pi} AG(\alpha)\,p(\alpha)d\alpha$$

- The instantaneous frequency of the received signal arriving at an angle α is given by:

$$f(\alpha) = f = \frac{v}{\lambda}\cos(\alpha) + f_c = f_m \cos\alpha + f_c$$

where f_m is the maximum Doppler shift.

- If *S(f)* is the power spectrum of the received signal, the differential variation of received power with frequency is given by

$$S(f)\,|\,df\,| = A\left[p(\alpha)G(\alpha) + p(-\alpha)G(-\alpha)\right]|d\alpha|$$

- Differentiation $f = f_m \cos\alpha + f_c$

$$\frac{|df|}{|d\alpha|} = f_m|-\sin\alpha| \qquad \Rightarrow \qquad |df| = |d\alpha||-\sin\alpha|\, f_m$$

On the other hand, we have $\alpha = \cos^{-1}\left[\dfrac{f - f_c}{f_m}\right]$

- This implies

$$\sin\alpha = \sqrt{1 - \left(\frac{f - f_c}{f_m}\right)^2}$$

- Finally, we have

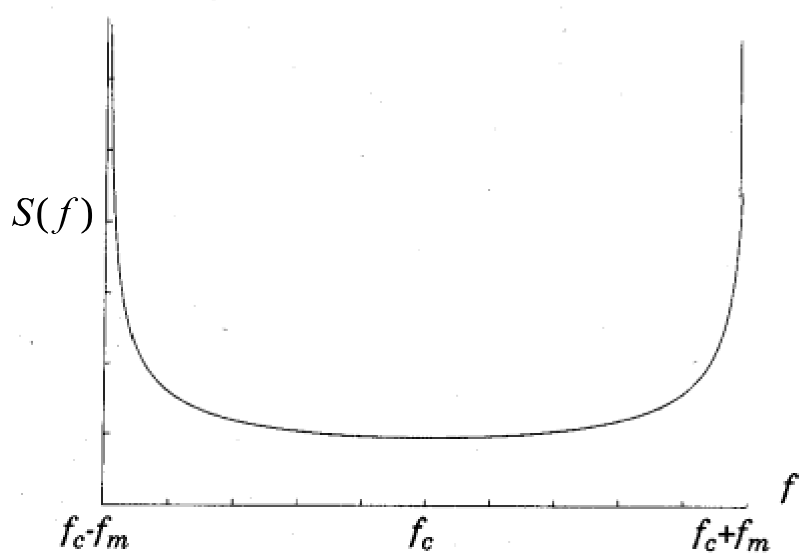
$$S(f) = \frac{A\left[p(\alpha)G(\alpha) + p(-\alpha)G(-\alpha)\right]}{f_m\sqrt{1-\left(\dfrac{f-f_c}{f_m}\right)^2}}$$

$$\text{where} \quad S(f) = 0, \qquad \left|f - f_c\right| > f_m$$

- The spectrum is centered on the carrier frequency and is zero outside the limits $f_c \pm f_m$.
- Each of the arriving waves has its own carrier frequency (due to its direction of arrival) which is slightly offset from the center frequency.

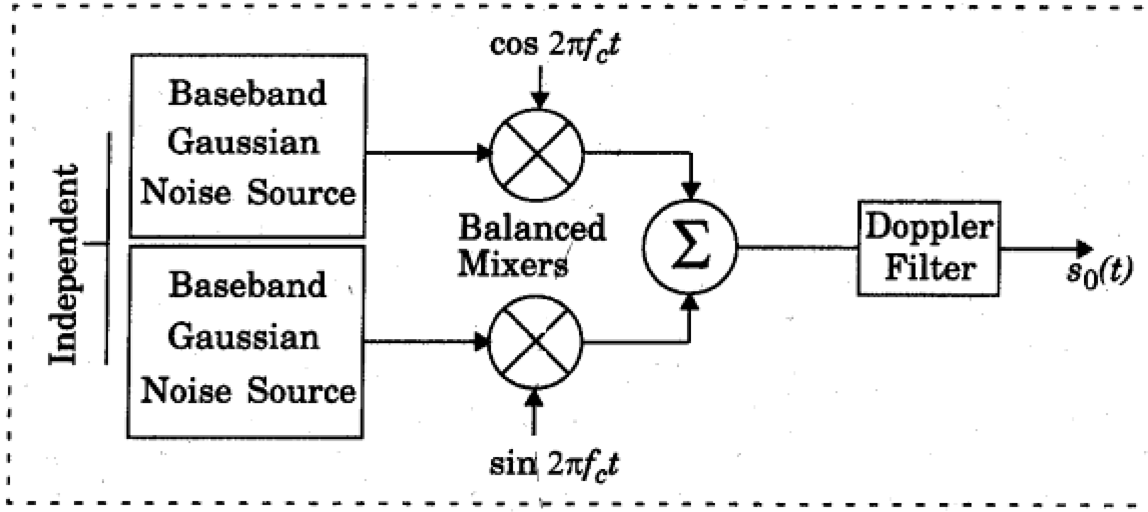
- Vertical $\lambda/4$ antenna ($G(\alpha)=1.5$).
- Uniform distribution $p(\alpha)=1/(2\pi)$ over 0 to 2π.
- The output spectrum

$$S(f)=\frac{1.5}{\pi f_m\sqrt{1-\left(\frac{f-f_c}{f_m}\right)^2}}$$

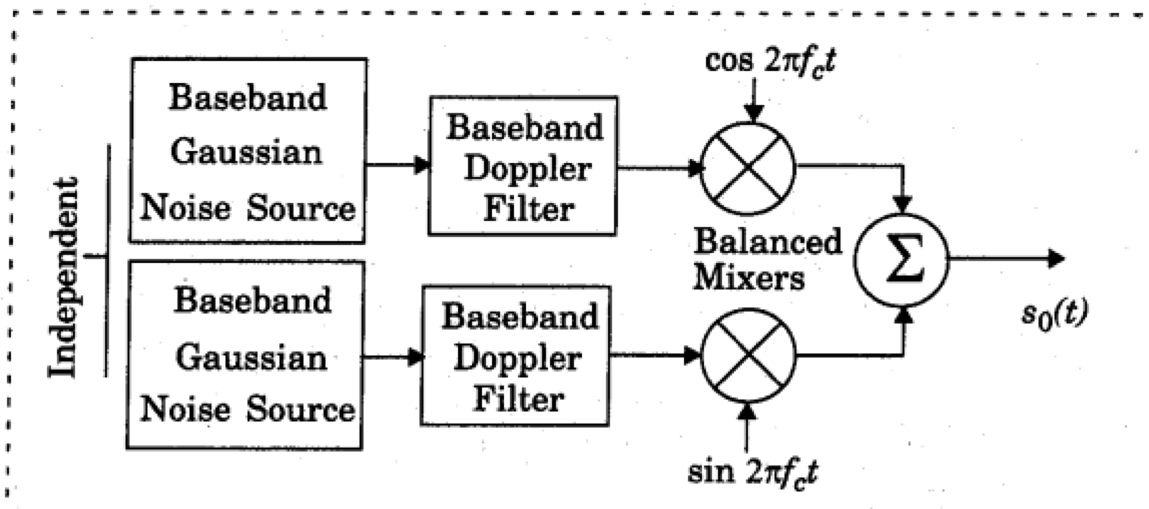


Simulation of Clarke Fading Model

- Produce a simulated signal with spectral and temporal characteristics very close to measured data.
- Two independent Gaussian low pass noise are used to produce the in-phase and quadrature fading branches.
- Use a spectral filter to sharp the random signal in the frequency domain by using fast Fourier transform (FFT).
- Time domain waveforms of Doppler fading can be obtained by using an inverse fast Fourier transform (IFFT).


cos $2\pi f_c t$
Baseband Gaussian Noise Source
Baseband Gaussian Noise Source
Independent
Balanced Mixers
Doppler Filter
$s_0(t)$
sin $2\pi f_c t$

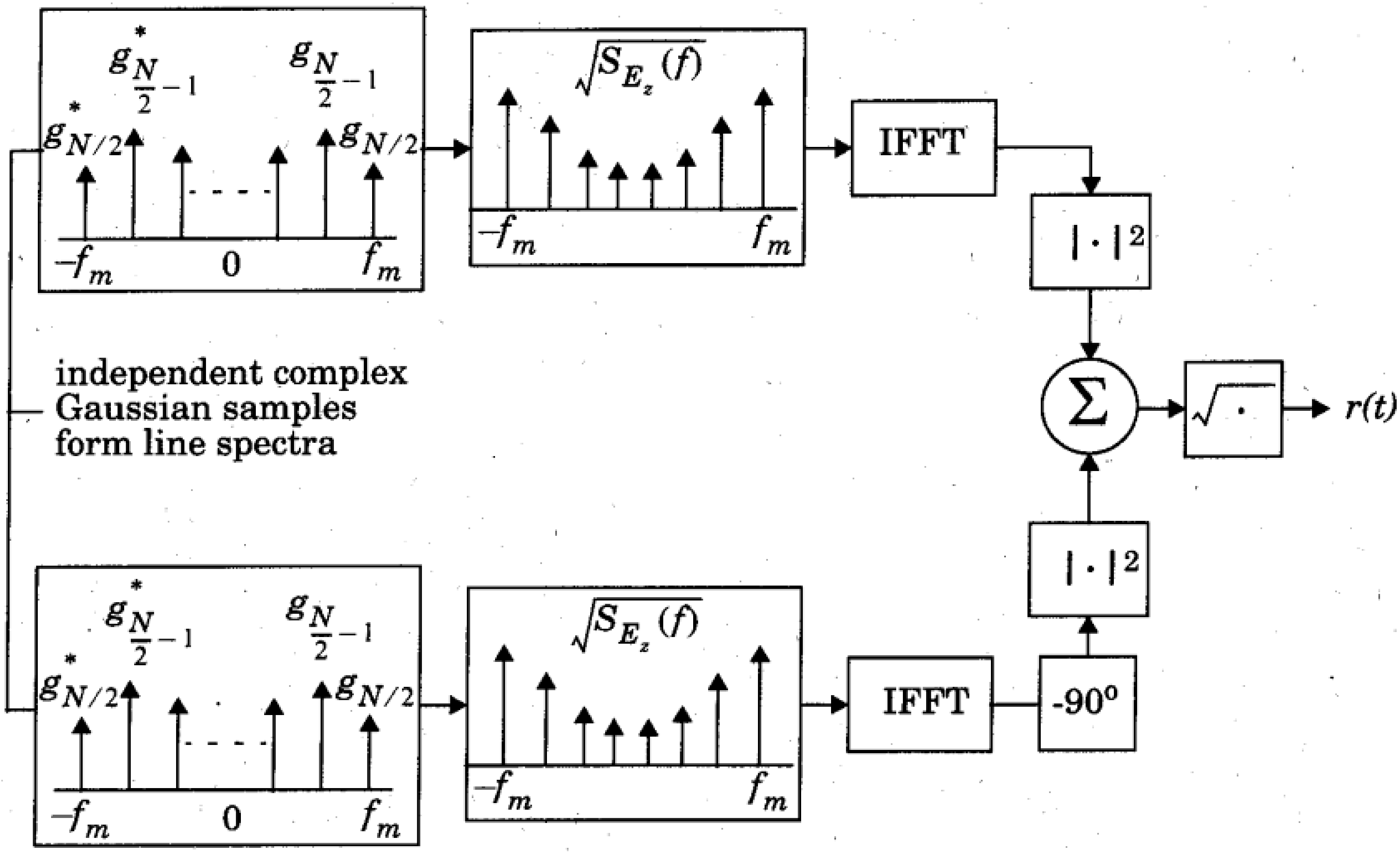
(a)


cos $2\pi f_c t$
Baseband Gaussian Noise Source
Baseband Gaussian Noise Source
Independent
Baseband Doppler Filter
Baseband Doppler Filter
Balanced Mixers
$s_0(t)$
sin $2\pi f_c t$

(b)

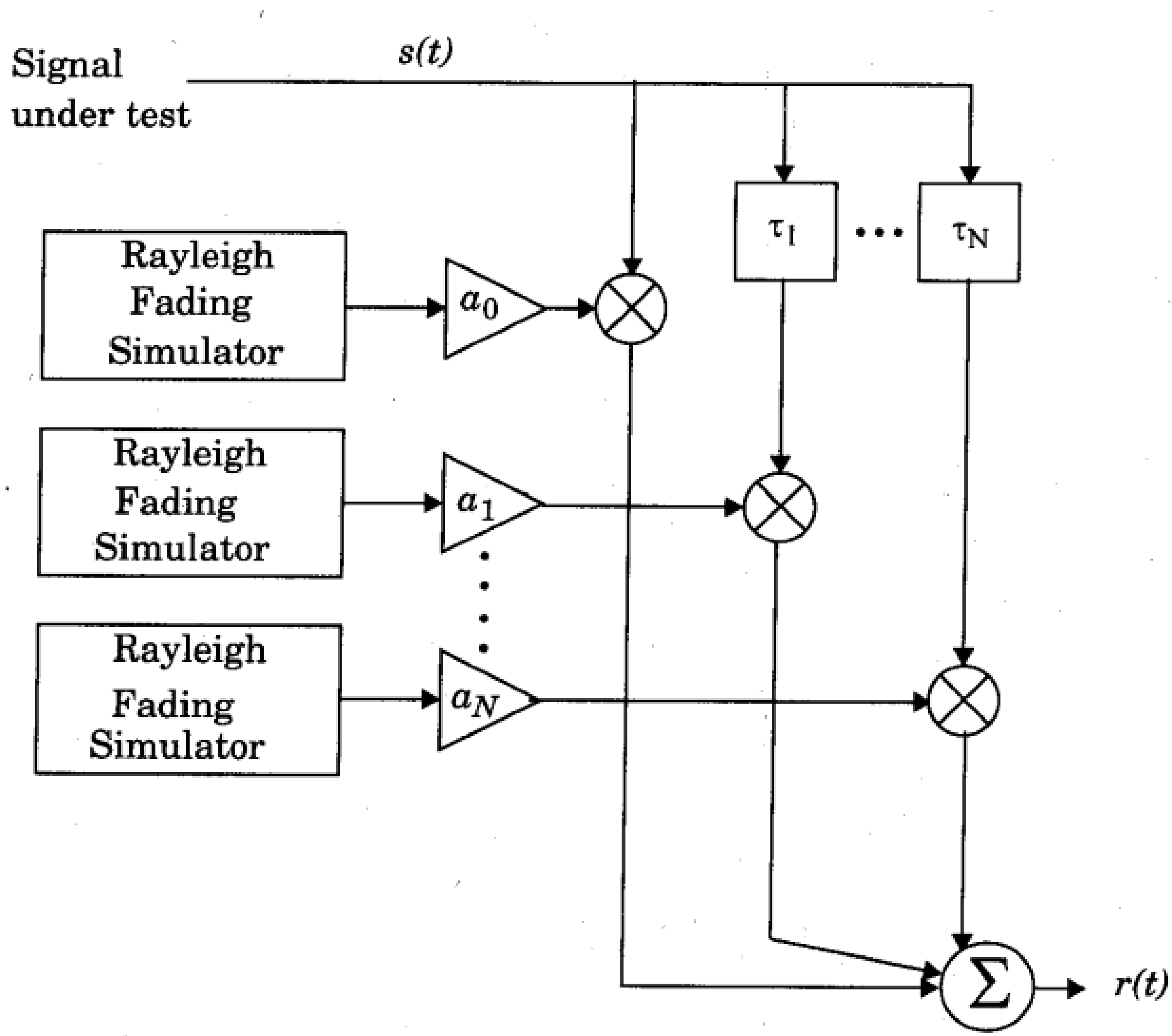
- Smith simulator using N carriers to generate fading signal

1. Specify the number of frequency domain points *N* used to represent $\sqrt{S(f)}$ and the maximum Doppler frequency shift f_m.
2. Compute the frequency spacing between adjacent spectral lines as $\Delta f = 2 f_m /(N-1)$. This defines the time duration of a fading waveform, $T = 1/\Delta f$
3. Generate complex Gaussian random variables for each of the *N/2* positive frequency components of the noise source.
4. Construct the negative frequency components of the noise source by conjugating positive frequency and assigning these at negative frequency values.
5. Multiply the in-phase and quadrature noise sources by the fading spectrum $\sqrt{S(f)}$.
6. Perform an IFFT on the resulting frequency domain signal from the in-phase and quadrature arms, and compute the sum of the squares of each signal.
7. Take the square root of the sum.



$g^*_{\frac{N}{2}-1}$
$g_{\frac{N}{2}-1}$
$g^*_{N/2}$
$g_{N/2}$
$-f_m$
0
f_m
$\sqrt{S_{E_z}(f)}$
IFFT
$|\cdot|^2$
Σ
$\sqrt{\cdot}$
$r(t)$
-90°
independent complex Gaussian samples form line spectra

- Frequency selection fading model



Level Crossing and Fading Statistics

- The level crossing rate (LCR) is defined as the expected rate at which the Rayleigh fading envelope crosses a specified level in a positive-going direction.
- Useful for designing error control codes and diversity.
- Relate the time rate of change of the received signal to the signal level and velocity of the mobile.
- The number of level crossing per second to the level *R* is given by

$$N_R = \int_0^\infty \dot{r} p(R, \dot{r}) d\dot{r} = \sqrt{2\pi} f_m \rho e^{-\rho^2} \qquad \text{(A)}$$

$\dot{r}$: time derivation of r(t) (slope)

$p(R, \dot{r})$: joint density function of r and $\dot{r}$ at $r = R$.

: value of the specified level *R*, normalized to the rms amplitude of the fading envelope.

f_m : maximum Doppler frequency

$\rho = R / R_{rms}$

- Average fading duration is defined as the average period of time for which the received signal is below a specified level *R*.
- For a Rayleigh Fading signal, this is given by

$$\bar{\tau} = \frac{1}{N_R} \Pr[r < R] \qquad \text{(B)}$$

with

$$\Pr[r < R] = \frac{1}{T} \sum_i \tau_i$$

where τ_i is the duration of the fade and *T* is the observation interval.

- For Rayleigh distribution

$$\Pr[r < R] = \int_0^R p(r)dr = 1 - \exp(-\rho^2) \qquad \text{(C)}$$

- Average fading duration, (using (A), (B), (C))

$$\bar{\tau} = \frac{e^{\rho^2} - 1}{\rho f_m \sqrt{2\pi}}$$

- The average duration of a signal fading helps determine the most likely number of signaling bits that nay be lost during a fade.
- Average fade duration primarily depends upon the speed of the mobile, and decreases as the maximum Doppler frequency f_m becomes large.

UNIT -3
MODULATION TECHNIQUES AND EQUALISATION

MINIMUM SHIFT KEYING (MSK)

- A special type of continuous phase FSK wherein the peak frequency deviation ($2\Delta f$) is equal to half the bit rate, that is, the modulation index is 0.5.

- A modulation index of 0.5 corresponds to the minimum frequency spacing that allows two FSK signals to be coherently orthogonal, and the name MSK implies the minimum frequency separation that allows orthogonal detection.

- Sometimes referred to as fast FSK, because the frequency spacing used is only half as much as that used in conventional noncoherent FSK.

- Figure 6.38 shows the power spectral density of an MSK signal

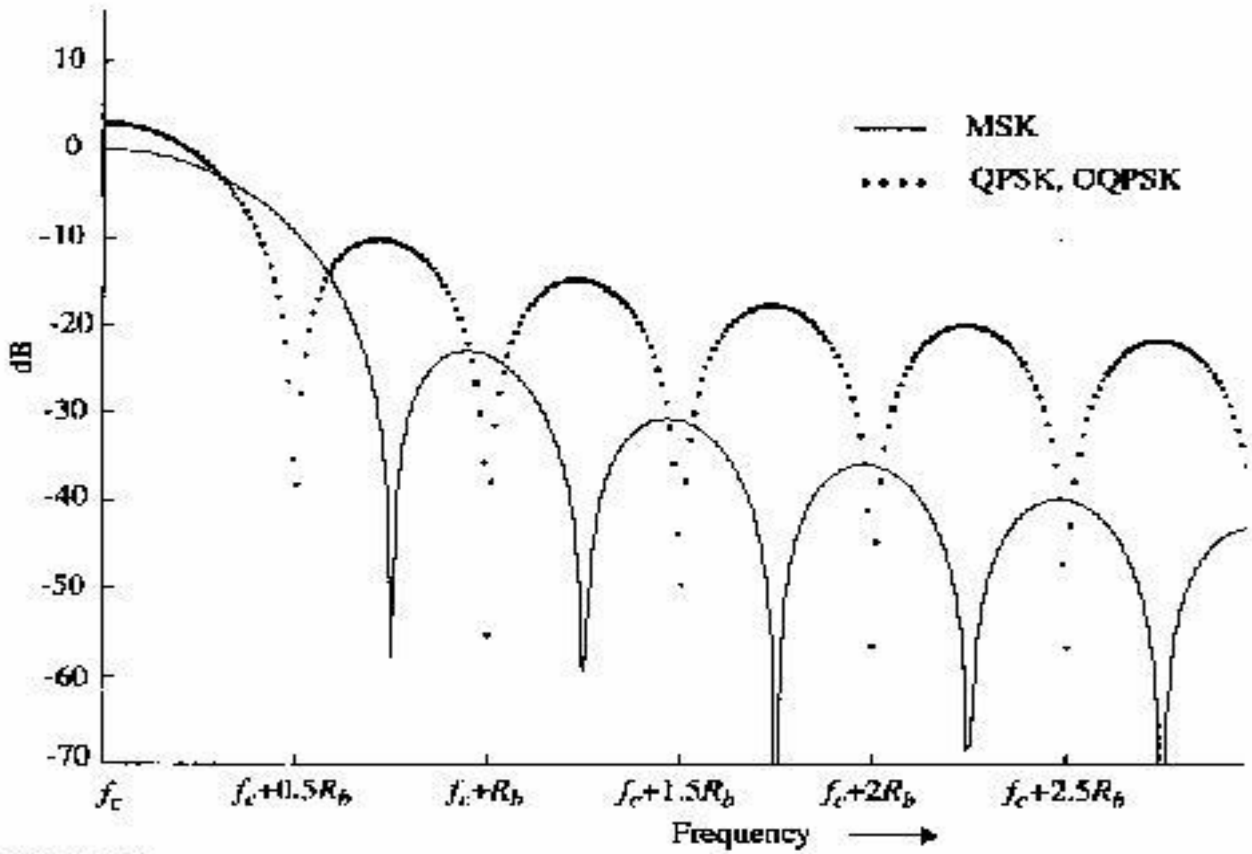


Figure 6.38
Power spectral density of MSK signals as compared to QPSK and OQPSK signals.

- MSK Transmitter and Receiver

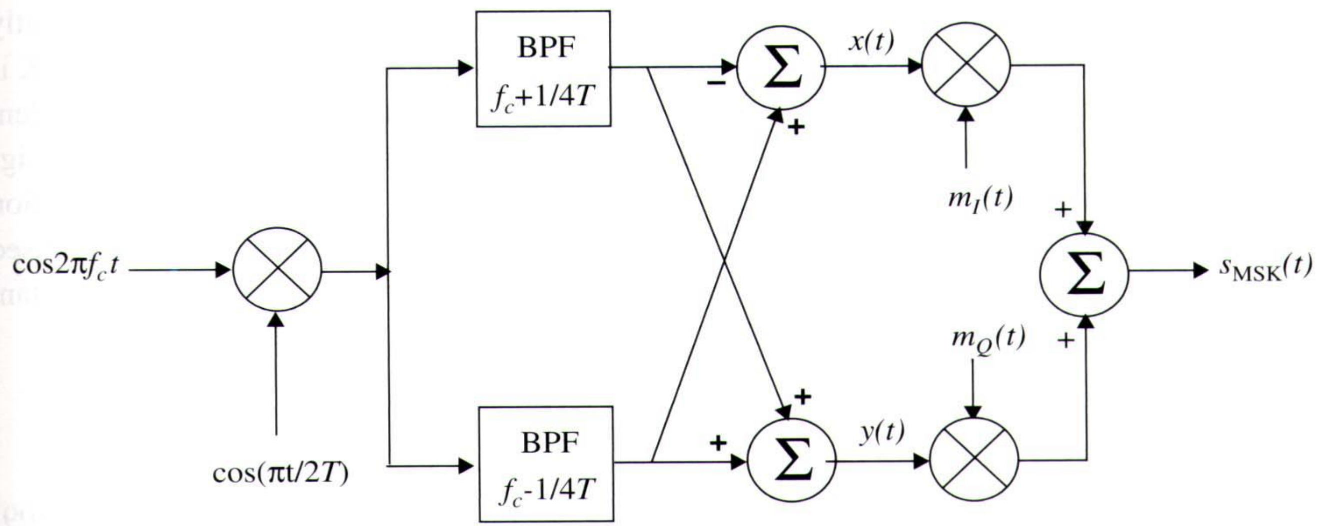


Figure 6.39 Block diagram of an MSK transmitter. Note that $m_I(t)$ and $m_Q(t)$ are offset by T_b.

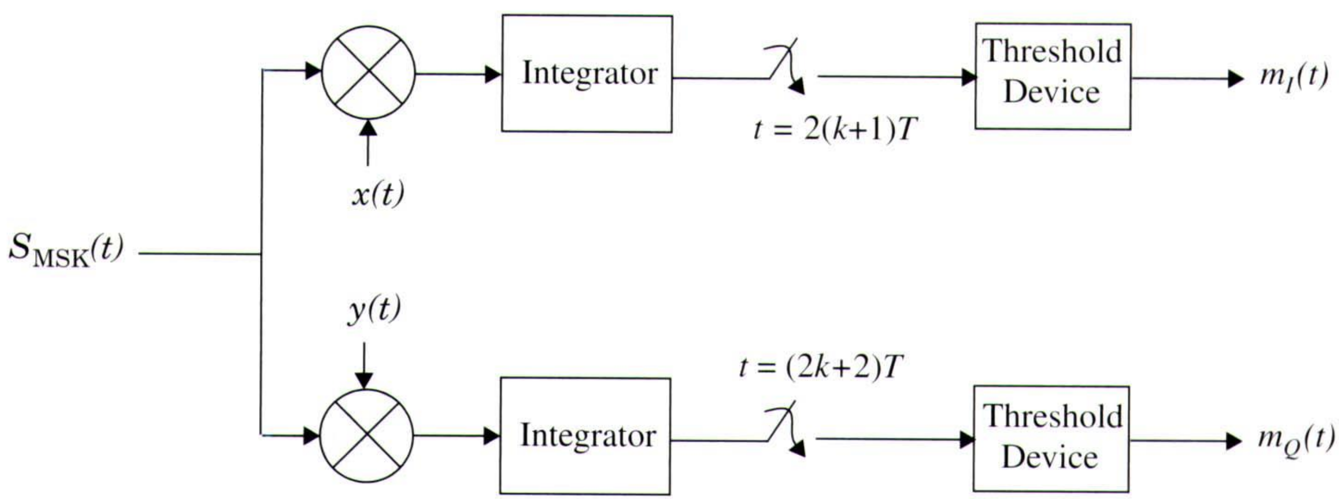


Figure 6.40 Block diagram of an MSK receiver.

GAUSSIAN MINIMUM SHIFT KEYING (GMSK)

- A derivation of MSK
- In GMSK, the sidelobe levels of the spectrum are further reduced by passing the modulating NRZ data waveform through a premodulation Gaussian pulse-shaping filter.

- Figure 6.41 shows the simulated RF power spectrum of the GMSK signal for various values of BT, where BT is the 3dB-bandwidth-bit duration product of the filter.

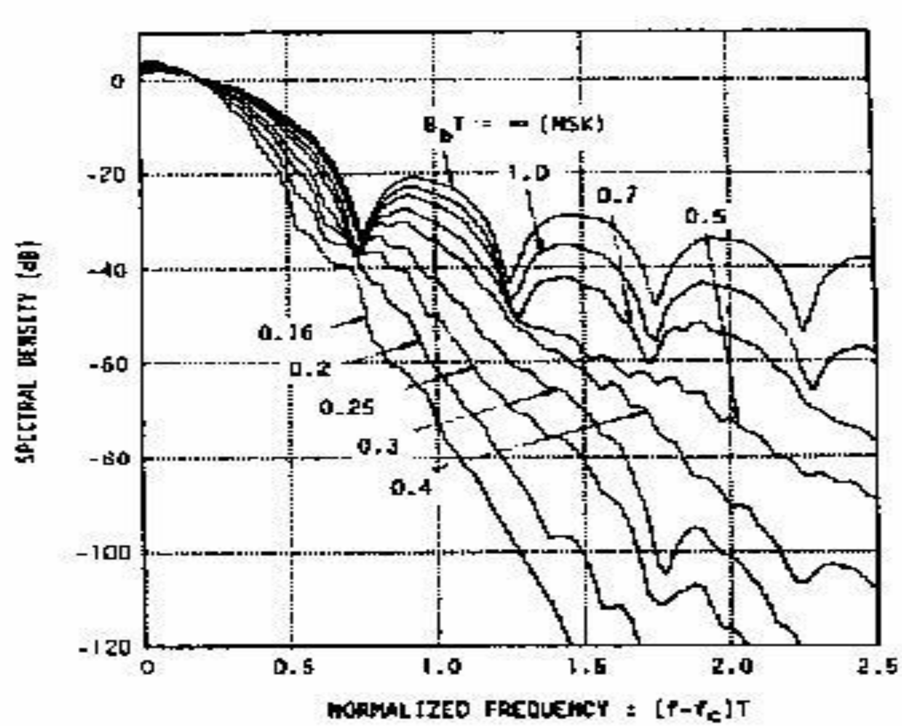


Figure 6.41
Power spectral density of a GMSK signal [From [Mur81] © IEEE].

- While the GMSK spectrum becomes more and more compact with decreasing BT value, the degradation due to ISI increases.

Table 6.3 Occupied RF Bandwidth (for GMSK and MSK as a fraction of R_b) Containing a Given Percentage of Power [Mur81]. Notice that GMSK is spectrally tighter than MSK.

BT	90%	99%	99.9%	99.99%
0.2 GMSK	0.52	0.79	0.99	1.22
0.25 GMSK	0.57	0.86	1.09	1.37
0.5 GMSK	0.69	1.04	1.33	2.08
MSK	0.78	1.20	2.76	6.00

- GMSK bit error rate

$$P_e = Q\left\{\sqrt{\frac{2\gamma E_b}{N_0}}\right\} \qquad .112a)$$

where γ is a constant related to BT by

$$\gamma \cong \begin{cases} 0.68 & \text{for GMSK with } BT = 0.25 \\ 0.85 & \text{for simple MSK } (BT = \infty) \end{cases}$$

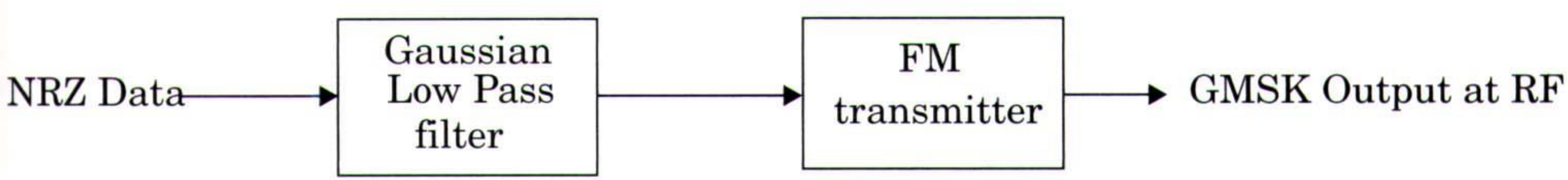


Figure 6.42 Block diagram of a GMSK transmitter using direct FM generation.

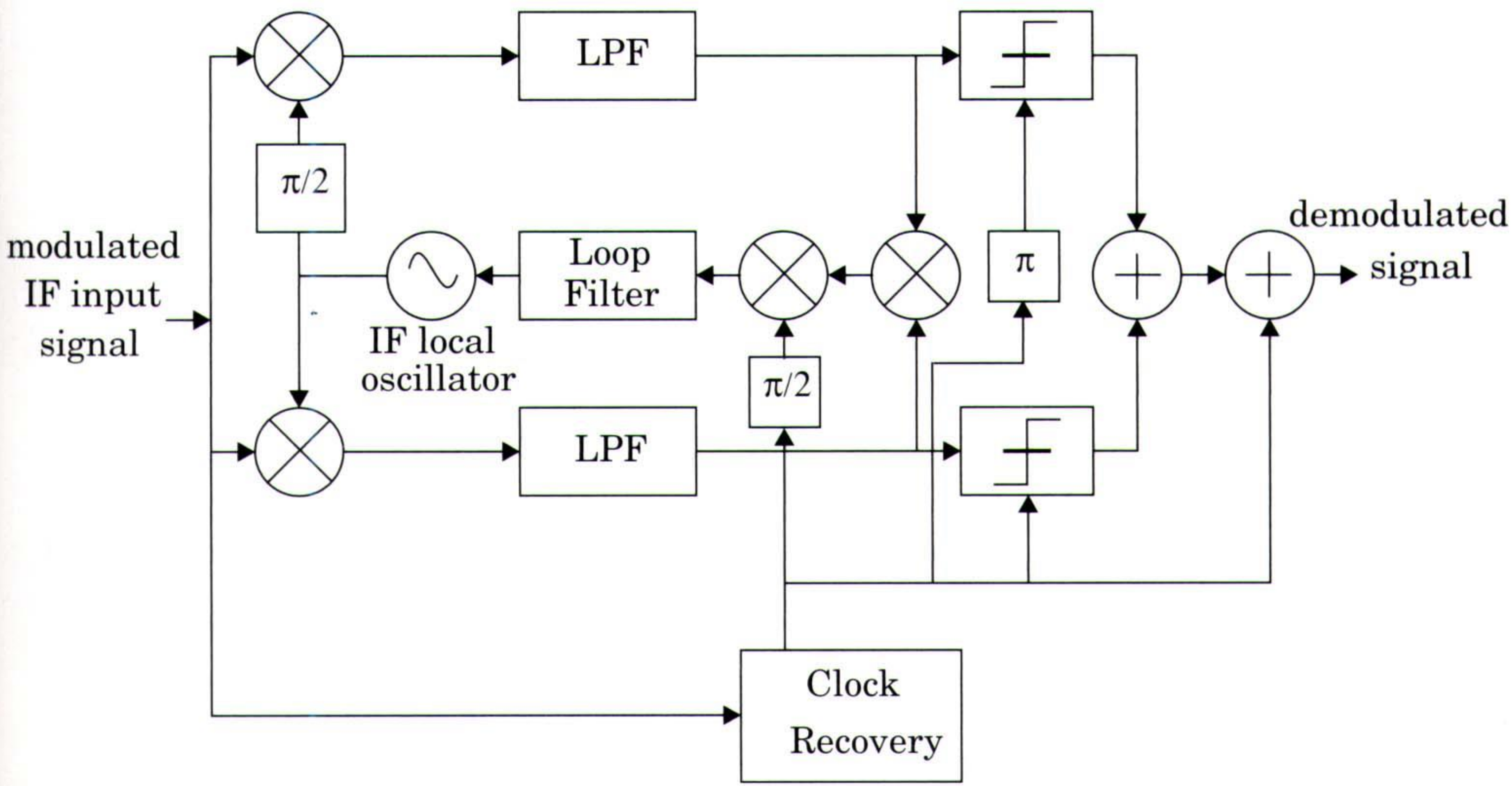


Figure 6.43 Block diagram of a GMSK receiver.

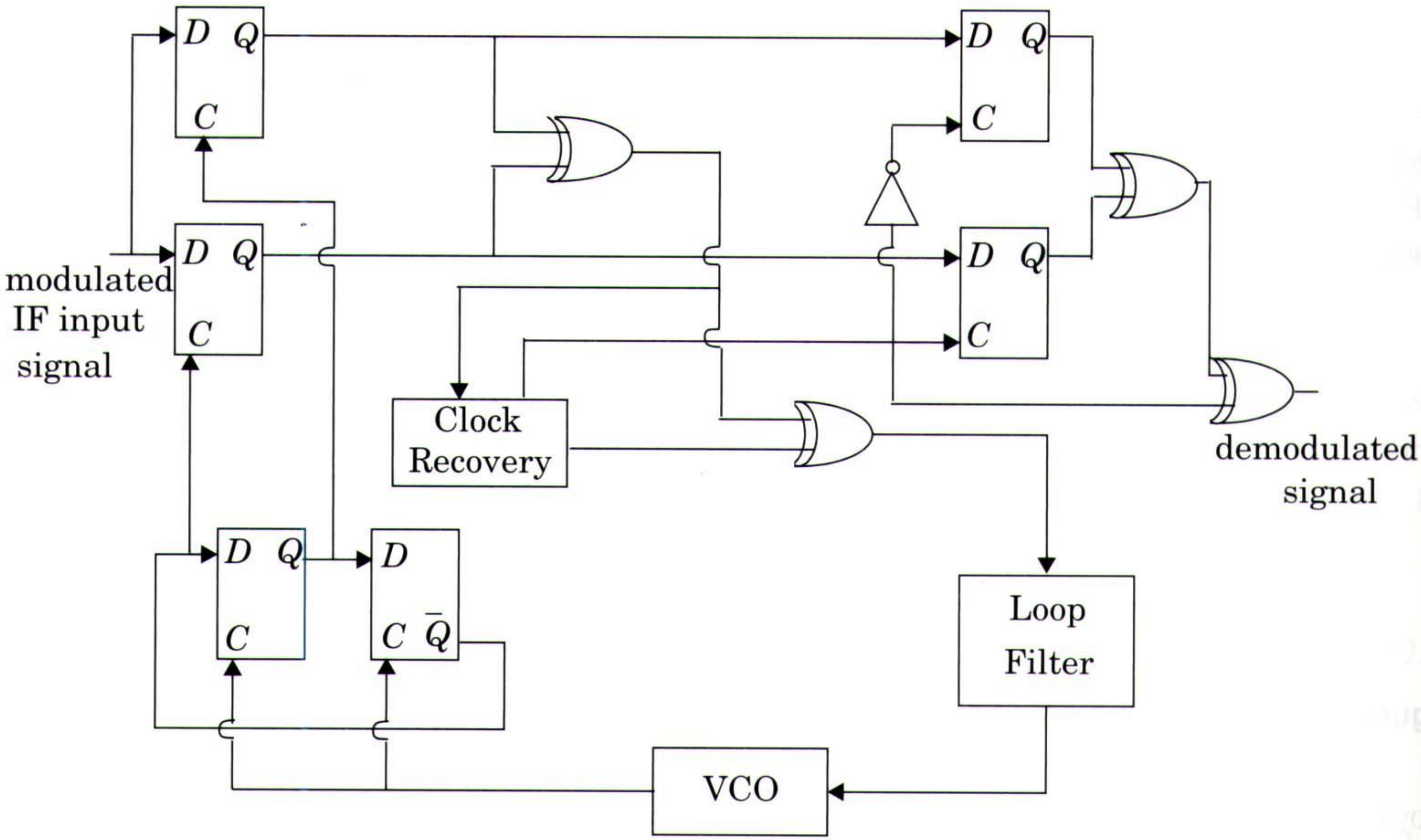


Figure 6.44 Digital logic circuit for GMSK demodulation [from [deB72] © IEEE].

Combined Linear and Constant Envelop Modulation Techniques

- Depending on whether the amplitude, phase, or frequency of the carrier is varied, the modulation scheme is called M-ary ASK, M-ary PSK, or M-ary FSK.
- In an M-ary signaling scheme, two or more bits are grouped together to form symbols and one of M possible signals, $s_1(t)$, $s_2(t),\ldots,s_M(t)$ is transmitted during each symbol period of duration T_s.
- M-ary modulation schemes achieve better bandwidth efficiency at the expense of power efficiency.

M-ary Phase Shift Keying (MPSK)

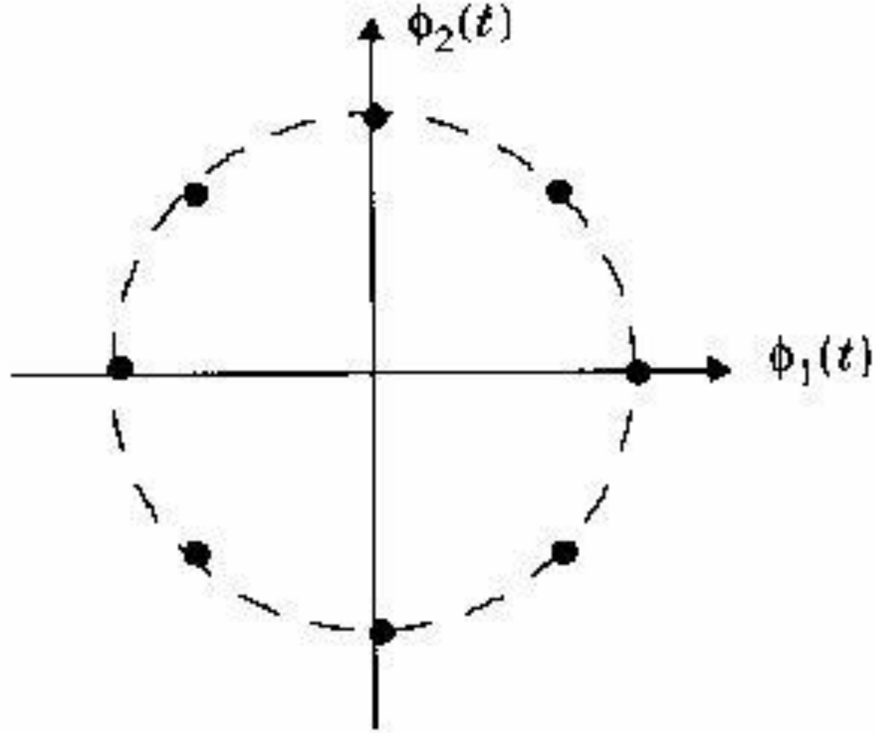


Figure 6.45
Constellation diagram of an M-ary PSK system (M=8).

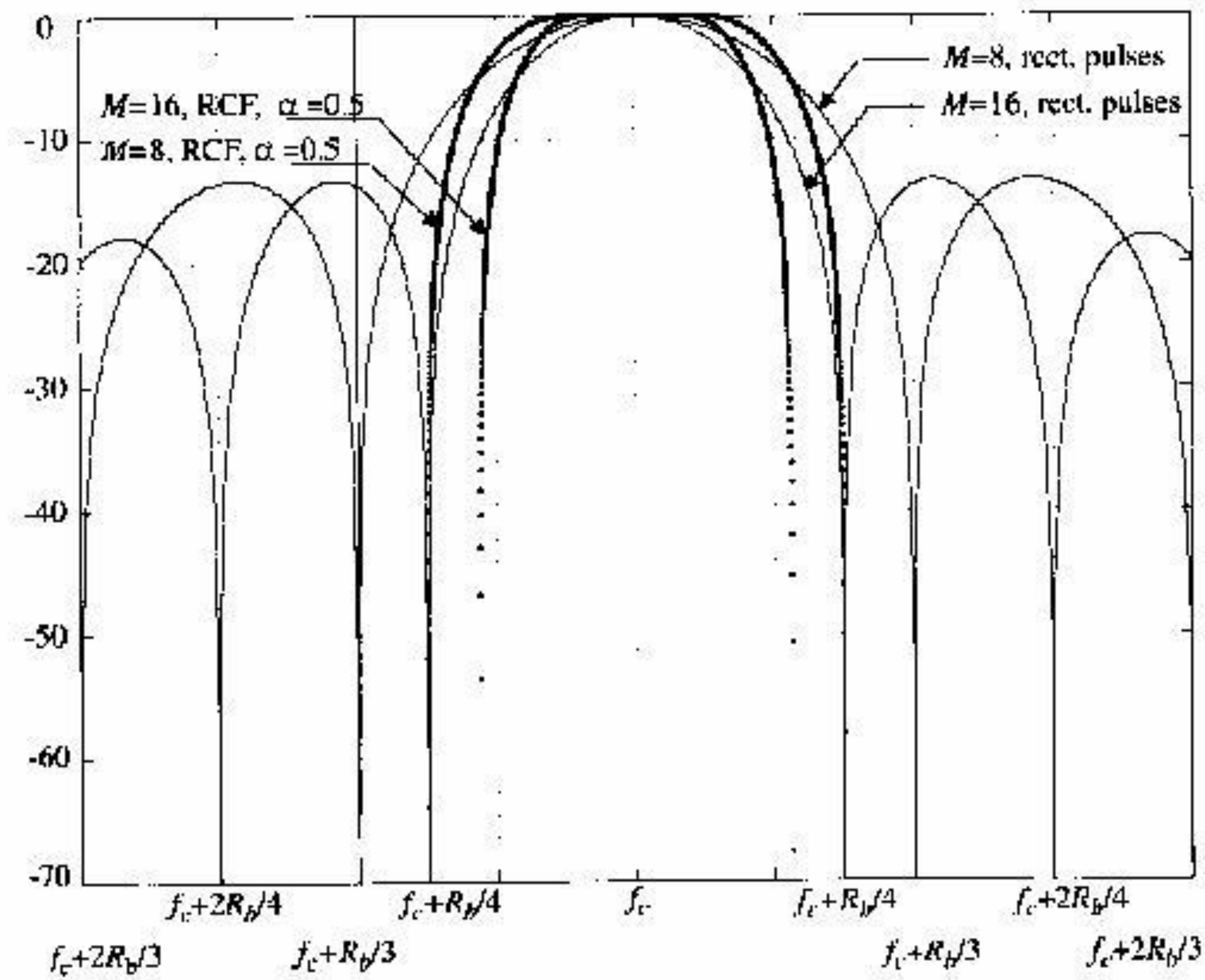


Figure 6.46

M-ary PSK power spectral density, for M=8, 16, (PSD for both rectangular and raised cosine filtered pulses are shown for fixed R_b).

Table 6.4 **Bandwidth and Power Efficiency of M-ary PSK Signals**

M	2	4	8	16	32	64
$\eta_B = R_b/B^*$	0.5	1	1.5	2	2.5	3
E_b/N_o for BER=10^{-6}	10.5	10.5	14	18.5	23.4	28.5

*. B: First null bandwidth of M-ary PSK signals

M-ary Quadrature Amplitude Modulation (QAM)

- In M-ary PSK, the envelop is a constant, thereby yielding a circular constellation.
- By allowing the amplitude to also vary with the phase, a new modulation scheme is called Quadrature Amplitude Modulation (QAM)

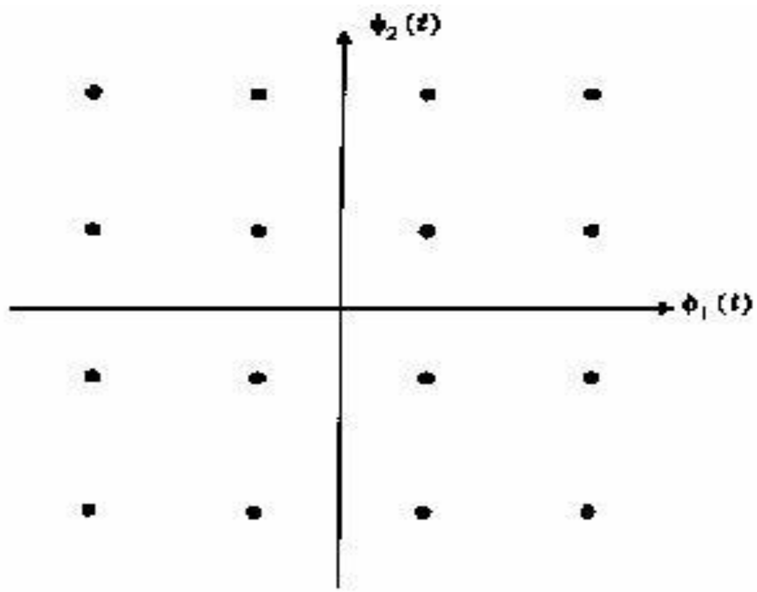


Figure 6.47
Constellation diagram of an M-ary QAM (M=16) signal set.

– The power spectrum and bandwidth efficiency of QAM modulation is identical to M-ary PSK modulation.

– In terms of power efficiency, QAM is superior to M-ary PSK.

Table 6.5 **Bandwidth and Power Efficiency of QAM [Zie92]**

M	4	16	64	256	1024	4096
η_B	1	2	3	4	5	6
E_b/N_o for BER=10^{-6}	10.5	15	18.5	24	28	33.5

M-ary Frequency Shift Keying (MFSK) and OFDM

– For a noncoherent MFSK, the channel bandwidth

$$B = \frac{R_b M}{2\log_2 M} \quad (6.132)$$

– This implies that the bandwidth efficiency ↓ with M ↑

Table 6.6 **Bandwidth and Power Efficiency of Coherent M-ary FSK [Zie92]**

M	2	4	8	16	32	64
η_B	0.4	0.57	0.55	0.42	0.29	0.18
E_b/N_o for BER=10^{-6}	13.5	10.8	9.3	8.2	7.5	6.9

- The orthogonality characteristic of MFSK has led to the idea of Orthogonal Frequency Division Multiplexing (OFDM) as a means of providing power efficient signaling for a large number of users on the same channel.

- MFSK and OFDM are being explored for high speed WLAN (IEEE 802.11a) and MMDS

Spread Spectrum Modulation Techniques

- Pseudo-Noise (PN) Sequences

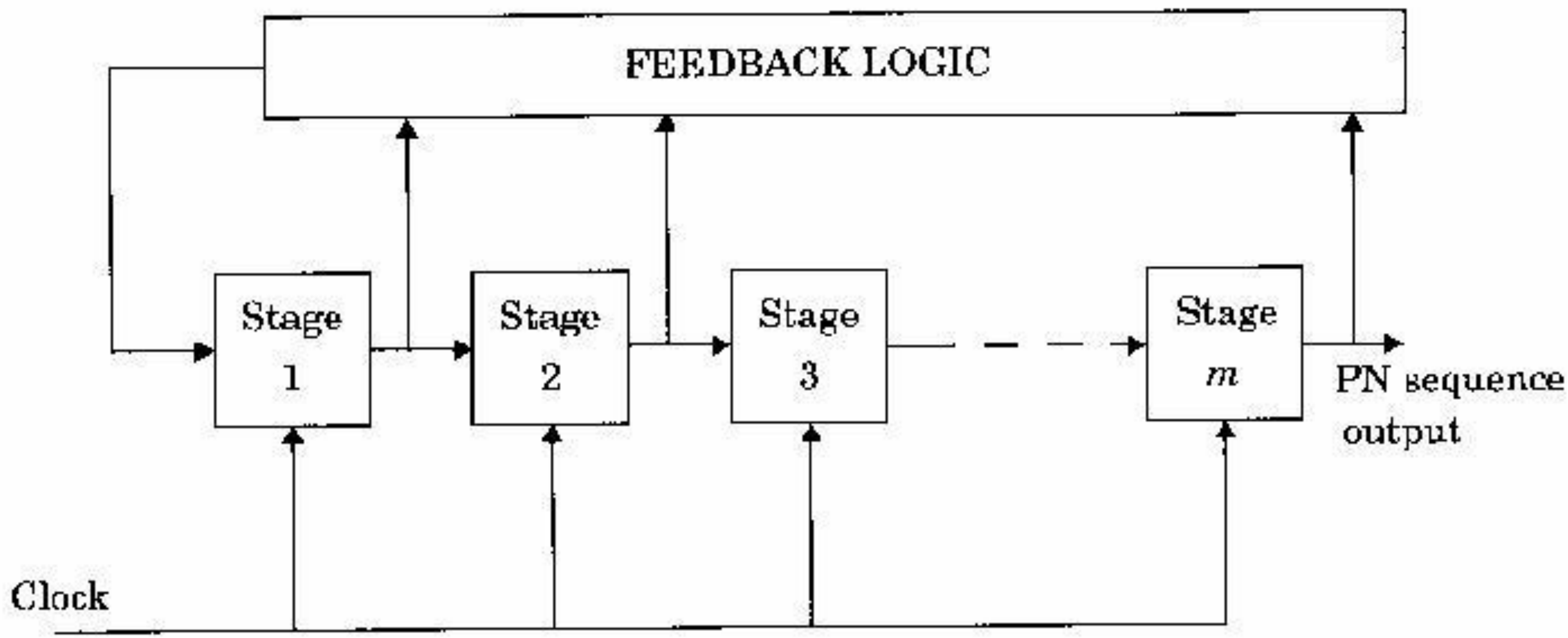


Figure 6.48
Block diagram of a generalized feedback shift register with m stages.

- Direct Sequence Spread Spectrum (DS-SS)

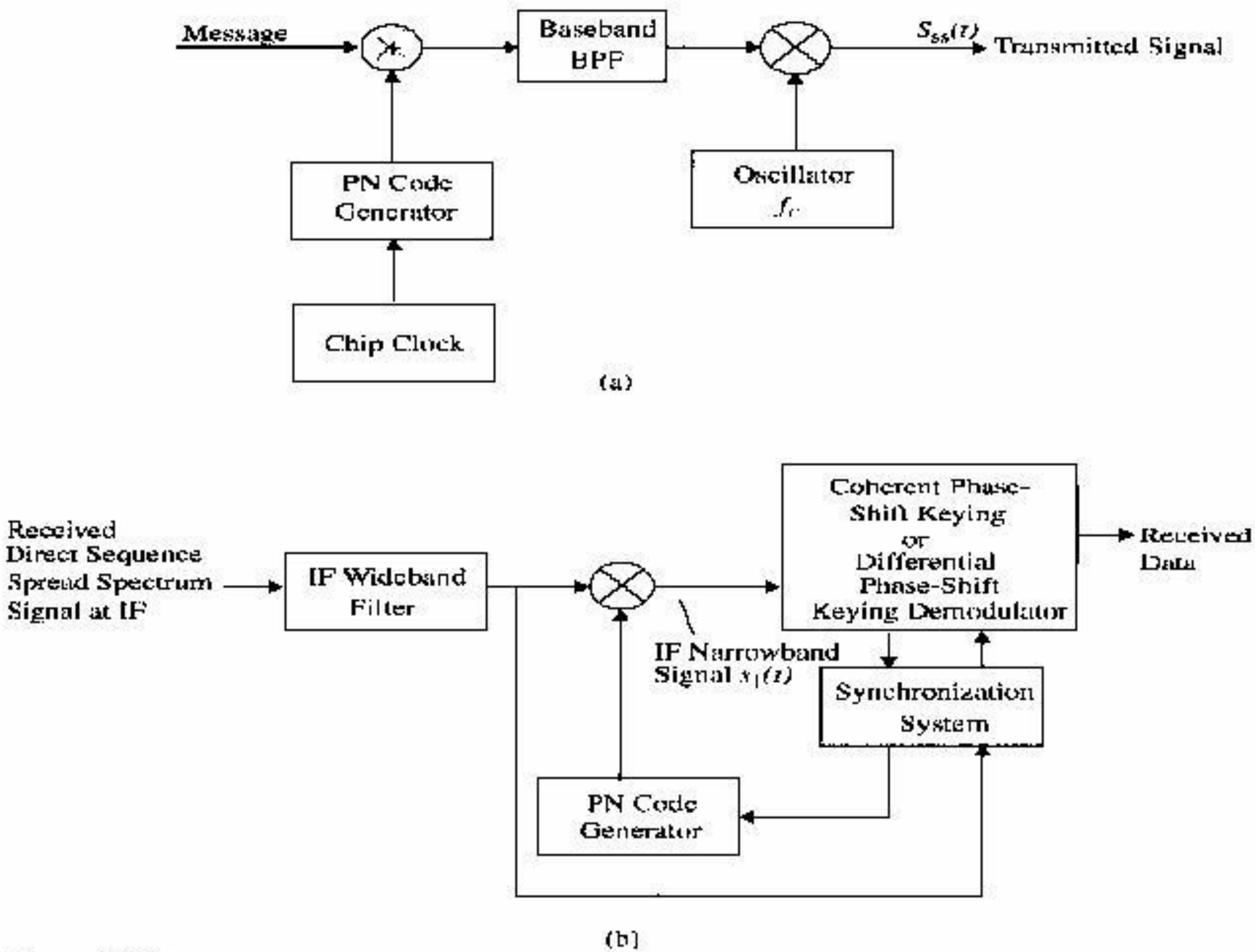


Figure 6.49
Block diagram of a DS-SS system with binary phase modulation: (a) transmitter and (b) receiver

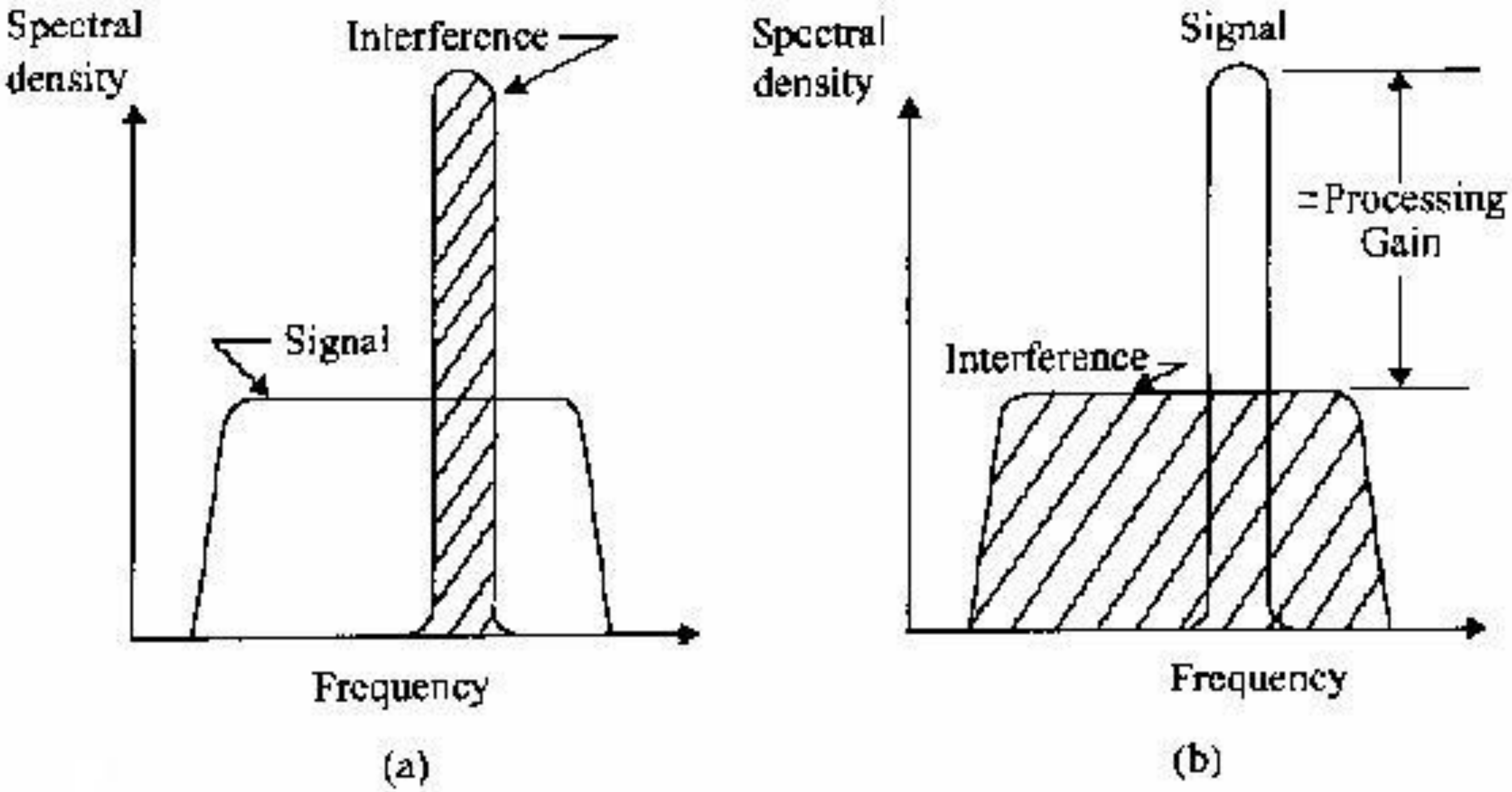


Figure 6.50
Spectra of desired received signal with interference: (a) wideband filter output and (b) correlator output after despreading.

- Frequency Hopped Spread Spectrum (FH-SS)

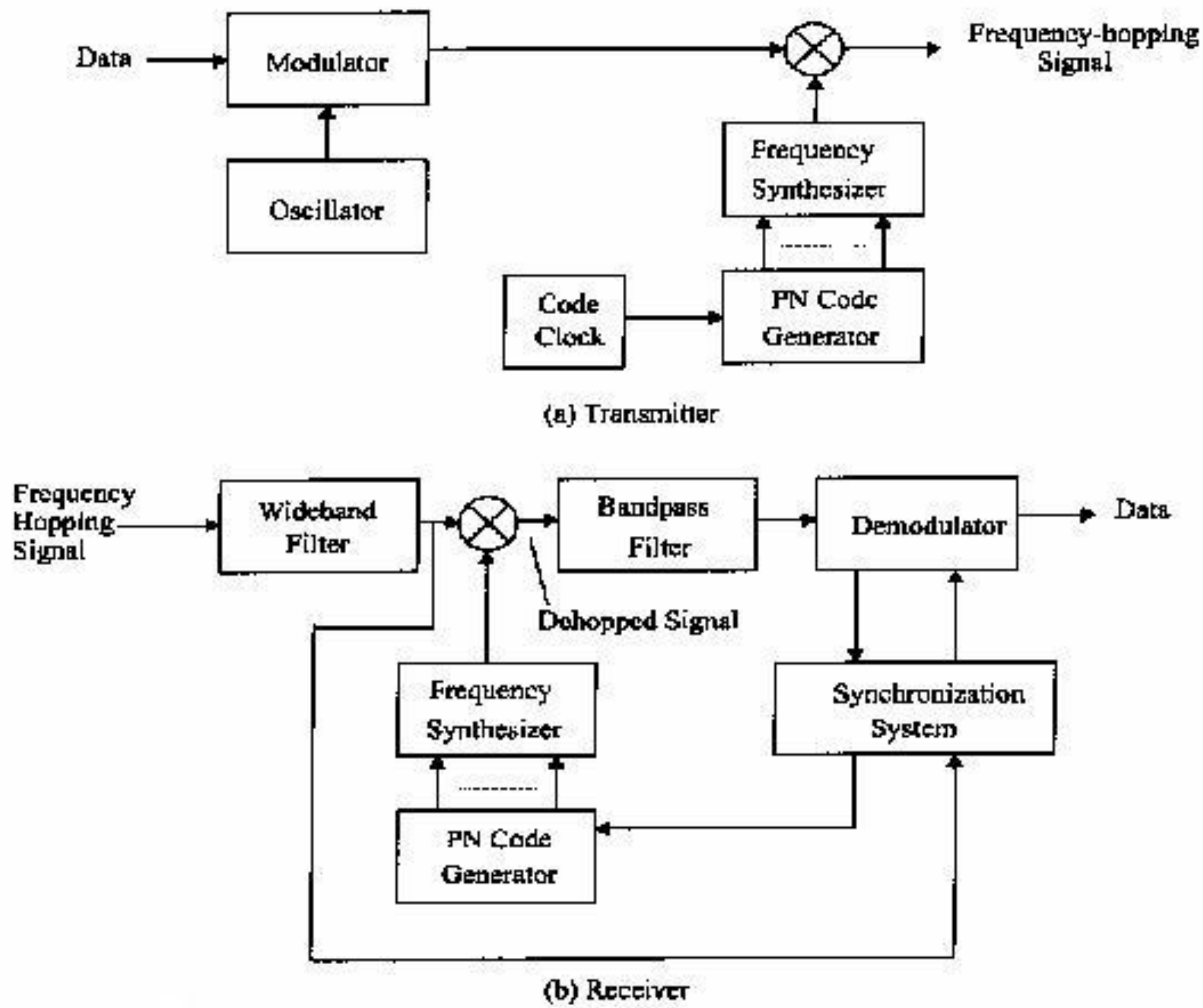


Figure 6.51
Block diagram of frequency hopping (FH) system with single channel modulation.

- Performance of DSSS

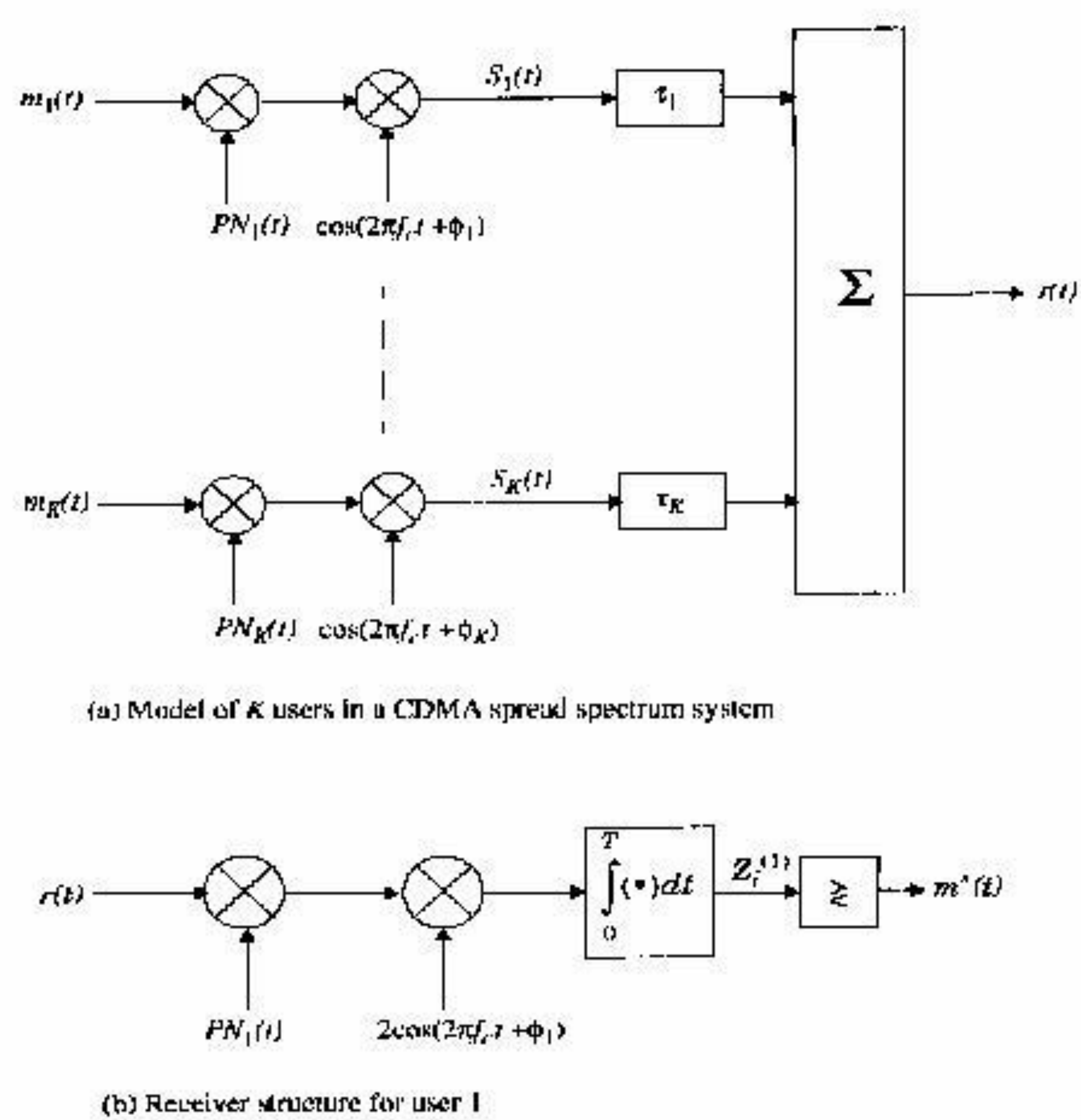


Figure 6.52
A simplified diagram of a DS-SS system with K users.

PERFORMANCE OF DIGITAL MODULATION IN SLOW FLAT-FADING CHANNELS

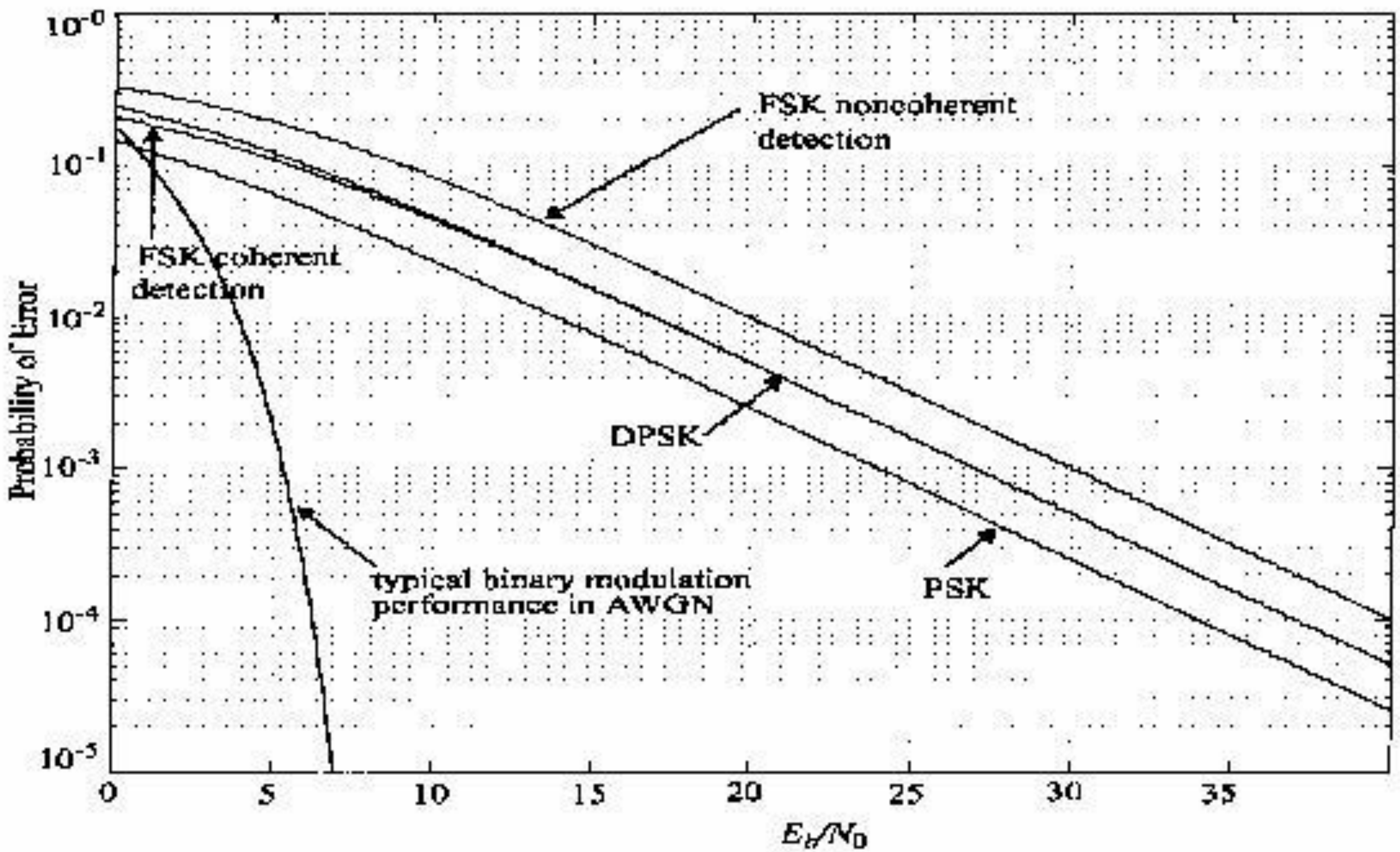


Figure 6.53
Bit error rate performance of binary modulation schemes in a Rayleigh, flat fading channel as compared to a typical performance curve in AWGN.

Digital Modulation in Frequency Selective Mobile Channels.

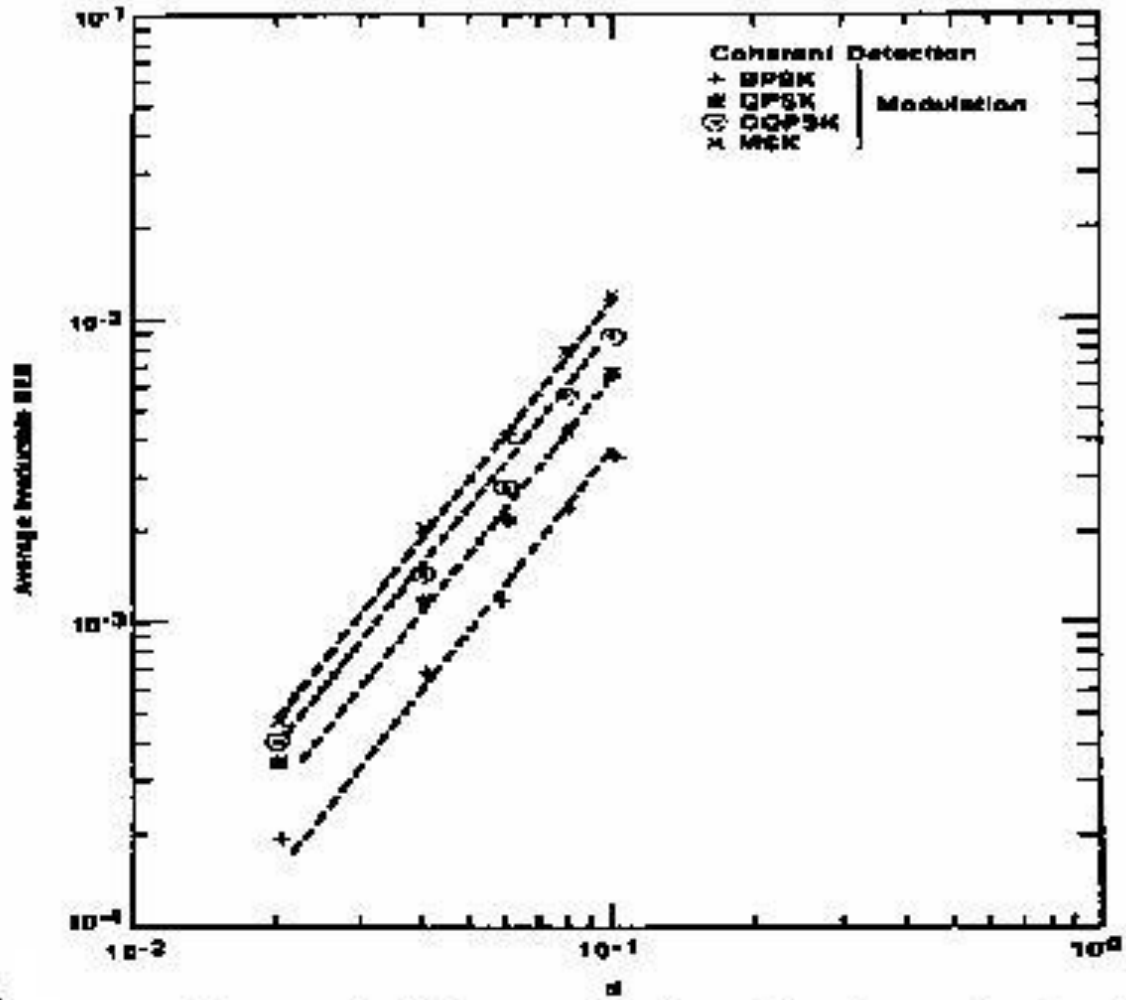


Figure 6.54
The irreducible BER performance for different modulations with coherent detection for a channel with a Gaussian shaped power delay profile. The parameter d is the rms delay spread normalized by the symbol period [From [Chu87] © IEEE].

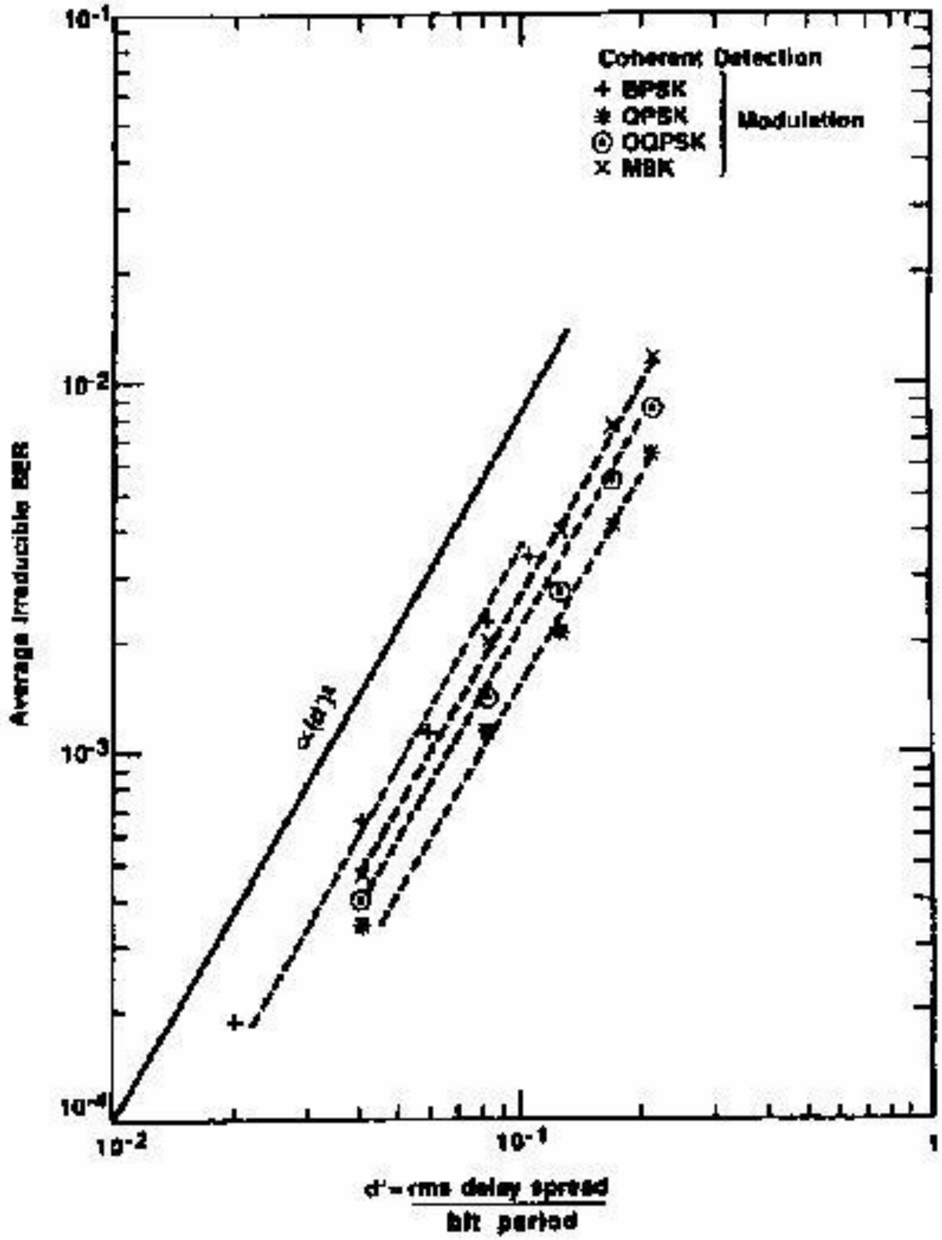


Figure 6.55
The same set of curves as plotted in Figure 6.54 plotted as a function of rms delay spread normalized by bit period [From [Chu87] © IEEE].

- Performance π/4 of DQPSK in Fading and Ii

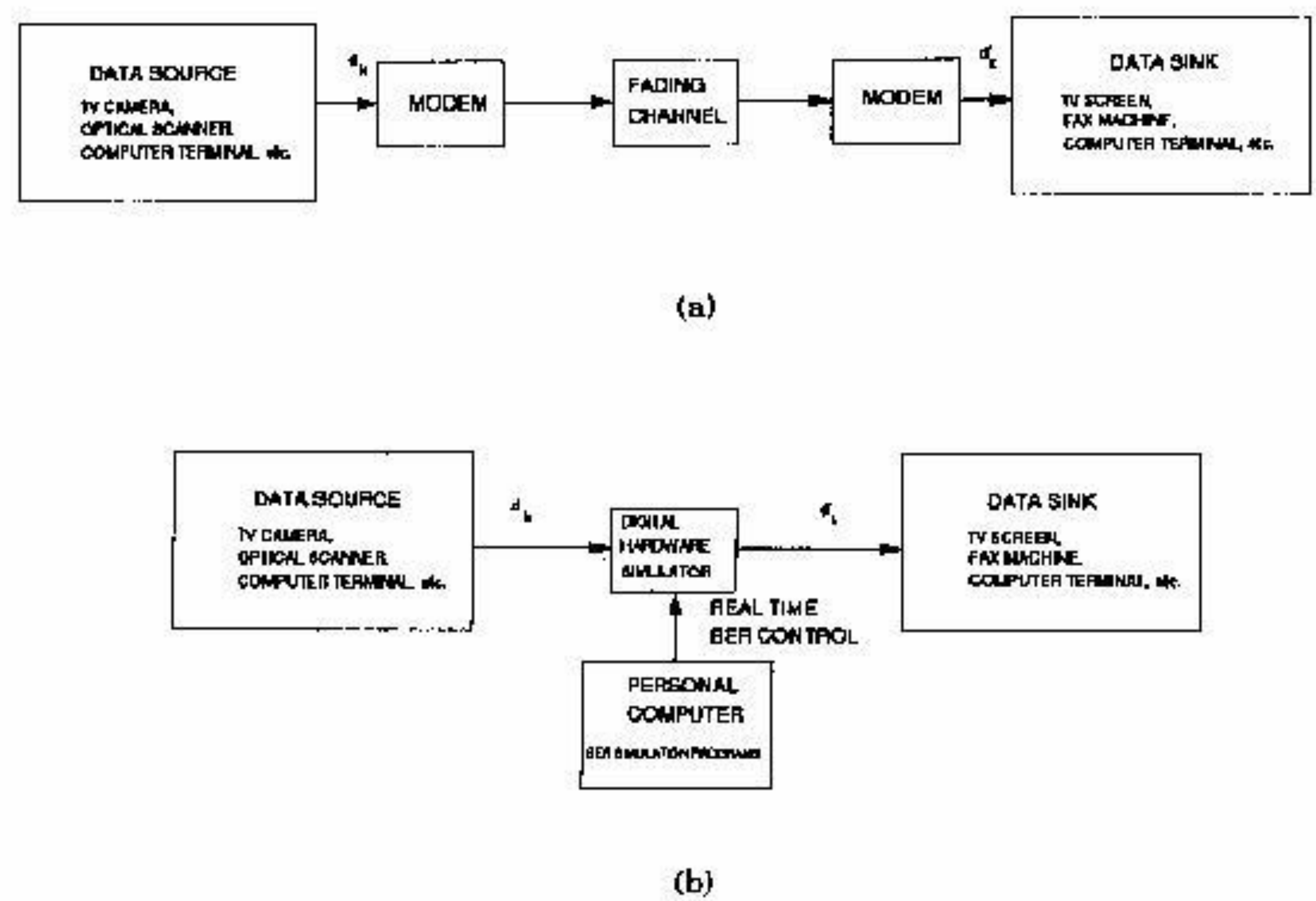


Figure *6.56*
The BERSIM concept. (a) Block diagram of actual digital communication system. (b) Block diagram of BERSIM using a baseband digital hardware simulator with software simulation as a driver for real-time BER control.

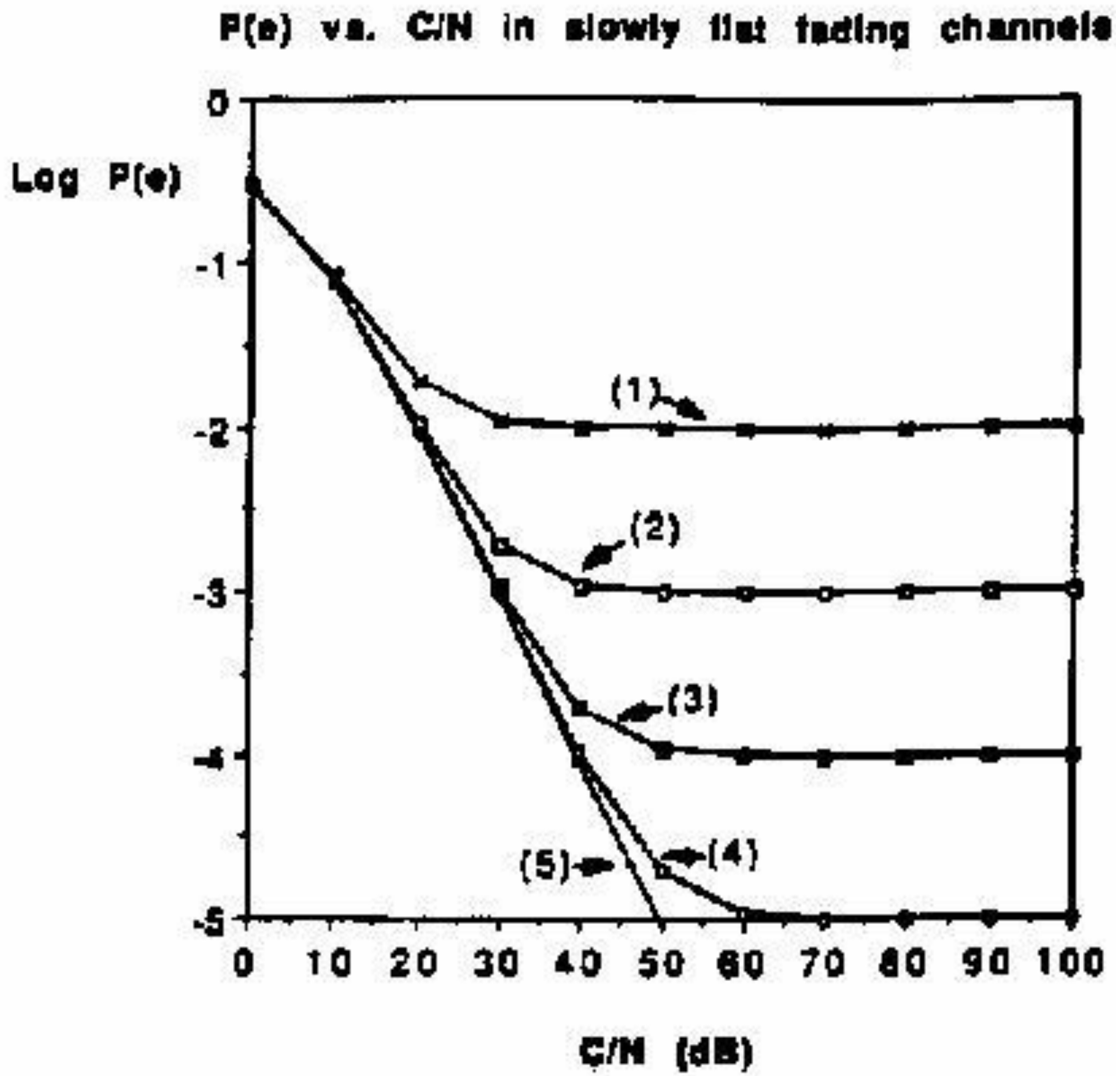


Figure *6.57*
BER performance of $\pi/4$ DQPSK in a flat slow fading channel corrupted by CCI and AWGN. f_c = 850MHz, f_s = 24$ksps$, raised cosine roll-off factor = 0.2, C/I = (1) 20 dB, (2) 30dB (3) 40dB (4) 50dB (5) infinity [From [Liu91]. © IEEE].

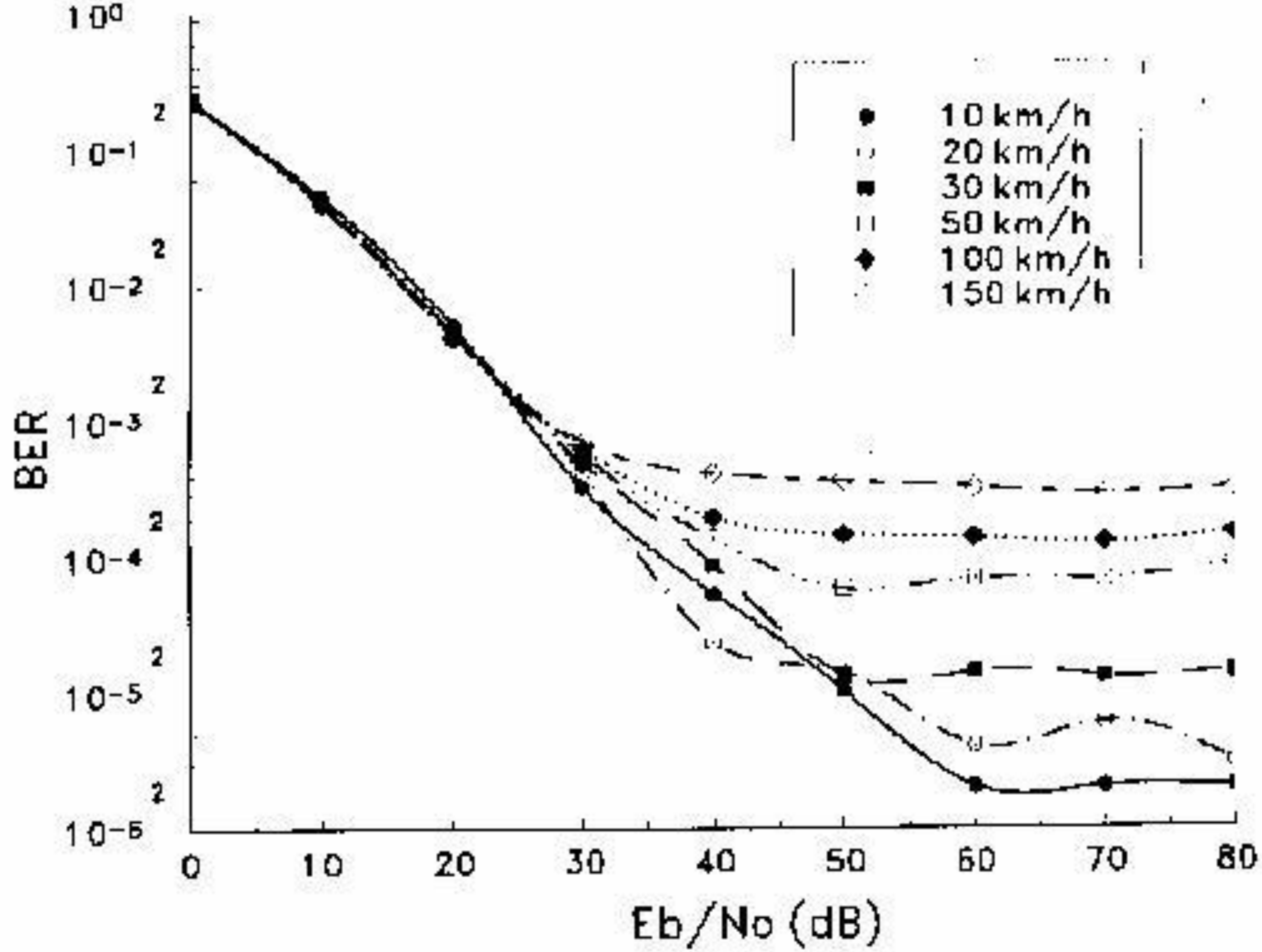


Figure 6.58

BER performance versus E_b/N_0 for $\pi/4$ DQPSK in a flat, Raleigh fading channel for various mobile speeds: f_c = 850 MHz, f_s = 24 ksps, raised cosine rolloff factor is 0.2, C/I = 100 dB. Generated by BERSIM [From [Fun93] © IEEE].

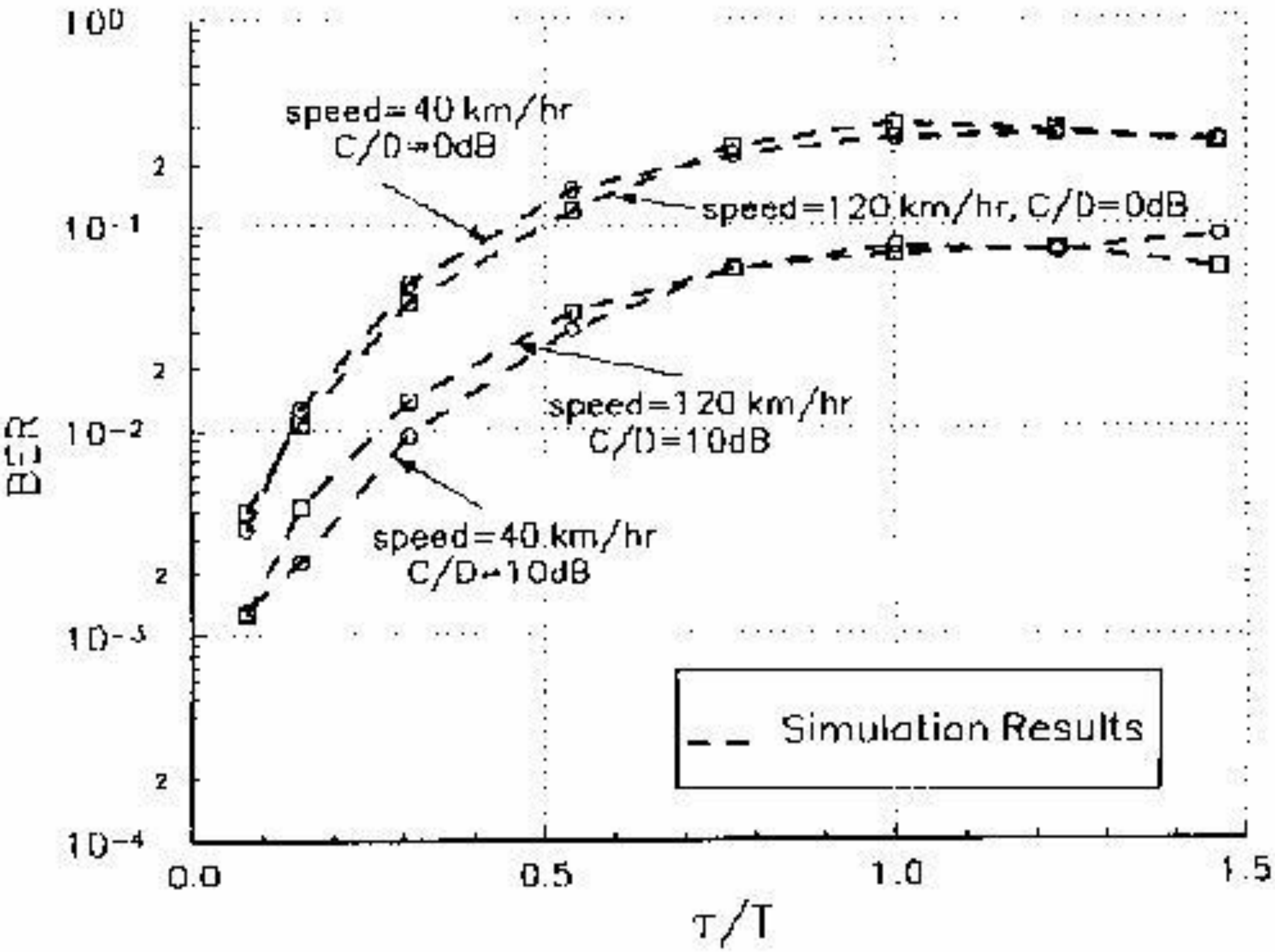


Figure 6.59
BER performance of π/4 DQPSK in a 2-ray, Rayleigh fading channel, where the time delay τ, and the power ratio C/D between the first and second ray are varied. f_c = 850 MHz, f_s = 24 ksps, raised cosine rolloff rate is 0.2, ν = 40 km/hr, 120 km/hr, E_b/N_0 = 100 dB. Produced by BERSIM [From [Fun93] © IEEE].

UNIT- 4
CODING AND MULTIPLE ACCESS

- To compress more speech channels within a given bandwidth, researchers are continuously in search of speech coders that will provide toll quality speech at lower bit rates.

- More specifically, in wireless communications, the goal of all speech coding systems is to
    - * transmit speech with the highest possible quality using the least possible channel capacity.
    - * consume little power when implemented
    - * maintain certain levels of complexity to reduce the processing delay and cost of implementation.

- A balance needs to be struck between the coder bit-rate efficiency and algorithmic complexity.

- The hierarchy of speech coders

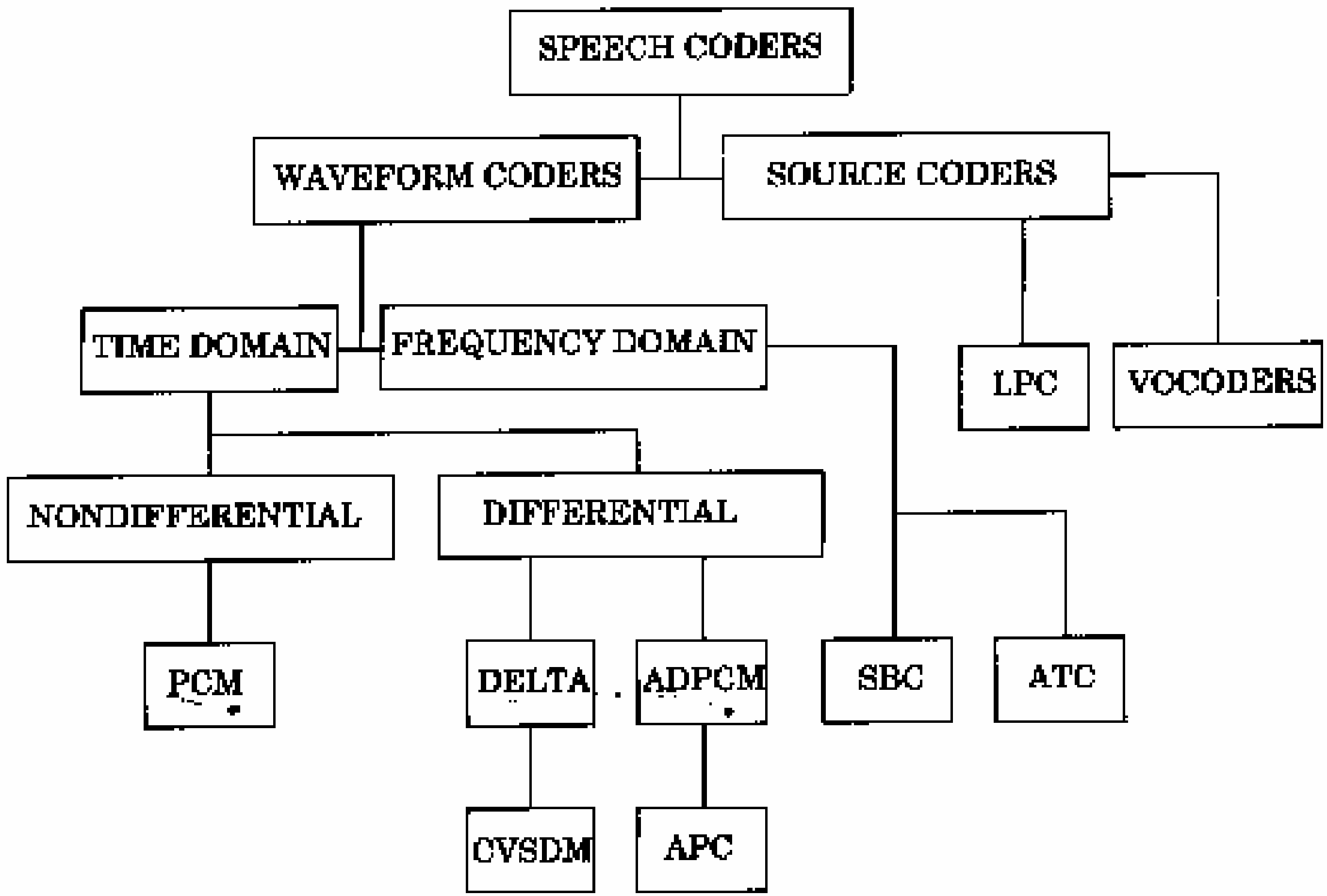


Figure 8.1
Hierarchy of speech coders (courtesy of R.Z. Zaputowycz).

- Waveform coders:
  - * strive to reproduce the time waveform of the speech signal as closely as possible.
  - * in principle, designed to be source independent and can hence code equally well a variety of signals.
  - * have the advantage of being robust for a wide range of speech characteristics and for noisy environments.
  - * minimal complexity, but achieve only moderate economy in transmission bit rate.
  - * Examples of waveform coders:
    - + pulse code modulation (PCM)
    - + differential pulse code modulation (DPCM)
    - + adaptive differential pulse code modulation (ADPCM)
    - + delta modulation (DM)
    - + continuously variable slope delta modulation (CVSDM)

- <u>Vocoders</u>
  * using a priori knowledge about the signal to be coded, and for this reason, they are, in general, signal specific.
  * can achieve very high economy in transmission bit rate, but more complex.

Characteristics of Speech Signals

- Speech waveforms have a number of useful properties that can be exploited when designing efficient coders.

- Some of the properties that are most often utilized in speech coder design include.

  * The most basic property of speech waveforms that is exploited by all speech coders is that they are <u>bandlimited</u>.

    A finite bandwidth means that it can be time-discretized (sampled) at a finite rate and reconstructed completely from its samples, provided that the sampling frequency is greater than twice the highest frequency component.

* While the bandlimited property of speech signals makes sampling possible, the other properties allow quantization to be performed with greater efficiency.

+ Nonuniform pdf of speech signal amplitude

$$p(x) = \frac{1}{\sqrt{2}\sigma_x} \exp(-\sqrt{2}|x|/\sigma_x)$$

the two-side exponential (Laplacian) function provides a good approximation

→nonuniform quantizers, including vector quantizers, are used to march the distribution.

→In the above equation it shows that a very high probability of near-zero amplitudes, a significant probability of very high amplitudes, and a monotonically decreasing function of amplitudes between these extremes.

+ Existing much correlation between successive speech signal samples.
  - →This implies that in every sample of speech, there is a large component that is easily predicted from the value of the precious samples with a small random error.
  - →All differential and predictive coding schemes are based on exploiting this property.
  - →Autocorrelation function (ACF)

$$C(k) = \frac{1}{N} \sum_{n=0}^{N-|k|-1} x(n)\,x(n+|k|)$$

  - →typical signals have an adjacent sample correlation, C(1), as high as 0.85 to 0.9.

+ nonflat characteristic of the power spectral density of speech

→makes it possible to obtain signification compression by coding speech in the frequency domain.

→That is, coding the speech signal separately in different frequency bands can leads to significant coding gain.

Quantization Techniques

- a process of mapping a continuous range of amplitudes of a signal into a finite set of discrete amplitudes.

- It determines to a great extent the overall distortion as well as the bit rate necessary to represent the speech waveform.

- A quantizer that uses n bits can have $M=2^n$ discrete amplitude levels.

- Uniform Quantization
  * The discrete levels are uniformly distributed over the range of speech signal amplitude.
  * The distortion is most often measured in mean square error (MSE)

$$MSE = E\left[(x - f_Q(x))^2\right] = \frac{1}{T}\int_0^T [f_Q(x) - x(t)]^2 dt$$

  * the distortion introduced by a quantizer is often modeled as additive quantization noise.

* The performance of a quantizer is measured as the output signal-to-quantization noise ratio (SQNR).
* PCM: first digital coding standard adopted for commercial telephony.
  + Using 8 bits per sample at a sampling frequency of 8KHz→64kbps.
  + The SQNR of PCM

$$(SQNR)_{dB} = 6.02n + \alpha$$

  + i.e., with every addition bit used for encoding, the output SQNR improves by 6 dB.

- Nonuniform Quantization
  - * Distributes the quantization levels in accordance with the pdf of the input waveform amplitude.
  - * For an input signal with a pdf p(x), the mean square distortion is given by

$$D = E\left[(x-f_Q(x))^2\right] = \int_{-\infty}^{\infty} [x-f_Q(x)]^2 p(x)\,dx$$

  - * the total distortion can be reduced by decreasing the quantization noise where the pdf, p(x), is large.

- Adaptive Quantization

  * The time-varying or nonstationary nature of speech signals results in a dynamic range of 40dB of more.

  * To accommodate such a huge dynamic range is to adopt a time varying quantization technique.

  * An adaptive quantizer varies its step size in accordance to the input speech signal power.

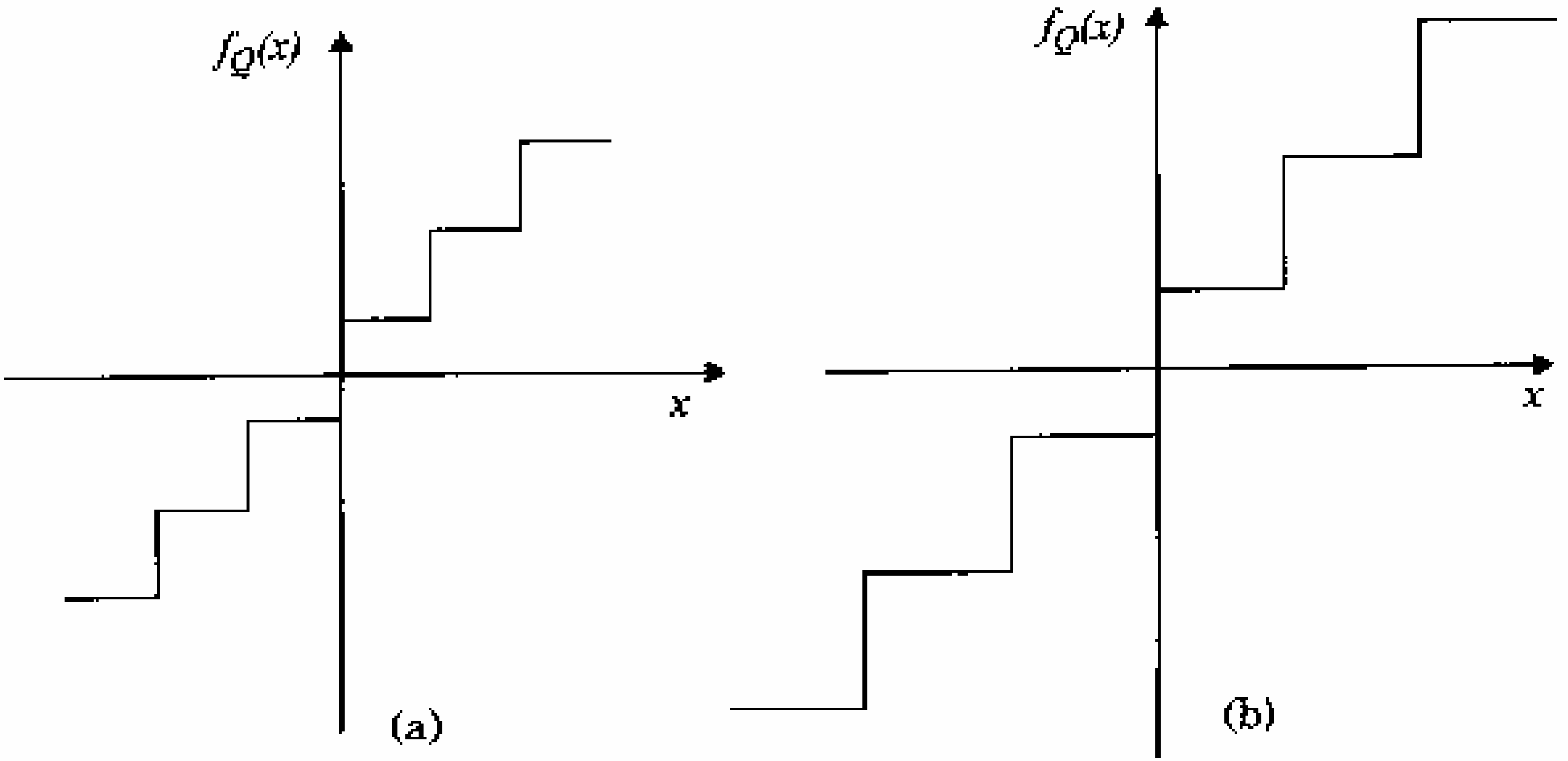


Figure 8.2
Adaptive quantizer characteristics (a) when the input signal has a low amplitude swing and (b) when the input signal has a large amplitude swing.

* The input power level of the speech signal varies slowly enough that simple adaptation algorithms can be easily designed and implemented.

- Vector Quantization (VQ)

  * Shannon predicted that better performance can be achieved by coding many samples at a time instead of one sample at a time.

  * VQ is a delayed- decision coding technique which maps a group of input samples (typically a speech frame), called a vector, to a code book index.

* Performance is greatly enhanced of there is strong correlation between samples in the group.

* VQ is know to be the most efficient at very low bit rates due to the use of larger vector to exploit the redundancies is the VQ sampling interval.

* VQ is a computationally intensive and is not often used to code speech signals directly.

* Instead, is used in many speech coding systems to quantize the speech analysis parameters.

* Improved versions of VQ algorithms: multistage VQ, tree-structure VQ, and shape-gain VQ etc.

Adaptive Differential Pulse Code Modulation (ADPCM)

- more efficient than PCM by removing the redundancies in the speech signal.
- Adjacent samples of a speech waveform are highly correlated.
- This means that the variance of the difference between adjacent speech amplitudes is much smaller than the variance of the speech signal itself.

- Allows speech to be encoded at a bit rate of 32 kbps, while retaining the same voice quality.
- CCITT G.721 ADPCM is used in CT2 and DECT.
- In practice, ADPCM encoders are implemented using signal prediction techniques.

- Instead of encoding the difference between adjacent samples, a linear predictor is used to predict the current sample.
- The difference between the predicted and actual sample called the prediction error is then encoded for transmission.
- Prediction is based on the knowledge of the autocorrelation properties of speech.

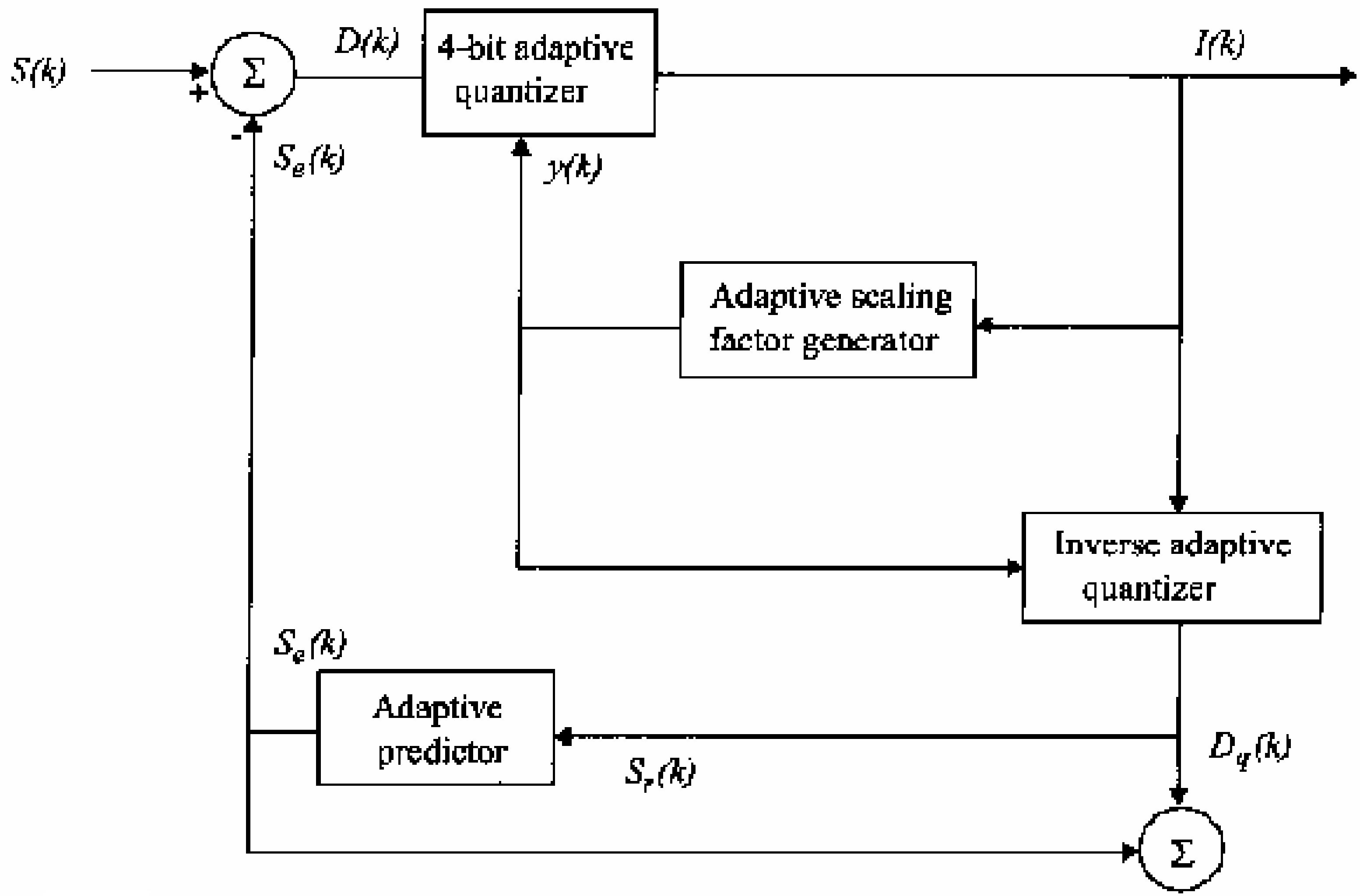


Figure 8.3
Block diagram of ADPCM encoder.

Frequency Domain coding of Speech

- can be thought of as a method of distributing quantization noise across the signal spectrum.
- The speech signal is divided into a set of frequency components which are quantized and encoded separately.
- Different to some perceptual criteria for each band, and hence the quantization noise be contained within bands.
- The number of bits used to encode each frequency component can be dynamically varied and shared among the different bands.

- Sub-band coding (SBC)

  * Divides the speech signal into many smaller sub-bands and encodes each sub-band separately according to some perceptual significance.

  * Speech is typically divided into 4 or 8 sub-bands by a bank of filters.

  * Can be used for coding speech at bit rates in the range 9.6 kbps to 32 kbps.

- In this range, speech quality is roughly equivalent to that of ADPCM at an equivalent bit rate.

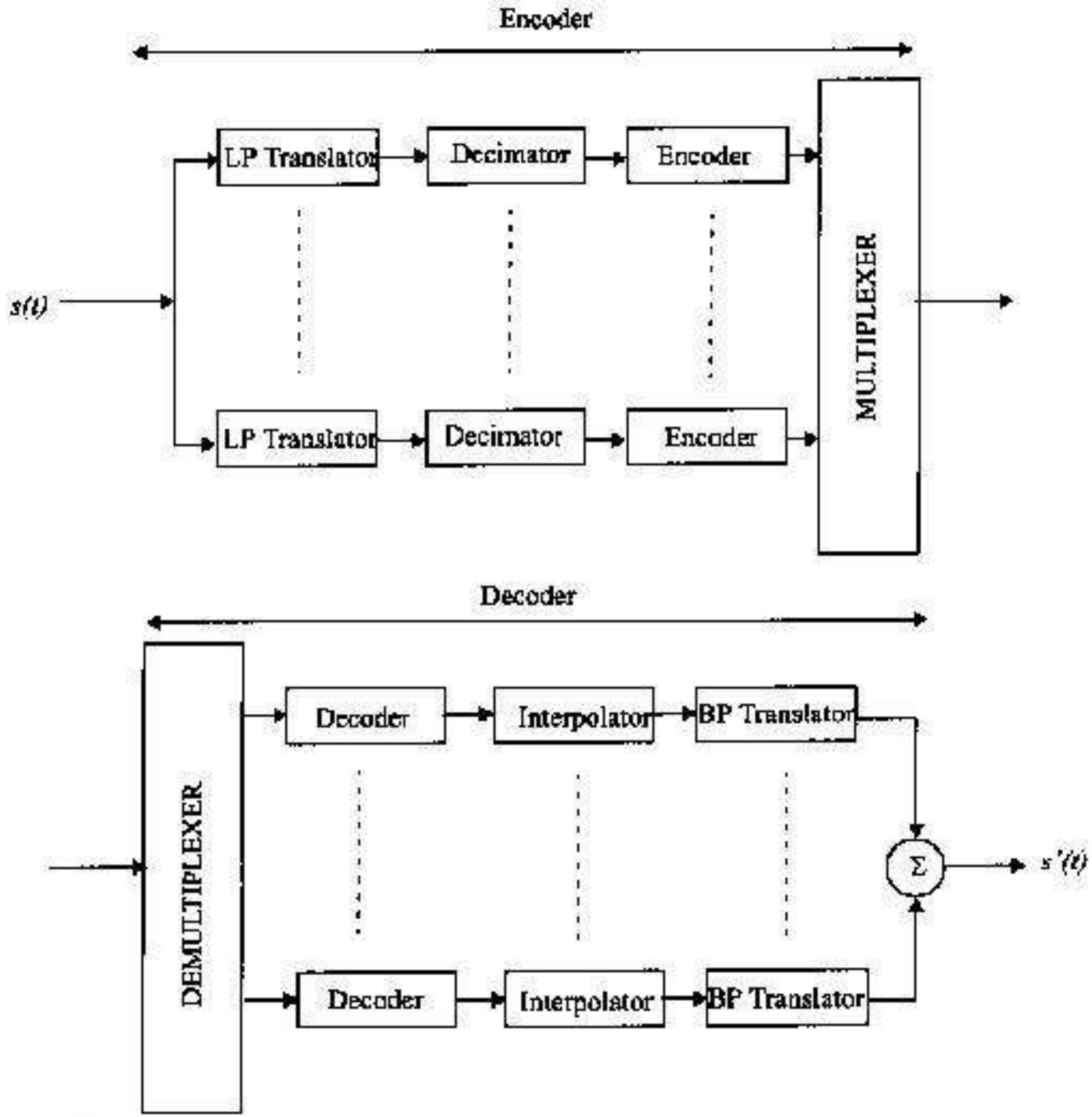


Figure 8.4
Block diagram of a sub-band coder and decoder.

- Adaptive Transform coding (ATC)

  * Involves block transformations of window input segments of the speech waveform.(a sequence of samples).

  * Each segment is represented by a set of transform coefficients, which are separately quantized with number of bits proportional to its perceptual significance.

  * Can be used to encode speech at bit rates in the range 9.6 kbps to 20 kbps.

  * One of the most frequently used transforms:

    The discrete cosine transforms (DCT)

    Per equation (7.11)

VOCODERS

- Analyze the voice signal at transmitter
- Transmit parameters derived from the analysis
- Then synthesis the voice at the receiver using those parameters.
- All vocoder systems try to model the speech generation process as a dynamic system and attempt to quantify certain physical constraints of the system.

- These physical constraints are then used to provide a parsimonious description the speech signal.

- In general much more complex than the waveform coders and achieve very high, and economy in transmission bit rate.

- However, less robust, and the performance tends to be talker dependent.

- The most popular among the vocoding schemes is the linear predictive coder (LPC).

- The other schemes include:

  * The channel vocoder

  * Format vocoder

  * Cepstrum voceder

  * Voice excited vocoder

- Fig8.5 shows the tranditional speech generation model that is the basis of all vocoding systems.

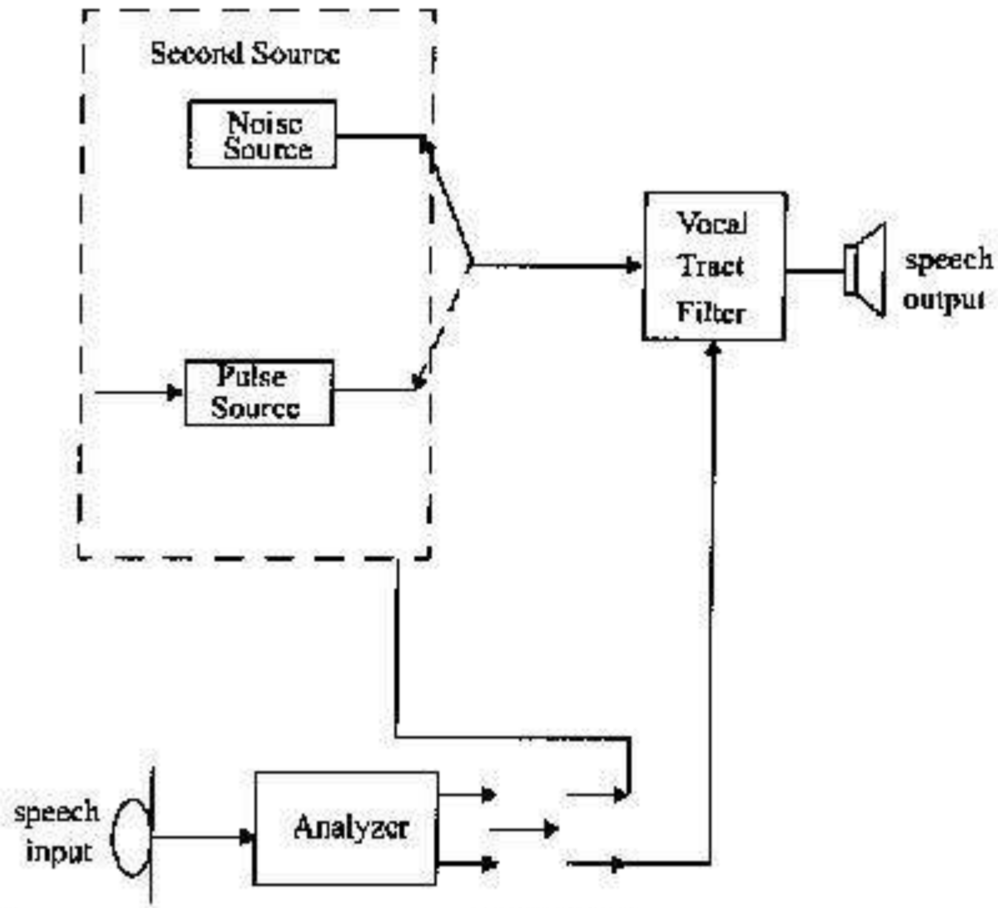


Figure 8.5
Speech generation model.

- The speech signal is assumed to be two types:

  Voiced (“m”, “n”, “v” pronunciations) and unvoiced (“f”, “s”, “sh” pronunciations) sounds. The parameters associated with a speech signal are the voice pitch, the pole frequencies of the modulation filter, and the corresponding amplitude parameters.

- Channel Vocoders

  * frequency domain vocoders

  * determine the envelope of the speech signal for a number of frequency bands.

  * along with the energy information about each band, the voice/ unvoiced decision, and the pitch frequency for voiced speech are also transmitted.

- Formant vocoders

  * instead of sending samples of the power spectrum envelop, the formant vocoder attempts to transmit the position of the peaks (formants) of the spectral envelope.

  * typically it must be able to identity at least three formants for representing the speech sounds, and also control the intensities of the formants.

- <u>Cepstrum Vocoders</u>
  - * separates the excitation and vocal tract spectrum by inverse Fourier transforming of the log magnitude spectrum to produce the cepstrum of the signal.
  - * the low frequency coefficients in the cepstrum correspond to the vocal tract spectral envelope, with the high frequency excitation coefficients forming a periodic pulse train at multiples of the sampling period.
- <u>Voice-Excited Vocoder</u>
  - * eliminate the need for pitch extraction and voicing detection operations.
  - * designed for operation at 7.2 kbps to 9.6 kbps.

LINEAR PREDICTIVE CODERS

- LPC Vocoders

  * The time domain class of vocoders

  * Attempts to extract the significant features of speech from the time waveform

  * Computationally intensive, but by far the most popular among the class of low bit rate vocoders

  * Possible to transmit good quality voice at 4.8 kbps.

* It models the vocal tract as an all pole linear filter with a transfer function

* The coefficients of the all pole filter are obtained in the time domain using linear prediction techniques.

* The prediction principles used are similar to those in ADPCM coders.

* However, instead of transmitting quantized values of the error signal, the LPC system transmits only selected characteristics of the error signal, including the gain factor, pitch information, and the voiced/unvoiced decision information.

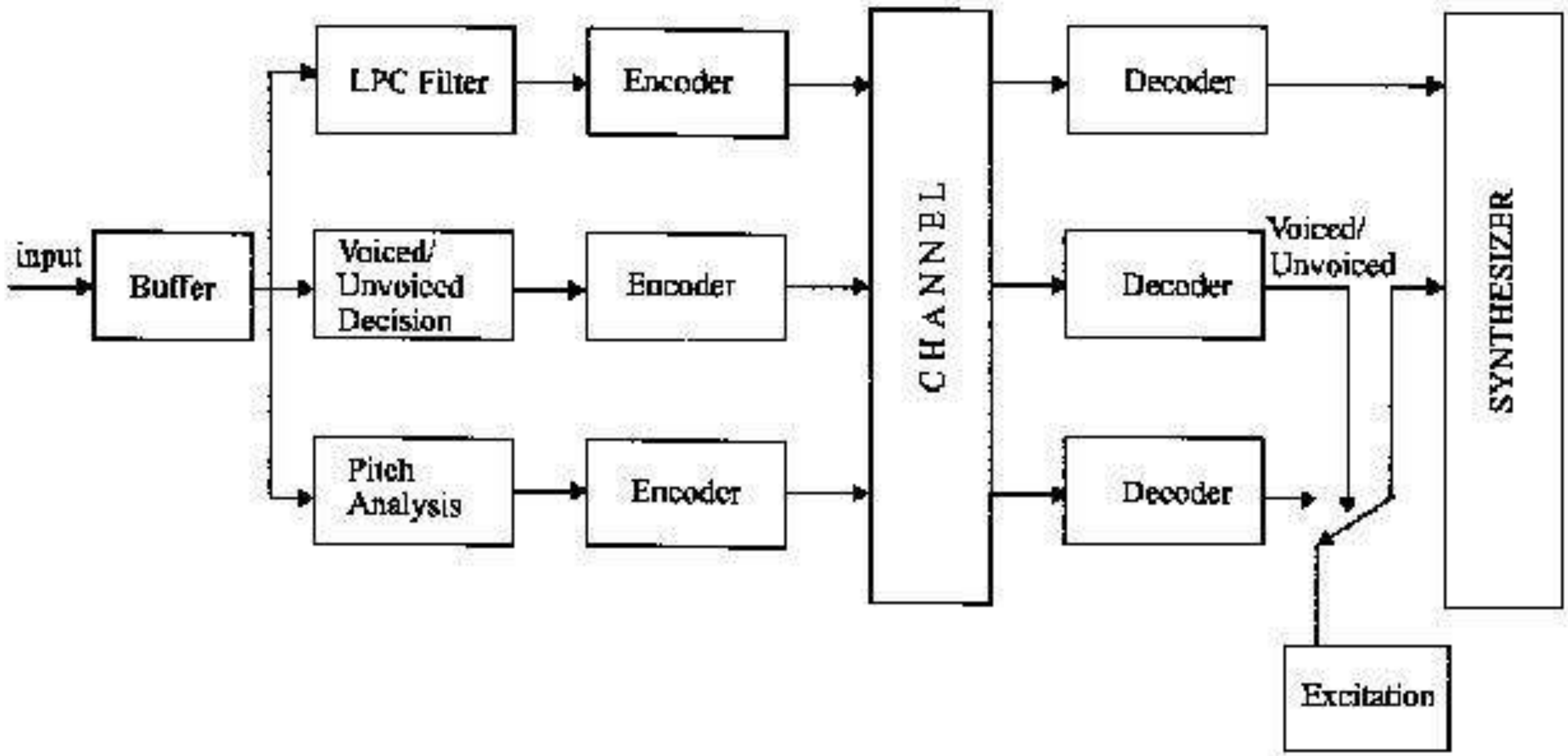


Figure 8.6
Block diagram of a LPC coding system.

* Various LPC schemes differ in the way they recreate the error signal (excitation) at the receiver.

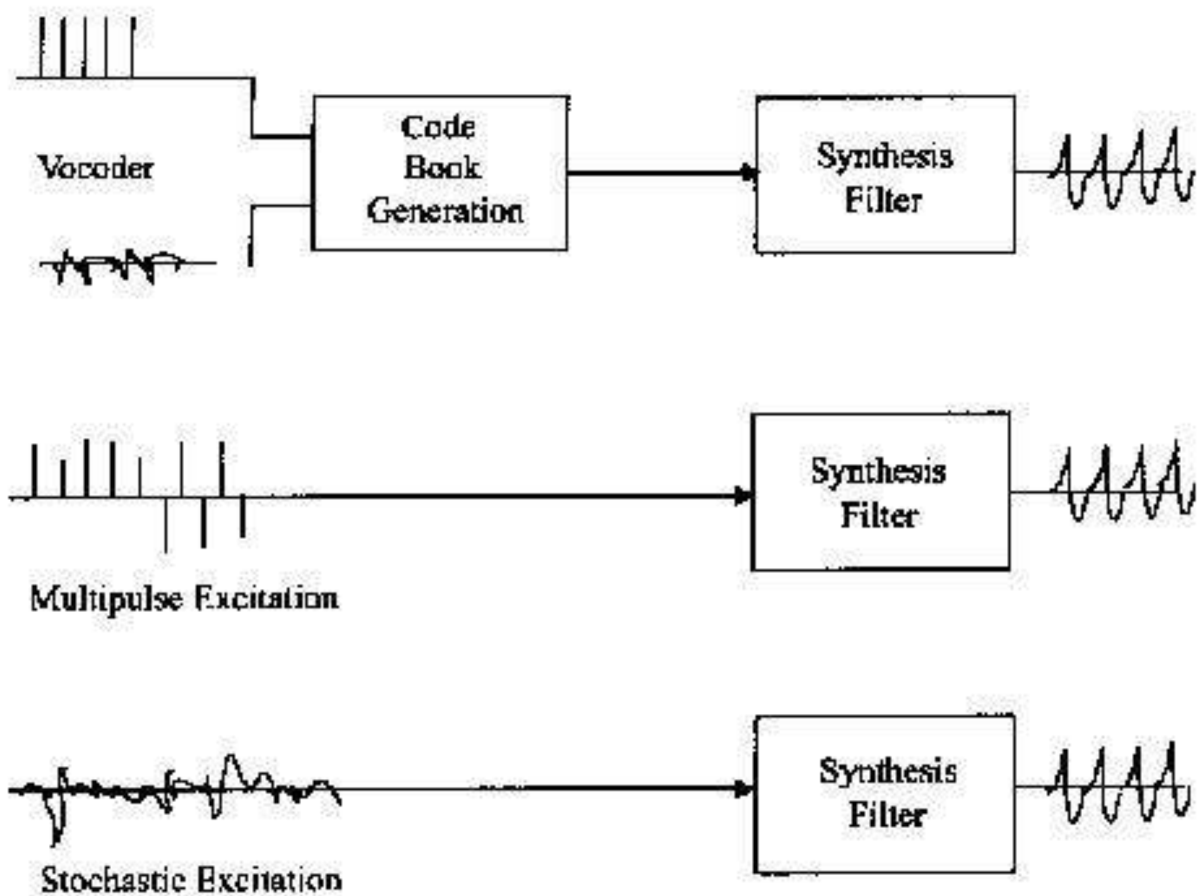


Figure 8.7
LPC excitation methods.

* The first one shows the most popular means. It uses two sources at the receiver, one of white noise and the other with a series of pulses at the current pitch rate.

* Multi-pulse excited LPC (MPE-LPC)

* Code excited LPC (CELP)

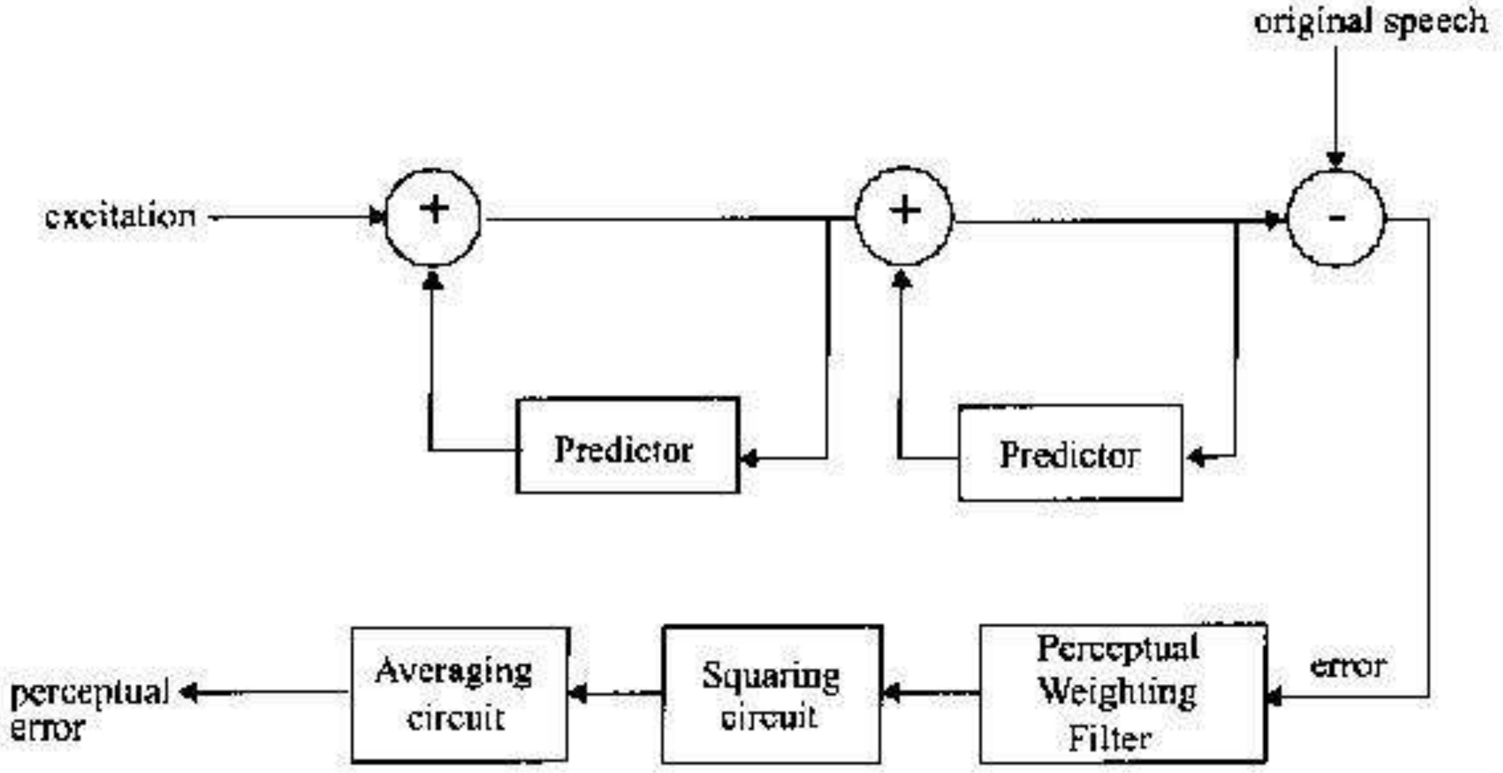


Figure 8.8
Block diagram illustrating the CELP code book search.

+ Computationally intensive, advances in DSP and VLSI technology have made real-time implementation of CELP codes possible.
+ The CDMA (IS-95) uses a variable rate CELP codec at 1.2 to 14.4 Kbps.

* Residual Excited LPC (RELP)

+ After estimating the model parameters (LP coefficients or related parameters) and excitation parameters (voiced/unvoiced decision, pitch, gain) from a speech frame, the speech is synthesized at the transmitter and subtracted from the original speech to form a residual signal.

+ The residual signal is quantized, coded and transmitted to the receiver along with the LPC model parameters.

+ At the receiver, the residual error signal is added to improve the quality of the synthesized speech.

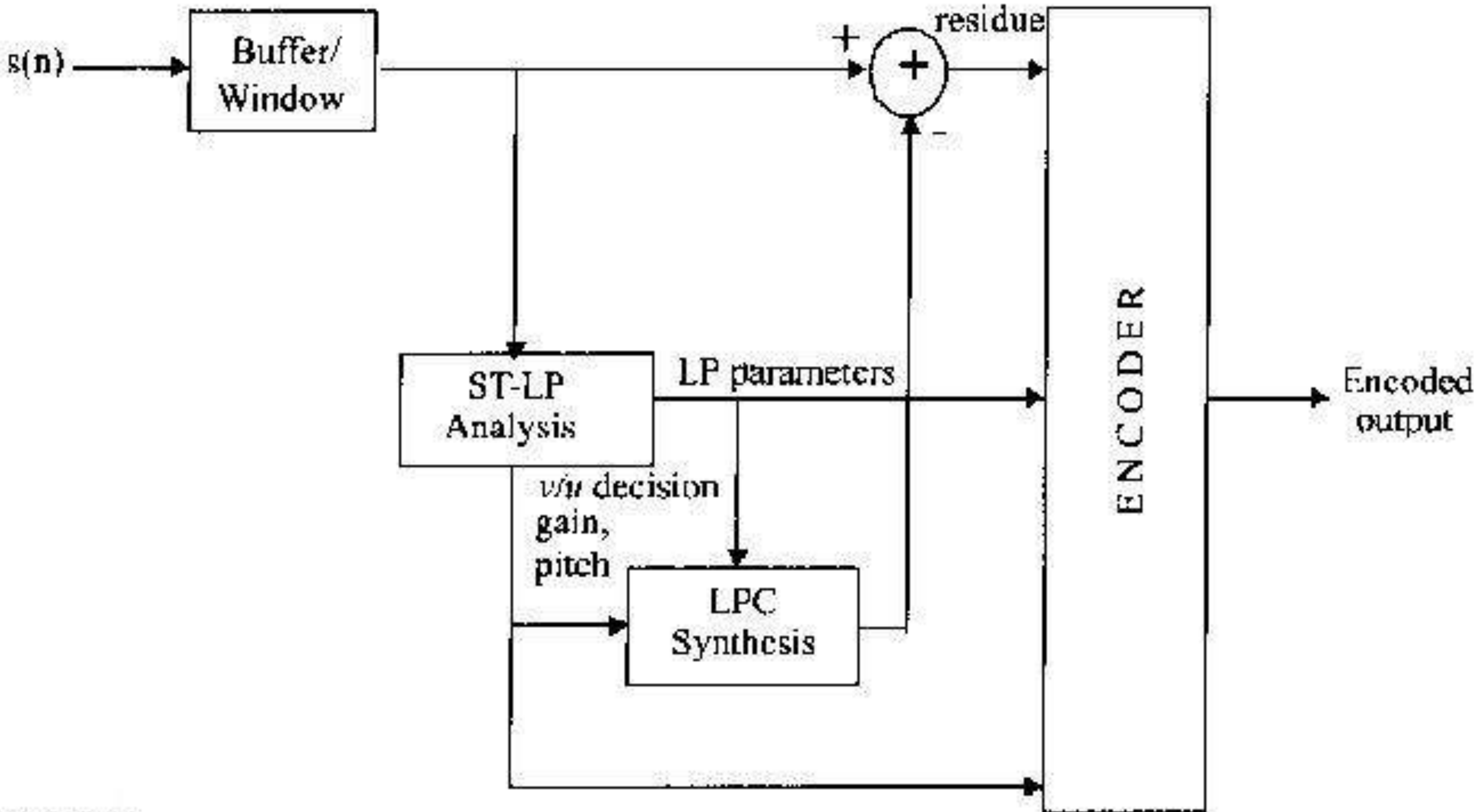


Figure 8.9
Block diagram of a RELP encoder.

CHOOSING SPEECH CODECS FOR MOBILE COMMUNICATIONS

- A balance must be struck between the perceived quality of the speech resulting from this compression and the overall system cost and capacity.

- Other factors include:
  - * The end-to-end encoding delay
  - * The algorithmic complexity if the coder
  - * The d.c. power requirements
  - * Computability with existing standards
  - * Robustness of the encodes speech to transmission errors due to fading and interference, etc.

- The choice of the speech coder will also depend on the cell size used.
- In CT2 and DECT, which use very small cells, 3Kbps ADPCM coders are used.
- In cellular systems operating with much larger cells and poorer channel conditions need to use error correcting coding, thereby requiring the speech codes to operate at lower bit rates.
- In satellite communications, it needs to use an even lower bit rate (3Kbps) of speech coder.

- The type of multiple access techniques used, having an important factor in determining the spectral efficiency of the system, also strongly influences the choice of speech codec. For example, U.S. TDMA (IS-54) increased the capacity of AMPS threefold by using an 8 Kbps VSELP codec.

- The type of modulation employed also has considerable impact on the choice of speech codec.

Table 8.1 **Speech Coders Used in Various Mobile Radio Systems**

Standard	Service Type	Speech Coder Type Used	Bit Rate (kbps)
GSM	Cellular	RPE-LTP	13
CD-900	Cellular	SBC	16
USDC (IS-54)	Cellular	VSELP	8
IS-95	Cellular	CELP	1.2, 2.4, 4.8, 9.6
IS-95 PCS	PCS	CELP	14.4
PDC	Cellular	VSELP	4.5, 6.7, 11.2
CT2	Cordless	ADPCM	32
DECT	Cordless	ADPCM	32
PHS	Cordless	ADPCM	32
DCS-1800	PCS	RPE-LTP	13
PACS	PCS	ADPCM	32

THE GSM CODEC

- It uses a codec named the regular pulse excited long term prediction (RPE-LTP) codec.

- Combines the advantages of the earlier French proposed baseband RELP codec with these of the multi-pulse excited long-term prediction (MPE-LTP) codec proposed by Germany.

- It is relatively complex and power hungry.

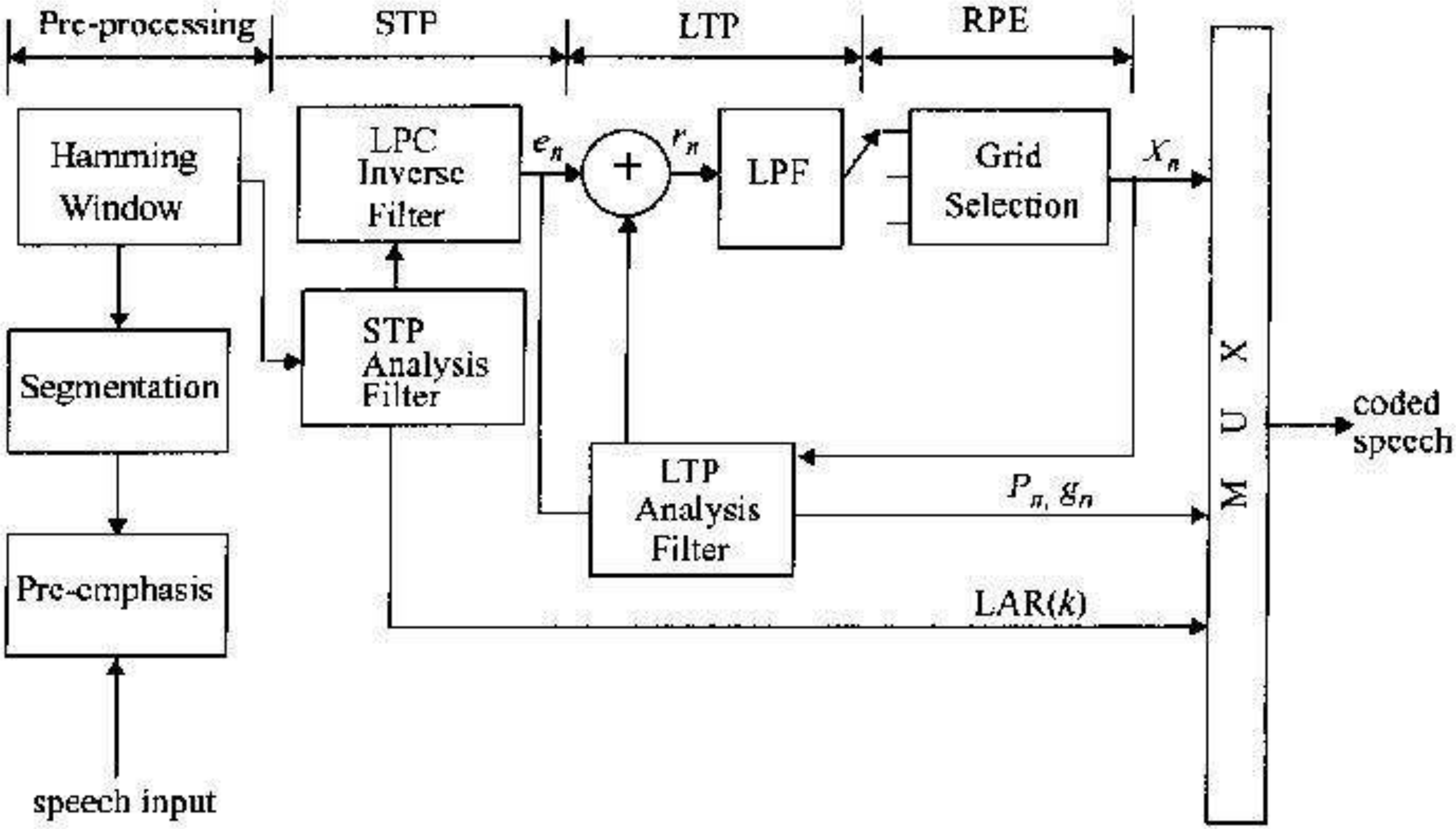


Figure 8.10
Block diagram of GSM speech encoder.

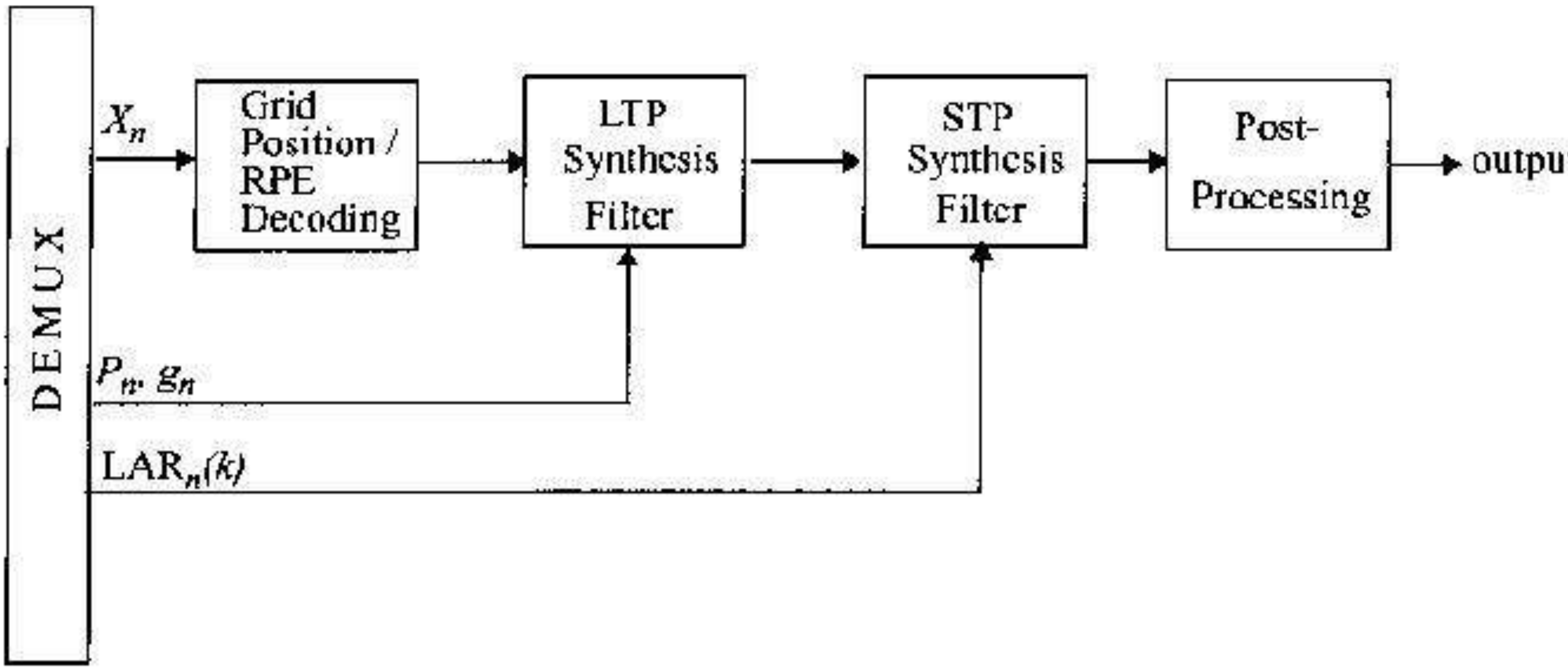


Figure 8.11
Block diagram of GSM speech decoder.

The USDC Codec

- IS-95 uses a vector sum excited linear predictive coder (VSELP).
- Is a variant of the CELP type vocoders.

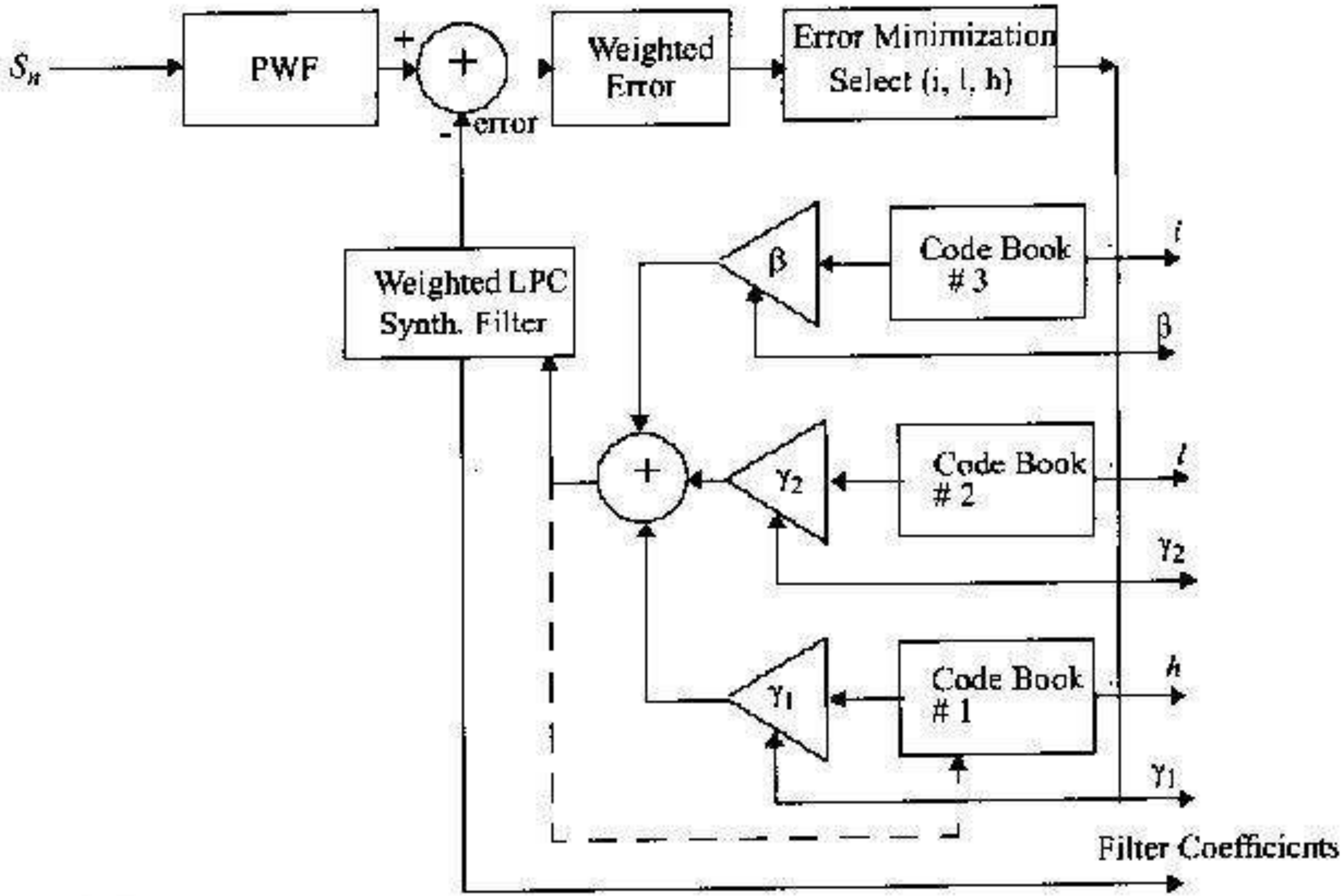


Figure 8.12
Block diagram of the USDC speech encoder.

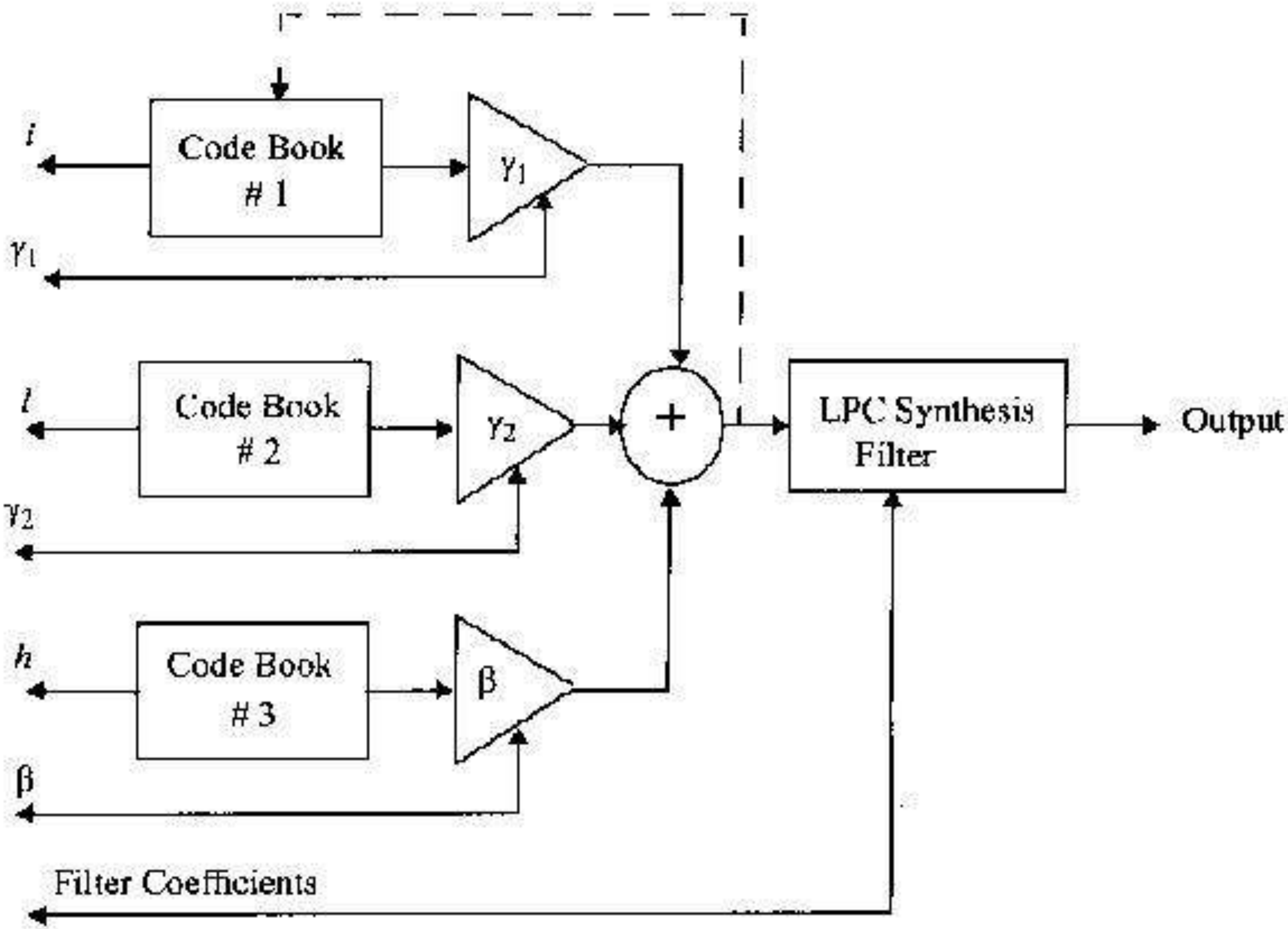


Figure 8.13
Block diagram of the USDC speech decoder.

Performance Evaluation of Speech Coders

- the mean Opinion Score (MOS) ranking

Table 8.2 **MOS Quality Rating [Col89]**

Quality Scale	Score	Listening Effort Scale
Excellent	5	No effort required
Good	4	No appreciable effort required
Fair	3	Moderate effort required
Poor	2	Considerable effort required
Bad	1	No meaning understood with reasonable effort

Table 8.3 **Performance of Coders [Jay90], [Gar95]**

Coder	MOS
64 kbps PCM	4.3
14.4 kbps QCELP13	4.2
32 kbps ADPCM	4.1
8 kbps ITU-CELP	3.9
8 kbps CELP	3.7
13 kbps GSM Codec	3.54
9.6 kbps QCELP	3.45
4.8 kbps CELP	3.0
2.4 kbps LPC	2.5

MULTIPLE ACCESS TECHNIQUES FOR WIRELESS COMMUNICATION

FDMA

TDMA

SDMA

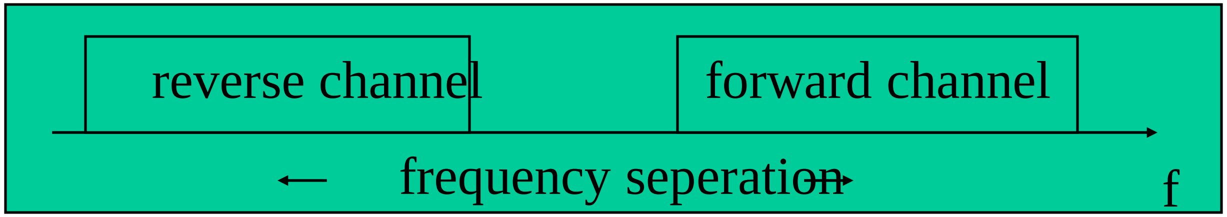
PDMA

Introduction

- many users at same time
- share a finite amount of radio spectrum
- high performance
- duplexing generally required
- frequency domain
- time domain

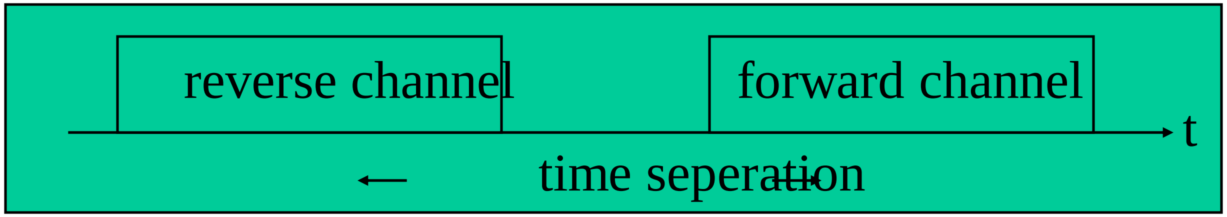
Frequency division duplexing (FDD)

- two bands of frequencies for every user
- forward band
- reverse band
- duplexer needed
- frequency seperation between forward band and reverse band is constant



Time division duplexing (TDD)

- uses time for forward and reverse link
- multiple users share a single radio channel
- forward time slot
- reverse time slot
- no duplexer is required



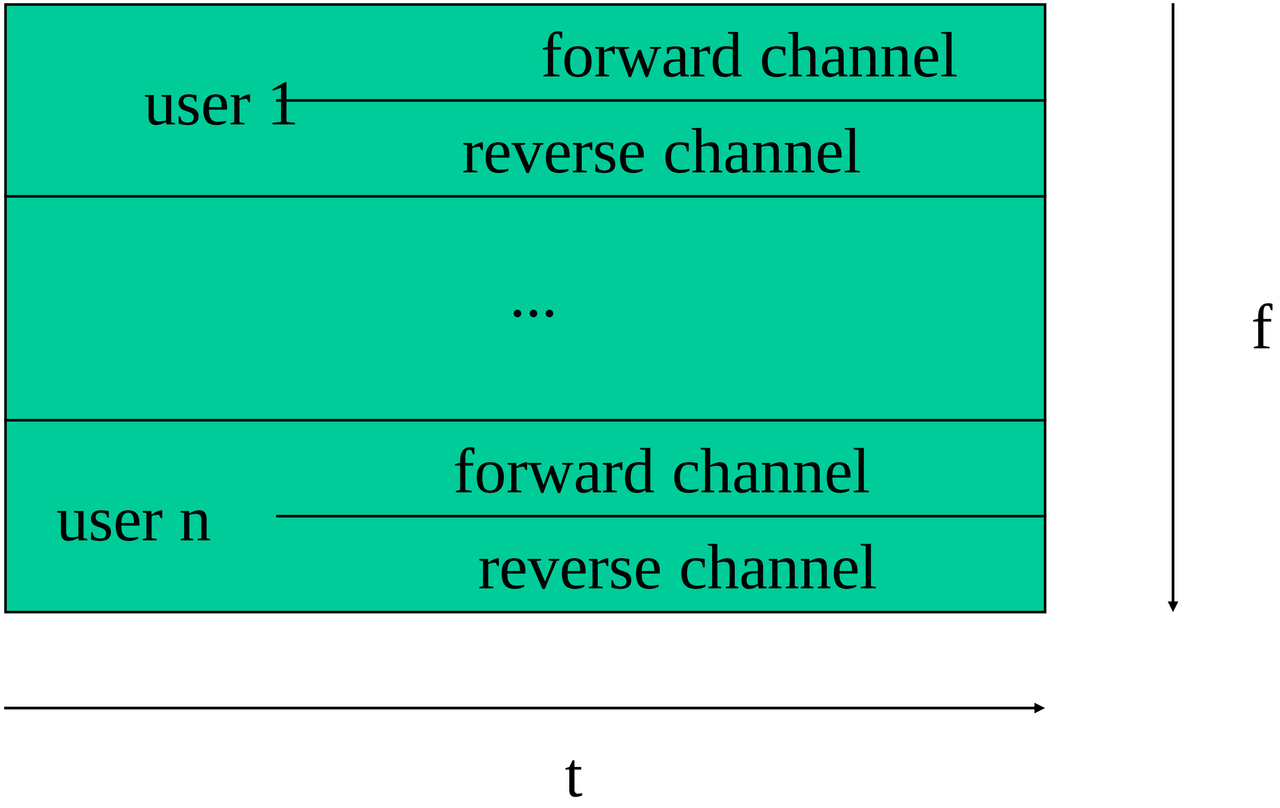
Multiple Access Techniques

- Frequency division multiple access (FDMA)
- Time division multiple access (TDMA)
- Code division multiple access (CDMA)
- Space division multiple access (SDMA)
- grouped as:
- narrowband systems
- wideband systems

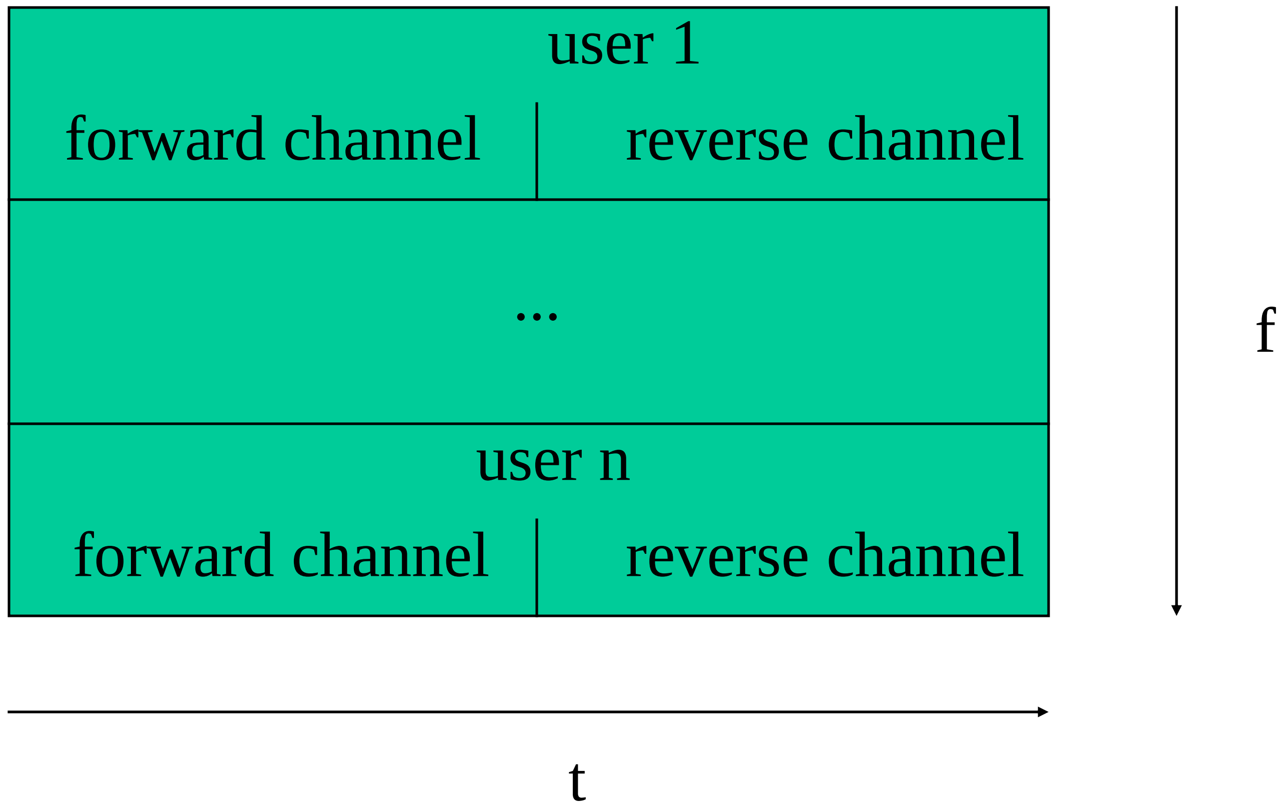
Narrowband systems

- large number of narrowband channels
- usually FDD
- Narrowband FDMA
- Narrowband TDMA
- FDMA/FDD
- FDMA/TDD
- TDMA/FDD
- TDMA/TDD

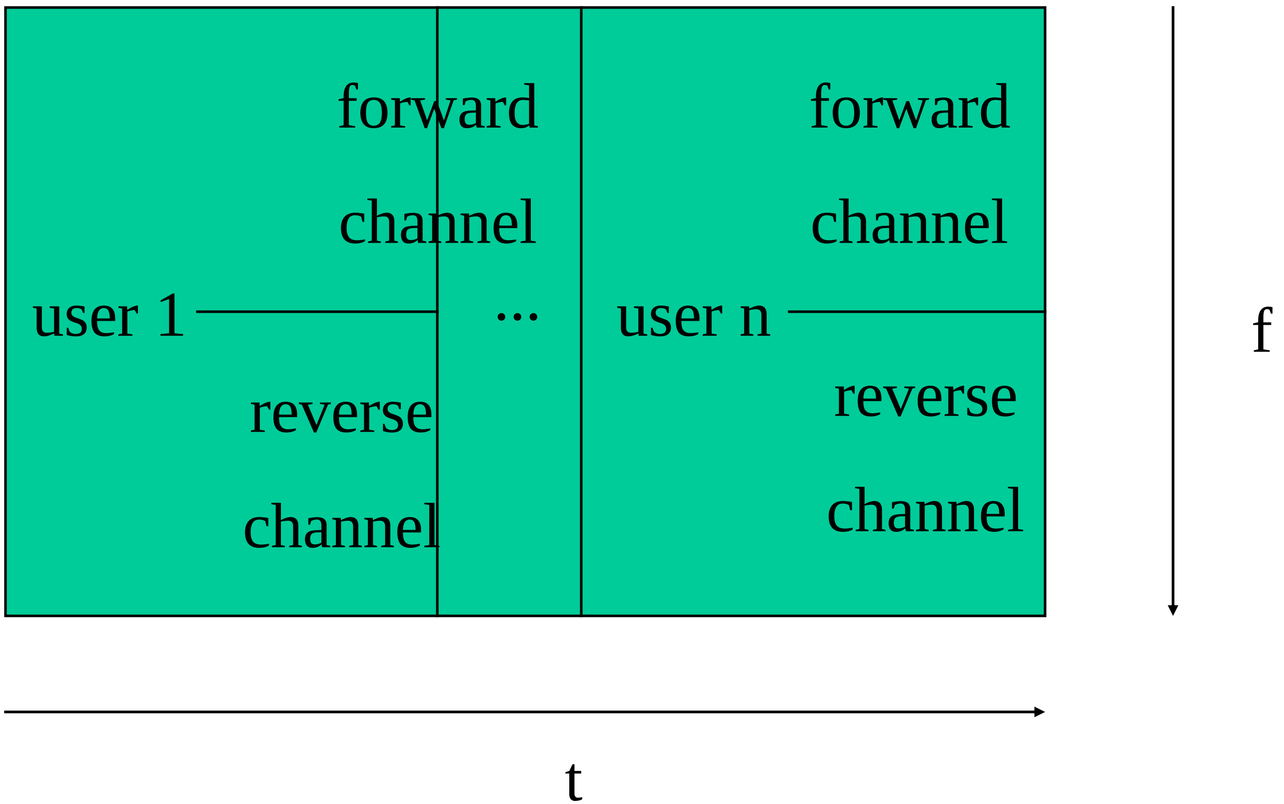
Logical separation FDMA/FDD



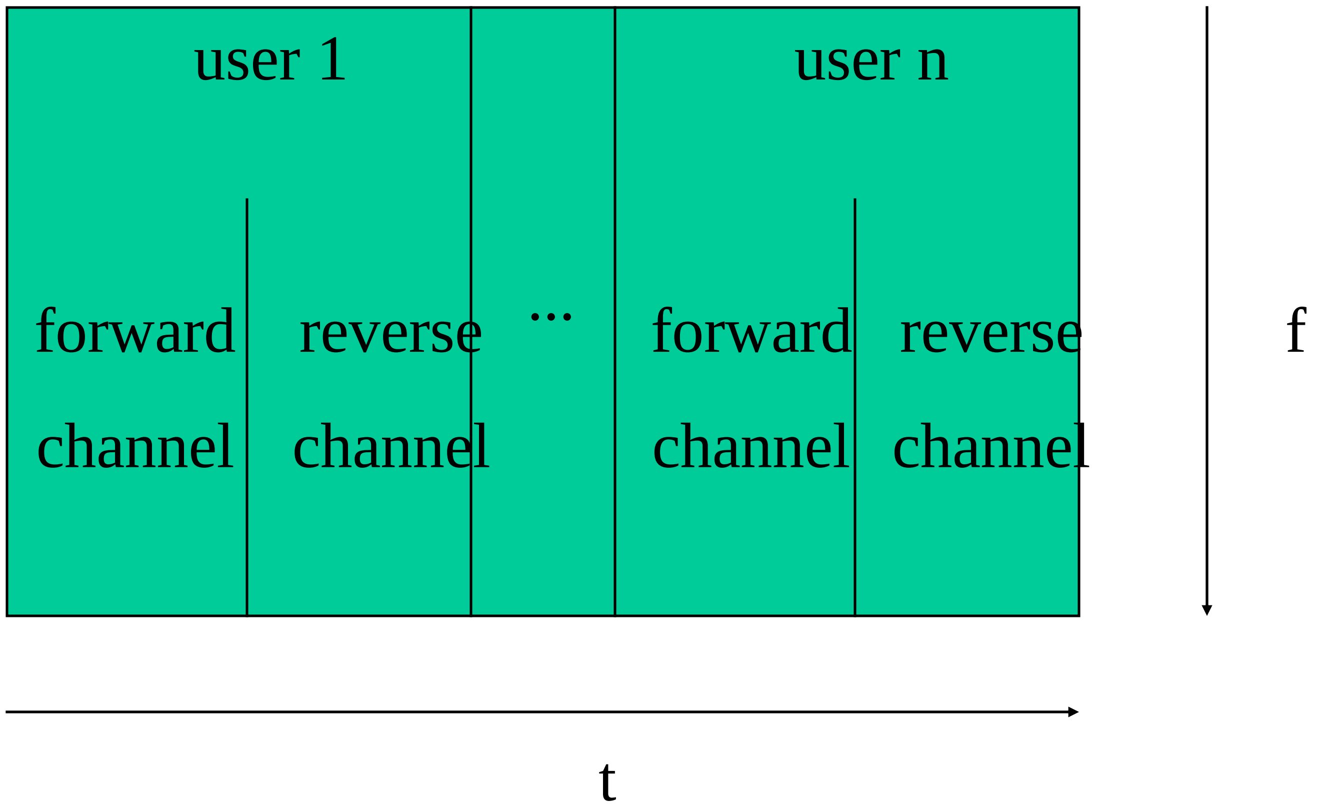
Logical separation FDMA/TDD



Logical separation TDMA/FDD



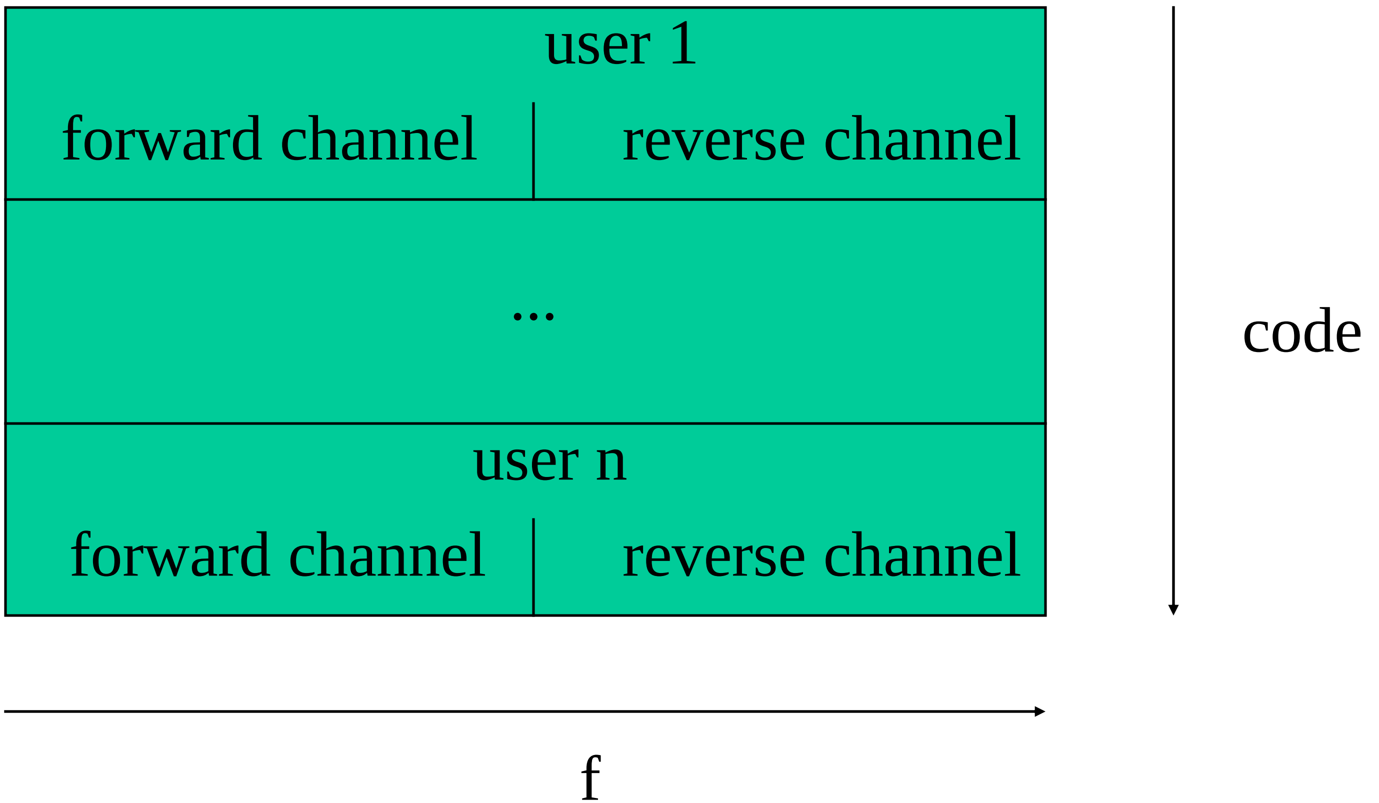
Logical separation TDMA/TDD



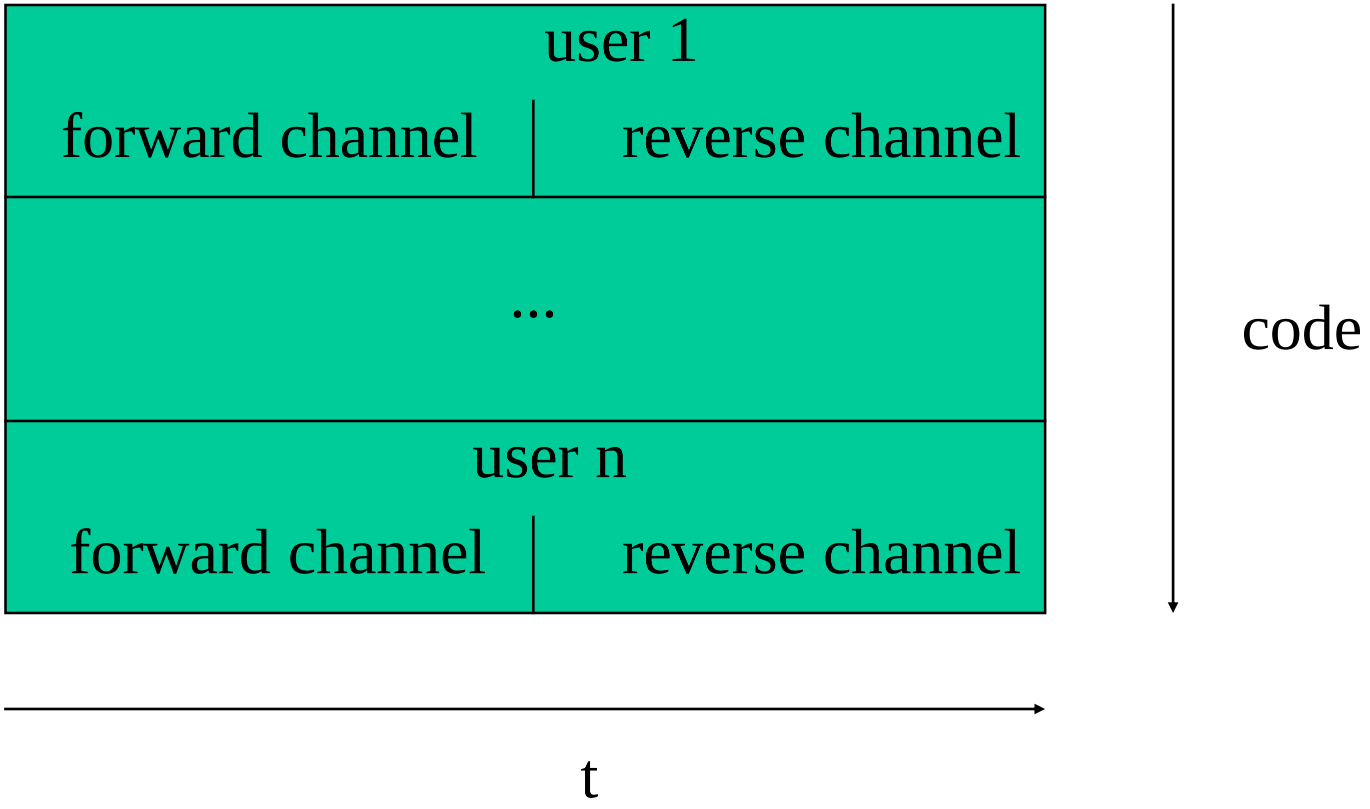
Wideband systems

- large number of transmitters on one channel
- TDMA techniques
- CDMA techniques
- FDD or TDD multiplexing techniques
- TDMA/FDD
- TDMA/TDD
- CDMA/FDD
- CDMA/TDD

Logical separation CDMA/FDD



Logical separation CDMA/TDD



Multiple Access Techniques in use

Cellular System	Multiple Access Technique
Advanced Mobile Phone System (AMPS)	FDMA/FDD
Global System for Mobile (GSM)	TDMA/FDD
US Digital Cellular (USDC)	TDMA/FDD
Digital European Cordless Telephone (DECT)	FDMA/TDD
US Narrowband Spread Spectrum (IS-95)	CDMA/FDD

Frequency division multiple access FDMA

- one phone circuit per channel
- idle time causes wasting of resources
- simultaneously and continuously transmitting
- usually implemented in narrowband systems
- for example: in AMPS is a FDMA bandwidth of 30 kHz implemented

FDMA compared to TDMA

- fewer bits for synchronization
- fewer bits for framing
- higher cell site system costs
- higher costs for duplexer used in base station and subscriber units
- FDMA requires RF filtering to minimize adjacent channel interference

Nonlinear Effects in FDMA

- many channels - same antenna
- for maximum power efficiency operate near saturation
- near saturation power amplifiers are nonlinear
- nonlinearities causes signal spreading
- intermodulation frequencies

Nonlinear Effects in FDMA

- IM are undesired harmonics
- interference with other channels in the FDMA system
- decreases user C/I - decreases performance
- interference outside the mobile radio band: adjacent-channel interference
- RF filters needed - higher costs

Number of channels in a FDMA system

$$N = \frac{B_t - B_{guard}}{B_c}$$

- N … number of channels
- Bt … total spectrum allocation
- Bguard … guard band
- Bc … channel bandwidth

Example: Advanced Mobile Phone System

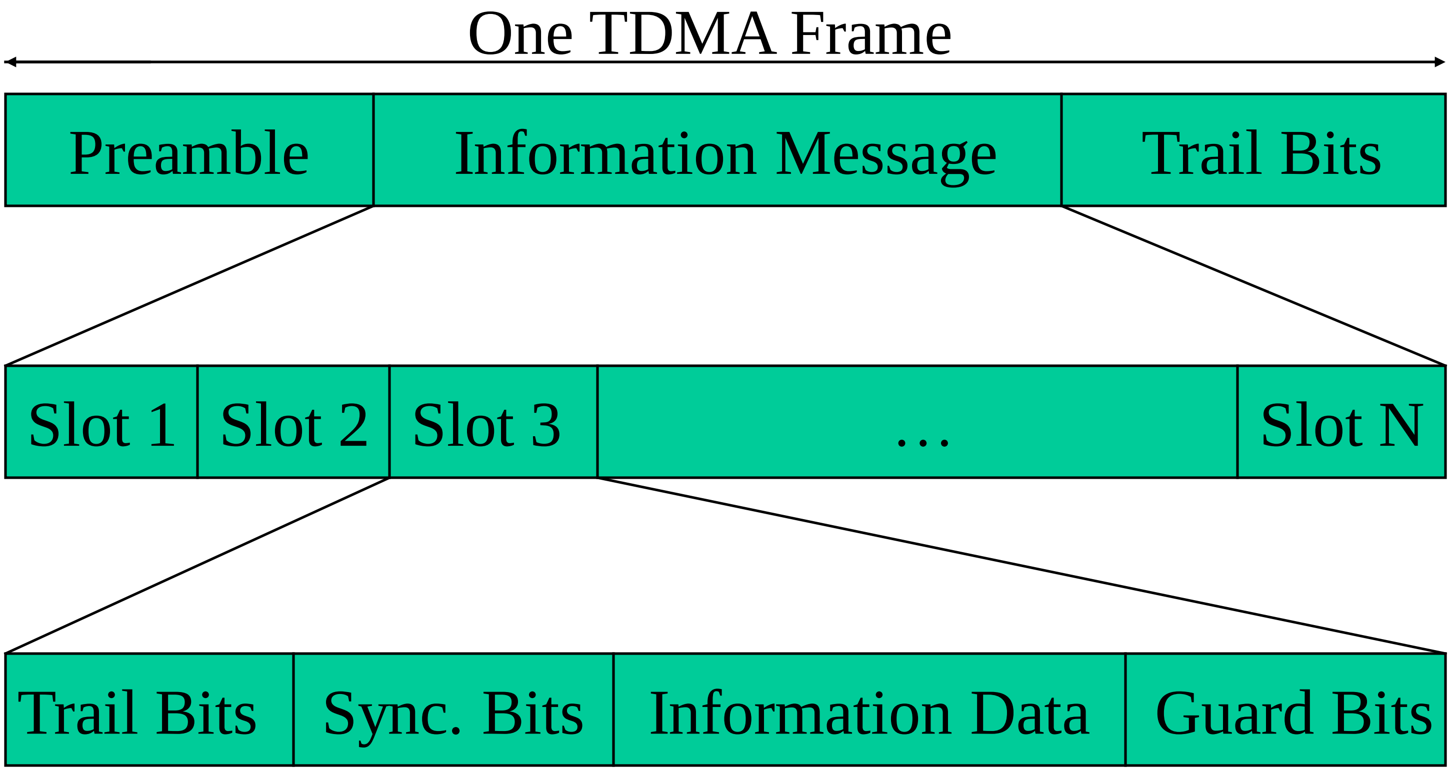
- AMPS
- FDMA/FDD
- analog cellular system
- 12.5 MHz per simplex band - Bt
- Bguard = 10 kHz ; Bc = 30 kHz

$$N = \frac{12.5\text{E}6 - 2*(10\text{E}3)}{30\text{E}3} = 416 \text{ channels}$$

Time Division Multiple Access

- time slots
- one user per slot
- buffer and burst method
- noncontinuous transmission
- digital data
- digital modulation

Repeating Frame Structure



The frame is cyclically repeated over time.

Features of TDMA

- a single carrier frequency for several users
- transmission in bursts
- low battery consumption
- handoff process much simpler
- FDD : switch instead of duplexer
- very high transmission rate
- high synchronization overhead
- guard slots necessary

Number of channels in a TDMA system

$$N = \frac{m*(B_{tot} - 2*B_{guard})}{B_c}$$

- N … number of channels
- m … number of TDMA users per radio channel
- Btot … total spectrum allocation
- Bguard … Guard Band
- Bc … channel bandwidth

Example: Global System for Mobile (GSM)

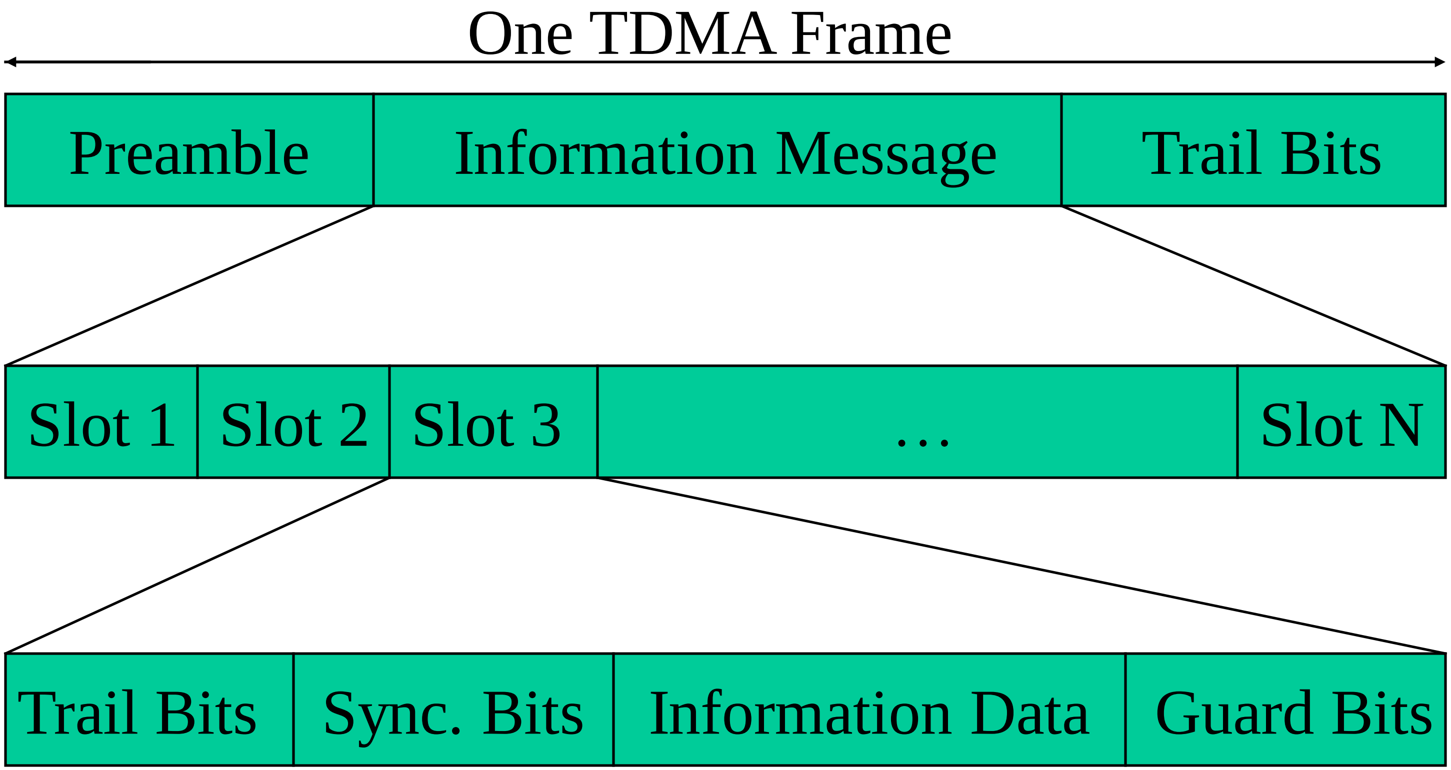
- TDMA/FDD
- forward link at Btot = 25 MHz
- radio channels of Bc = 200 kHz
- if m = 8 speech channels supported, and
- if no guard band is assumed :

$$N = \frac{8*25E6}{200E3} = 1000 \text{ simultaneous users}$$

Efficiency of TDMA

- percentage of transmitted data that contain information
- frame efficiency ηf
- usually end user efficiency < ηf ,
- because of source and channel coding
- How get ηf ?

Repeating Frame Structure



The frame is cyclically repeated over time.

Efficiency of TDMA

$$b_{OH} = N_r * b_r + N_t * b_p + N_t * b_g + N_r * b_g$$

- bOH … number of overhead bits
- Nr … number of reference bursts per frame
- br … reference bits per reference burst
- Nt … number of traffic bursts per frame
- bp … overhead bits per preamble in each slot
- bg … equivalent bits in each guard time intervall

Efficiency of TDMA

$$b_T = T_f * R$$

- b_T … total number of bits per frame
- T_f … frame duration
- R … channel bit rate

Efficiency of TDMA

$$\eta_f = (1 - b_{OH}/b_T) * 100\%$$

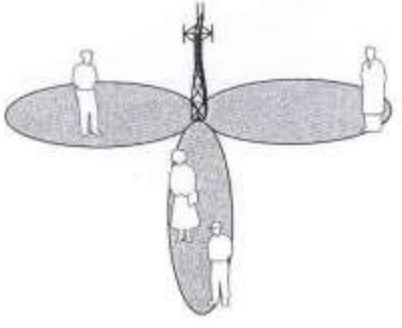
- η_f … frame efficiency
- b_{OH} … number of overhead bits per frame
- b_T … total number of bits per frame

Space Division Multiple Access

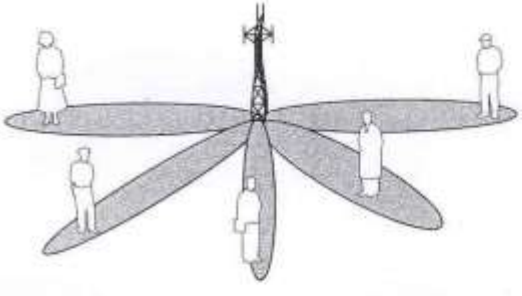
- Controls radiated energy for each user in space
- using spot beam antennas
- base station tracks user when moving
- cover areas with same frequency:
- TDMA or CDMA systems
- cover areas with same frequency:
- FDMA systems

Space Division Multiple Access

- primitive applications are “Sectorized antennas”



- in future adaptive antennas simultaneously steer energy in the direction of many users at once



Reverse link problems

- general problem
- different propagation path from user to base
- dynamic control of transmitting power from each user to the base station required
- limits by battery consumption of subscriber units
- possible solution is a filter for each user

Solution by SDMA systems

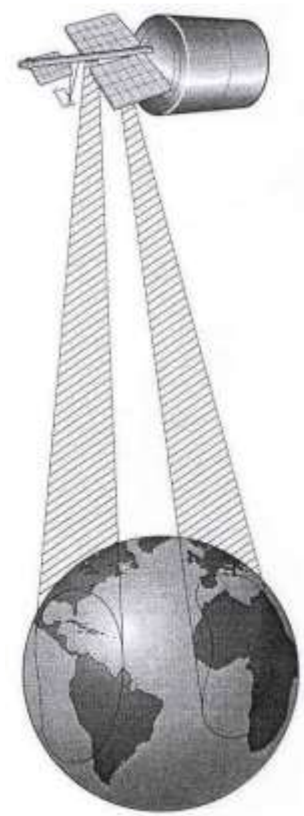
- adaptive antennas promise to mitigate reverse link problems
- limiting case of infinitesimal beamwidth
- limiting case of infinitely fast track ability
- thereby unique channel that is free from interference
- all user communicate at same time using the same channel

Disadvantage of SDMA

- perfect adaptive antenna system: infinitely large antenna needed
- compromise needed

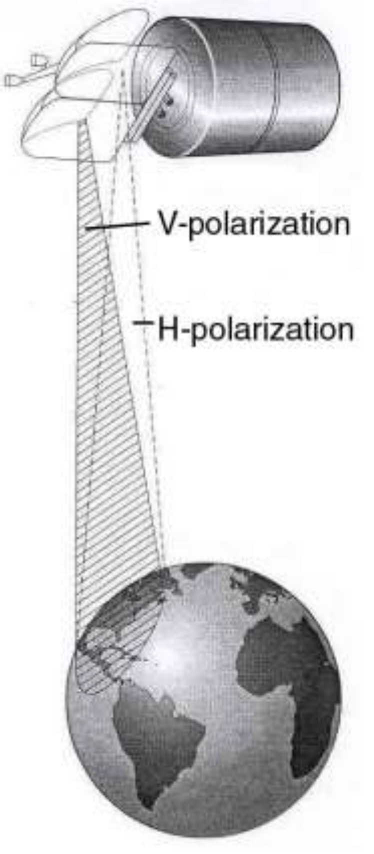
SDMA and PDMA in satellites

- INTELSAT IVA
- SDMA dual-beam receive antenna
- simultaneously access from two different regions of the earth



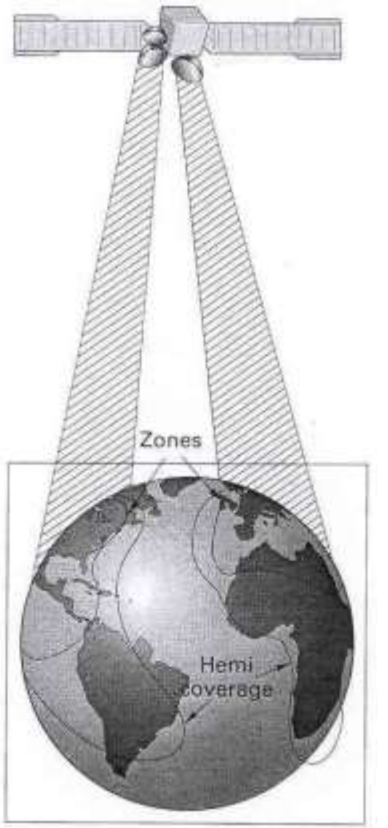
SDMA and PDMA in satellites

- COMSTAR 1
- PDMA
- separate antennas
- simultaneously access from same region



SDMA and PDMA in satellites

- INTELSAT V
- PDMA and SDMA
- two hemispheric coverages by SDMA
- two smaller beam zones by PDMA
- orthogonal polarization



Capacity of Cellular Systems

- channel capacity: maximum number of users in a fixed frequency band
- radio capacity : value for spectrum efficiency
- reverse channel interference
- forward channel interference
- How determine the radio capacity?

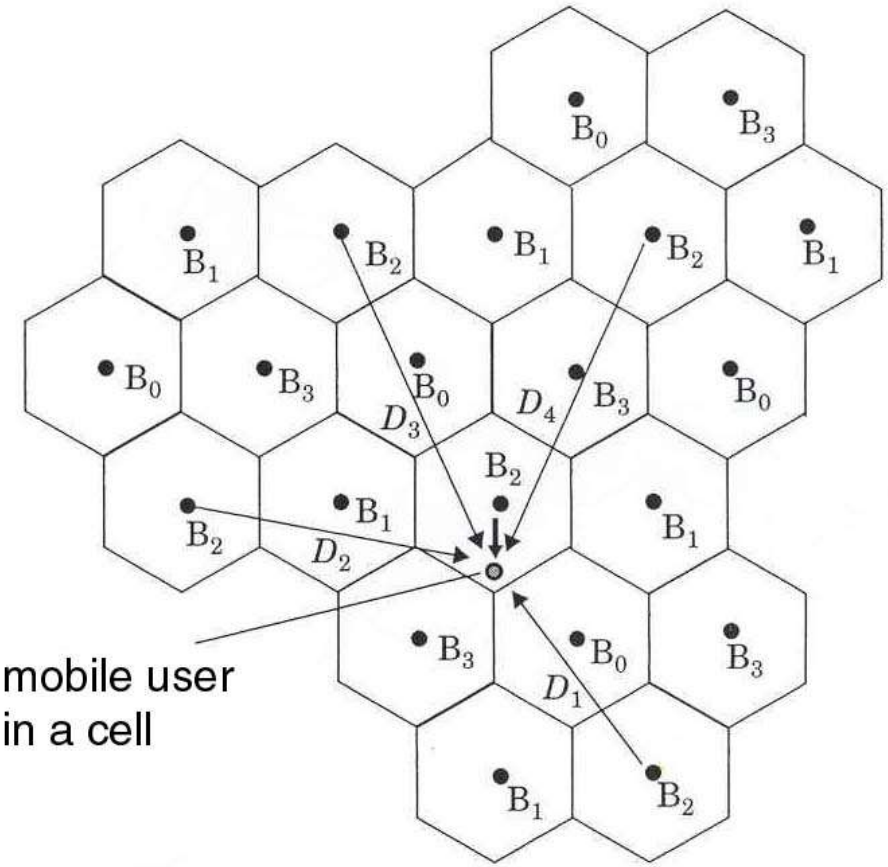
Co-Channel Reuse Ratio Q

$$Q = D/R$$

- Q … co-channel reuse ratio
- D … distance between two co-channel cells
- R … cell radius

Forward channel interference

- cluster size of 4
- D0 … distance serving station to user
- DK … distance co-channel base station to user



Carrier-to-interference ratio C/I

- M closest co-channels cells cause first order interference

$$\frac{C}{I} = \frac{D_0^{-n_0}}{\sum_{k=1}^{M} D_K^{-n_k}}$$

- n_0 … path loss exponent in the desired cell
- n_k … path loss exponent to the interfering base station

Carrier-to-interference ratio C/I

- Assumption:
- just the 6 closest stations interfere
- all these stations have the same distance D
- all have similar path loss exponents to n0

$$\frac{C}{I} = \frac{D_0^{-n}}{6 * D^{-n}}$$

Worst Case Performance

- maximum interference at D0 = R
- (C/I)min for acceptable signal quality
- following equation must hold:

$$1/6 * (R/D)^{-n} \geqq (C/I)_{min}$$

Co-Channel reuse ratio Q

$$Q = D/R = (6*(C/I)_{min})^{1/n}$$

- D … distance of the 6 closest interfering base stations
- R … cell radius
- (C/I)min … minimum carrier-to-interference ratio
- n … path loss exponent

Radio Capacity m

$$m = \frac{B_t}{B_c * N} \quad \text{radio channels/cell}$$

- B_t … total allocated spectrum for the system
- B_c … channel bandwidth
- N … number of cells in a complete frequency reuse cluster

Radio Capacity m

- N is related to the co-channel factor Q by:

$$Q = (3*N)^{1/2}$$

$$m = \frac{B_t}{B_c * (Q^2/3)} = \frac{B_t}{B_c * \left(\frac{6}{3^{n/2}} * \left(\frac{C}{I}\right)_{min}\right)^{2/n}}$$

Radio Capacity m for n = 4

$$m = \frac{B_t}{B_c * \sqrt{2/3 * (C/I)_{min}}}$$

- m … number of radio channels per cell
- $(C/I)_{min}$ lower in digital systems compared to analog systems
- lower $(C/I)_{min}$ imply more capacity
- exact values in real world conditions measured

Compare different Systems

- each digital wireless standard has different (C/I)min
- to compare them an equivalent (C/I) needed
- keep total spectrum allocation Bt and number of rario channels per cell m constant to get (C/I)eq :

Compare different Systems

$$\left(\frac{C}{I}\right)_{eq} = \left(\frac{C}{I}\right)_{min} * \left(\frac{Bc}{Bc'}\right)^2$$

- Bc … bandwidth of a particular system
- (C/I)min … tolerable value for the same system
- Bc' … channel bandwidth for a different system
- (C/I)eq … minimum C/I value for the different system

C/I in digital cellular systems

$$\frac{C}{I} = \frac{E_b * R_b}{I} = \frac{E_c * R_c}{I}$$

- R_b … channel bit rate
- E_b … energy per bit
- R_c … rate of the channel code
- E_c … energy per code symbol

C/I in digital cellular systems

- combine last two equations:

$$\frac{(C/I)}{(C/I)_{eq}} = \frac{(E_c * R_c)/I}{(E_c' * R_c')/I'} = \left(\frac{B_c'}{B_c}\right)^2$$

- The sign ' marks compared system parameters

C/I in digital cellular systems

- Relationship between Rc and Bc is always linear (Rc/Rc' = Bc/Bc')
- assume that level I is the same for two different systems (I' = I) :

$$\frac{Ec}{Ec'} = \left(\frac{Bc'}{Bc}\right)^3$$

Compare C/I between FDMA and TDMA

- Assume that multichannel FDMA system occupies same spectrum as a TDMA system
- FDMA : C = Eb * Rb ; I = I0 * Bc
- TDMA : C’ = Eb * Rb’ ; I’ = I0 * Bc’
- Eb … Energy per bit
- I0 … interference power per Hertz
- Rb … channel bit rate
- Bc … channel bandwidth

Example

- A FDMA system has 3 channels , each with a bandwidth of 10kHz and a transmission rate of 10 kbps.
- A TDMA system has 3 time slots, a channel bandwidth of 30kHz and a transmission rate of 30 kbps.
- What's the received carrier-to-interference ratio for a user ?

Example

- In TDMA system C'/I' be measured in 333.3 ms per second - one time slot

$$\frac{C'}{I'} = \frac{E_b \cdot R_b'}{I_0 \cdot B_c'} = \frac{1/3 \cdot (E_b \cdot 10E4 \text{ bits})}{I_0 \cdot 30\text{kHz}} = \frac{3 \cdot R_b \cdot E_b}{3 \cdot I} = \frac{3 \cdot C}{3 \cdot I}$$

C' = Eb*Rb' = 1/3*(Eb*10E4 bits) = 3*Rb*Eb=3*C
I' = I0*Bc' = I0*30kHz = 3*I

- In this example FDMA and TDMA have the same radio capacity (C/I leads to m)

Example

- Peak power of TDMA is 10logk higher then in FDMA (k … time slots)
- in practice TDMA have a 3-6 times better capacity

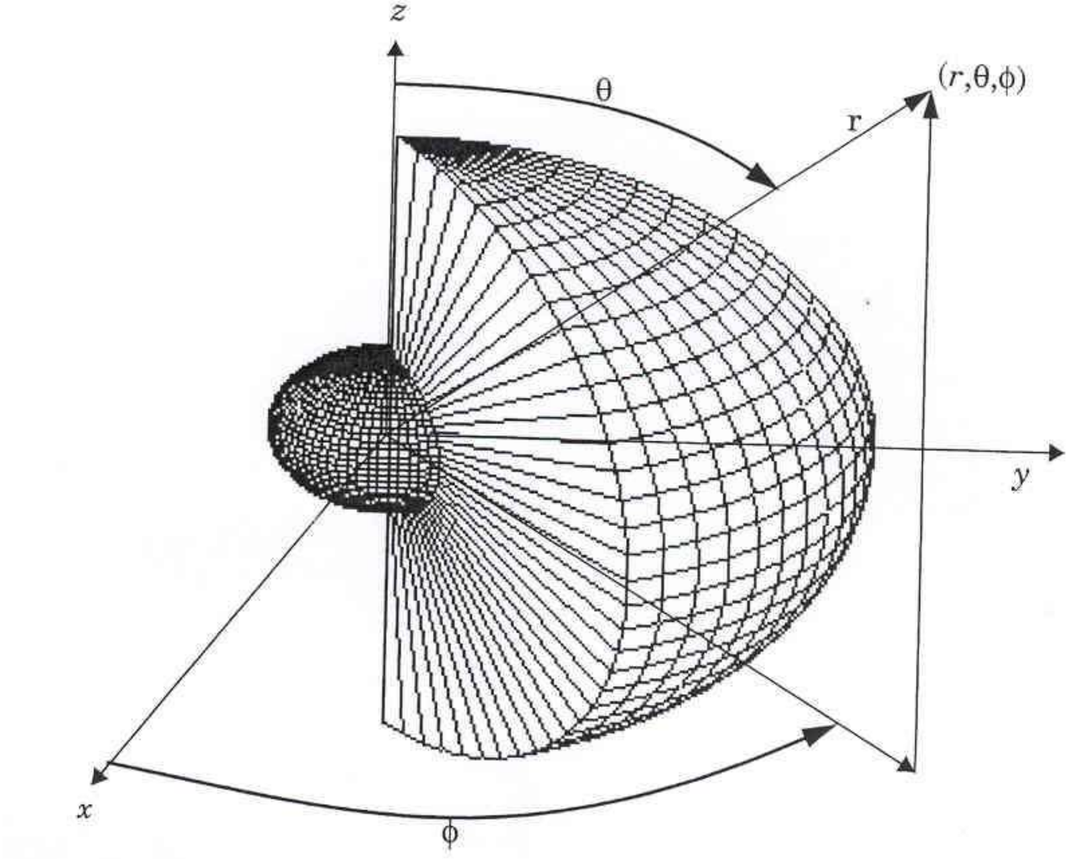
Capacity of SDMA systems

- one beam each user
- base station tracks each user as it moves
- adaptive antennas most powerful form
- beam pattern G(♐) has maximum gain in the direction of desired user
- beam is formed by N-element adaptive array antenna

Capacity of SDMA systems

- G(♐) steered in the horizontal ♐ -plane through 360°
- G(♐) has no variation in the elevation plane to account which are near to and far from the base station
- following picture shows a 60 degree beamwidth with a 6 dB sideslope level

Capacity of SDMA systems



Capacity of SDMA systems

- reverse link received signal power, from desired mobiles, is Pr;0
- interfering users i = 1,…,k-1 have received power Pr;I
- average total interference power I seen by a single desired user:

Capacity of SDMA

$$I = E\,\{\ \overset{K-1}{\underset{i=1}{\text{🌢}}}\ G(\text{☞}_i)\ P_{r;I}\}$$

- ☞i … direction of the i-th user in the horizontal plane
- E … expectation operator

Capacity of SDMA systems

- in case of perfect power control (received power from each user is the same) :

$$P_{r;I} = P_c$$

- Average interference power seen by user 0:

$$I = P_c \, E\left\{ \sum_{i=1}^{K-1} G(\phi_i) \right\}$$

Capacity of SDMA systems

- users independently and identically distributed throughout the cell:

$$I = P_c *(k -1) * 1/D$$

- D … directivity of the antenna - given by max(G(☞))
- D typ. 3dB …10dB

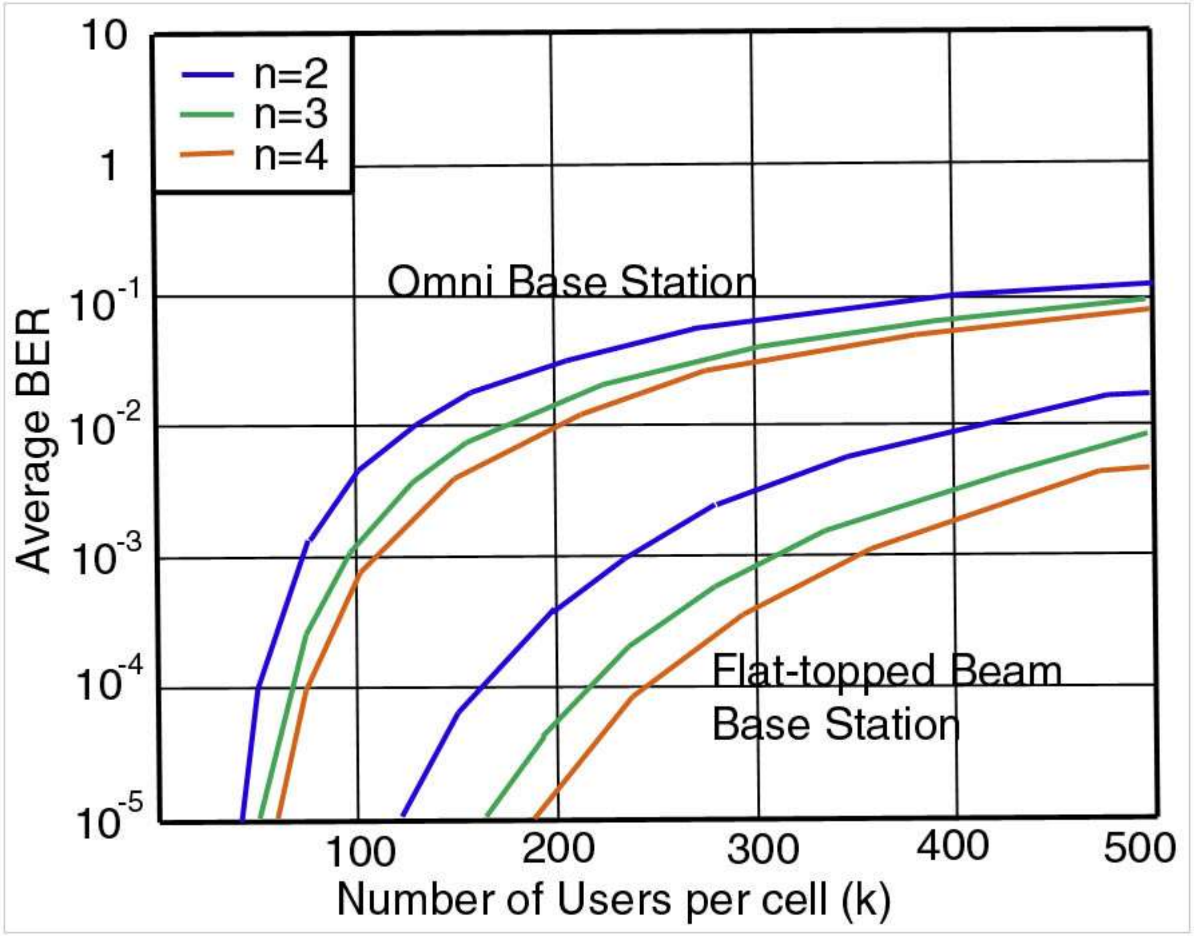
Capacity of SDMA systems

- Average bit error rate Pb for user 0:

$$P_b = Q\left(\sqrt{\frac{3\,D\,N}{K-1}}\right)$$

- D … directivity of the antenna
- Q(x) … standard Q-function
- N … spreading factor
- K … number of users in a cell

Capacity of SDMA systems



UNIT – 5
WIRELESS SYSTEMS ANTENNAS AND STANDARDS

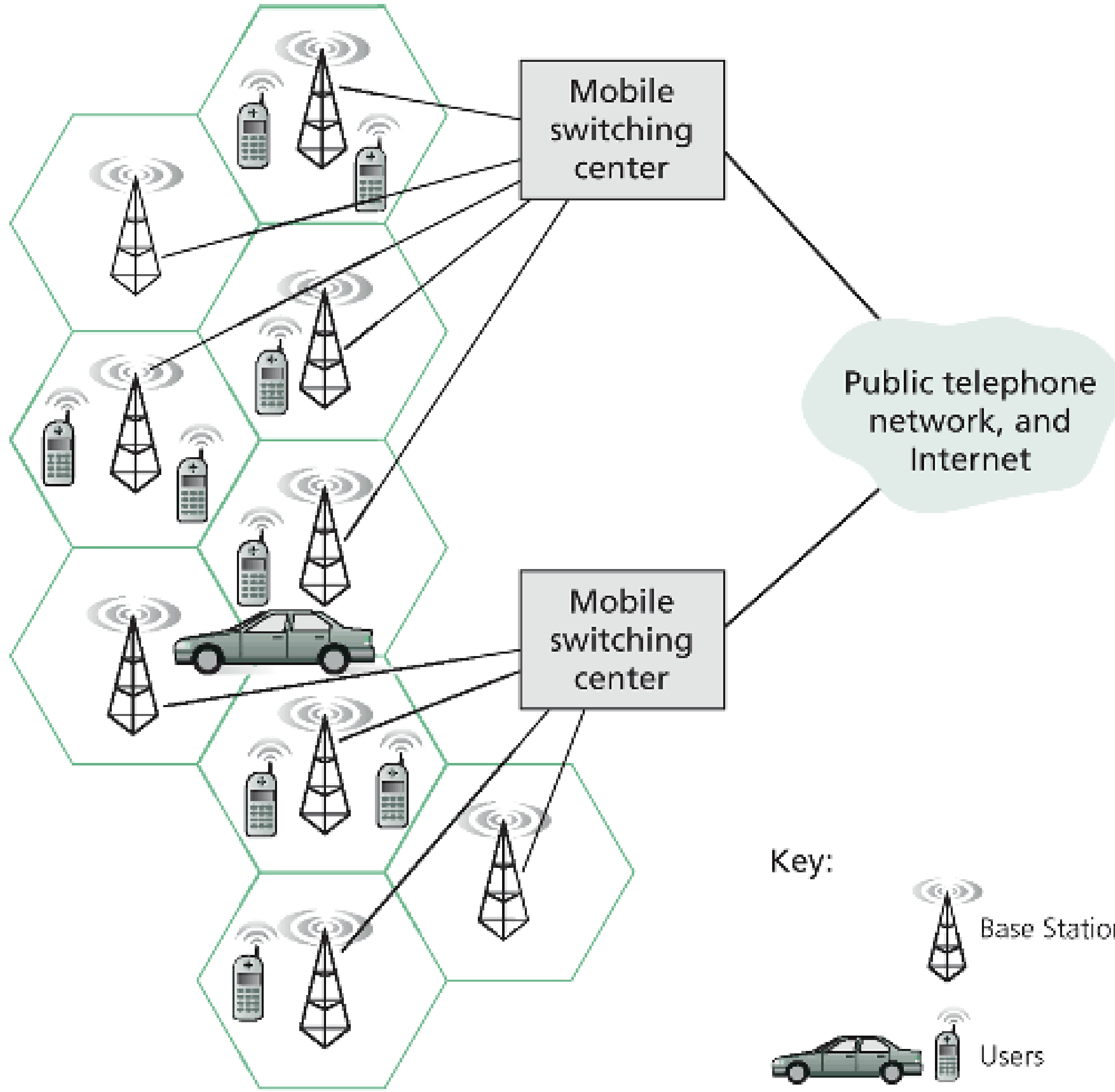
Cellular Wireless Network

- Cellular network was primarily developed to provide mobile telephone.
  - Designed to transfer voice.
  - Use circuit switching technology.
- Over the time, the cellular network has evolved in the following ways:
  - Use of digital data (voice data is digitized).
  - Provide data transfer capability (this allows us to access the Internet).

Cellular Wireless Network Architecture

- A cellular network is divided into a number of cells which are viewed as hexagons.
  - This is the reason why a mobile phone is also called a cell phone.
- Each cell is allocated a band of frequencies and served by a base station.
  - Adjacent cells are assigned different frequencies to avoid interference.
  - However, cells sufficiently distant from each other can use the same frequency band.

Cellular Wireless



Cellular Wireless Network Architecture

- A base station consists of:
  - An antenna.
  - A controller.
  - A number of transceivers for communicating on the channel assigned to the cell.
- Each base station is connected to a mobile switching center (MSC).
  - This link can either be wired or wireless (normally wired).
- One MSC may be serving multiple base stations.
- The MSC is then connected to the public telephone network.

Cellular Wireless Network Architecture

- An MSC performs the following tasks:
  - Assign voice channel to each call.
  - Perform handoffs.
  - Monitors the call for billing information.
- There are two types of channels available between a mobile unit and the base station.
  - Control channels: used to setup and maintain calls and also establish relationship between the base station and the mobile unit.
  - Traffic channels: used to carry voice or data connection.

Cellular Standards and Technologies

- Cellular technologies are classified into several “generations”: 1G, 2G, 3G, etc.
- These generations may differ in terms of:
  - Data rate
  - Capacity
  - Signal quality
  - Applications and services that can be offered
- 1G systems are pretty much extinct.
- Most cellular networks today use 2G technologies and above.

First Generation (1G)

- Designed to carry only analog voice.
  - The data is analog (voice), similar to the public telephone network.
- Uses FDMA (Frequency Division Multiple Access) technology for allocating channels to users. Each user is given one channel.
- The most popular 1G technology is AMPS (Advanced Mobile Phone Service)
  - Used in the early 1980s.
- Other 1G technologies: NMT, C-Nets, TACS.

Second Generation (2G)

- The second generation systems are developed to provide:
  - Higher quality signals.
  - Higher data rates to support digital services.
  - Higher capacity.
- The main difference between 1G and 2G is that 2G systems send digital data.
  - Voice is digitized before it is sent.
  - But transmission is done using analog signal (all wireless signal is analog).
  - Allows for services such as SMS.

2G Technologies

- IS-136 TDMA (Time Division Multiple Access)
  - A combined FDM/TDM system that evolved from 1G FDMA technology.
  - Widely deployed in North America.
- GSM (Global System for Mobile Communications).
  - Uses combined FDM/TDM.
  - Started off in Europe in the early 1990s.
  - Also used in Asia and North America.
- IS-95A CDMA (Code Division Multiple Access).
  - Also knows as CDMAOne.
  - As the name suggests, it uses the CDMA technology.
  - Widely deployed in North America and Korea.

2G Technologies

- Since 2G technologies convert voice to digital data before transmission, they can also be used to carry data (i.e. application data).
  - They can act as a modem.
- Although it works, this is not an effective method for data transmission.
  - Circuit switching is used – highly inefficient for bursty traffic.
  - Data rate is very slow.
    - GSM – 9.6 kbps
    - CDMA – 14.4 kbps

Transition from Second to Third Generation (2.5G)

- The 2G systems are optimized for voice service and not well adapted for data communication.
- In the 1990s, standard organizations have started developing 3G cellular technology targeted to carry both voice and data.
- Since 3G deployment may take many years, companies developed interim standards that enable data transmission over existing 2G infrastructures.

2.5G Technologies

- GPRS (General Packet Radio Services)
  - Evolved from GSM and uses the underlying GSM network.
  - A number of slots are set aside for data communications.
  - Mobile device can use more than one time slot within a given channel in an on-demand basis.
  - Slots are dynamically allocated to mobile device when there is data to send.
  - Maximum data rate: 115 kbps.
  - Typical data rate: 40 to 60 kbps.

2.5G Technologies

- EDGE (Enhanced Data Rates for Global Evolution)
  - Increase the capacity of GSM/GPRS network.
  - Achieve higher data rates by replacing GSM’s modulation scheme with a more powerful scheme.
  - Maximum data rate: 385 kbps.
  - Typical data rate: 144 kbps
  - Some books / web sites categorize EDGE as 3G, and some categorize it as 2.75G.

2.5G Technologies

- CDMAOne (IS-95B)
  - This is basically an enhanced version of CDMAOne (IS-95A) to support 2.5G capabilities.
  - Requires very minor upgrades in CDMAOne (IS-95A) networks.
  - Maximum data rate: 115 kbps.
  - Average data rate: < 64 kbps.

Third Generation (3G)

- 3G wireless communication technologies are designed to provide fairly high-speed wireless communication to support multimedia, data and video in addition to voice.
- Referred to as IMT-2000 by ITU-R.
- Among the required 3G capabilities include:
  - Voice quality comparable to public-switched telephone network.
  - 144 kbps at driving speeds.
  - 384 kbps for outside stationary or walking speeds.
  - 2 Mbps for office use (indoor).

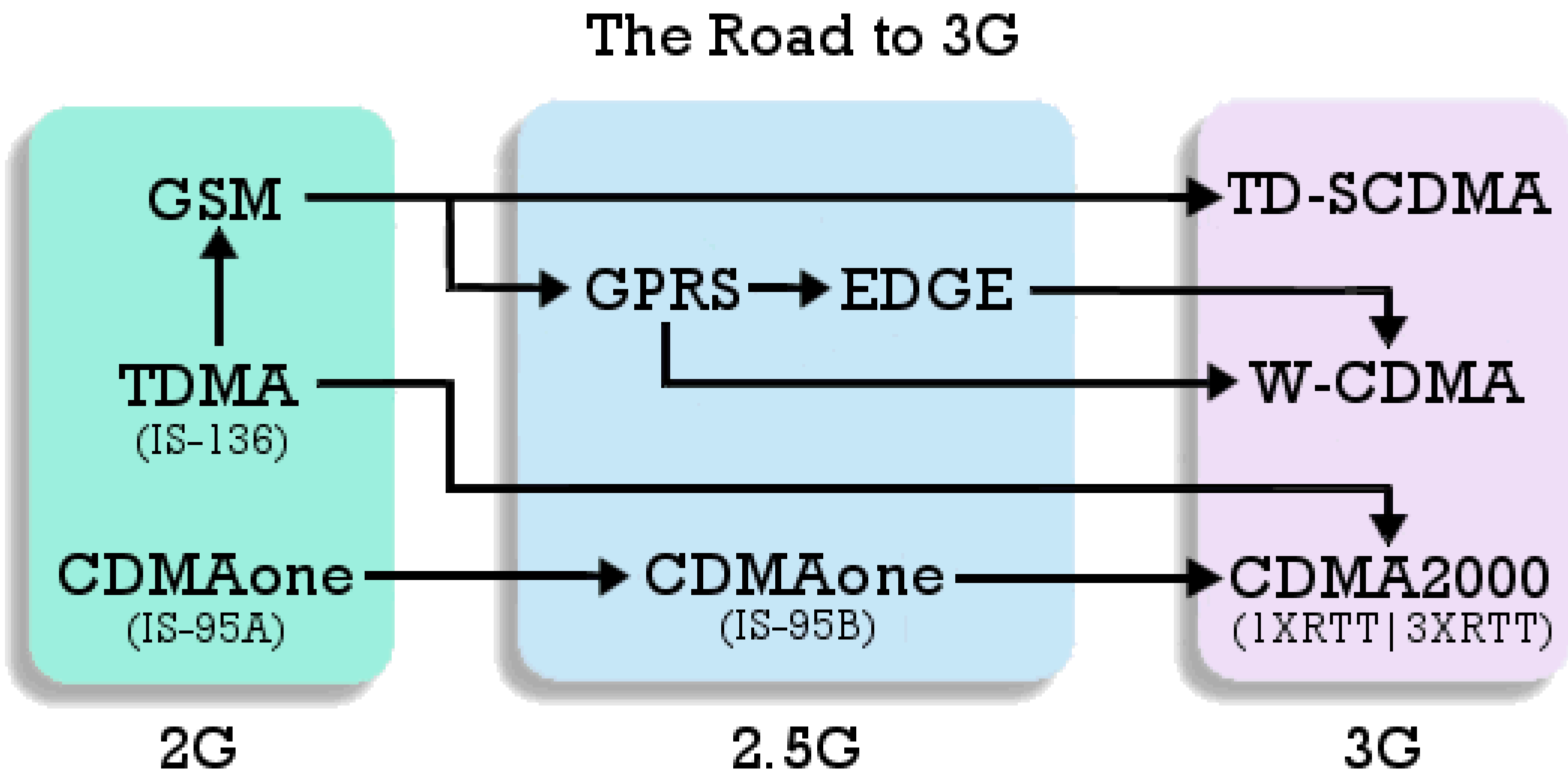
3G Technologies

- UMTS (Universal Mobile Telecommunications Service)
  - Also known as W-CDMA (Wideband CDMA), although W-CDMA is actually the name of the air interface technique used.
  - Used by GSM networks to upgrade to 3G.
  - Maximum data rate: 2 Mbps
  - Typical data rate: 144 to 384 kbps.

3G Technologies

- CDMA2000
  - Used by CDMAOne networks to upgrade to 3G.
  - There are several variants of CDMA2000:
    - 1xRTT (Radio Transmission Technology) and 3xRTT.
    - 1xEV-DO (Evolution – Data Only)
    - 1xEV-DV (Evolution – Data Voice).
- TD-CDMA (Time Division CDMA)
  - Intended to be used by TDMA networks to upgrade to 3G.
  - Use unpaired spectrum.
    - A single channel is used for both uplink and downlink, but each uses different slots.
    - Very suitable for Internet data.
  - Maximum data rate: 3.3 Mbps

3G Technologies



What Can You Do With a 3G-enabled Devices?

- A 3G-enabled devices can act like a PC connected to the Internet. You can:
  - Browse the Web using a Web browser.
  - Read and reply emails.
  - Chat using instant messaging application.
  - Perform file transfer (FTP).
  - Play online games.
  - Watch live TV (or other streaming videos).
  - Make a video call.

3.5G and Pre-4G

- Refers to intermediate technologies between 3G and 4G.
- Provides higher data rates compared to 3G technologies.
  - Done by improving the modulation scheme and refining the protocols between mobile phones and base stations.
  - Some of the standards may also provide all-IP network and QoS support.
- Standards categorized under this category:
  - 3.5G: HSPA (High Speed Packet Access)
  - Pre-4G: LTE (3GPP Long Term Evolution) and WiMAX 802.16e.

3.5G Technology: HSPA

- An upgrade to UMTS.
- Sometimes marketed as 3GX, 3G+, Turbo 3G.
- HSDPA (High-speed Downlink Packet Access)
  - Designed to have faster downlink compared to uplink.
  - Maximum downlink data rate: 14.4 Mbps.
  - Maximum uplink data rate: 384 Kbps.
- HSUPA (High-speed Uplink Packet Access)
  - Designed to have faster uplink compared to downlink.
  - Maximum uplink data rate: 5.76 Mbps
- HSPA+ (Evolved HSPA)
  - Current implementation of HSPA+ can go up to 42 Mbps.

Pre-4G Technology: LTE

- Provides an all-IP network.
- Peak data rate of 300 Mbps (downlink) and 75 Mbps (uplink).
- Provides QoS provisioning that allows for RTT less than 10 milliseconds.
- Provides seamless handover between older technologies such as GSM and UMTS.
  - For many LTE implementations, GSM or UMTS is still used for voice transmission.

Fourth Generation (4G) – Beyond 3G

- Referred to as IMT-Advanced by ITU-R.
- According to ITU-R, among others, a 4G network must include the following features:
  - A data rate of 100 Mbps when client is moving at high speed in relative to the base station.
  - A data rate of 1 Gbps when device and base station are in relatively static position.
  - Smooth handoff across heterogeneous network.
  - Seamless roaming / connectivity across multiple networks.
  - High QoS support for next generation multimedia (e.g. real time audio, HDTV video content, mobile TV, etc).
  - An all IP, packet-switched network.

Fourth Generation (4G) – Beyond 3G

- Standards that fully comply with the ITU-R specified 4G definition are yet to be released.
- However, the following pre-4G standards are commonly advertised as 4G:
  - LTE (3GPP Long Term Evolution)
  - IEEE 802.16e (Mobile WiMAX)
- The following standards are currently being developed to fully with comply with the 4G definition:
  - LTE Advanced (Long Term Evolution Advanced)
  - IEEE 802.16m

Ad-hoc Networks

- In addition to infrastructure-based network technologies, ad-hoc network technology is gaining more interest these days.
- There are many situations where the use of infrastructure-based network is not possible.
  - Communication in remote areas where network infrastructure is not available.
  - After natural disaster.
  - During war.
  - When network infrastructure is controlled by an opposing group.
- Ad-hoc networks will make communication possible in these situations.

Ad-hoc Networks

- In an ad-hoc network, each host will also take the role of a routing node.
  - Hosts need to have routing capability.
  - Data is transmitted by being forwarded from one host to another.
- Hosts may join or leave the network at any time. Hosts may also move around.
  - This makes routing much more difficult.
  - This can also cause a number of security issues.
- Examples of routing protocols designed for ad-hoc networks:
  - Ad-hoc On-demand Distance Vector (AODV)
  - Optimized Link-state Routing Protocol (OLSR)

Ad-hoc Networks

- There are several different types of ad-hoc networks. Examples:
  - Mobile ad-hoc network (MANET)
  - Vehicular ad-hoc network (VANET)
  - Wireless sensor network (WSN)
- Many aspects of ad-hoc networks are being widely studied by researchers.
- However, a number of ad-hoc networks have already been deployed and seen real use.
  - Search and rescue mission after natural disaster.
  - Military operations.
  - Data collection in wide, remote areas.

WIRELESS LOCAL LOOP

Wireless Local Loop

- Wired technologies responding to need for reliable, high-speed access by residential, business, and government subscribers
  - ISDN, xDSL, cable modems
- Increasing interest shown in competing wireless technologies for subscriber access
- Wireless local loop (WLL)
  - Narrowband – offers a replacement for existing telephony services
  - Broadband – provides high-speed two-way voice and data service

WLL Configuration

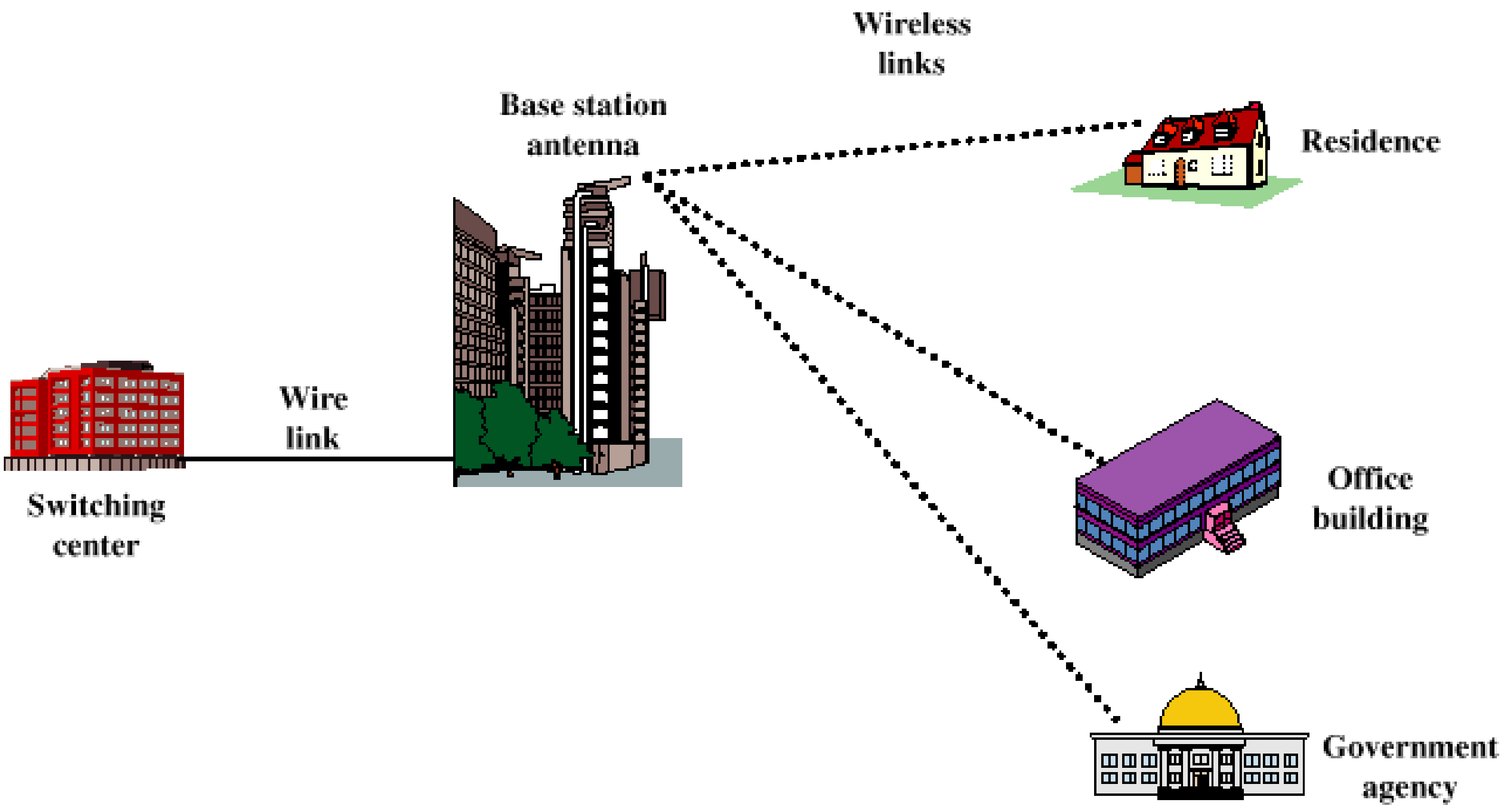


Figure 11.9 WLL Configuration

Advantages of WLL over Wired Approach

- Cost – wireless systems are less expensive due to cost of cable installation that's avoided
- Installation time – WLL systems can be installed in a small fraction of the time required for a new wired system
- Selective installation – radio units installed for subscribers who want service at a given time
  - With a wired system, cable is laid out in anticipation of serving every subscriber in a given area

Propagation Considerations for WLL

- Most high-speed WLL schemes use millimeter wave frequencies (10 GHz to about 300 GHz)
  - There are wide unused frequency bands available above 25 GHz
  - At these high frequencies, wide channel bandwidths can be used, providing high data rates
  - Small size transceivers and adaptive antenna arrays can be used

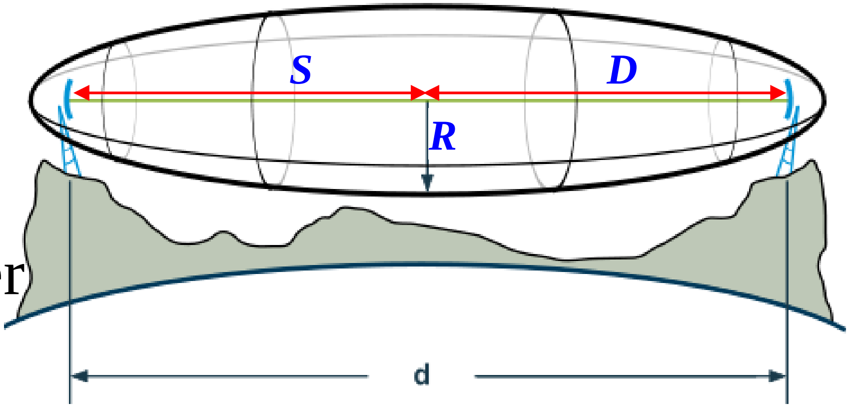
Propagation Considerations for WLL

- Millimeter wave systems have some undesirable propagation characteristics
  - Free space loss increases with the square of the frequency; losses are much higher in millimeter wave range
  - Above 10 GHz, attenuation effects due to rainfall and atmospheric or gaseous absorption are large
  - Multipath losses can be quite high

Fresnel Zone

- How much space around direct path between transmitter and receiver should be clear of obstacles?
  - Objects within a series of concentric circles around the line of sight between transceivers have constructive/destructive effects on communication
- For point along the direct path, radius of first Fresnel zone:

$$R = \sqrt{\frac{\lambda SD}{S+D}}$$



  - S = distance from transmitter
  - D = distance from receiver

Atmospheric Absorption

- Radio waves at frequencies above 10 GHz are subject to molecular absorption
  - Peak of water vapor absorption at 22 GHz
  - Peak of oxygen absorption near 60 GHz
- Favorable windows for communication:
  - From 28 GHz to 42 GHz
  - From 75 GHz to 95 GHz

Effect of Rain

- Attenuation due to rain
  - Presence of raindrops can severely degrade the reliability and performance of communication links
  - The effect of rain depends on drop shape, drop size, rain rate, and frequency
- Estimated attenuation due to rain:

$$A = aR^b$$

  - A = attenuation (dB/km)
  - R = rain rate (mm/hr)
  - a and b depend on drop sizes and frequency

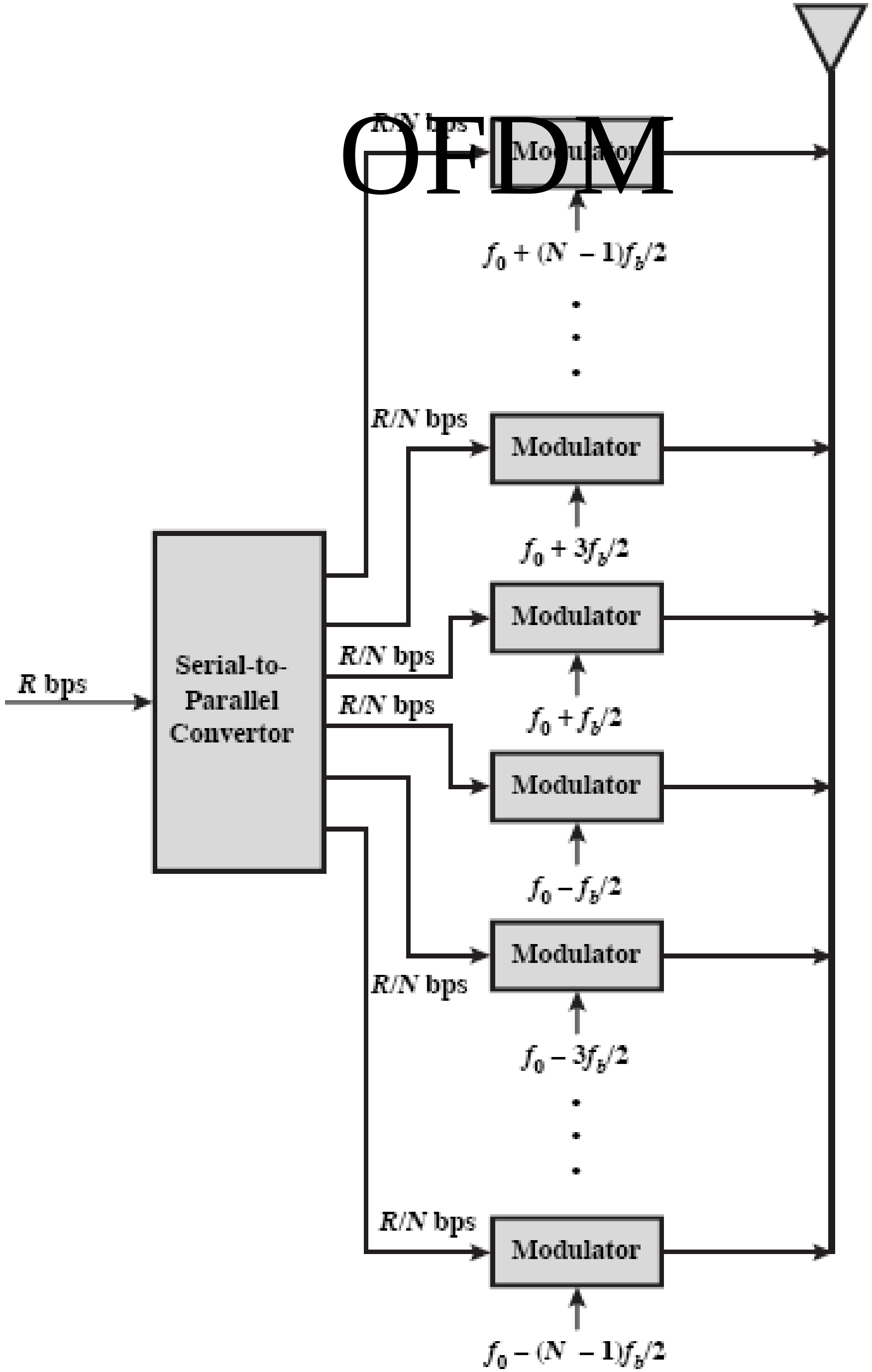
Effects of Vegetation

- Trees near subscriber sites can lead to multipath fading
- Multipath effects from the tree canopy are diffraction and scattering
- Measurements in orchards found considerable attenuation values when the foliage is within 60% of the first Fresnel zone
- Multipath effects highly variable due to wind

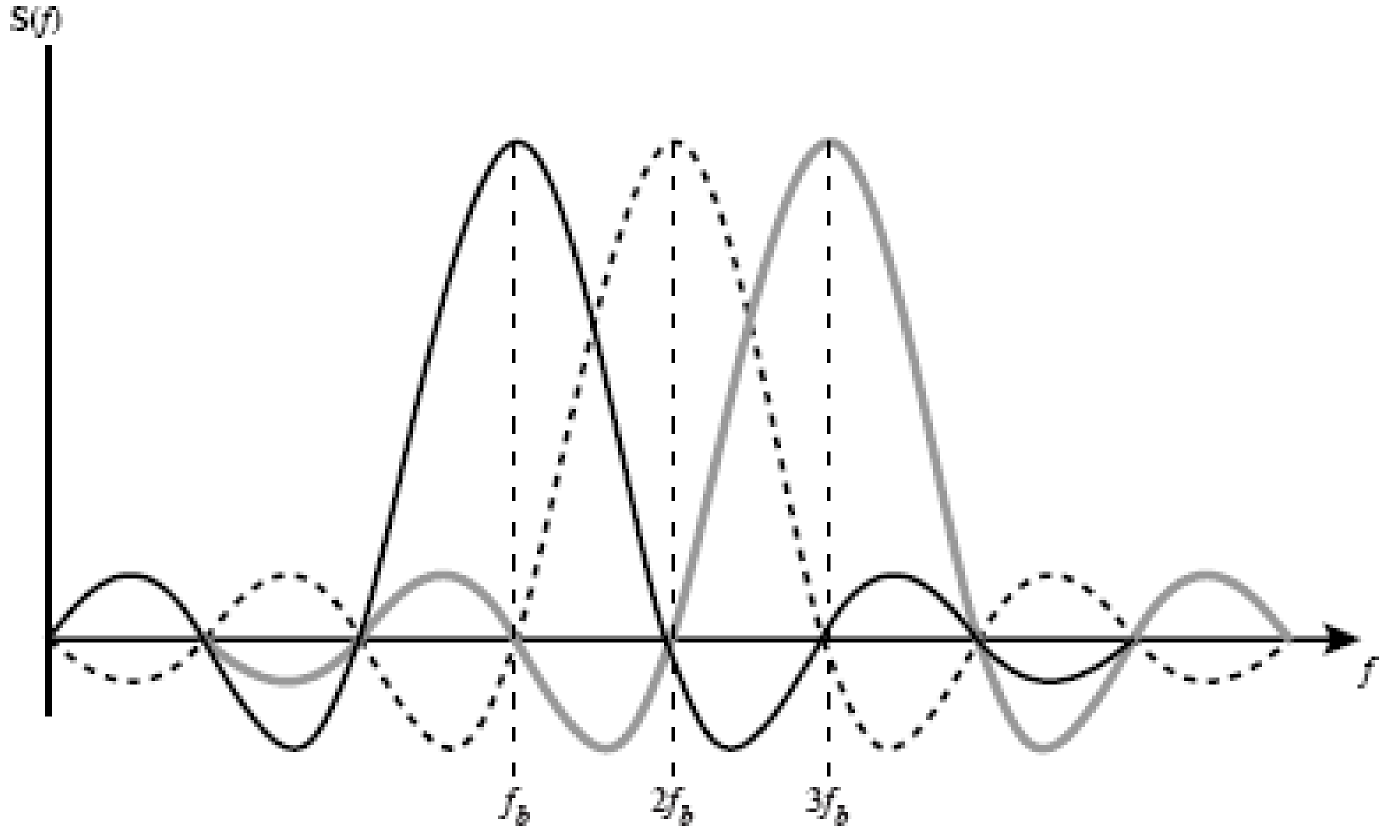
OFDM (Orthogonal FDM)

- Split a data source of R bps into N substreams of R/N bps.
- Expand bit duration from $1/R$ to N/R, to overcome intersymbol interference (ISI).
- All substreams are transmitted over multiple orthogonal subcarriers.
- Orthogonality: the peaks of the power spectral density of each subcarrier occurs at a point at which the power of other subcarriers is zero.

OFDM


R bps
Serial-to-Parallel Convertor
R/N bps
Modulator
f_0 + (N − 1)f_b/2
f_0 + 3f_b/2
f_0 + f_b/2
f_0 − f_b/2
f_0 − 3f_b/2
f_0 − (N − 1)f_b/2

OFDM



(b) Three subcarriers in frequency domain

Multipoint Distribution Service (MDS)

- Multichannel Multipoint Distribution Service (MMDS)
  - Also referred to as wireless cable
  - Used mainly by residential subscribers and small businesses
- Local Multipoint Distribution Service (LMDS)
  - Appeals to larger companies with greater bandwidth demands

Advantages of MMDS

- MMDS signals have larger wavelengths and can travel farther without losing significant power
- Equipment at lower frequencies is less expensive
- MMDS signals don't get blocked as easily by objects and are less susceptible to rain absorption

Advantages of LMDS

- Relatively high data rates
- Capable of providing video, telephony, and data
- Relatively low cost in comparison with cable alternatives

Communications Bands Allocation

Frequency (GHz)	Usage
2.1500 to 2.1620	Licensed MDS and MMDS; two bands of 6 MHz each
2.4000 to 2.4835	Unlicensed ISM
2.5960 to 2.6440	Licensed MMDS; eight bands of 6 MHz each
2.6500 to 2.6560	Licensed MMDS
2.6620 to 2.6680	Licensed MMDS
2.6740 to 2.6800	Licensed MMDS
5.7250 to 5.8750	Unlicensed ISM-UNII
24.000 to 24.250	Unlicensed ISM
24.250 to 25.250	Licensed
27.500 to 28.350	Licensed LMDS (Block A)
29.100 to 29.250	Licensed LMDS (Block A)
31.000 to 31.075	Licensed LMDS (Block B)
31.075 to 31.225	Licensed LMDS (Block A)
31.225 to 31.300	Licensed LMDS (Block B)
38.600 to 40.000	Licensed

BLUETOOTH

What is Bluetooth?

- A **cable-replacement** technology that can be used to connect almost any device to any other device
- Radio interface enabling electronic devices to communicate wirelessly via short range (10 meters) ad-hoc radio connections
- a standard for a **small , cheap radio chip to be plugged into computers, printers, mobile phones, etc**

What is Bluetooth?

- Uses the radio range of 2.45 GHz
- Theoretical maximum bandwidth is 1 Mb/s
- Several Bluetooth devices can form an ad hoc network called a “piconet”
  - In a piconet one device acts as a master (sets frequency hopping behavior) and the others as slaves
  - Example: A conference room with many laptops wishing to communicate with each other

History

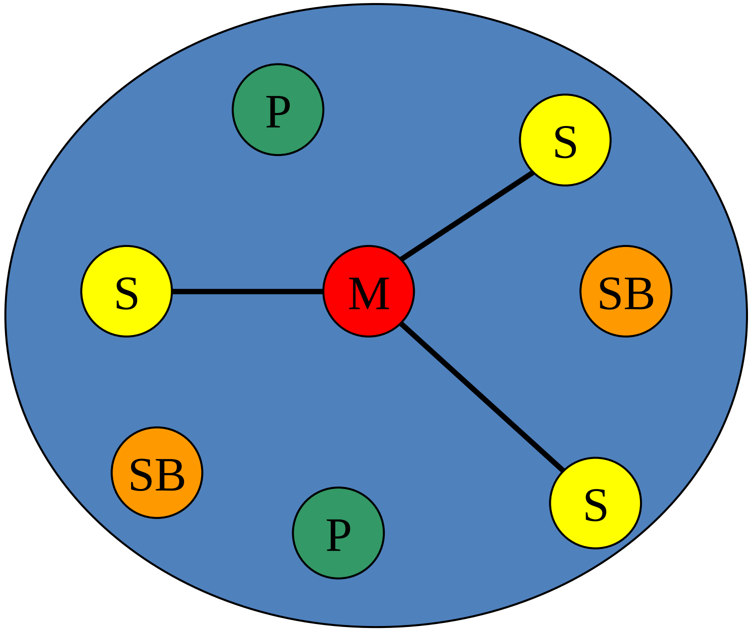
- Harald Bluetooth : 10th century Danish King, managed to unite Denmark and Norway
- Bluetooth SIG (Special Interest Group) :
  - Founded in 1998 by : Ericsson, Intel, IBM, Toshiba and Nokia
  - Currently more than 2500 adopter companies
  - Created in order to promote, shape an define the specification and position Bluetooth in the market place Current specification : Bluetooth 2.1

Bluetooth Architecture

- Piconet
  - Each piconet has one master and up to 7 simultaneous slaves
    - Master : device that initiates a data exchange.
    - Slave : device that responds to the master
- Scatternet
  - Linking of multiple piconets through the master or slave devices
  - Bluetooth devices have point-to-multipoint capability to engage in Scatternet communication.

Piconet

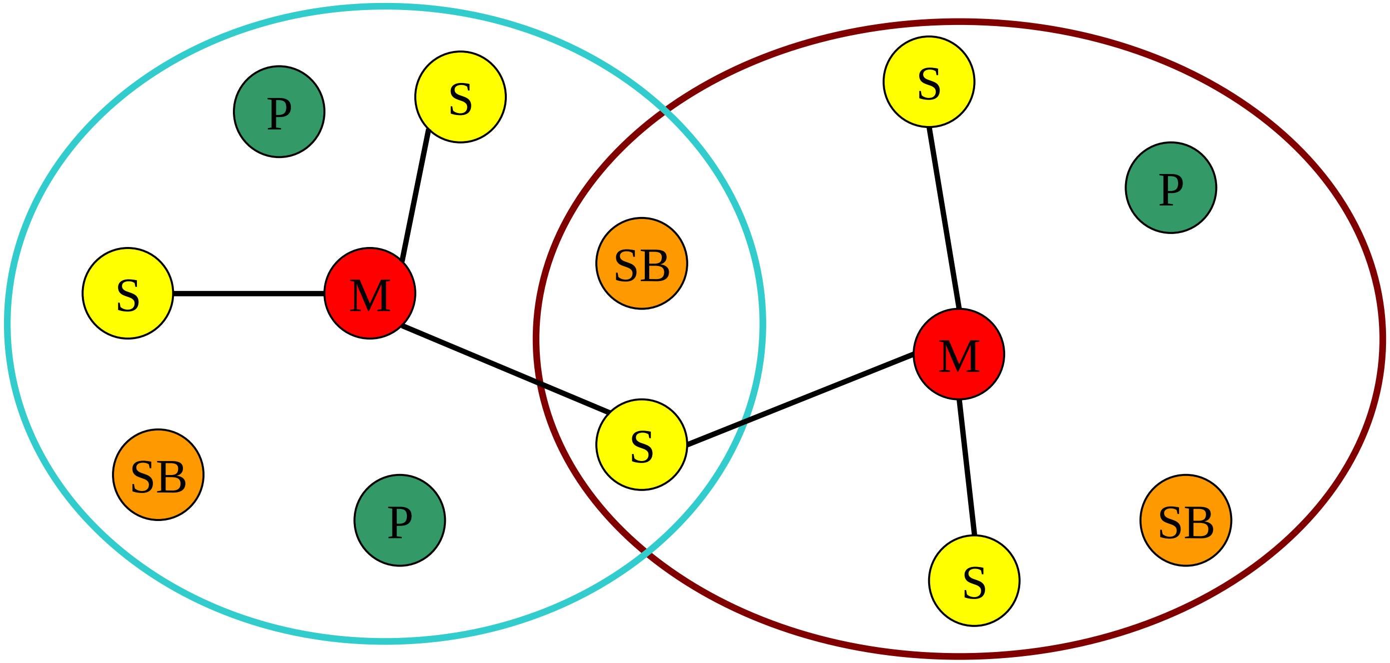
- All devices in a piconet hop together
  - Master gives slaves its clock and device ID
- Non-piconet devices are in standby



M=Master P=Parked
S=Slave SB=Standby

Scatternet

- Devices can be slave in one piconet and master of another



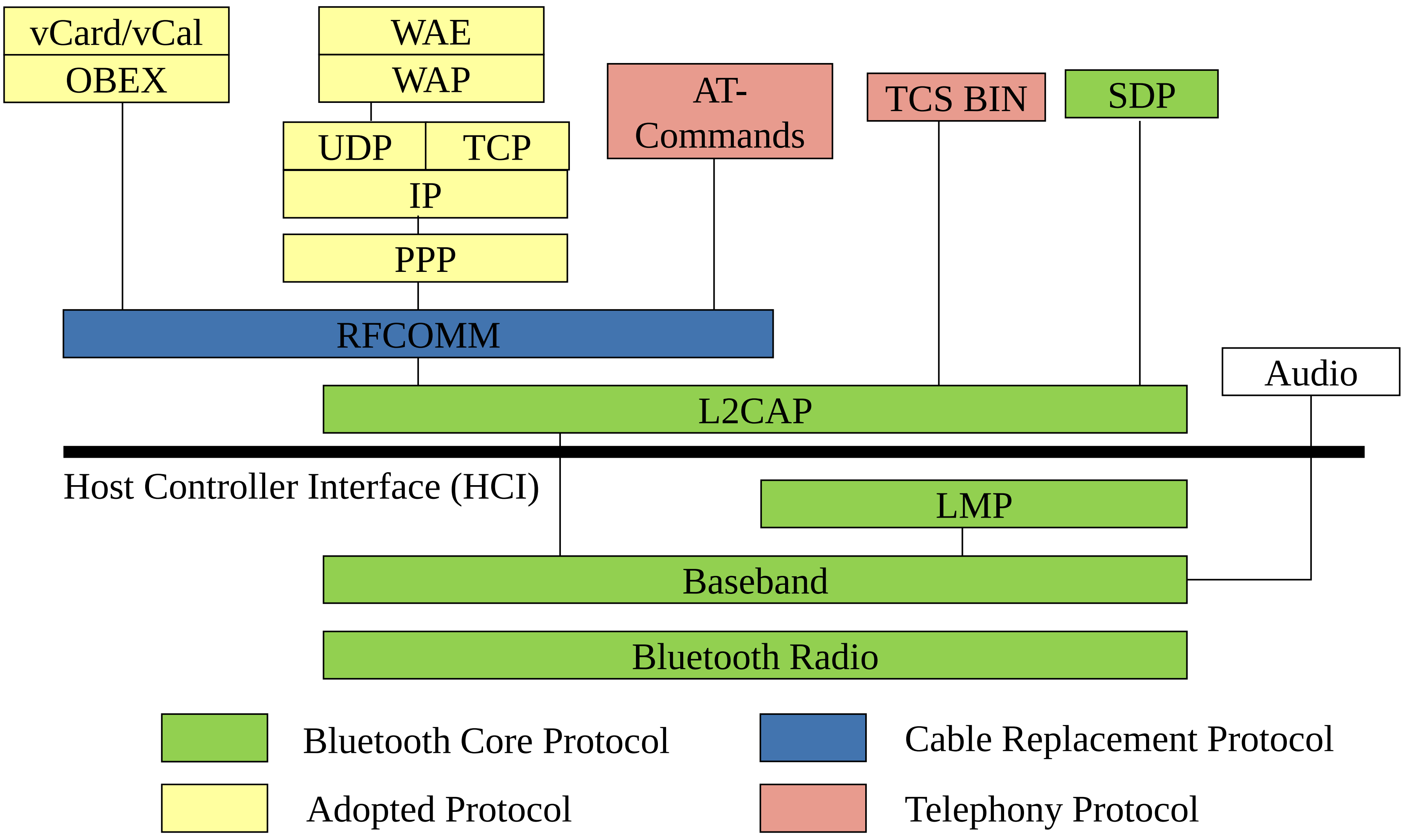
Physical links

- Between master and slave(s), different types of links can be established. Two link types have been defined:
  - Synchronous Connection-Oriented (SCO) link
  - Asynchronous Connection-Less (ACL) link

Physical links

- Synchronous Connection Oriented (SCO)
  – Support symmetrical, circuit-switched, point-to-point connections
  – Typically used for voice traffic.
  – Data rate is 64 kbit/s.
- Asynchronous Connection-Less (ACL)
  – Support symmetrical and asymmetrical, packet-switched, point-to-multipoint connections.
  – Typically used for data transmission .
  – Up to 433.9 kbit/s in symmetric or 723.2/57.6 kbit/s in asymmetric

Bluetooth Protocol Stack



Bluetooth Protocol Stack

- **Bluetooth Radio** : specifics details of the air interface, including frequency, frequency hopping, modulation scheme, and transmission power.

- **Baseband**: concerned with connection establishment within a piconet, addressing, packet format, timing and power control.

- **Link manager protocol (LMP)**: establishes the link setup between Bluetooth devices and manages ongoing links, including security aspects (e.g. authentication and encryption), and control and negotiation of baseband packet size

Bluetooth Protocol Stack

- **Logical link control and adaptation protocol (L2CAP)**: adapts upper layer protocols to the baseband layer. Provides both connectionless and connection-oriented services.

- **Service discovery protocol (SDP)**: handles device information, services, and queries for service characteristics between two or more Bluetooth devices.

- **Host Controller Interface (HCI):** provides an interface method for accessing the Bluetooth hardware capabilities. It contains a command interface, which acts between the Baseband controller and link manager

Bluetooth Protocol Stack

- **TCS BIN (Telephony Control Service)**: bit-oriented protocol that defines the call control signaling for the establishment of voice and data calls between Bluetooth devices.

- **OBEX(OBject EXchange)** : Session-layer protocol for the exchange of objects, providing a model for object and operation representation

- **RFCOMM**: a reliable transport protocol, which provides emulation of RS232 serial ports over the L2CAP protocol

- **WAE/WAP**: Bluetooth incorporates the wireless application environment and the wireless application protocol into its architecture.

Connection Establishment States

- **Standby**
  - State in which Bluetooth device is inactive, radio not switched on, enable low power operation.

- **Page**
  - Master enters page state and starts transmitting paging messages to Slave using earlier gained access code and timing information.

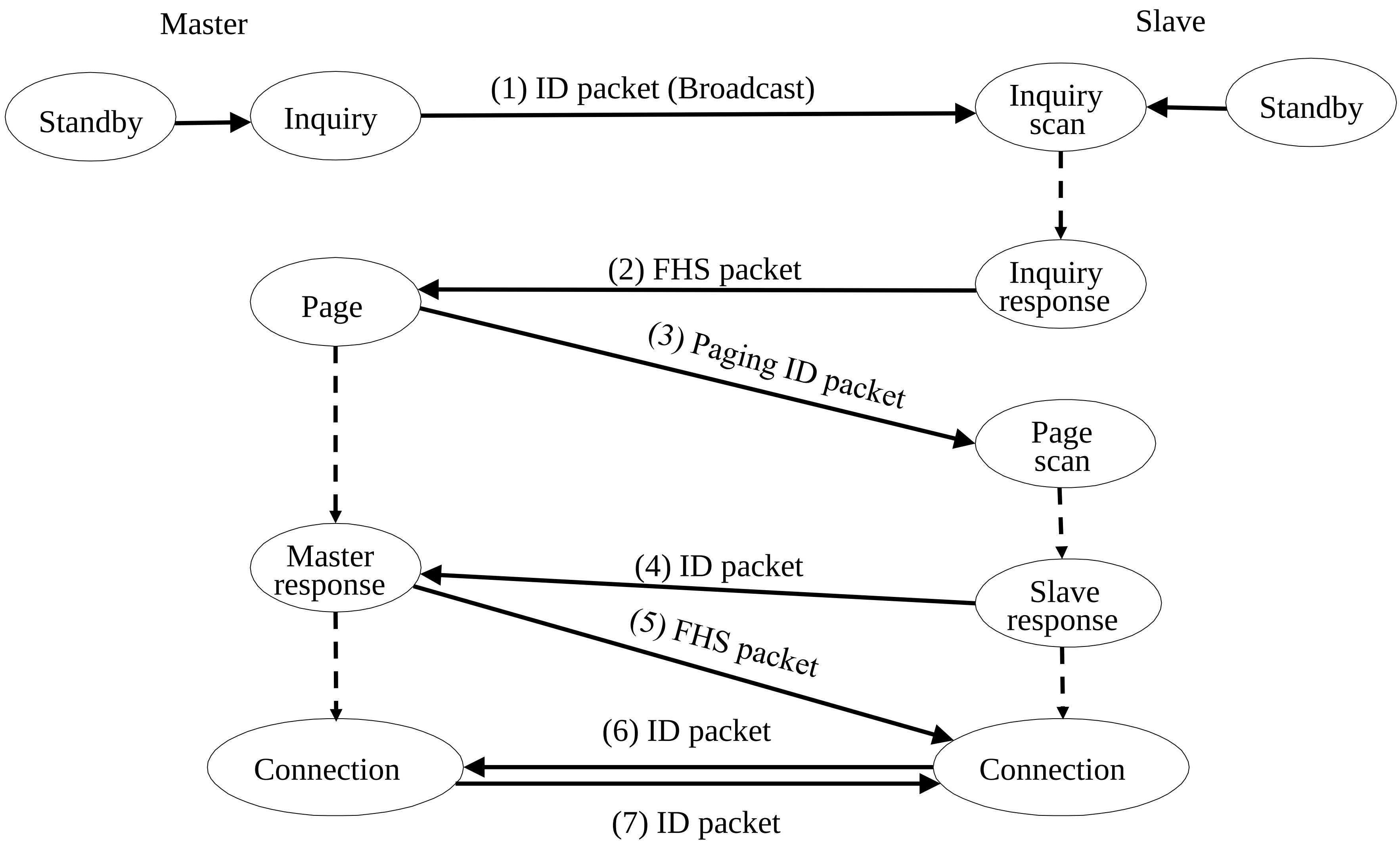
- **Page Scan**
  - Device periodically enters page state to allow paging devices to establish connections.

Connection Establishment States

- **Inquiry**
  - State in which device tries to discover all Bluetooth enabled devices in the close vicinity.

- **Inquiry scan**
  - Most devices periodically enter the inquiry scan state to make themselves available to inquiring devices.

Inquiry and Page



Bluetooth Security

- There are three modes of security for Bluetooth access between two devices.
  - non-secure
  - service level enforced security
  - link level enforced security
- Device security level
  - Trusted
  - untrusted
- Service security level
  - Authorization and Authentication
  - Authentication only
  - Open to all devices

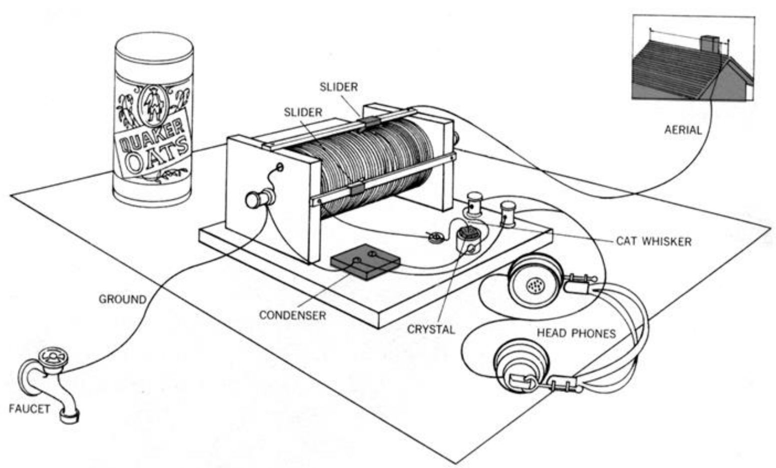
Bluetooth Security

- The following are the three basic security services specified in the Bluetooth standard:
  - **Authentication**
    - verifying the identity of communicating devices. User authentication is not provided natively by Bluetooth.
  - **Confidentiality**
    - preventing information compromise caused by eavesdropping by ensuring that only authorized devices can access and view data.
  - **Authorization**
    - allowing the control of resources by ensuring that a device is authorized to use a service before permitting it to do so.

AMPS

Introduction

- 1906: 1st radio transmission of Human voice.
  - What's the medium?
  - Used an RC circuit to modulate a carrier frequency that radiated up and down an antenna.
  - Receiver had a matched RC circuit with an antenna



From Electronics in The West by Jane Morgan

Introduction

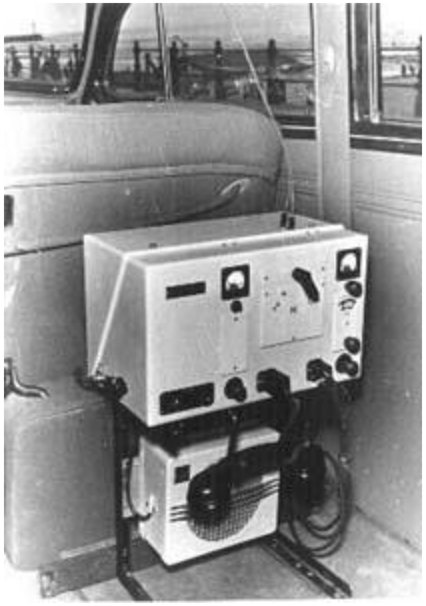
- 1910: Lars Ericsson in Sweden invents the first car phone.
- However, Morse Code continues to be the primary method of sending information without a wire.

Introduction

- 1934: Federal Communications Commission is founded by Roosevelt's New Deal. Charged to allocate the radio spectrum with the public interest in mind.
- The FCC was corrupt until the mid 60's, it propped up AM radio for years to keep out newer FM stations.
- The FCC gave priority in terms of broadcast channels to emergency and government units.

Introduction

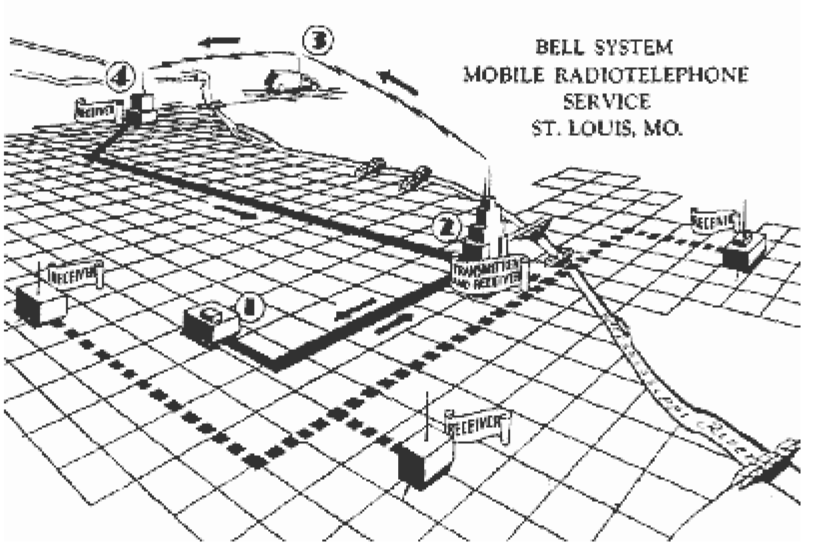
- WW2: Many innovations, including RADAR.
- Also the first mobile FM Transmitter/Receiver.
  - Weighed over 30 lbs.
  - More like a Walkie Talkie.
  - Developed by Motorola.



Introduction

- 1946: In St. Louis, AT&T and Southwestern Bell introduced the first mobile telephone service.
  - There were 6 channels in the 150 MHz band with 60 KHz allocated to each channel.
  - A very powerful antennae sat atop a centrally located building. All calls were routed through here.
  - Not full duplex; it was like a walkie/talkie.
  - Operators routed all calls

Introduction

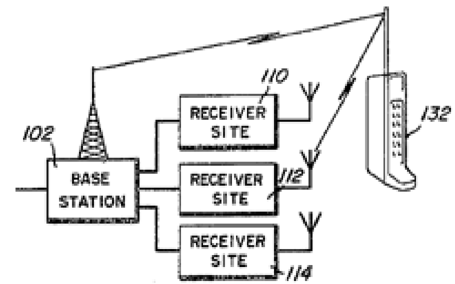


Introduction

- 1954/1958: Silicon transistor and integrated circuits are invented at Texas Instruments.
  - Walkie/Talkies were now the size of a large shoe.
- 1960: Bell employees informally outline a cellular plan and request 75 MHz of bandwidth around the 800 MHz band.
  - Everything that was needed to have mobile communications was invented at this point except the microprocessor (1971 by Intel).

Introduction

- 1973: Martin Cooper from Motorola files for a patent on the first handheld mobile phone.
  - He didn’t invent cellular phones, however,
  - Bell had a working system on trains 4 years earlier, but it wasn’t handheld.
  - They were both cellular with frequency reuse.
- 1974: The FCC releases all the requested bandwidth.



Part of one diagram in US Patent 3,906,166

Introduction

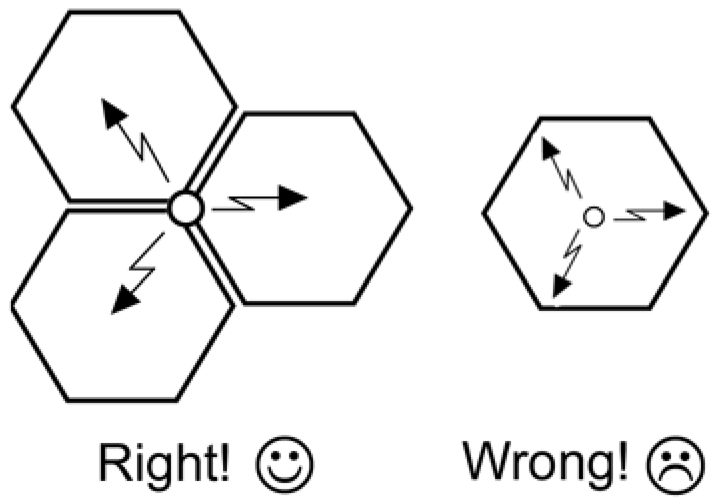
- 1975: Bell receives permission to start a commercial cellular network in Chicago.
  - They order 135 phones at a cost of over $500,000
- 1979: Lucent makes the first DSP on one chip.
- October 12, 1983: Bell rolls out the first full-scale cellular network in Chicago.
  - Covers 2100 square miles with 12 cellular sites.
  - Uses a system called AMPS
  - Operated in the 800 MHz band that had been allocated by the FCC.
  - Telephones were expensive suit case type phones

Cellular Terms/Concepts used in AMPS

- Users are Mobile
  - Must transfer call from one region to another
- Low powered, handheld transmitters
  - Must be relatively close to a receiver (<20 miles)
- Frequencies are reused in other cells
- In band signaling
- Paging
- Frequency Modulation
  - Helps remove noise.

Cells

- A cell is an area covered by a transponder.



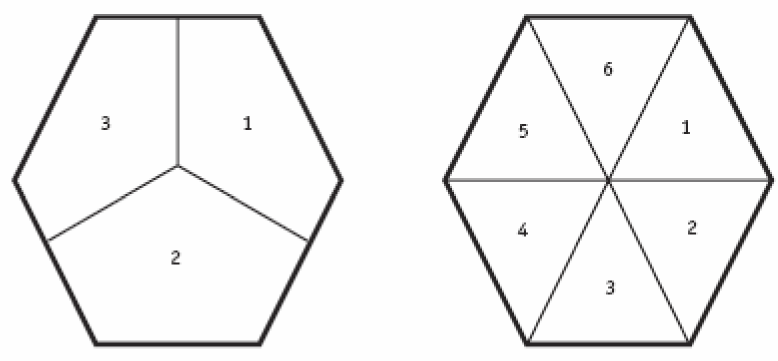
A cell site lies at the edge of several cells, not at the center.

Cells

- The antenna are directional.
- Each cell has 4 antennas, 1 for control, 1 for voice, and 2 for receive.

Cell Sectorization

- Cells can be divided into sectors to provide a smaller coverage area, and therefore, more frequency reuse.



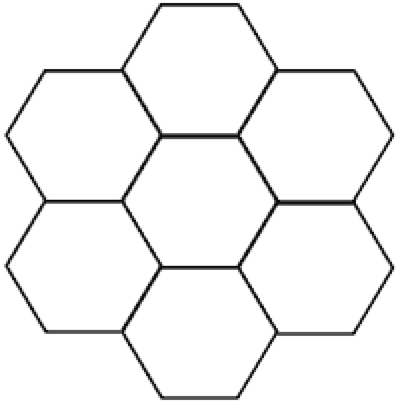
(a) Three sectors (b) Six sectors

Cell Area

- Cellular areas aren’t really circular as the area depends on the terrain and the interference that’s present.

Why Hexagons?

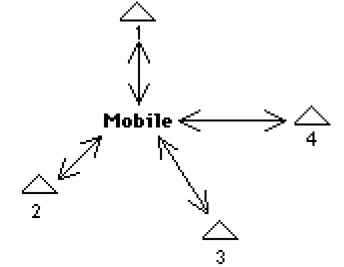
- Using hexagons, as opposed to circles or boxes, allows for a better visualization of the coverage areas.
- Also, a system of hexagons helps offset cells from linear road boundaries (where cell phones were envisioned to be used).



AMPS in General

- AMPS: Advanced Mobile Phone System
- Known as First Generation Wireless
- **Analog** channels of 30 KHz.
- Uses Frequency Division Multiple Access
- Uses frequency reuse – people in other cells can use your frequency without interference.
- Very susceptible to static.
- Very easy to ease drop.
- Introduced in 1983.
  - Must be supported by every wireless carrier until February, 2008.
- OnStar still uses AMPS.
  - In 2005, 15% of Alltel's customers were still using AMPS.
  - Replaced by TDMA and now CDMA (all digital) technologies.

Basic Theory for all Cell Technologies



Upon turning on your phone the mobile switch gathers signal strength reports from the different cells and assigns your phone to the cell with the strongest reading. In this simplified example, 1 represents the strongest signal and 4 is the weakest. Although it is easy to say that the cell site nearest you gets your call, it may not, depending on topography and other factors.

- Each cell site has a computerized transceiver and antenna.
  - Range is between 2 and 10 miles in radius.
- When you turn on your phone, the Mobile Telephone Switching Office (MTSO) assigns a vacant radio channel in that cell to carry the call.
  - It selects the cell to carry your call by measuring signal strength.
- Once you have been assigned a channel, you can send and receive calls.
- Since you might move between cells, handoffs need to occur between cells.
  - A request is made by the base station to the MTSO that the signal strength that it is receiving is too low.
  - The MTSO assigns a new channel and a new cell and a handoff occurs
    - Takes around 200 ms.

Cellular Frequencies

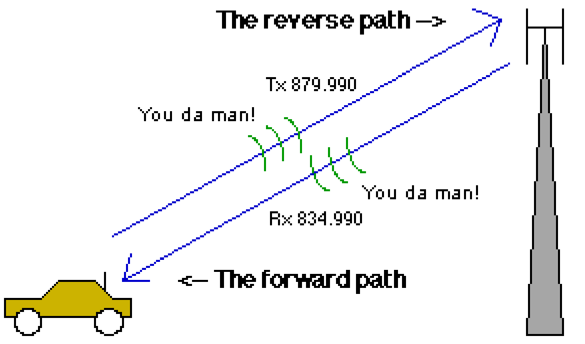
- Cellular development didn't start in earnest until 1984, until after the Bell breakup.
- The FCC allocated space in the 800 MHz FM band.
  - 824.04 to 848.97 MHz and 869.04 to 893.97 MHz are the ranges used.
    - Airphone, Nextel, SMR, and public emergency services take up the 849 – 869 MHz
    - Cellular phones take up 50 MHz total, which is quite a chunk.
      - AM broadcast takes up 1.17 MHz, from 530 KHz to 1.7 MHz with 107 frequencies to broadcast on with a channel of only 10 KHz.
      - FM broadcast takes up 20 MHz, from 88 MHz to 108 MHz with 133 stations to broadcast on with a channel of 150 KHz.
  - Cellular uses a channel that is 30 KHz wide.

Cellular Frequencies

- Cellular uses 2 frequencies, 1 to receive from the base station on and 1 to send to the base station on.
  - These frequencies must be separated by 45 MHz to avoid interference.
  - So, cellular channels always come in pairs.
    - This allows you to talk and listen at the same time.
- Originally, Bell requested room for 1000 channels, however the FCC only granted them 666. That's why the cellular frequency band is discontinuous.

Cellular Frequencies

- Cell Phone to tower is called the reverse voice path.
- Tower to cell phone is called the forward voice path.



- The number of channels and what frequency pairs are used depends on the terrain and interference levels of the engineer.
  - Adding the original channels requires days of work for a radio engineer.
  - Some cells have as few as 4 channels on them.
  - Adding new channels requires tuning of the whole network and the engineer must physically go to the cell site.
- The MTSO (mobile switch) can only select from a list of channels that a cell site supports, it can't assign new ones.

Cellular Frequencies

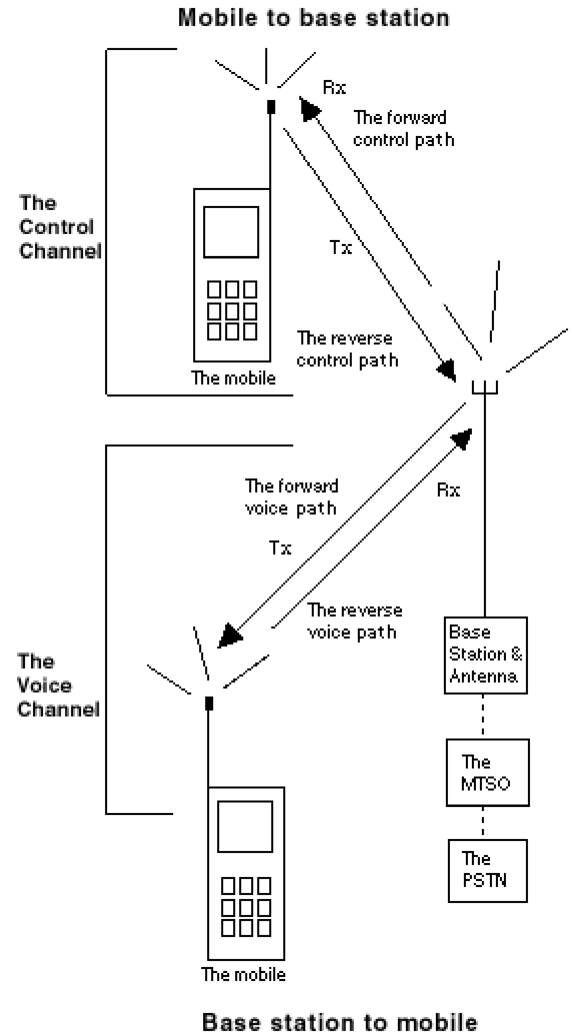
- A dedicated pair of frequencies are called a channel.
  - As an aside, the cell phone network took part of the bandwidth that was assigned to UHF television
    - It took channels 70 – 83.
- However, the first channel in each cell or sector is a control channel.
  - This channel is used to pass data back and forth to setup the call.
  - It drops out of the picture once the call is made.

Control Channels

- Cell phone providers have agreed that only 21 frequency pairs can be control channels.
  - So, the cell phone must scan only 21 frequencies to find its control channel.
- The control channels are called:
  - Forward control path: Base station to mobile
  - Reverse control path: Mobile to base station
- So, there are actually 4 communication frequencies involved in cellular communications.
- The control channel is no longer used once the mobile has been assigned a voice channel.
  - Signaling is done in band from then on out.

Control Channels

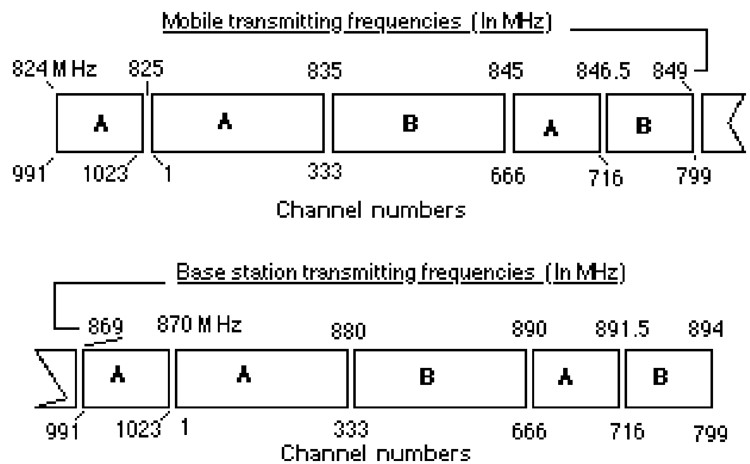
- We now have a pair of data channels and a pair of voice channels.
- We will talk about what's passed on the control channels shortly.



Cellular Licenses

- In 1984, the FCC decided to license to cellular carriers in each geographical area.
  - 1 automatically went to the local exchange carrier.
  - The other one went to a business or group who bid for it and one the lottery for it.
- The frequency spectrum was split in 2, half going to the LEC and the other going to the lottery winner.
  - Called the A and B band.
- Each band had 21 control channels and 416 voice channels (after 1989 when the FCC expanded the frequency range).

Cellular Licenses



Receiving a Call Outline

- 1: Registration with the network and idling.
- 2: Paging
- 3: Dial Tone / SAT / Blank and Burst /Ring
- 4. Answer the call

Making a Call Outline

- More difficult than receiving a call; we will talk about this next week.

The MTSO | The Cell Site | The Mobile

GETTING A CALL WITH A MOBILE PHONE

1 The cell site constantly transmits identifying information or *overhead* on its forward control channel . . .

2 Meanwhile, the mobile is turned on . . .

3 It scans the forward control channels (FCCs), searching for the one with the strongest signal . . .

4 The mobile locks on to the strongest channel and then transmits identifying information to the cell site on the reverse control channel or path . . .

5 The cell site gets that info and relays it to the MTSO . . .

6 The MTSO checks out the information by itself and with network resources . . .

7 It begins monitoring for incoming calls to the mobile if the information checks out . . .

8 ALERT! INCOMING CALL FOR MR. MOBILE!

In the meantime, the mobile idles, waiting for an incoming call by monitoring the control, setup, or paging channel.

9 The switch sends a paging message out to all cell sites . . .

10 Each cell site in the system sends a digital paging message for the mobile on the forward control channel . . .

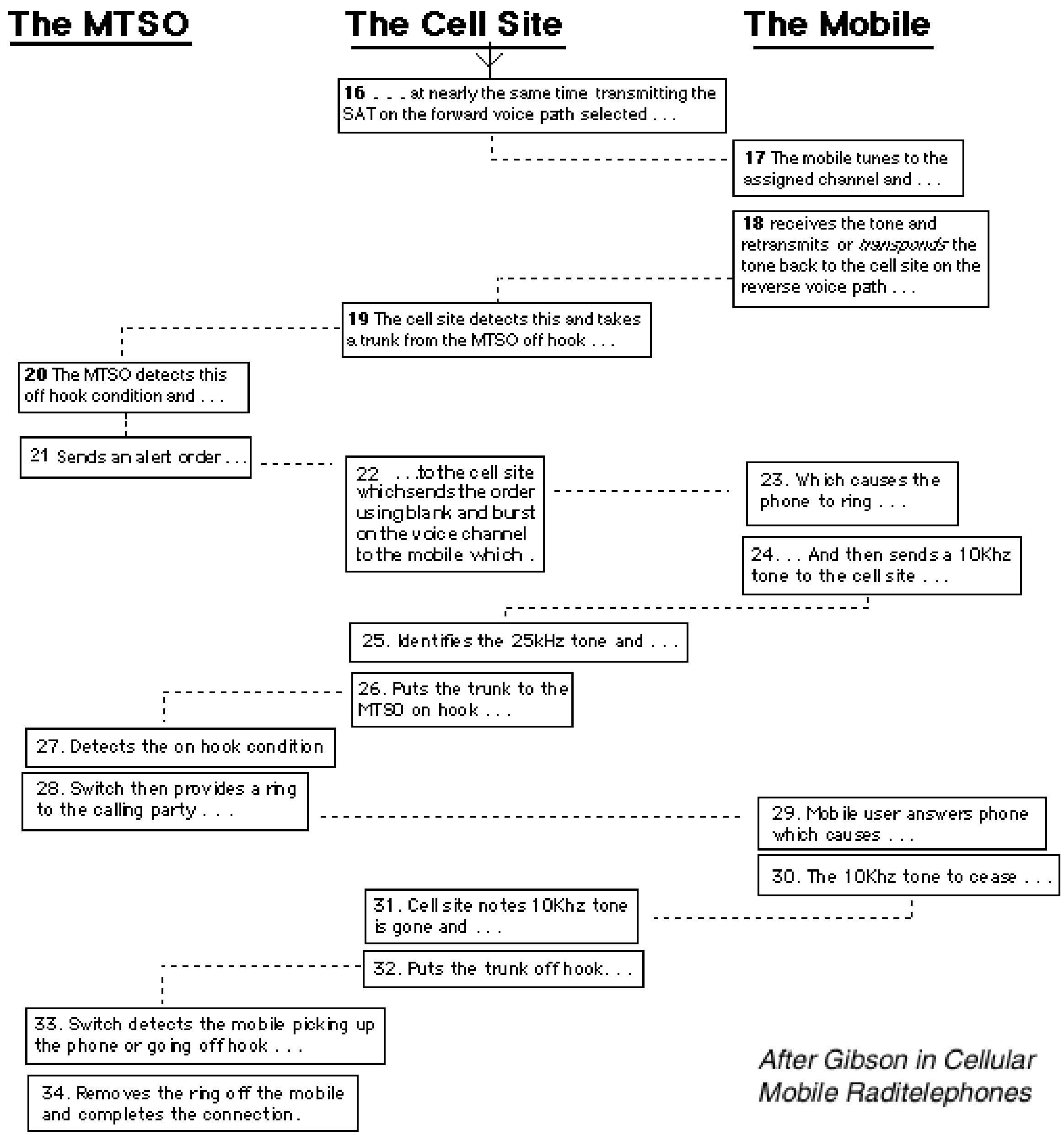
11 The mobile gets the page and confirms it by . . .

12 Seizing the control channel and sending a service request to the MTSO, letting the switch know that the mobile is turned on and not *off hook* or in use . . .

13 Takes the digital message and sends it in the proper form to the MTSO . . .

14 The MTSO picks a voice channel for the conversation and sends that assignment to the cell site . . .

15 The base station sends a digital message conveying the channel assignment to the mobile on the forward control path while . . .



After Gibson in Cellular Mobile Raditelephones

Registration

- When you first turn your phone on, it does a self diagnostic check.
- It then scans each of the 21 forward control channels (base station to cellular), camping on the strongest one.
  - The phone rescans every 7 seconds to make sure that this channel is still the strongest.
- The mobile then decodes the data stream being sent by the base station.
  - Note: The data paths are actually digital. So, AMPS is actually a hybrid system, though the voice is analog.
  - The data stream has information on what network the phone is on.
    - Using this, the phone can decided if it is roaming.

Registration

- The phone then waits for an idle time slot bit to be sent by the base station.
- The phone then sends its phone number, electronic serial number, and home network to the base station.
  - This is where a lot of fraud occurred in AMPS.
- The base station then receives this information and passes it to the MTSO (switch).
  - This is checked against various databases and the user is validated or invalidated.
- The cell phone then monitors the 21 forward control channels waiting for a paging bit to be set so that it knows a call is coming to it.
- A phone re-registers every 15 minutes or whenever the phone moves cell areas.
- This whole process takes around 200 ms.

Registration Data Stream

- The control data is passed digitally at a rate of 10, 000 bps.
  - But, because analog waves experience a lot of interference, everything is sent at least twice.
- The actual data rate is on average 1200 bps.
- Slow, but it gets the job done.

Paging

- Remember, the base station and cell phone are both low power
  - Cell Phone: Max of 7 watts
  - Tower: Max of 100 watts
- Your cell phone camps on the strongest forward control channel.
  - This channel is actually digital
- Your cell phone listens for its phone/serial number on the control channel.
  - When it has heard its number, it responds to the base station saying that it is ready to take a call.

SAT

- After the base station is notified that the cell phone is ready, it sends:
  - The channel frequencies that the voice conversation will be carried on
  - An SAT tone.
    - SAT – Supervisory Audio Tone
- The SAT tone is used to identify users on the same operating frequencies, but in different cells

SAT

- The SAT is an inaudible, high pitched tone that is at 1 of 3 frequencies:
  - 5970, 6000 and 6030 Hz
- The cell phone then transmits this tone back to the base station during the entire conversation.
  - If no tone or the wrong tone is detected, the voice channel needs reassigned.
  - The SAT is filtered out by both your phone and the base station so that you can’t even detect it.

SAT

- In AMPS, the call is dropped after 5 seconds if the SAT isn't received or if the wrong SAT is transmitted.
- Once the SAT has been received by the base station, your cellular phone rings.
  - The ring tone is actually produced by your phone and not the centrol office or MTSO.

ST

- ST: Signaling tone
  - Another inaudible, 10 KHz tone that the cellular phone transmits to the base station so that the base station knows that the phone is still ringing.
- Once answered, the ST tone stops.
- When you hang up, the ST is sent to the base station for 1.8 seconds to let the base station know that you wish to terminate the call.
- The ST is also sent for 50 ms to both base stations during a handoff.
- The ST lets the cell phone communicate to the base station without tying up a data channel.

Conclusion of Answering a Call

- We are done with how a call is answered in AMPS.
- Making a call is similar, but there are a few more steps as the switch must find out who and how much to bill for the call.

Making a Call

- Dial the Number.
- Press send.
- That #, your # and serial # are sent by the mobile on the strongest reverse control channel to the base station.
- The MTSO validates you and assigns a voice channel by using the forward control channel.
- The base station sends the SAT on the new voice channel and the mobile must send it back.
- Once received, the base station sends an ST from the other phone so that your mobile will know that it is ringing on the other end.
- Once answered, the ST stops and you can talk.

PreCall Validation

- Your phone sends:
  - It's phone number (10 digits)
  - Serial number (32 bits)
    - Burned into ROM
  - Network Provider ID (5 digits)
    - Indicates whether you are using Cingular, Alltel, Sprint, etc…
  - Station Class Mark
    - What power level your phone is operating at.
    - The base station can change this to avoid interference.
- You can clone a phone permanently if you capture this information.
  - A big security risk.
  - Some carriers have disallowed out of country dialing in certain towns due to the drug trade.
- Once you have been validated, you proceed with the other steps in making a call.

AMPS Review

- Uses 4 frequencies to make a phone call.
  - 2 for control, 2 for voice.
- Channels are 30 KHz wide.
- Operates in the 800 MHz band.
- The voice is analog.
- Every carrier must support until February of 2008.

GSM ARCHITECTURE

Network Structure

- **Cell**

A cell is the basic unit of a cellular system and is defined as the radio coverage given by one BTS.

Network Structure

LOCATION AREA

A LA is defined as a group of cells.Within the network, a subsriber's location is known by the LA which they are in.

The identity of the LA in which an MS is currently located is stored in the VLR. (LAI)

Network Structure

- **MSC Service Area**

An MSC Service Area is made up of LAs and represents the geographical part of the network controlled by one MSC.

Network Structure

- **PLMN SERVICE AREA**

A PLMN service area is the entire set of cells served by one network operator

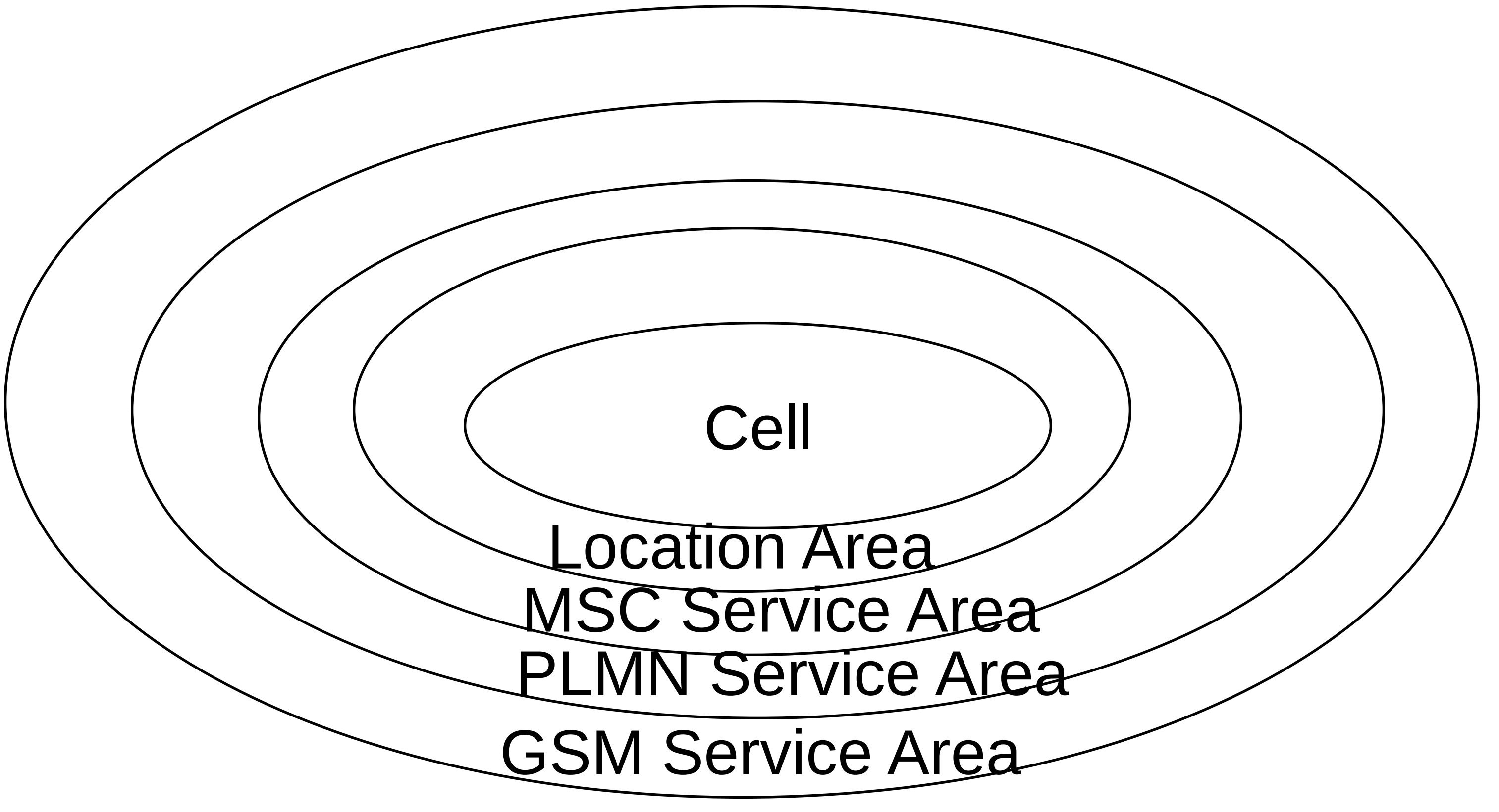
and is defined as the area in which an operator offers radio coverage and access to its network.

Network Structure

- **GSM SERVICE AREA**

The GSM service area is the entire geographical area in which a subscriber can gain access to a GSM network.

Relation between areas in GSM



Mobile Station

GSM MSs consist of:

- **Mobile Equipment**
- **Subscriber Identity Module**

Functions of Mobile Station

- Voice and data transmission & receipt
- Frequency and time synchronization
- Monitoring of power and signal quality of the surrounding cells
- Provision of location updates even during inactive state

Mobile Station

- Can receive, store, send SMS up to 160 characters.
- MS identified by unique IMEI shown on pressing *#06#.
- Power levels of 20W, 8W, 5W, 2W and .8W

SIM

SIM has microprocessor and memory.

Fixed data stored for the subscription:

- IMSI,
- Authentication Key, Ki
- Security Algorithms:kc,A3,A8
- PIN & PUK

Network Identities

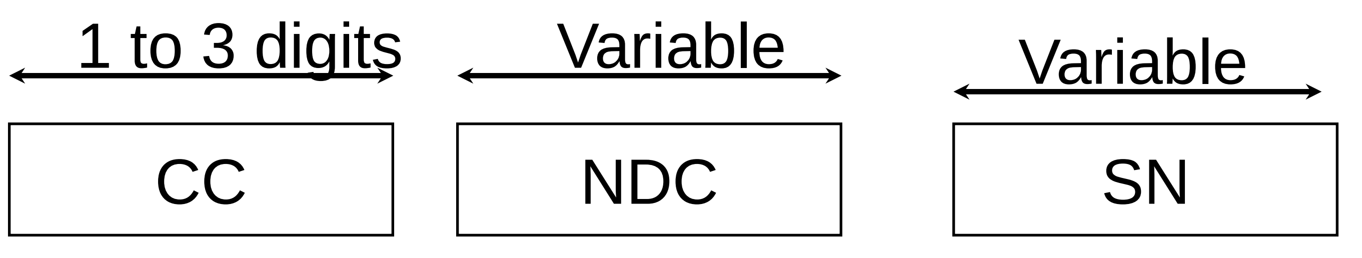
- IMEI
- MSISDN
- IMSI
- TMSI
- MSRN

IMEI

- **International Mobile Equipment Identity**
- The IMEI is an unique code allocated to each mobile equipment. It is checked in the EIR.
- IMEI check List
    - White List
    - Grey List
    - Black List

MSISDN

- **Mobile Station ISDN Number**
- **The MSISDN is registered in the telephone directory and used by the calling party for dialing.**
- **MSISDN shall not exceed 15 digits.**
- **NDC--National Destination Code**
- **SN--Subscriber Number**



IMSI

- **International mobile subscriber Identity**
- The IMSI is an unique identity which is used internationally and used within the network to identify the mobile subscribers.
- The IMSI is stored in the subscriber identity module (SIM), the HLR, VLR database.

Temporary Mobile subscriber Identity

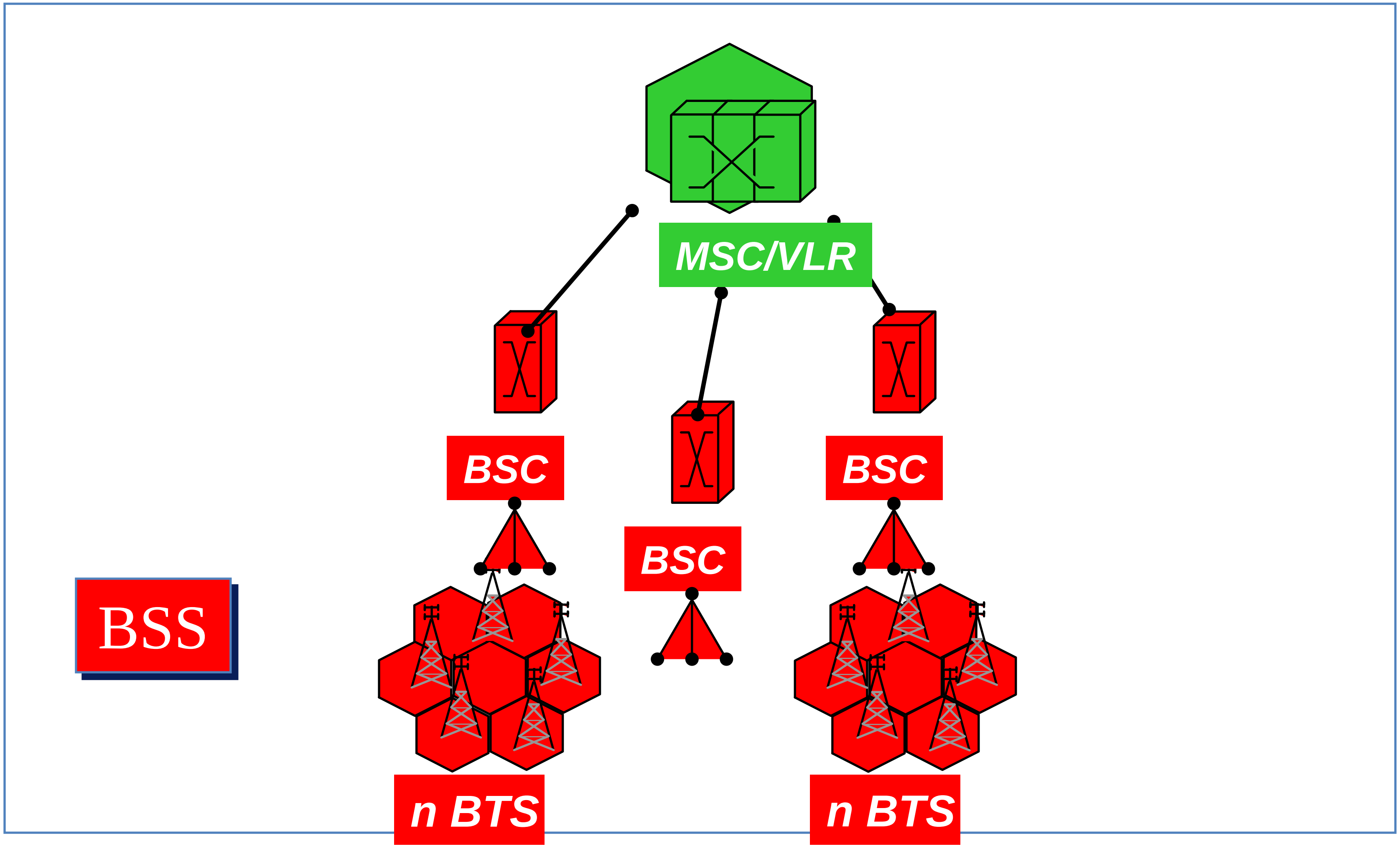
- **TMSI is a temporary IMSI no. made known to an MS at registration.**
- **The VLR assigns a TMSI to each mobile subscribers entering the VLR area.**
- **Assigned only after successful authentication.**

MSRN

Mobile Station Roaming Number

- **The MSRN is used in the GMSC to set up a connection to the visited MSC/VLR.**
- **MSRN--is a temporary identity which is assigned during the establishment of a call to a roaming subs.**

BASE STATION SYSTEM (BSS)



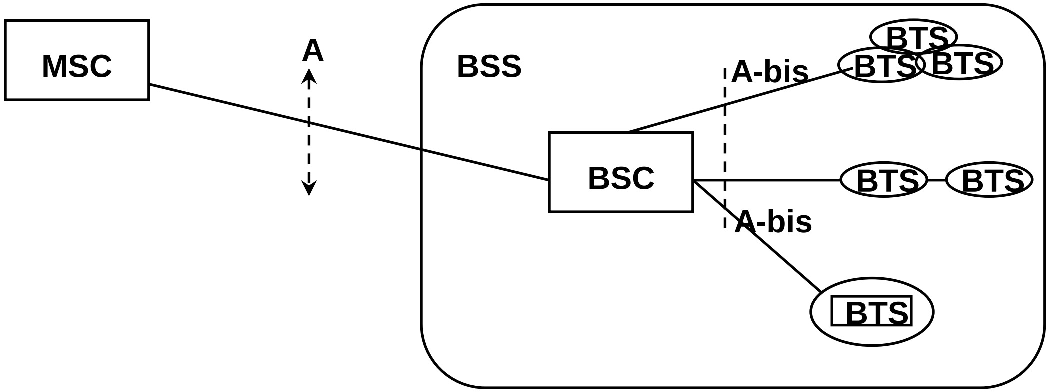
FUNCTIONS OF BTS (Base Transceiver Station)

- Radio resources
- Signal Processing
- Signaling link management
- Synchronization
- Local maintenance handling
- Functional supervision and Testing

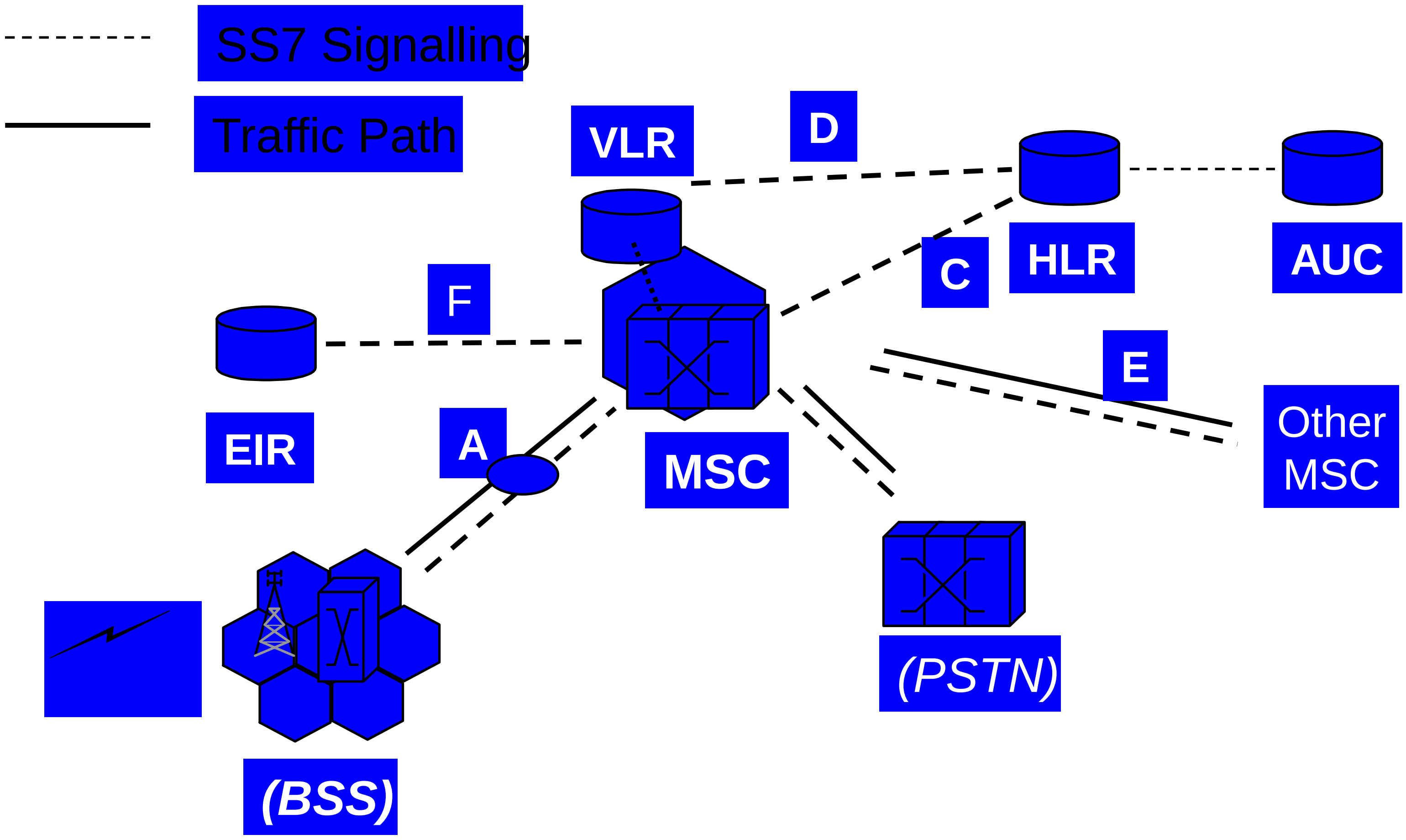
FUNCTIONS OF BSC

- Radio Resource management
- Internal BSC O&M
- Handling of MS connections

MSC-BSS Configurations



Switching System (SS)



MSC Functions

- **Switcing and call routing**
- **Charging**
- **Service provisioning**
- **Communication with HLR**
- **Communication with VLR**
- **Communication with other MSCs**
- **Control of connected BSCs**

MSC Functions

- Echo canceller operation control
- Signaling interface to databases like HLR, VLR.
- Gateway to SMS between SMS centers and subscribers
- Handle interworking function while working as GMSC

VISITOR LOCATION REGISTER (VLR)

- It contains data of all mobiles roaming in its area.
- One VLR may be incharge of one or more LA.
- VLR is updated by HLR on entry of MS its area.
- VLR assigns TMSI which keeps on changing.

Data in VLR

- IMSI & TMSI
- MSISDN
- MSRN.
- Location Area
- Supplementary service parameters
- MS category
- Authentication Key

Home Location Register(HLR)

- **Reference store for subscriber's parameters, numbers, authentication & Encryption values.**

- **Current subscriber status and associated VLR.**

- **Both VLR and HLR can be implemented in the**
same equipment in an MSC.

- **one PLMN may contain one or several HLR.**

Home Location Register(HLR)

- Permanent data in HLR
- ***Data stored is changed only by commands.***
- **IMSI, MS-ISDN number.**
- **Category of MS (whether pay phone or not)**
- **Roaming restriction (allowed or not).**
- **Supplementary services like call forwarding**

Home Location Register(HLR)

- **Temporary data in HLR**
- ***The data changes from call to call & is dynamic***
- **MSRN**
- **RAND /SRES and Kc**
- **VLR address , MSC address.**
- **Messages waiting data used for SMS**

EQUIPMENT IDENTITY REGISTER (EIR)

- **This data base stores IMEI for all registered mobile equipments and is unique to every ME.**

- **Only one EIR per PLMN.**

- ***White list*** **: IMEI, assigned to valid ME.**
- ***Black list*** **: IMEI reported stolen**
- ***Gray list*** **: IMEI having problems like faulty software, wrong make of equipment etc.**

AUthentication Center (AUC)

To authenticate the subs. attempting to use a network.

AUC is connected to HLR which provides it with authentication parameters and ciphering keys used to ensure network security.

AUC Functions

To perform subscriber authentication and to establish ciphering procedures on the radio link between the network and MS.

AUC Functions

Information provided is called a **TRIPLET** consists of:

1. RAND(non predictable random number)
2. SRES(Signed response)
3. Kc(ciphering key)

Operations and Maintenance Centre OMC

The centralized operation of the various units in the system and functions needed to maintain the subsystems.

Dynamic monitoring and controlling of the network

Functions Of OMC

-O&M data function

-Configuration management

--Fault report and alarm handling

-Performance supervision/management

-Storage of system software and data

IS-95 / CDMA

Outline

- CDMA Definition
- IS95 – CDMA One
  - WCDMA - UMTS
- Who uses it
  - Sprint
- PN sequences / Orthogonal Vectors Example
- CDMA Benefits

CDMA

- CDMA – Code Division Multiple Access
  - Fully digital wireless data transmission system
    - Not designed for voice at all
  - Uses special random numbers to encode bits of information.
  - Allows multiple access by assigning different users different random numbers on the same channel.
    - Users have control of a very wide channel bandwidth 1.5 to 5 MHz
  - The only limit to the system is the computing prowess of the base station and it's ability to separate noise from actual data.
    - Shannon's Theorem / SQR

IS-95

- CDMA is an access method.
- IS-95 was the first 'operating system' to use CDMA
  - Invented by Qualcomm
  - Began production in 1995.
  - At this point, this is still called 2G wireless.
    - Known as a narrowband system.
- Being supplanted by CDMA2000 (WCDMA) and UMTS, fully 3G systems.
  - They both use CDMA.
  - Known as wideband systems.

How IS-95 Works

- Operates in the same bandwidth as GSM:
  - 1850 to 1910 MHz Mobile to Base
  - 1930 – 1990 MHz Base to Mobile
- Channels are 1.25 MHz
  - 3.75 MHz in CDMA 2000, 5 MHZ in UMTS
  - Results in approximately only 48 forward/reverse channel pairs in IS-95.
- Adjacent cell phone towers use the exact same channels as all other towers.
  - This is a major difference.
  - Allows for much better frequency reuse and makes setting up a cellular network much easier.

How IS-95 Works

- When a phone is turned on, it scans one of the forward channels to find a base station identifier.
  - Camps on the strongest signal.
- The phone sends out an encrypted pass key and gains access to the network.
- It can then send and receive calls.
  - It is assigned a 1.25 MHz wide frequency to operate on.
- It listens for pages on the forward channel to let it know it has a call incoming.
- This is all very similar to how GSM operates so far.

IS-95 Vocoders

- IS-95 uses extremely advanced vocoders that use variable encoding rates just like GSM.
- They operate at variable rates, up to a maximum of 9600 bps.
- At a minimum, it encodes 1200 bps, so that the phone doesn’t seem dead.
- The quality, though less than AMPS, is much higher than GSM, on average.

IS-95 Vocoders

- However, due to the nature of CDMA, a CRC code is automatically appended in order to do error checking / error correcting.

How IS-95 Works

- The access method is what makes IS-95 different.
  - The access method is called CDMA.
- CDMA is a transmission technique to pass information from the mobile to the base station and from the base station back to the mobile.

CDMA Analogy

- 10 people in a room.
  - 5 speak English, 2 speak Spanish, 2 speak Chinese, and 1 speaks Russian.
- Everyone is talking at relatively the same time over the same medium – the air.
- Who can listen to whom and why?
- Who can't you understand?
- Who can't speak to anyone else?

CDMA

- Spread Spectrum.
  - A signal takes up 6 – 10 times the bandwidth that it needs at a minimum.
    - This seems deliberately inefficient.
  - The military used spread spectrum communications because the signal is:
    - Difficult to block.
    - Difficult to listen in on.
    - Difficult to even identify from noise.
      - Much more difficult to tune into a certain frequency.

CDMA

- In CDMA, all users share the same 1.25 MHz bandwidth.
  - They all transmit a signal that's the exact same size, 1.25 MHz
    - There's actually .02 MHz of a guard band, meaning that the actual bandwidth is 1.23 MHz.
  - This would be like 100 AM radio stations all transmitting on the exact same frequency.
- However, with CDMA, unique digital codes are used to separate each of the mobile phones.
  - Essentially, this makes each mobile phone speak a different language.
    - Also, it's language is very unpredictable, it starts at a random language and changes in random fashion with a given seed.
    - Also, the base station can speak every language as long as it is synchronized.
    - Also, the languages are special in that they will be able to mathematically never interfere with each other.
  - Each bit of the conversation is encoded with this special code.

CDMA Codes Part 1

- In IS-95, the mobile and base station must be synchronized to a nearly perfect time clock.
- CDMA actually uses GPS satellites to obtain a very accurate, system wide clock.
  - This clock is obtained by every cell phone tower and is used to seed the code generation process.

CDMA Codes Part 2

- The base station and mobile phone have an algorithm for generating pseudo random numbers.
  - Uses something called Walsh Vectors.
    - This mathematical function has a way to generate 128 bit random numbers that are orthogonal to every other random number that is has generated.
  - This random number generator has a very large period.
  - When they both start at the same seed (the time), both the mobile and base station should generate the same random numbers.
    - The random number is actually only 32 bits.

CDMA Codes Part 3

- This random number is convoluted with the data.
  - Also, a time stamp is added.
  - And error codes are added.
- The result is 128 bits that represent only 1 bit of data.
  - This is a very computationally intense process.
    - But, modern cell phones have fast processors.
- So, the original 9600 bps of conversation has been multiplied to 1.23 Mbps.

CDMA Codes Example

- These codes are designed to never interfere with any other codes to a very high probability.
- Example (on board)
- The base station, using the mobile's known code, can convolute this code with everything that it received.
  - This convolution results in only what the mobile sent.
- The base station does have to be smart enough to recognize between voice traffic and noise.

CDMA Handoffs

- A CDMA telephone gets to decide on the handoff.
  - This is different than GSM

Advantages of GSM

- GSM is mature, this maturity means a more stable network with robust features.
- Less signal deterioration inside buildings.
- Ability to use repeaters
- The availability of Subscriber Identity Modules allows users to switch networks and handsets at will.
- GSM covers virtually all parts of world so international roaming is not a problem.

Disadvantages of GSM

- Pulse nature of transmission interferes with some electronics, especially certain audio amplifiers.
- Intellectual property is concentrated among a few industry participants, creating barriers to entry for new entrants and limiting competition among phone manufacturers.
- GSM has a fixed maximum cell site range of 35 km, which is imposed by technical limitations.

Advantages of CDMA

- Capacity is CDMA's biggest asset. It can accommodate more users per MHz of bandwidth than any other technology.
  - 3 to 5 times more than GSM
- CDMA has no built-in limit to the number of concurrent users.
- CDMA uses precise clocks that do not limit the distance a tower can cover.
- CDMA consumes less power and covers large areas so cell size in CDMA is larger.
- CDMA is able to produce a reasonable call with lower signal (cell phone reception) levels.
- CDMA uses Soft Handoff, reducing the likelihood of dropped calls.
- CDMA's variable rate voice coders reduce the rate being transmitted when speaker is not talking, which allows the channel to be packed more efficiently.
- Has a well-defined path to higher data rates.

Disadvantages of CDMA

- Most technologies are patented and must be licensed from Qualcomm.
- *Breathing* of base stations, where coverage area shrinks under load. As the number of subscribers using a particular site goes up, the range of that site goes down.
- Currently CDMA covers a smaller portion of the world as compared to GSM which has more subscribers and is in more countries overall worldwide.

DIGITAL EUROPEAN CORDLESS TELEPHONE

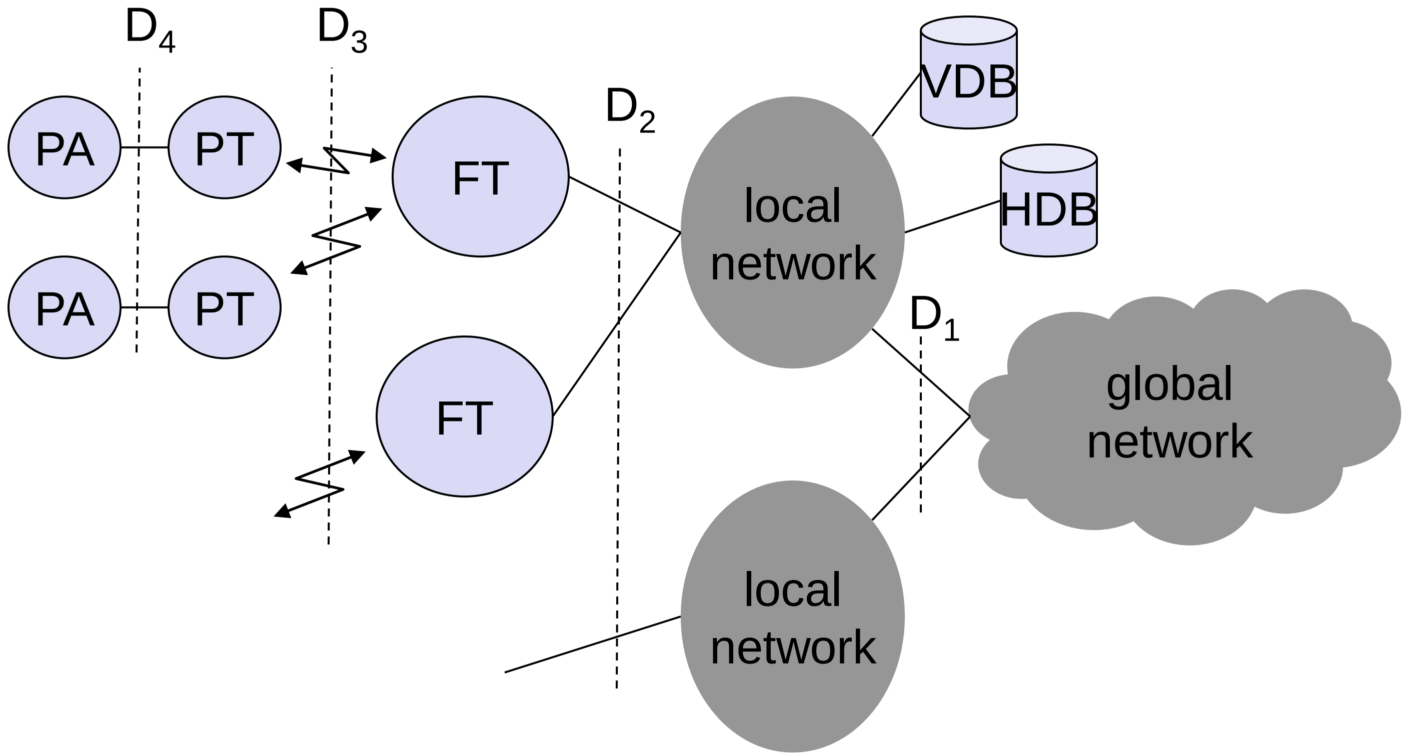
DECT

DECT (Digital European Cordless Telephone)

standard describes air interface between base-station and mobile phone

- DECT has been renamed for international marketing reasons into „Digital Enhanced Cordless Telecommunication“
- Characteristics
  - frequency: 1880-1990 MHz
  - channels: 120 full duplex
  - duplex mechanism: TDD (Time Division Duplex) with 10 ms frame length
  - multplexing scheme: FDMA with 10 carrier frequencies,
TDMA with 2x 12 slots
  - modulation: digital, Gaußian Minimum Shift Key (GMSK)
  - power: 10 mW average (max. 250 mW)
  - range: ca 50 m in buildings, 300 m open space

DECT system architecture reference model



Global network : PSTN,ISDN,PLMN(Public Land Mobile Network)

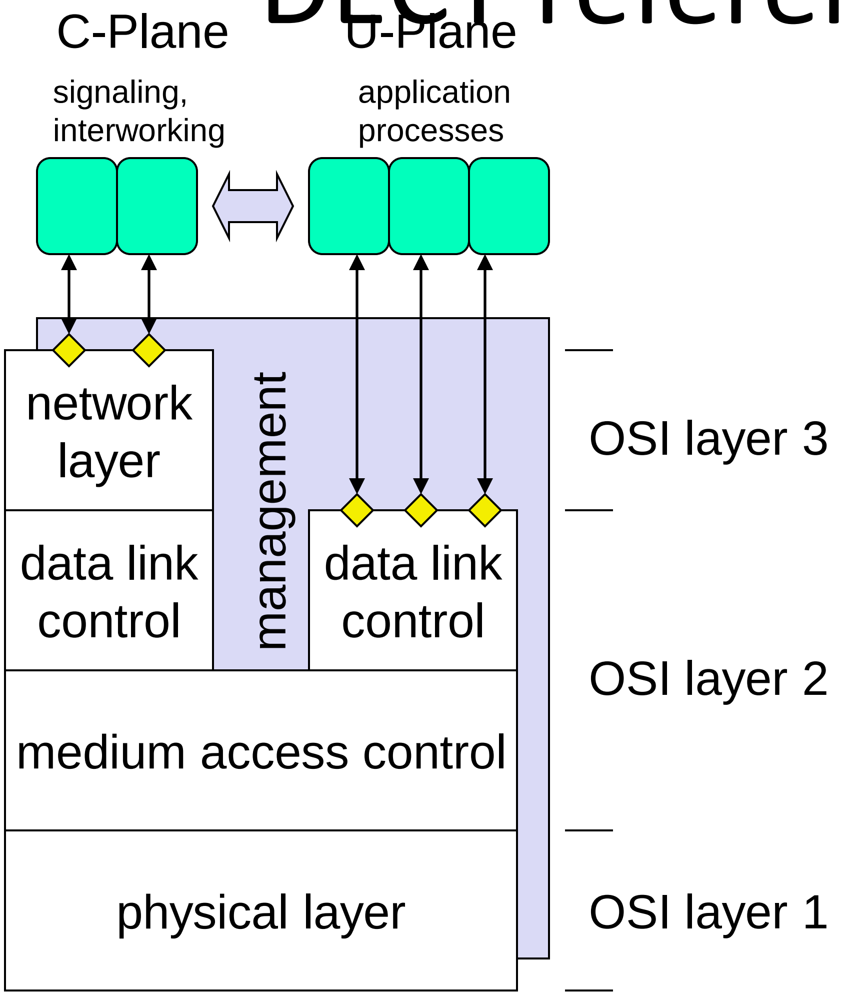
Local network: simple Switching, Intelligent call forwarding, address translation(LAN)

HDB: Home data base

VDB: Visitor Data Base

The local network has fixed Termination (Ft) and Portable radio Termination(PT)

DECT reference model



- close to the OSI reference model
- management plane over all layers
- several services in C(ontrol)- and U(ser)-plane
- Call Control, Supplementary Services, Connectionless message services, Connection oriented message service, mobility management

The data link layer establishes reliable transmission using known data, link control procedures.Data link layer provide,

- Call control including connection setup and release
- Supplementary services
- Connectionless message service
- Connection oriented message service

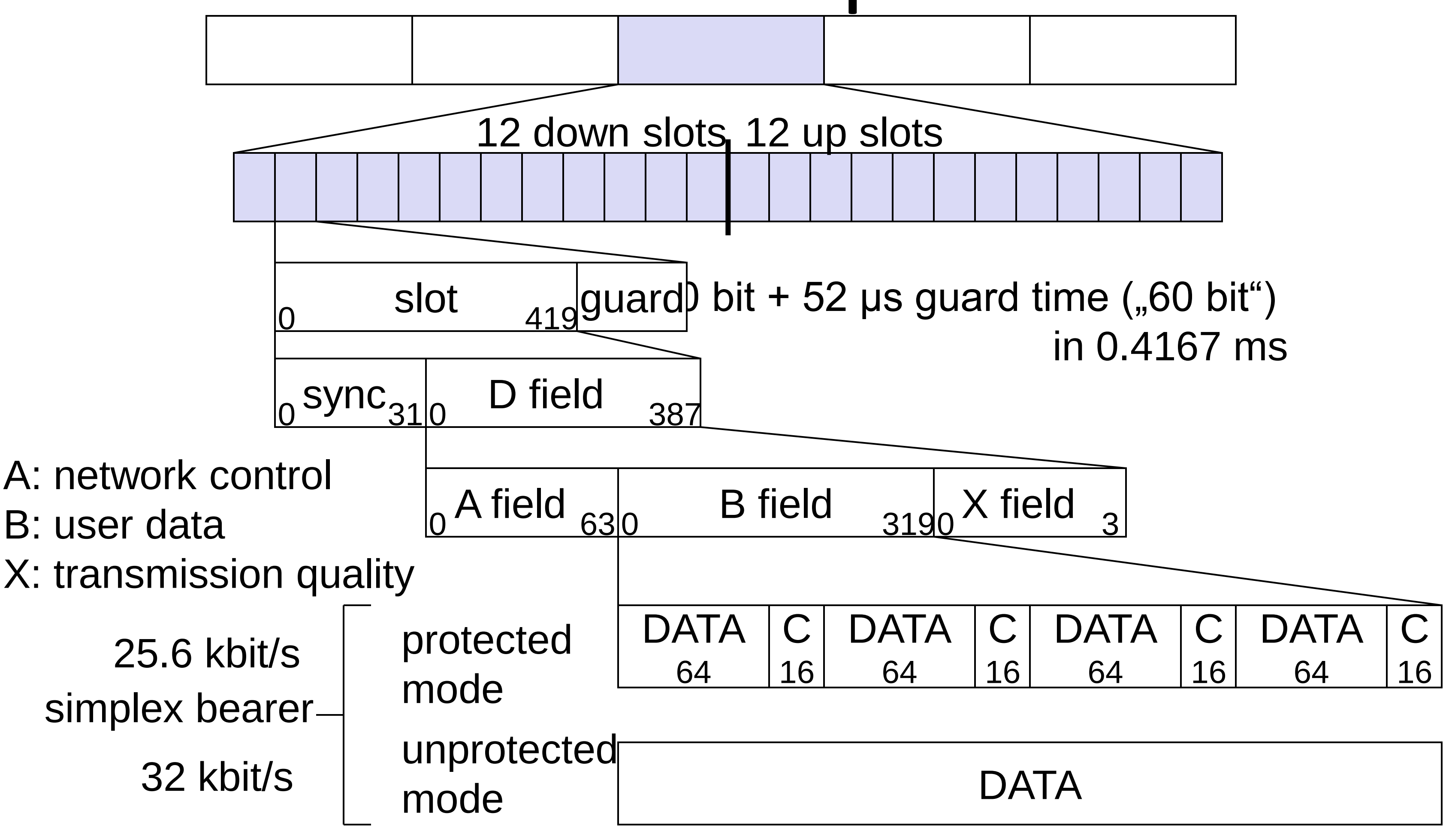
Mobility management is an important function in DECT. It handles

- Identity procedures,
- Authentication procedure,
- Location procedure,
- Access rights procedure,
- Key allocation procedure,
- parameter retreavel procedure,
- ciphering related procedure.

DECT layers I

- Physical layer
  - modulation/demodulation
  - generation of the physical channel structure with a guaranteed throughput
  - controlling of radio transmission
    - channel assignment on request of the MAC layer
    - detection of incoming signals
    - sender/receiver synchronization
    - collecting status information for the management plane
- MAC layer
  - maintaining basic services, activating/deactivating physical channels
  - multiplexing of logical channels
    - e.g., C: signaling, I: user data, P: paging, Q: broadcast
  - segmentation/reassembly
  - error control/error correction

DECT time multiplex frame



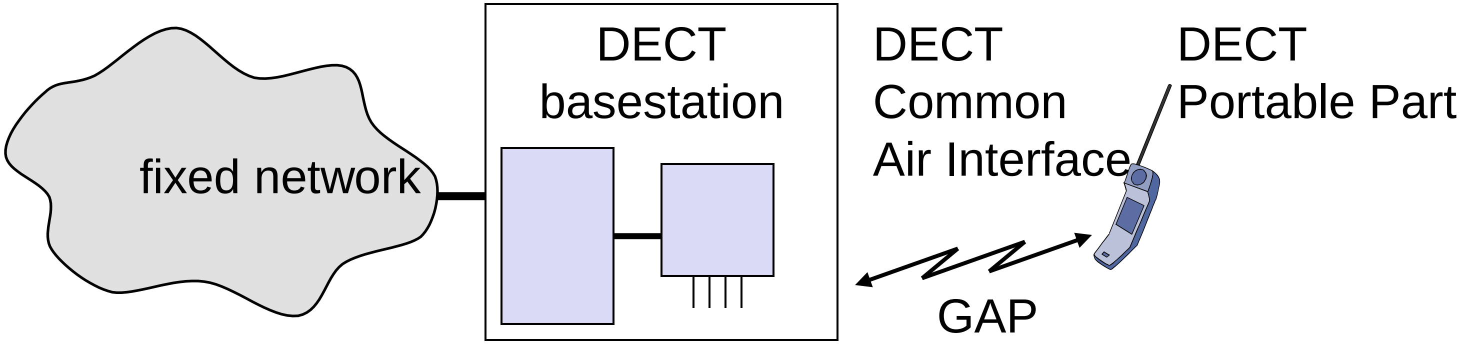
DECT layers II

- Data link control layer
  - creation and keeping up reliable connections between the mobile terminal and basestation
  - two DLC protocols for the control plane (C-Plane)
    - connectionless broadcast service:
      paging functionality
    - protocol:
      in-call signaling adapted to the underlying MAC service
  - several services specified for the user plane (U-Plane)
    - null-service: offers unmodified MAC services
    - frame relay: simple packet transmission
    - frame switching: time-bounded packet transmission
    - error correcting transmission: for delay critical, time-bounded services
    - bandwidth adaptive transmission
    - „Escape“ service: for further enhancements of the standard

Enhancements of the standard

Several „DECT Application Profiles“ in addition to the DECT specification

- GAP (Generic Access Profile) standardized by ETSI in 1997
  - assures interoperability between DECT equipment of different manufacturers (minimal requirements for voice communication)
  - enhanced management capabilities through the fixed network: Cordless Terminal Mobility (CTM)



- DECT/GSM Interworking Profile (GIP): connection to GSM
- ISDN Interworking Profiles (IAP, IIP): connection to ISDN
- Radio Local Loop Access Profile (RAP): public telephone service
- CTM Access Profile (CAP): support for user mobility

TETRA - Terrestrial Trunked Radio

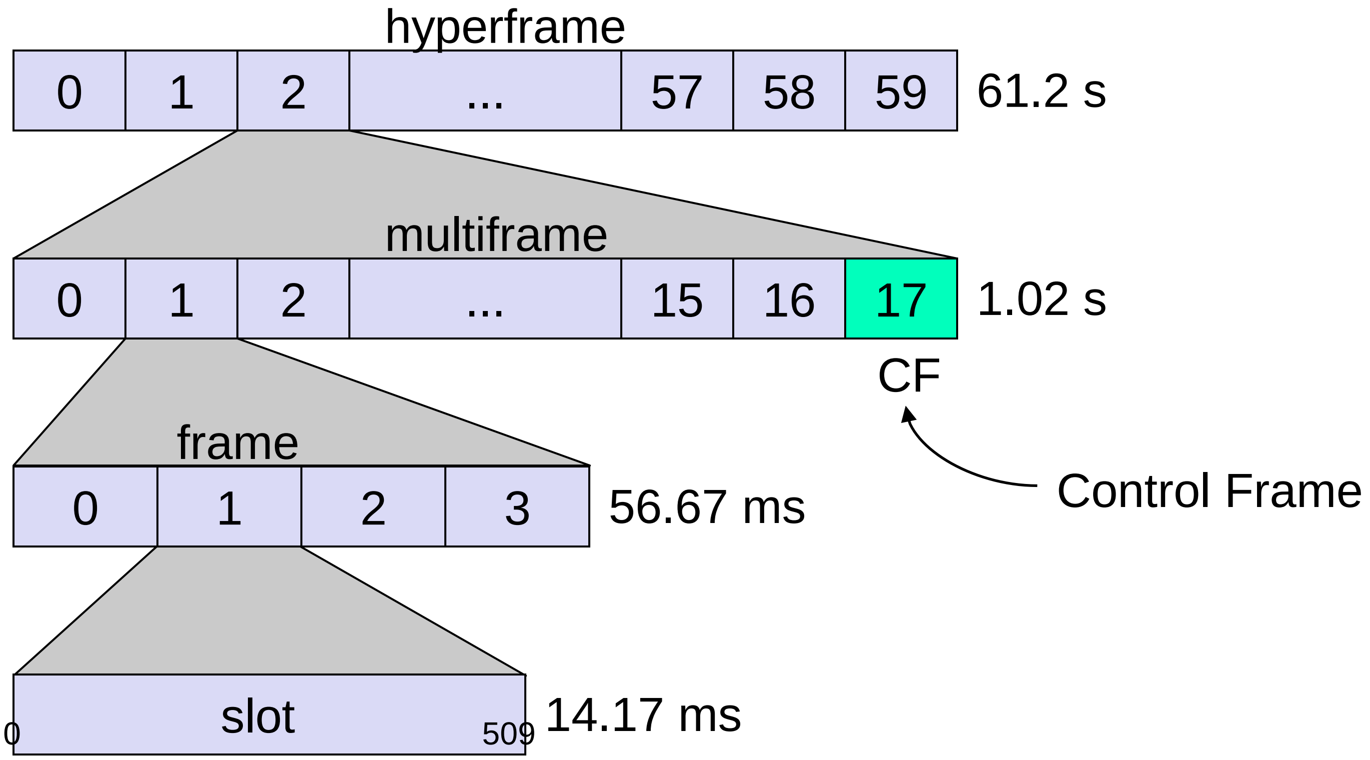
Trunked radio systems

- many different radio carriers
- assign single carrier for a short period to one user/group of users
- taxi service, fleet management
- interfaces to public networks, voice and data services
- very reliable, fast call setup, local operation

TETRA

- formerly: Trans European Trunked Radio
- offers Voice+Data and Packet Data Optimized service
- point-to-point and point-to-multipoint
- ad-hoc and infrastructure networks
- several frequencies: 380-400 MHz, 410-430 MHz
- FDD, DQPSK
- group call, broadcast, sub-second group-call setup

TDMA structure of the voice+data system



RFID ANTENNA

Overview

- What is RFID?
- How RFID Works
- Current Applications
- Future Applications
- Potential Research
- Discussion

What is RFID?

- Radio Frequency Identification
- The use of radio frequency tags to identify real objects.

Identification

- Assign IDs to objects
- Link the ID to additional information about the object
- Link the ID to complementary info
- Find similar objects

Identification Examples

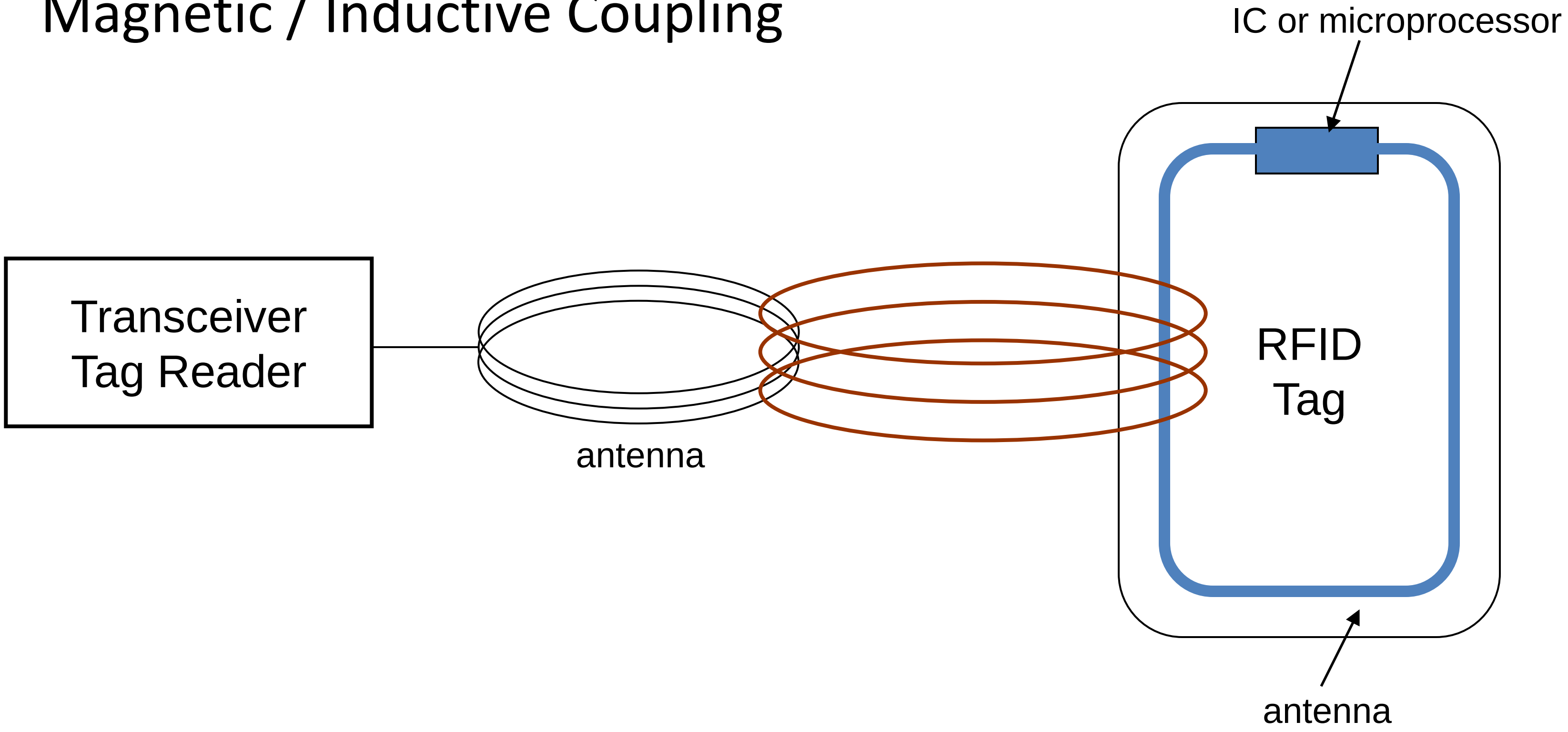
- Bar Codes
- License Plates
- Social Security Numbers
- Student ID
- Serial Numbers
- Car Keys
- Database Keys

How Does RFID Work?

- 3 Components
  - Transceiver – Tag Reader
  - Transponder – RFID tag
  - Antenna

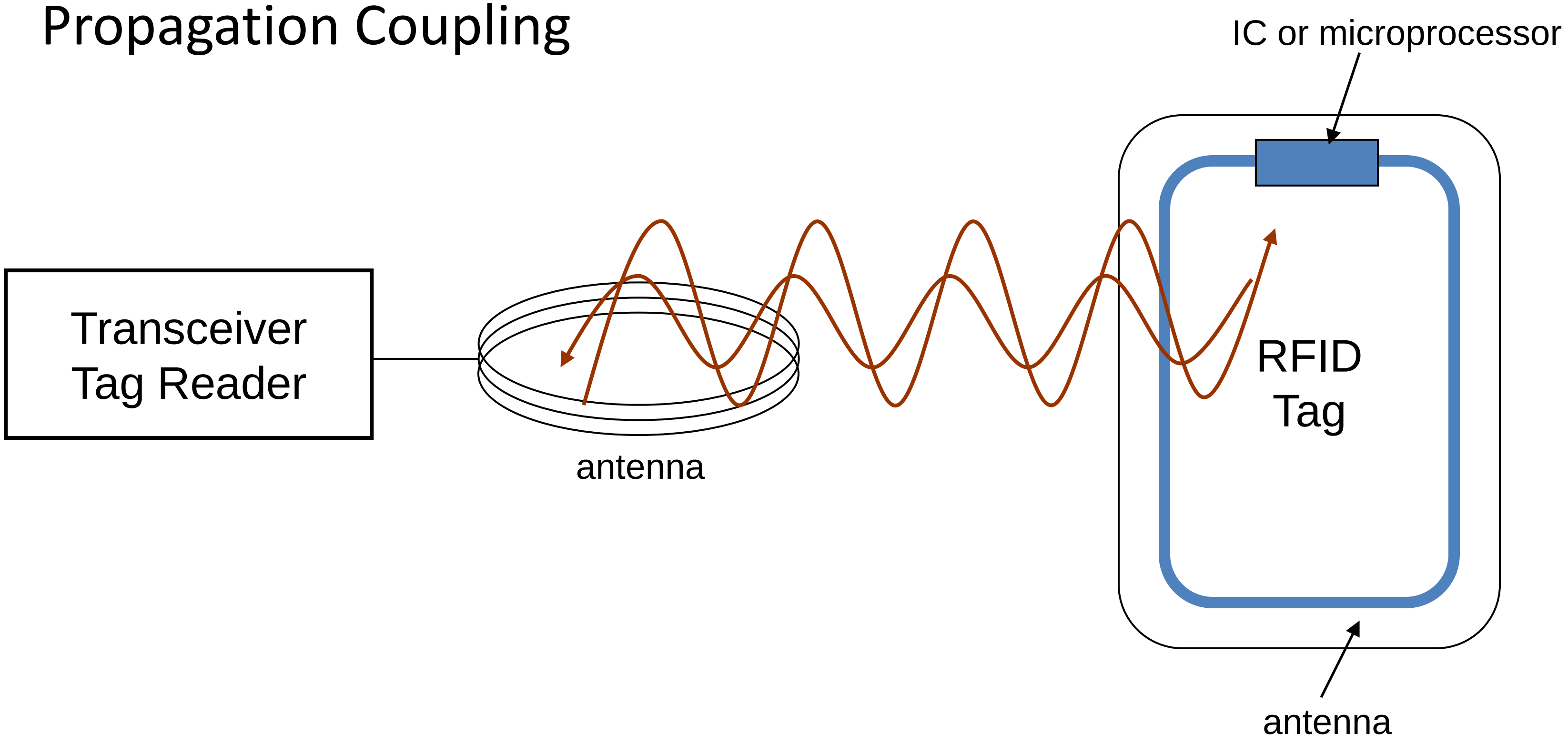
RFID Hardware

Magnetic / Inductive Coupling



RFID Hardware

Propagation Coupling



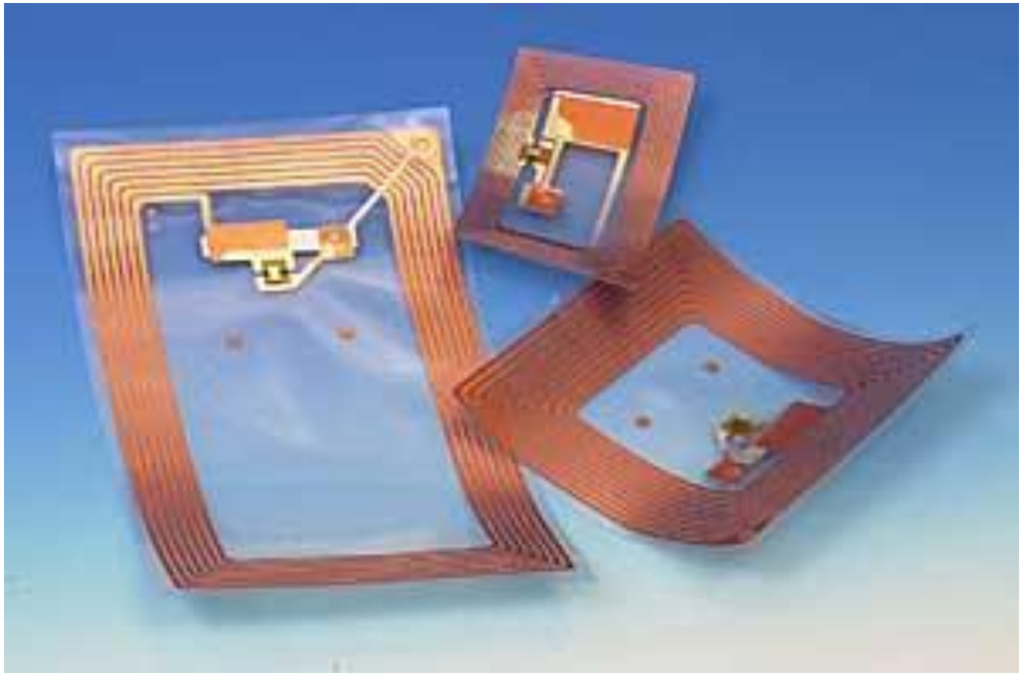
Types of Tags

- Passive Tags
  - No battery
  - Low cost
- Active Tags
  - On-board transceiver
  - Battery – must be replaced
  - Longer range
  - High cost

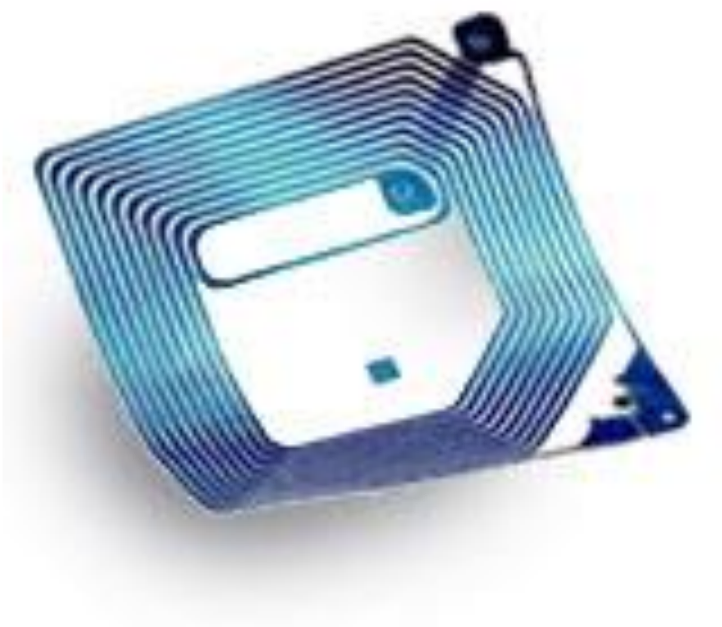
Types of Tags

- Read Only
  - factory programmed
  - usually chipless
- Read / Write
  - on-board memory
  - can save data
  - can change ID
  - higher cost

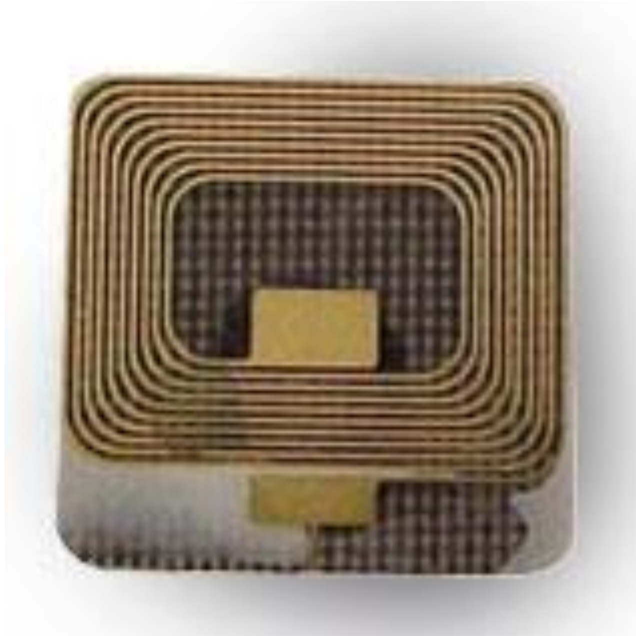
Real Tags



Real Tags



Real Tags



Data Transfer

- Amplitude Modulation (AM)
- Frequency Shift Keying (FSK)
- Phase Shift Keying (PSK)

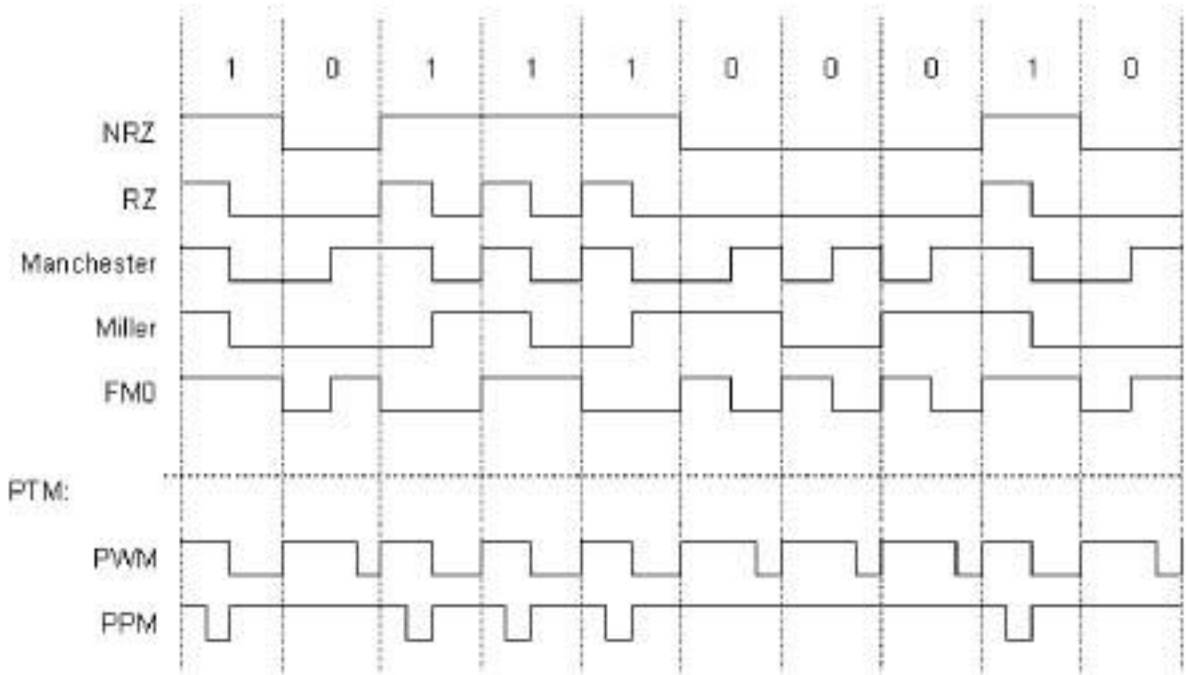
Frequency Shift Keying

- Fc/8/10
  - 0’s are the carrier divided by 8
  - 1’s are the carrier divided by 10
- Count clock cycles between changes in frequency
- Slows the data rate
- Provides for a simple reader design
- Fair noise immunity

Phase Shift Keying

- One frequency
  - Change the phase on the transition between a 0 to 1 or 1 to 0
- Faster data rate than FSK
- Noise immunity
- Slightly more difficult to build a reader than FSK

Data Encoding



Collision Avoidance

- Similar to network collision avoidance
- Probabilistic
  - Tags return at random times
- Deterministic
  - Reader searches for specific tags

Frequency Ranges

- Low – 100-500 kHz
  - – short range, low data rate, cost, & power
- Intermediate – 10-16 MHz
  - – medium range and data rate
- High – 850-950 MHz & 2.4-5.8GHz
  - – large range, high cost, high data rate
  - – needs line of sight

Frequency Ranges

- 8 total ranges around the world
- No standards … yet

Frequency Trade-Offs

Frequency

- Power
- Cost
- Bandwidth
- Line of Sight

- Lifespan
- Range

Current Applications

- Livestock Tagging
- Wild Animal Tracking
- Electronic Article Surveillance (EAS)
- Automated Toll Collection
- Animal Husbandry
- Vehicle Anti-Theft

More Applications

- Passive / Secure Entry
- Airline Baggage Tracking
- Postal Package Tracking
- Time and Attendance

Security

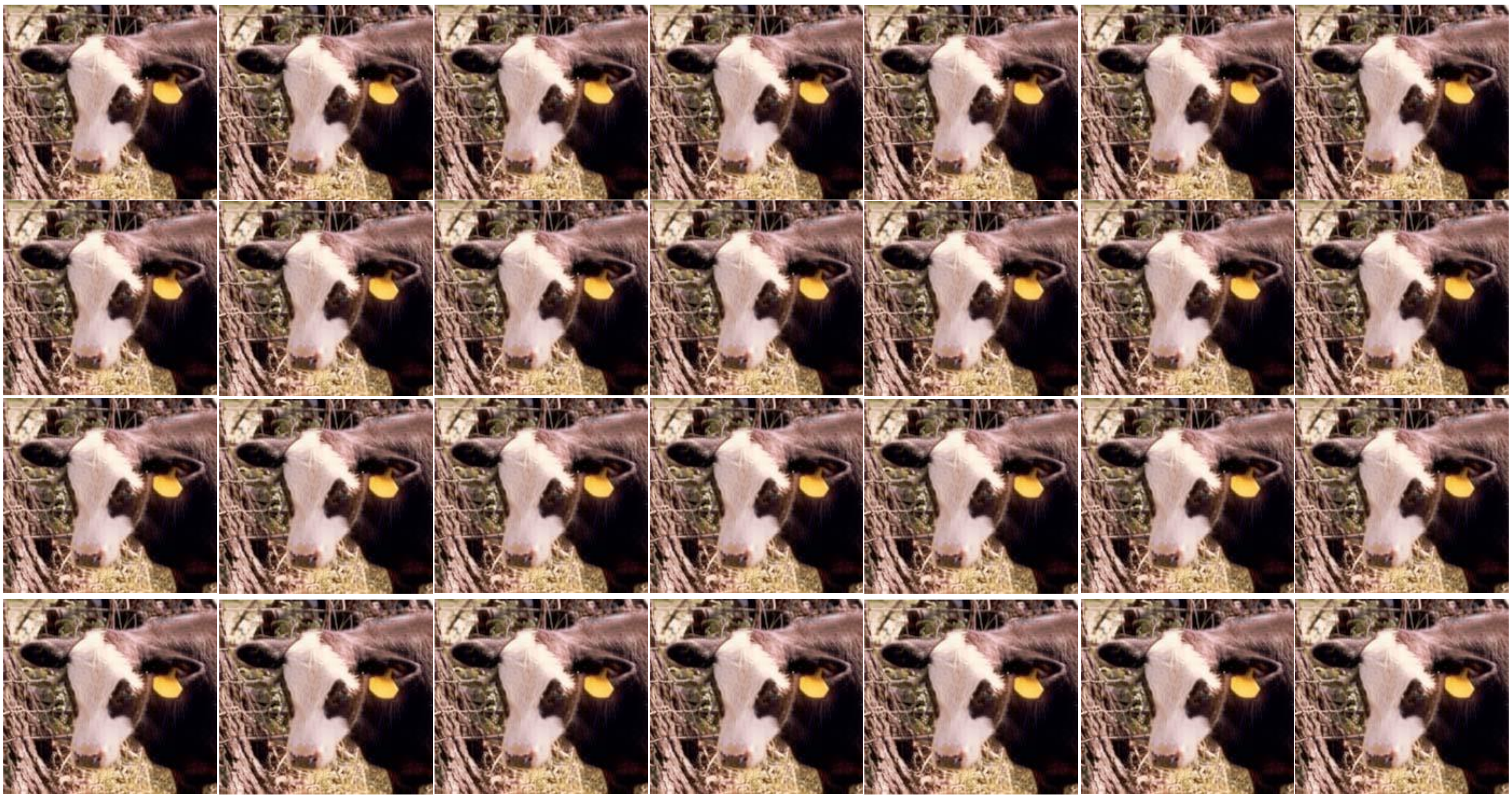
- RFID used to grant entry to secure areas
- Tracks time and movement of people
- Dynamically change access codes
- Provide automated entry

Livestock Tagging

Meet Bobby the Cow

Bobby has an old fashioned ear tag for identification.

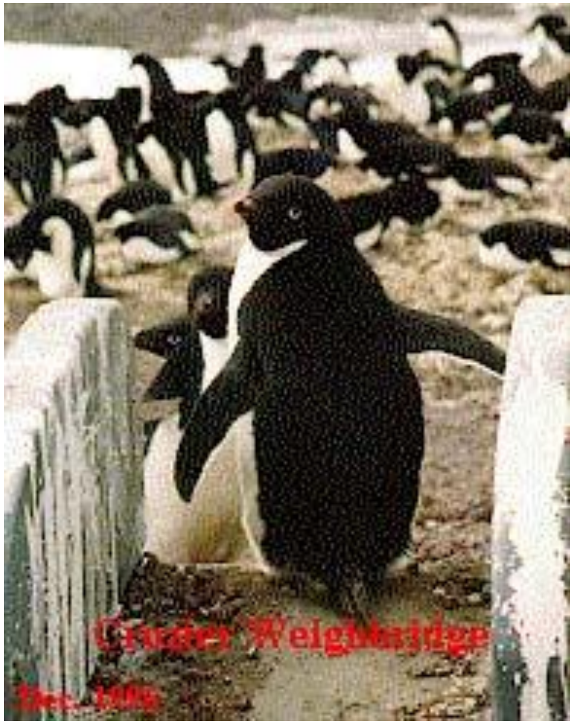
Bobby's Part of a Herd

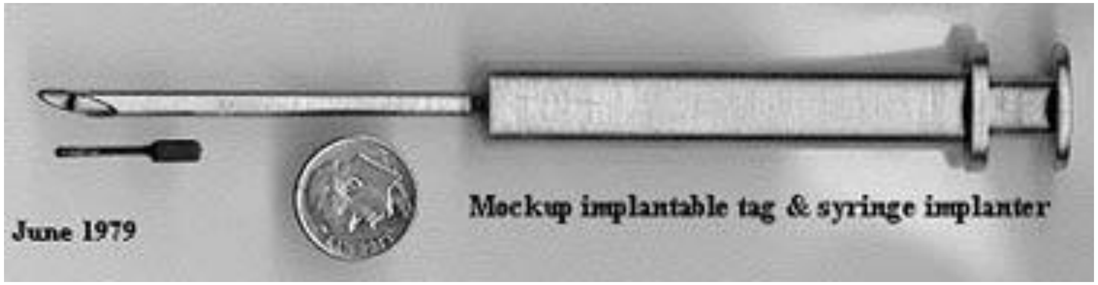


Bobby Needs His Shots

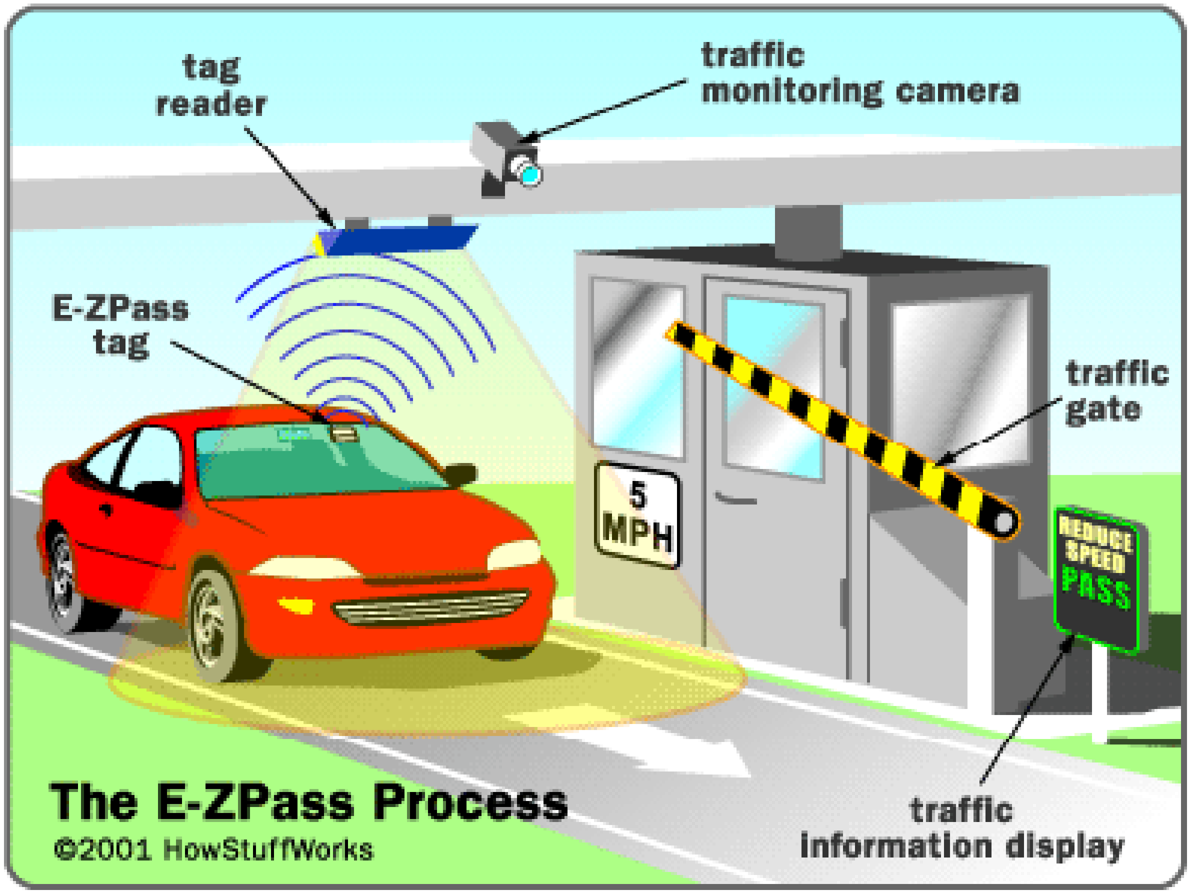
- All of Bobby's herd need their shots
- Each one needs to be recorded
- Why use RFID tags instead of the old-fashioned tags?
  - cows get dirty
  - herds can be large

Tracking Penguins

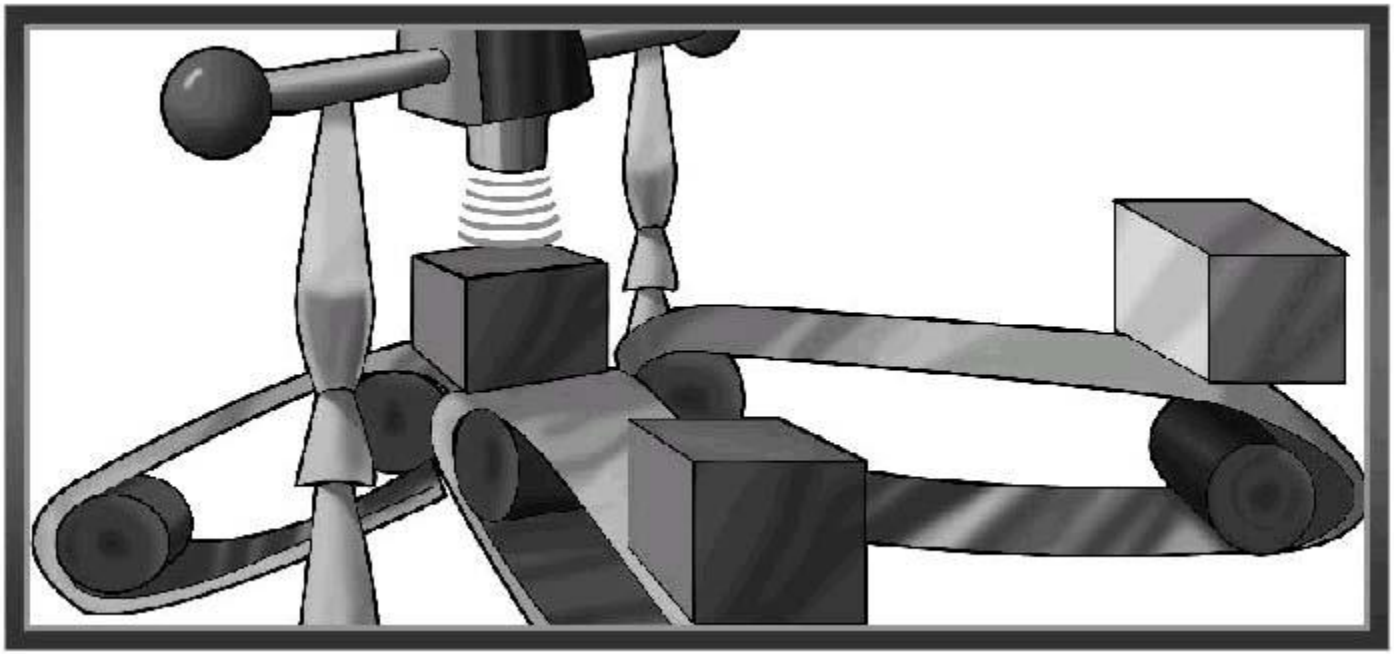




Automated Toll Collection



Package Tracking



Picture courtesy Texas Instruments

Potential Applications

- Smart Grocery Store
- Smart Kitchen
- Smart Sitterson

Smart Grocery Store

- Every item in the store already has a bar code.
- Why not use an RFID tag?
- Speed up checkouts

Smart Grocery Store

- Several carts this full in early evening could seriously slow down the checkout process.
- How much do cashiers cost?

Smart Grocery Store

- Add an RFID tag to all items in the grocery.
- As the cart leaves the store, it passes through an RFID transceiver
- The cart is rung up in seconds.

RFID UPC

Smart Groceries Enhanced

- Track products through their entire lifetime.

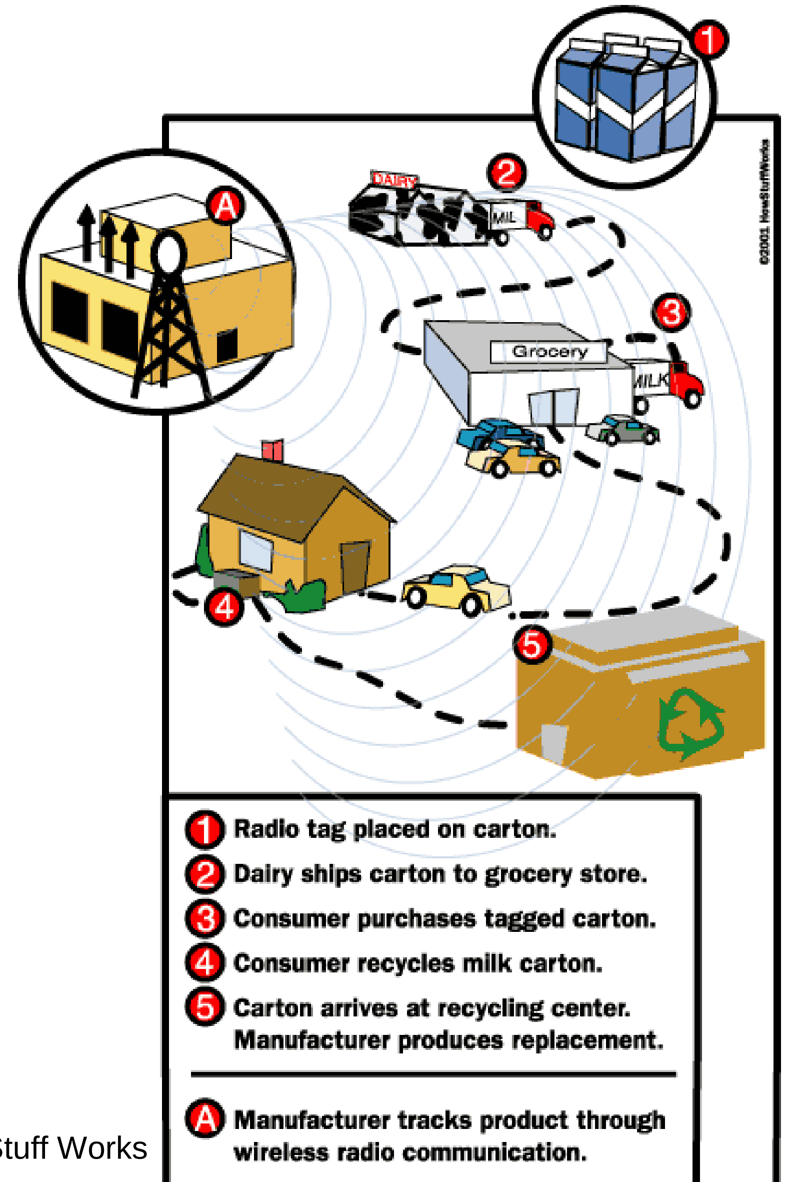


Diagram courtesy How Stuff Works

Smart Fridge

- Recognizes what’s been put in it
- Recognizes when things are removed
- Creates automatic shopping lists
- Notifies you when things are past their expiration

RFID Chef

- Uses RFID tags to recognize food in your kitchen
- Shows you the recipes that most closely match what is available

Smart Sitterson

- Tag locations throughout Sitterson
- User walks around with handheld and transceiver
- RFID tags point the handheld to a webpage with more information about their location or the object of interest

RFID’s Advantages

- Passive
  - wireless
- Store data on a tag
- Can be hidden
- Work in harsh environments
- Low cost?

RFID’s Disadvantages

- Lack of standards!
- Short range
- Cost

MOBILE ANTENNAS

HISTORY

- The first antennas were built in 1888 by German physicist Heinrich Hertz in his pioneering experiments to prove the existence of electromagnetic waves predicted by the theory of James Clerk Maxwell.
- Hertz placed dipole antennas at the focal point of parabolic reflectors for both transmitting and receiving. He published his work in Annalen der Physik und Chemie (vol. 36, 1889).

INTRODUCTION

- An antenna is an electrical device which converts electric currents into radio waves, and vice versa. It is usually used with a radio transmitter or radio receiver.
- In transmission, a radio transmitter applies an oscillating radio frequency electric current to the antenna's terminals, and the antenna radiates the energy from the current as electromagnetic waves (radio waves).

- Transmitting Antenna: Any structure designed to efficiently radiate electromagnetic radiation in a preferred direction is called a *transmitting antenna*.
- In reception, an antenna intercepts some of the power of an electromagnetic wave in order to produce a tiny voltage at its terminals, that is applied to a receiver to be amplified. An antenna can be used for both transmitting and receiving.
- Receiving Antenna: Any structure designed to efficiently receive electromagnetic radiation is called a receiving antenna

BASIC STRUCTURE

- It is a metallic conductor system capable of radiating and receiving em waves.
- Typically an antenna consists of an arrangement of metallic conductors (“elements"), electrically connected (often through a transmission line) to the receiver or transmitter.
- An oscillating current of electrons forced through the antenna by a transmitter will create an oscillating magnetic field around the antenna elements, while the charge of the electrons also creates an oscillating electric field along the elements.

- These time-varying fields radiate away from the antenna into space as a moving electromagnetic field wave.
- Conversely, during reception, the oscillating electric and magnetic fields of an incoming radio wave exert force on the electrons in the antenna elements, causing them to move back and forth, creating oscillating currents in the antenna.
- Antenna reciprocity : can be used as transmitter and receiver.In two way communication same antenna can be used as transmitter and receiver.

- Antennas may also contain reflective or directive elements or surfaces not connected to the transmitter or receiver, such as parasitic elements, parabolic reflectors or horns, which serve to direct the radio waves into a beam or other desired radiation pattern.
- Antennas can be designed to transmit or receive radio waves in all directions equally (omnidirectional antennas), or transmit them in a beam in a particular direction, and receive from that one direction only (directional or high gain antennas).

WHY ANTENNAS ?

- Need of antenna arisen when two person wanted to communicate between them when separated by some distance and wired communication is not possible.
- Antennas are required by any radio receiver or transmitter to couple its electrical connection to the electromagnetic field.
- Radio waves are electromagnetic waves which carry signals through the air (or through space) at the speed of light with almost no transmission loss.

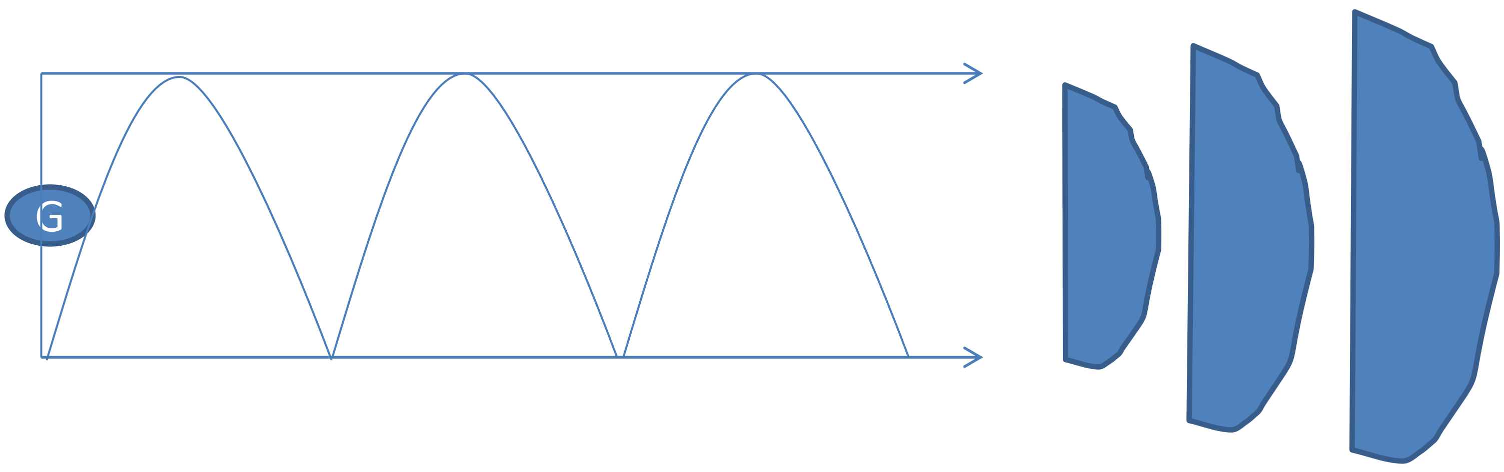
- Radio transmitters and receivers are used to convey signals (information) in systems including broadcast (audio) radio, television, mobile telephones , point-to-point communications links (telephone, data networks), satellite links.
- Radio waves are also used directly for measurements in technologies including Radar, GPS, and radio astronomy.
- In each and every case, the transmitters and receivers involved require antennas, although these are sometimes hidden (such as the antenna inside an AM radio or inside a laptop computer equipped with wi-fi).

WHERE USED?

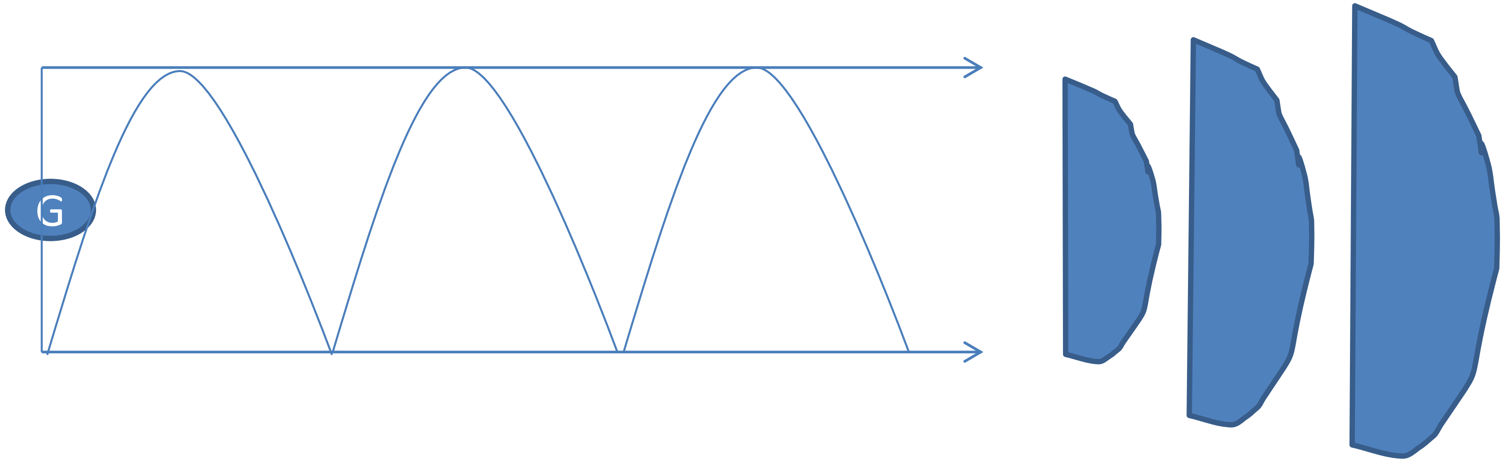
- Antennas are used in systems such as radio and television broadcasting, point to point radio communication, wireless LAN, radar and space exploration
- Antennas are most utilized in air or outer space
- But can also be operated under water or even through soil and rock at certain frequencies for short distances

RADIATION MECHANISM

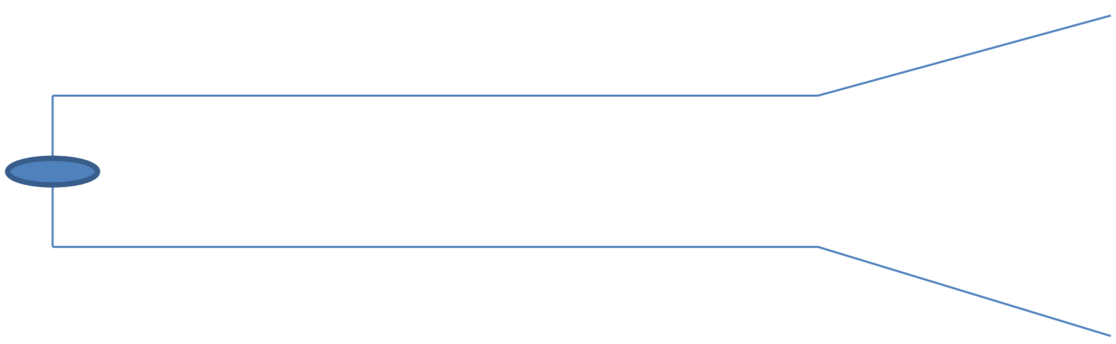
- Ideally all incident energy must be reflected back when open circuit. But practically a small portion of electromagnetic energy escapes from the system that is it gets radiated.
- This occurs because the line of force don't undergo complete phase reversal and some of them escapes.



- The amount of escaped energy is very small due to mismatch between transmission line and surrounding space.
- Also because two wires are too close to each other, radiation from one tip will cancel radiation from other tip.(as they are of opposite polarities and distance between them is too small as compared to wavelength)



- To increase amount of radiated power open circuit must be enlarged , by spreading the two wires.
- Due to this arrangement, coupling between transmission line and free space is improved.
- Also amount of cancellation has reduced.
- The radiation efficiency will increase further if two conductors of transmission line are bent so as to bring them in same line.



TYPES OF ANTENNAS

- According to their applications and technology available, antennas generally fall in one of two categories:

  1. Omnidirectional or only weakly directional antennas which receive or radiate more or less in all directions. These are employed when the relative position of the other station is unknown or arbitrary. They are also used at lower frequencies where a directional antenna would be too large, or simply to cut costs in applications where a directional antenna isn't required.

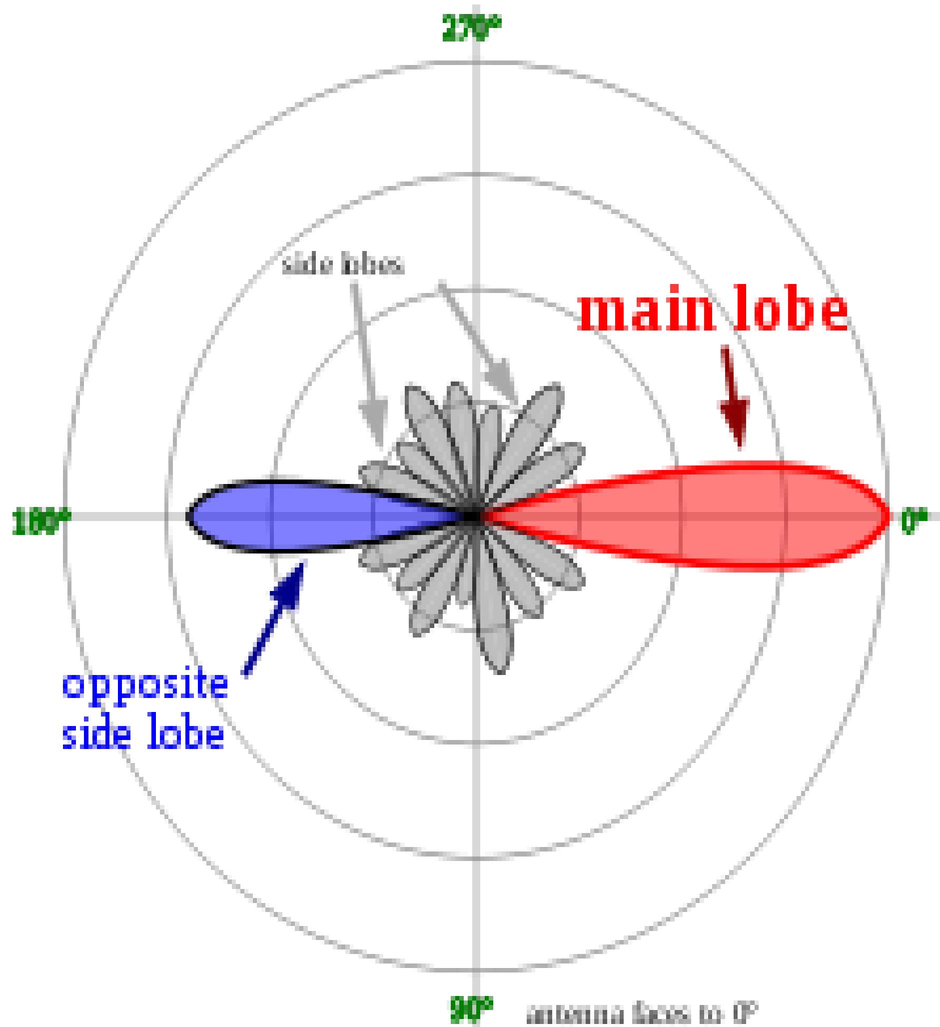
  2. Directional or *beam* antennas which are intended to preferentially radiate or receive in a particular direction or directional pattern.

- According to length of transmission lines available, antennas generally fall in one of two categories:

  1. Resonant Antennas – is a transmission line, the length of which is exactly equal to multiples of half wavelength and it is open at both ends.

  2. Non-resonant Antennas – the length of these antennas is not equal to exact multiples of half wavelength. In these antennas standing waves are not present as antennas are terminated in correct impedance which avoid reflections. The waves travel only in forward direction .Non-resonant antenna is a unidirectional antenna.

RADIATION PATTERN



- The radiation pattern of an antenna is a plot of the relative field strength of the radio waves emitted by the antenna at different angles.
- It is typically represented by a three dimensional graph, or polar plots of the horizontal and vertical cross sections. It is a plot of field strength in V/m versus the angle in degrees.
- The pattern of an ideal isotropic antenna , which radiates equally in all directions, would look like a sphere.
- Many non-directional antennas, such as dipoles, emit equal power in all horizontal directions, with the power dropping off at higher and lower angles; this is called an omni directional pattern and when plotted looks like a donut.

- The radiation of many antennas shows a pattern of maxima or "*lobes*" at various angles, separated by “*nulls*", angles where the radiation falls to zero.
- This is because the radio waves emitted by different parts of the antenna typically interfere, causing maxima at angles where the radio waves arrive at distant points in phase, and zero radiation at other angles where the radio waves arrive out of phase.
- In a directional antenna designed to project radio waves in a particular direction, the lobe in that direction is designed larger than the others and is called the "*main lobe*".
- The other lobes usually represent unwanted radiation and are called “*sidelobes*". The axis through the main lobe is called the "*principle axis*" or “*boresight axis*".

ANTENNA GAIN

- Gain is a parameter which measures the degree of directivity of the antenna's radiation pattern. A high-gain antenna will preferentially radiate in a particular direction.
- Specifically, the *antenna gain*, or *power gain* of an antenna is defined as the ratio of the intensity (power per unit surface) radiated by the antenna in the direction of its maximum output, at an arbitrary distance, divided by the intensity radiated at the same distance by a hypothetical isotropic antenna.

- The gain of an antenna is a passive phenomenon - power is not added by the antenna, but simply redistributed to provide more radiated power in a certain direction than would be transmitted by an isotropic antenna.
- High-gain antennas have the advantage of longer range and better signal quality, but must be aimed carefully in a particular direction.
- Low-gain antennas have shorter range, but the orientation of the antenna is relatively inconsequential.

- For example, a dish antenna on a spacecraft is a high-gain device that must be pointed at the planet to be effective, whereas a typical Wi-Fi antenna in a laptop computer is low-gain, and as long as the base station is within range, the antenna can be in any orientation in space.
- In practice, the half-wave dipole is taken as a reference instead of the isotropic radiator. The gain is then given in **dBd** (decibels over **d**ipole)

ANTENNA EFFICIENCY

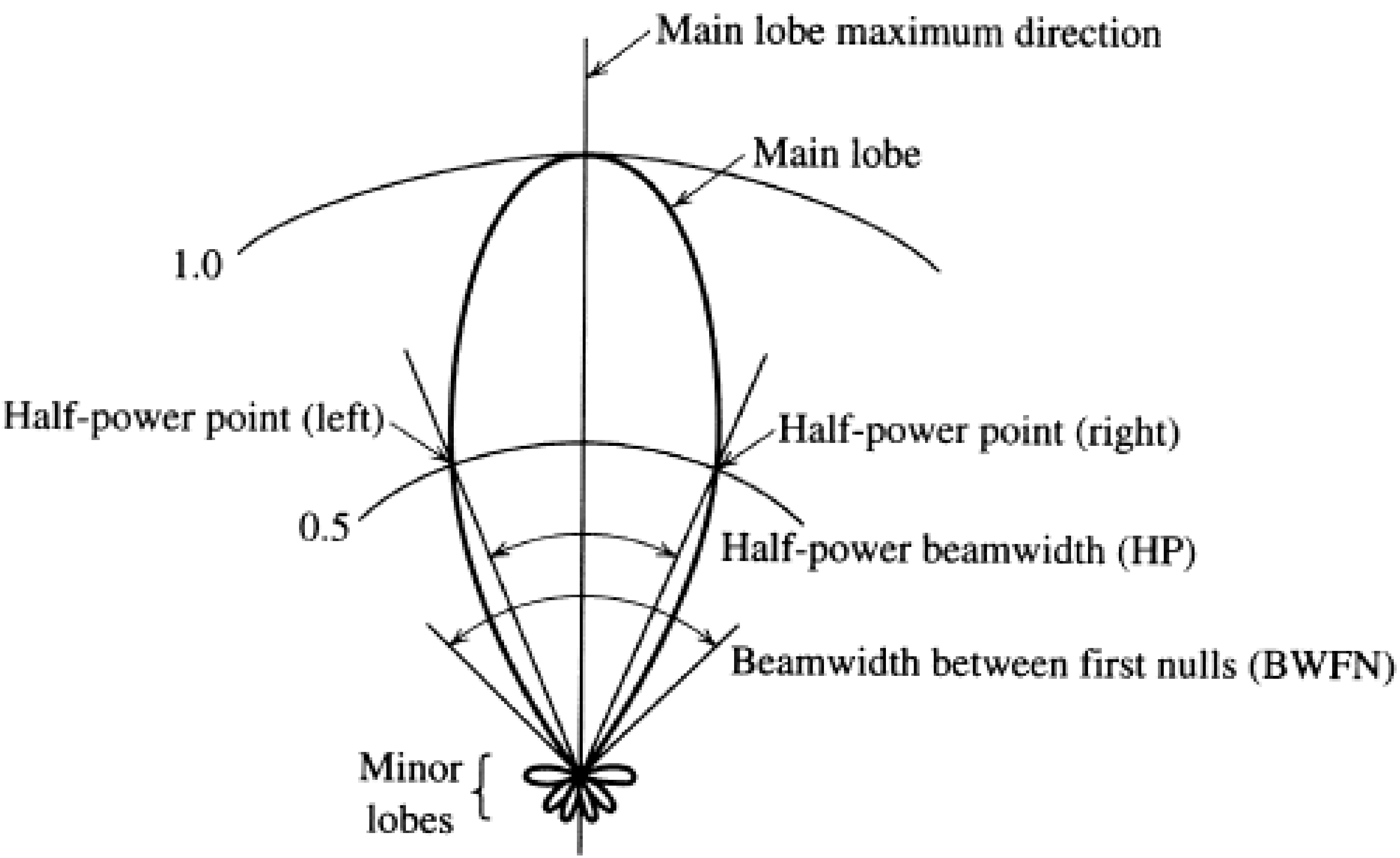
- Efficiency of a transmitting antenna is the ratio of power actually radiated (in all directions) to the power absorbed by the antenna terminals.
- The power supplied to the antenna terminals which is not radiated is converted into heat. This is usually through loss resistance in the antenna's conductors, but can also be due to dielectric or magnetic core losses in antennas (or antenna systems) using such components.

POLARIZATION

- The polarization of an antenna is the orientation of the electric field (E-plane) of the radio wave with respect to the Earth's surface and is determined by the physical structure of the antenna and by its orientation.
- A simple straight wire antenna will have one polarization when mounted vertically, and a different polarization when mounted horizontally.
- Reflections generally affect polarization. For radio waves the most important reflector is the ionosphere - signals which reflect from it will have their polarization changed
- LF,VLF and MF antennas are vertically polarized

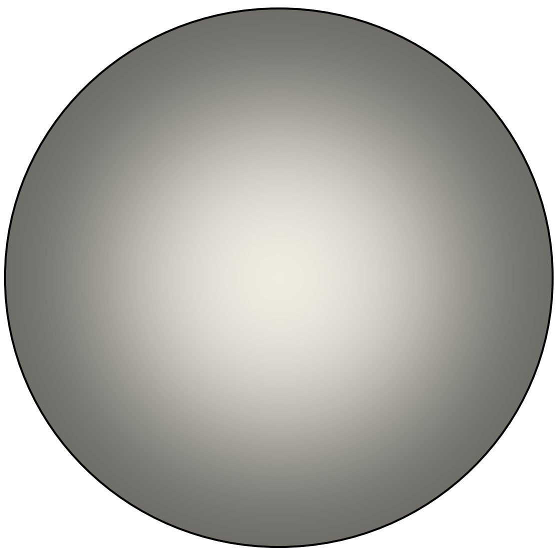
BEAM-WIDTH

- Beam-width of an antenna is defined as angular separation between the two half power points on power density radiation pattern OR
- Angular separation between two 3dB down points on the field strength of radiation pattern
- It is expressed in degrees



Main lobe maximum direction
Main lobe
1.0
Half-power point (left)
Half-power point (right)
0.5
Half-power beamwidth (HP)
Beamwidth between first nulls (BWFN)
Minor lobes

ISOTROPIC ANTENNA



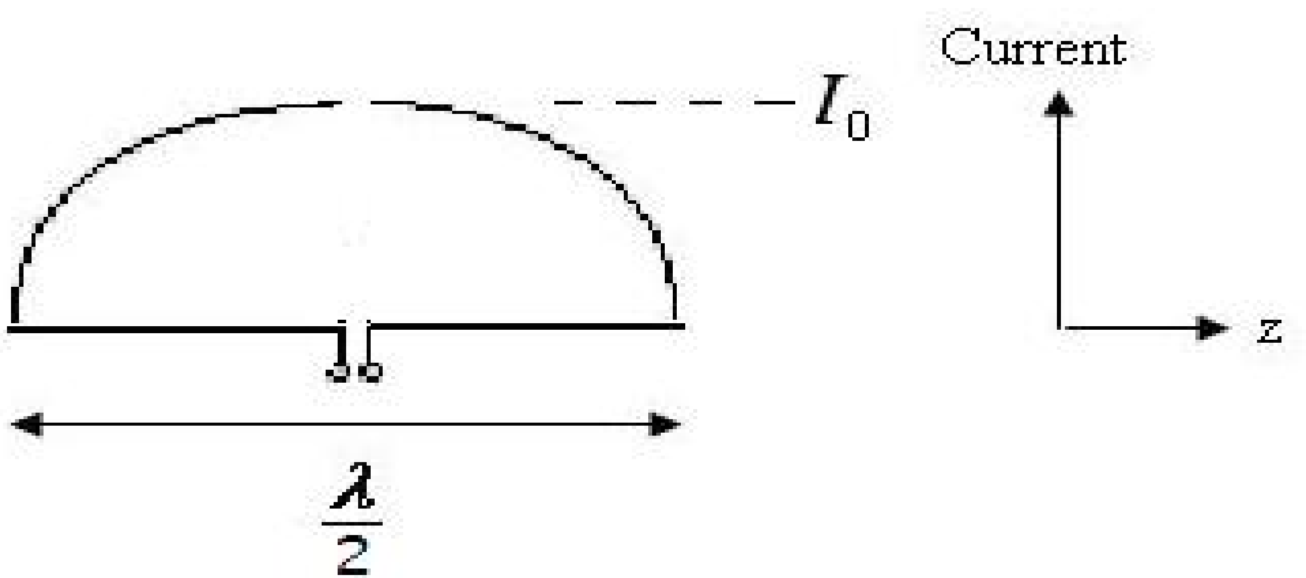
- ***Isotropic antenna or isotropic radiator*** is a hypothetical (not physically realizable) concept, used as a useful reference to describe real antennas.
- Isotropic antenna radiates equally in all directions.
  - Its radiation pattern is represented by a sphere whose center coincides with the location of the isotropic radiator.

- It is considered to be a point in space with no dimensions and no mass. This antenna cannot physically exist, but is useful as a theoretical model for comparison with all other antennas.
- Most antennas' gains are measured with reference to an isotropic radiator, and are rated in dBi (decibels with respect to an isotropic radiator).

HALF WAVE DIPOLE ANTENNA

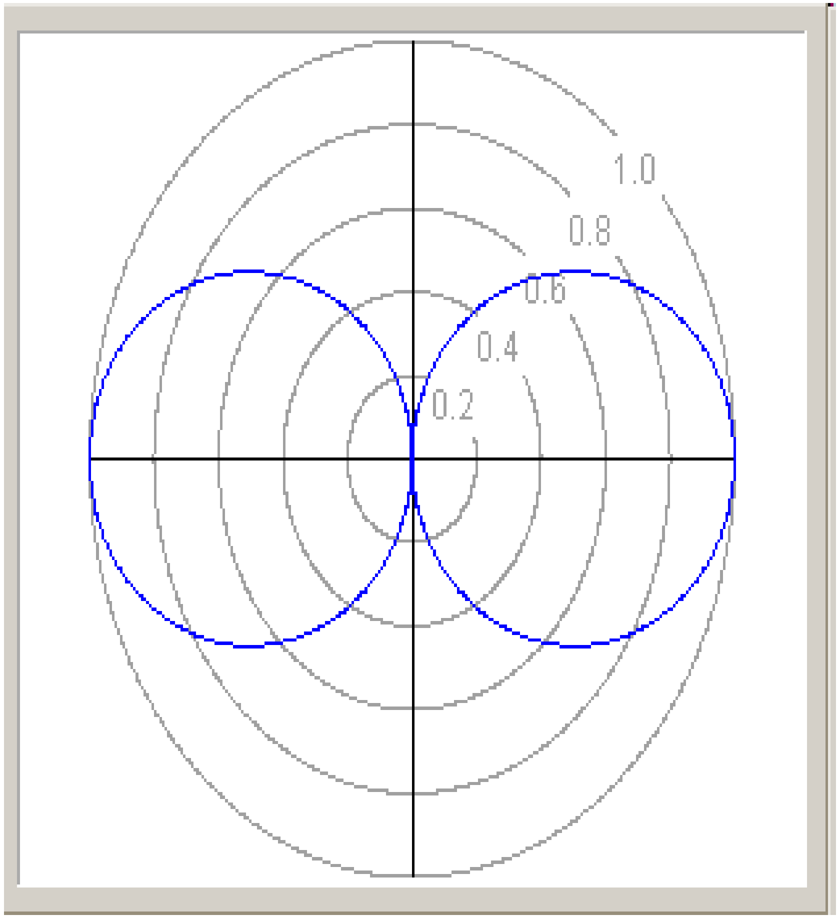
- The **half-wave dipole antenna** is just a special case of the dipole antenna.
- Half-wave term means that the length of this dipole antenna is equal to a half-wavelength at the frequency of operation.
- The dipole antenna, is the basis for most antenna designs, is a balanced component, with equal but opposite voltages and currents applied at its two terminals through a balanced transmission line.

- To make it crystal clear, if the antenna is to radiate at 600 MHz, what size should the half-wavelength dipole be?
- One wavelength at 600 MHz is $= c / f = 0.5$ meters. Hence, the half-wavelength dipole antenna's length is 0.25 meters.
- The half-wave dipole antenna is as you may expect, a simple half-wavelength wire fed at the center as shown in Figure



Current
I_0
z
$\frac{\lambda}{2}$

- Dipoles have an radiation pattern, doughnut symmetrical about the axis of the dipole. The radiation is maximum at right angles to the dipole, dropping off to zero on the antenna's axis.



FOLDED DIPOLE

- Folded antenna is a single antenna but it consists of two elements.
- First element is fed directly while second one is coupled inductively at its end.
- Radiation pattern of folded dipole is same as that of dipole antenna i.e figure of eight (8).

Advantages

- Input impedance of folded dipole is four times higher than that of straight dipole.
- Typically the input impedance of half wavelength folded dipole antenna is 288 ohm.
- Bandwidth of folded dipole is higher than that of straight dipole.

HERTZ ANTENNA

- The Hertzian dipole is a theoretical short dipole (significantly smaller than the wavelength) with a uniform current along its length.
- A true Hertzian dipole cannot physically exist, since the assumed current distribution implies an infinite charge density at its ends, and significant radiation requires a very high current over its very short length.

LOOP ANTENNA

- A **loop antenna** is a radio antenna consisting of a loop of wire with its ends connected to a balanced transmission line
- It is a single turn coil carrying RF current through it.
- The dimensions of coil are smaller than the wavelength hence current flowing through the coil has same phase.
- Small loops have a poor efficiency and are mainly used as receiving antennas at low frequencies. Except for car radios, almost every AM broadcast receiver sold has such an antenna built inside of it or directly attached to it.

- A technically small loop, also known as a magnetic loop, should have a circumference of one tenth of a wavelength or less. This is necessary to ensure a constant current distribution round the loop.
- As the frequency or the size are increased, a standing wave starts to develop in the current, and the antenna starts to have some of the characteristics of a folded dipole antenna or a self-resonant loop.
- Self-resonant loop antennas are larger. They are typically used at higher frequencies, especially VHF and UHF, where their size is manageable. They can be viewed as a form of folded dipole and have somewhat similar characteristics. The radiation efficiency is also high and similar to that of a dipole.

- Radiation pattern of loop antenna is a doughnut pattern.
- Can be circular or square loop
- No radiation is received normal to the plane of loop and null is obtained in this direction.
- Application: Used for direction finding applications

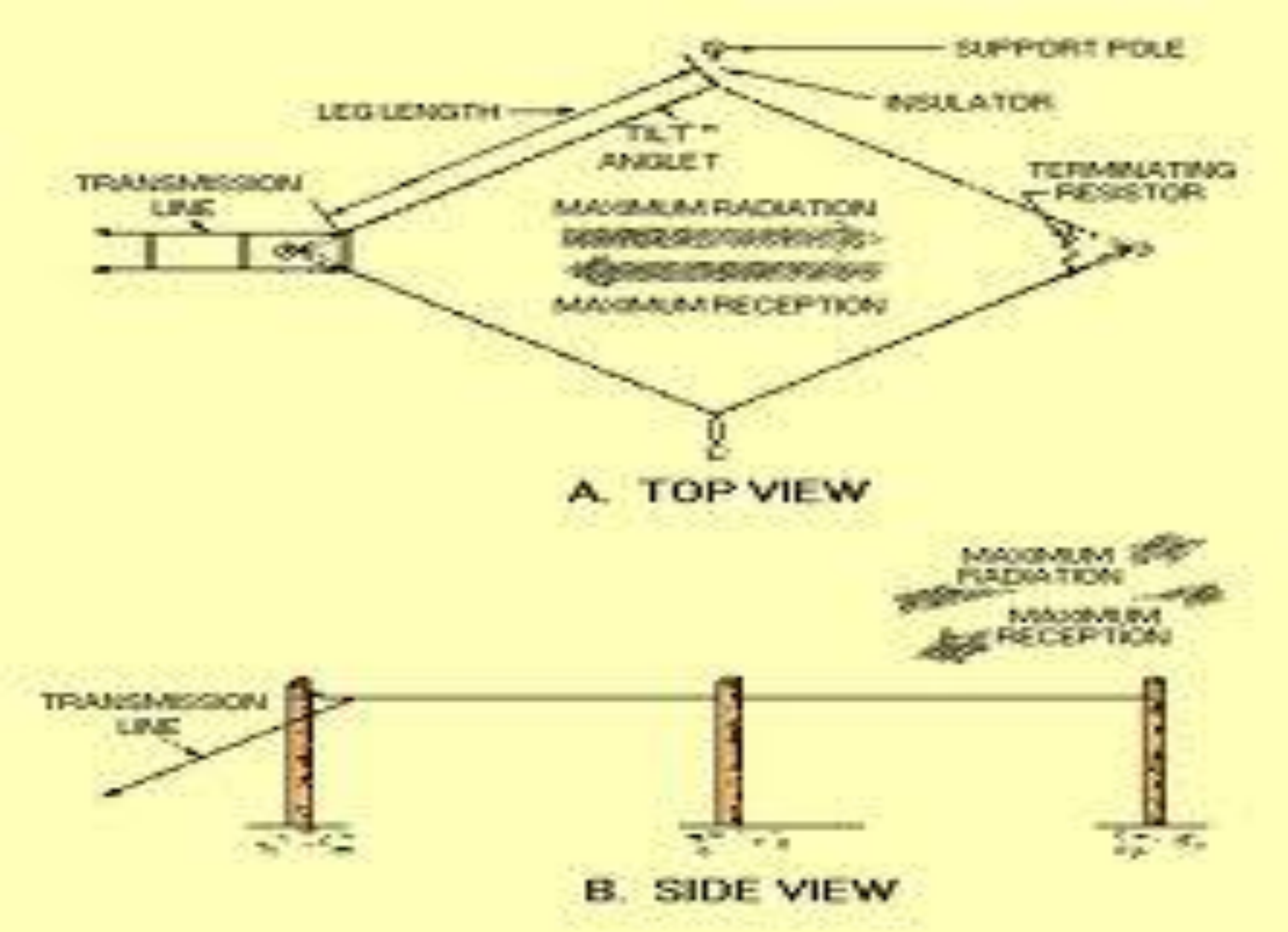
TURNSTILE ANTENNA

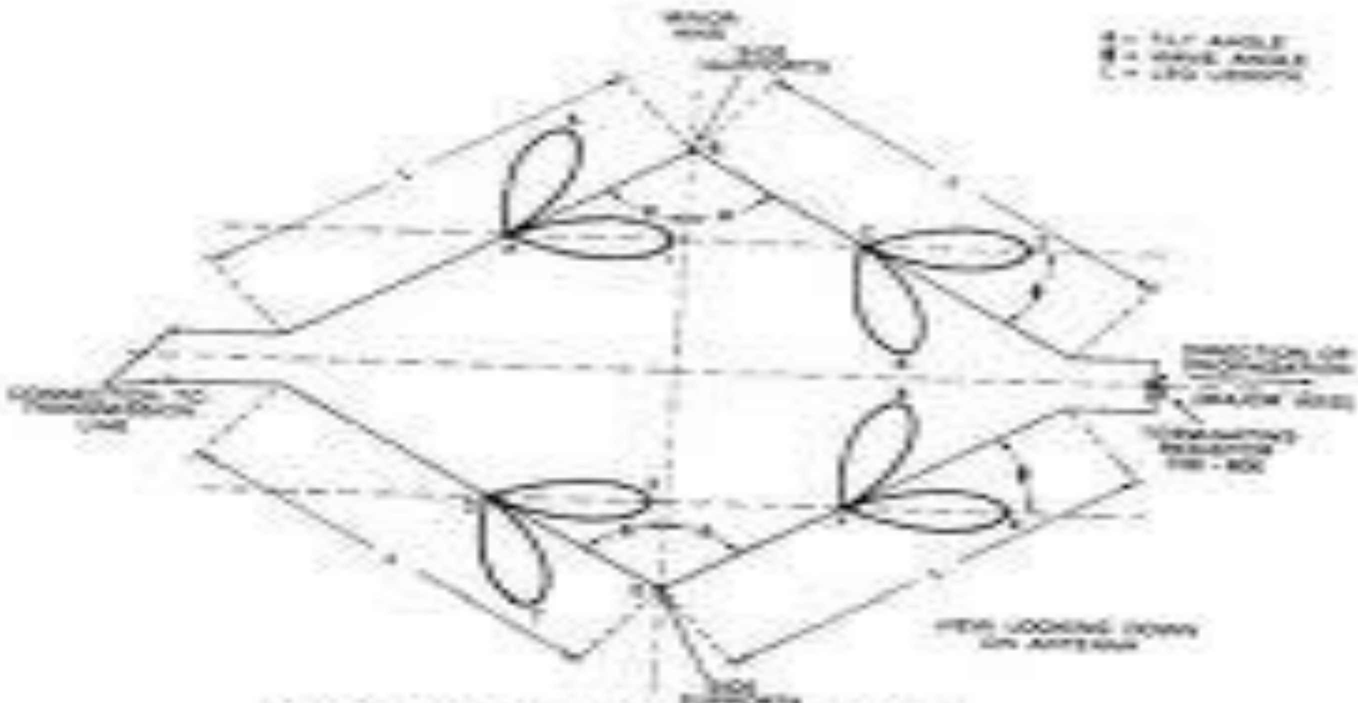
- A **turnstile antenna** is a set of two dipole antennas aligned at right angles to each other and fed 90 degrees out-of-phase.
- The name reflects that the antenna looks like a turnstile when mounted horizontally.
- When mounted horizontally the antenna is nearly omnidirectional on the horizontal plane.

- When mounted vertically the antenna is directional to a right angle to its plane and is circularly polarized.
- The turnstile antenna is often used for communication satellites because, being circularly polarized, the polarization of the signal doesn't rotate when the satellite rotates.

RHOMBIC ANTENNA

- Structure and construction
  - 4 wires are connected in rhombic shape and terminated by a resistor.
  - Mounted horizontally and placed > ^/2 from ground.
- Highest development of long wire antenna is rhombic antenna.


SUPPORT POLE
INSULATOR
LEG LENGTH
TILT ANGLE
TRANSMISSION LINE
TERMINATING RESISTOR
MAXIMUM RADIATION
MAXIMUM RECEPTION
A. TOP VIEW
MAXIMUM RADIATION
MAXIMUM RECEPTION
TRANSMISSION LINE
B. SIDE VIEW



A. FULL - RHOMBIC TRANSMITTING ANTENNA

B. NON - RESONANT HORIZONTAL THREE - WIRE RHOMBIC

- Advantages
  - Easier to construct
  - Its i/p impedance and radiation pattern are relatively constant over range of frequencies.
  - Maximum efficiency
  - High gain can be obtained.
- Disadvantages
  - Large site area and large side lobes.

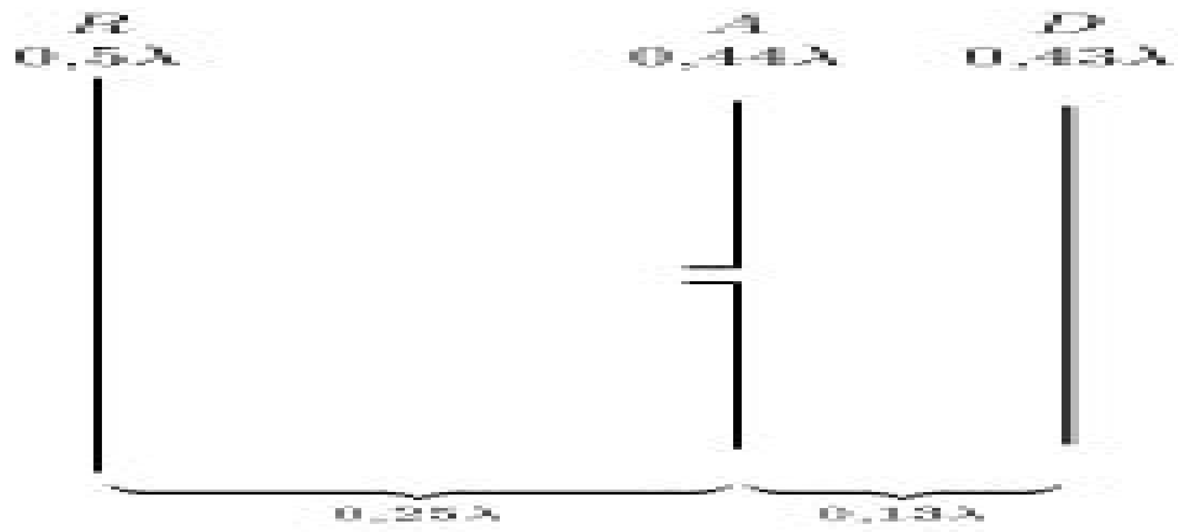
- Application
  - Long distance communication, high frequency transmission and reception.
  - Point to point communication.
  - Radio communication.
  - Short wave radio broadcasting.

ANTENNA ARRAYS

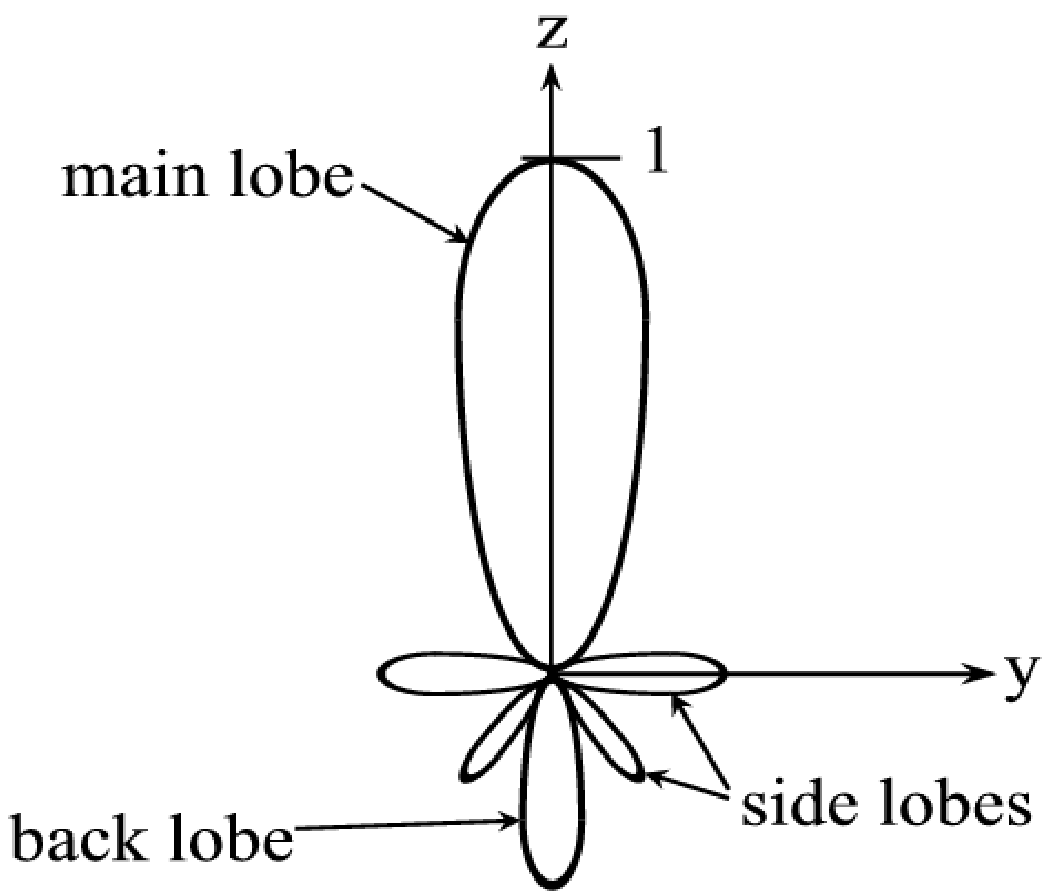
- Antenna arrays is group of antennas or antenna elements arranged to provide desired directional characteristics.
- Generally any combination of elements can form an array.
- However equal elements of regualar geometry are usually used.

YAGI-UDA ANTENNA

- It is a directional antenna consisting of a driven element (typically a dipole or folded dipole) and additional parasitic elements (usually a so-called *reflector* and one or more *directors*).
- All the elements are arranged collinearly and close together.
- The reflector element is slightly longer (typically 5% longer) than the driven dipole, whereas the so-called directors are a little bit shorter.
- The design achieves a very substantial increase in the antenna's directionality and gain compared to a simple dipole.


R
0,5λ
A
0,44λ
D
0,43λ
0,25λ
0,13λ

- Typical spacing between elements vary from about 1/10 to 1/4 of a wavelength, depending on the specific design.
- The elements are usually parallel in one plane.
- Radiation pattern is modified figure of eight
- By adjusting distance between adjacent directors it is possible to reduce back lobe
- Improved front to back ratio



(a)

ANTENNA APPLICATIONS

They are used in systems such as

- Radio broadcasting
- Broadcast television
- Two-way radio
- Communication receivers
- Radar
- Cell phones
- Satellite communications.

ANTENNA CONSIDERATIONS

- The space available for an antenna
- The proximity to neighbors
- The operating frequencies
- The output power
- Money

General Packet Radio Service (GPRS)

A new Dimension to Wireless Communication

Constraints with existing network

- Data Rates too slow – about 9.6 kbps
- Connection setup time too long
- Inefficient resource utilization for bursty traffic
- Proves expensive for bursty traffic utilization
- No efficient method for packet transfers

Comparison of GSM & GPRS

	GSM	GPRS
Data Rates	9.6 Kbps	14.4 to 115.2 Kbps
Modulation Technique	GMSK	GMSK
Billing	Duration of connection	Amount of data transferred
Type of Connection	Circuit – Switched Technology	Packet - Switched Technology

GPRS in INDIA

- BPL Mobile
- Bharti Cellular
- Hutchison Max
- Hutchison Essar
- Idea Cellular

What is GPRS ?

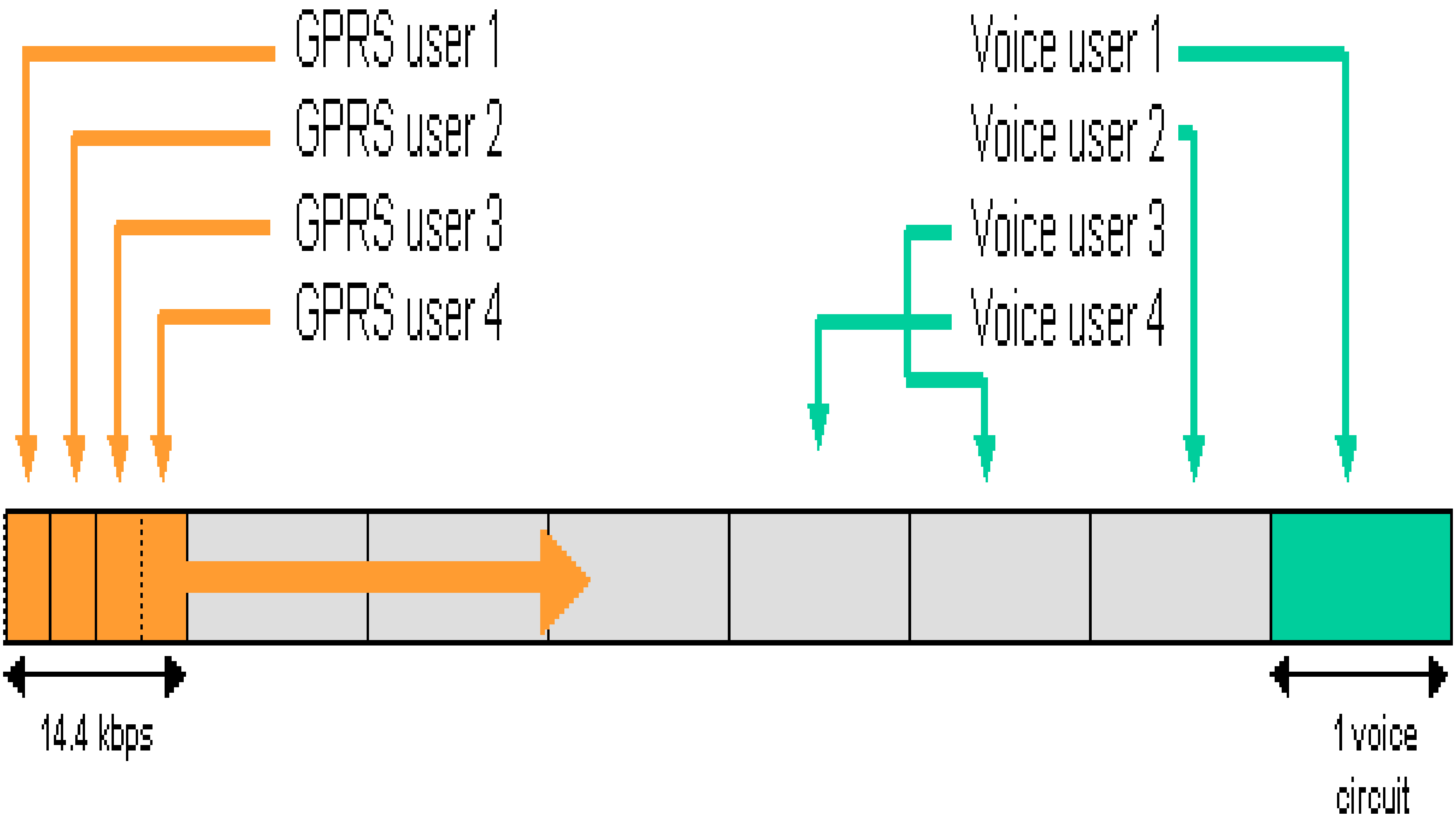
- General Packet Radio Service (GPRS) is a new bearer service for GSM that greatly improves and simplifies wireless access to packet data networks

- GPRS applies packet radio principal to transfer user data packets in an efficient way b/w MS & external packet data network

Benefits of GPRS

- New Data Services
- High Speed (Data Rate 14.4 – 115 kbps)
- Efficient use of radio bandwith (Statistical Multiplexing)
- Circuit switching & Packet Switching can be used in parallel
- Constant connectivity

Statistical Multiplexing



Salient Features of GPRS

- Important step on the path to 3G
- Standardized by ETSI
- GPRS is an overlay network over the GSM
- Provides Data Packet delivery service
- Support for leading internet communication protocols
- Billing based on volume of data transferred
- Utilizes existing GSM authentication and privacy procedures.

High Data Rate

- GPRS uses radio channel i.e. 200 kHz wide
- Radio channel carries digital data stream of 271 kbps
- This rate is divided into 8 time slots each carrying 34 kbps per time slot
- Data rate 14 kbps per time slot achieved after corrections
- GPRS can combine upto 8 time slots giving data rate of 114 kbps

GPRS Services

- Offers end-to-end packet switched data transfer
- **Bearer Services**
  - PTP - Point-To-Point service (CLNS mode)
  - PTM - Point-To-Multipoint service(CONS Mode)
    - PTM-M Multicast service
    - PTM-G Group call service
- **Supplementary Services**
  - SMS Short Message Service
  - CFU Call Forwarding Unconditional

GPRS Services (Contd.)

- CFNRc Call Forwarding on mobile subscriber not reachable
- CUG Closed User Group
- Tele action, access to data bases

- **Quality of Service**
  - GPRS allows defining QoS profiles
  - Service precedence, reliability, delay,throughput

GPRS Terminals

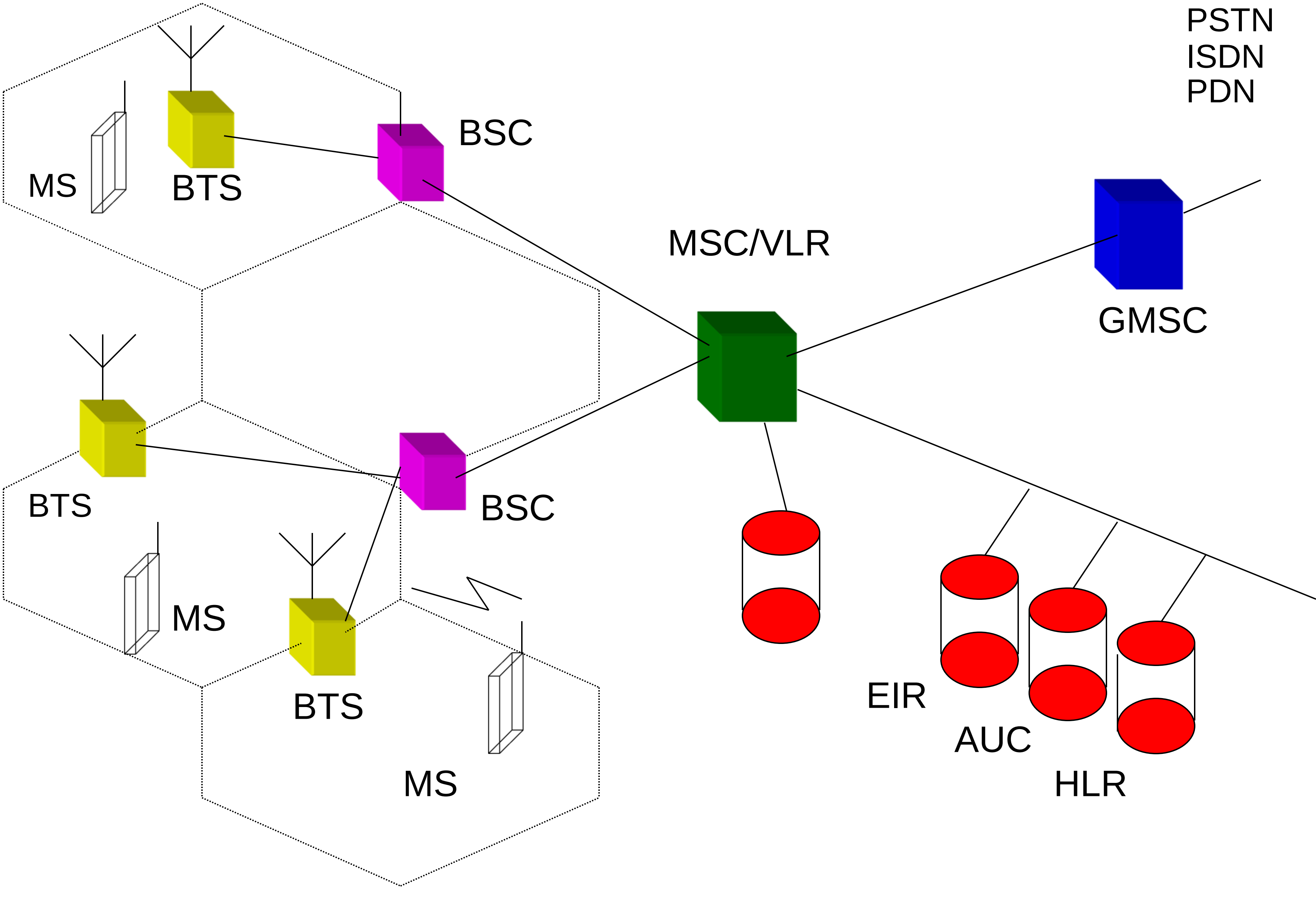
- **Class A**
  – MS supports simultaneous operation of GPRS and GSM services
- **Class B**
  – MS able to register with the n/w for both GPRS & GSM services simultaneously. It can only use one of the two services at a given time.
- **Class C**
  - MS can attach for either GPRS or GSM services

GPRS Network Elements

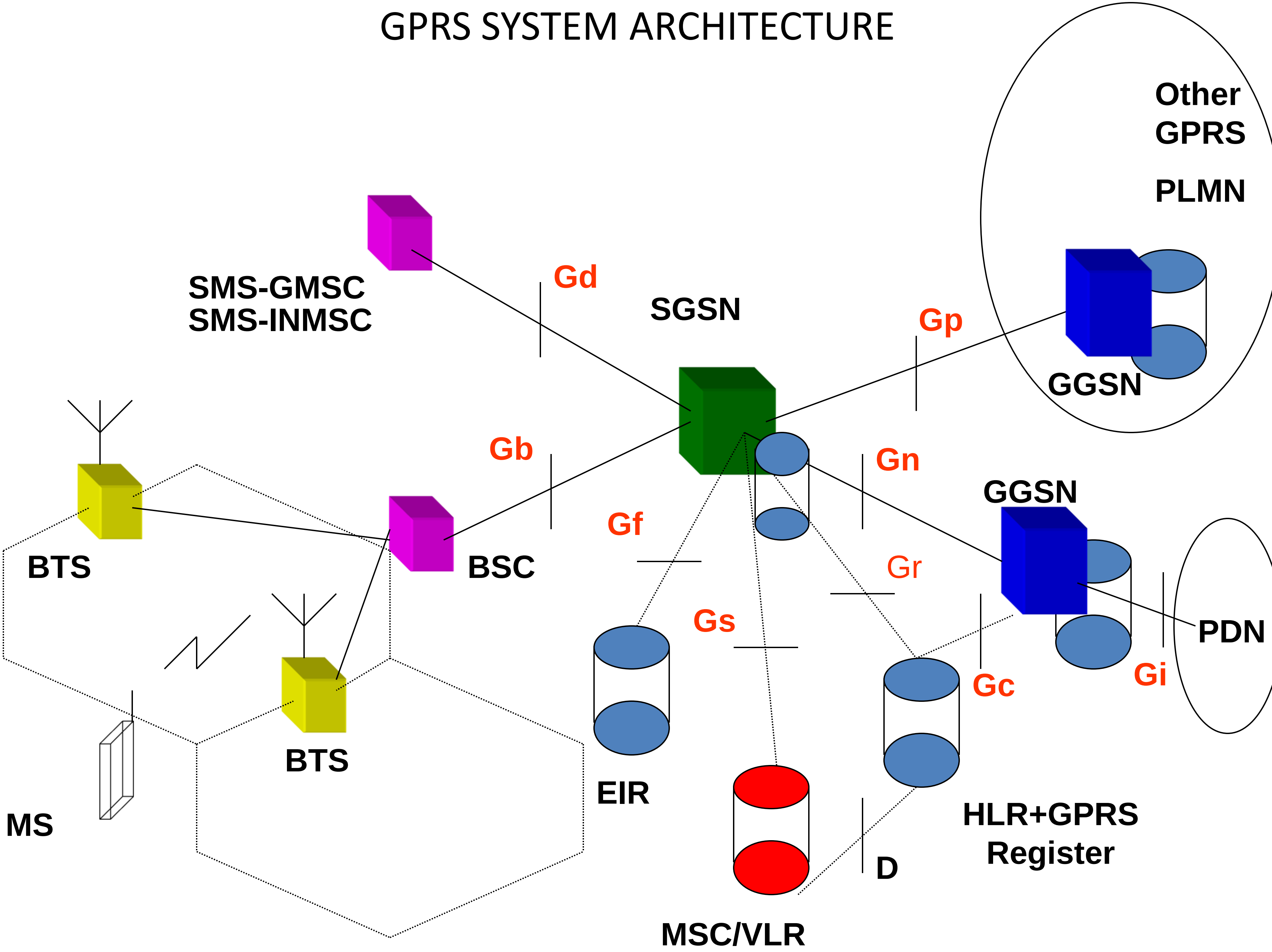
GPRS Architecture is same as GSM except few hardware modifications :

- GPRS includes GSNs
  - SGSN : Serving GPRS Support Node
  - GGSN : Gateway GPRS Support Node
- GPRS Register

GSM SYSTEM ARCHITECTURE



GPRS SYSTEM ARCHITECTURE



Interfaces

- Gb – Connects BSC with SGSN
- Gn – SGSN – SGSN/GGSN (in the same network)
- Gp – SGSN –GGSN (in different networks)
- Gf – For equipment querying at registering time
- Gi – Connects PLMN with external Packet Data Networks (PDNs)
- Gr – To exchange User profile between HLR & SGSN
- Gs – To exchange Database between SGSN & MSC
- Gd – Interface between SMS & GPRS

SGSN – Serving GPRS Support Node

- Delivers data packets to mobile stations & vice-versa
- Detect and Register new GPRS MS in its serving area
- Packet Routing, Transfer & Mobility Management
- Authentication, Maintaining user profiles
- Its location register stores location info. & user profiles

GGSN – Gateway GPRS Support Node

- Interfaces GPRS backbone network & external packet data networks
- Converts the GPRS packets from SGSN to the PDP format
- Converts PDP addresses change to GSM addresses of the destination user
- Stores the current SGSN address and profile of the user in its location register
- Performs authentication
- Many-to- many relations among SGSNs & GGSNs

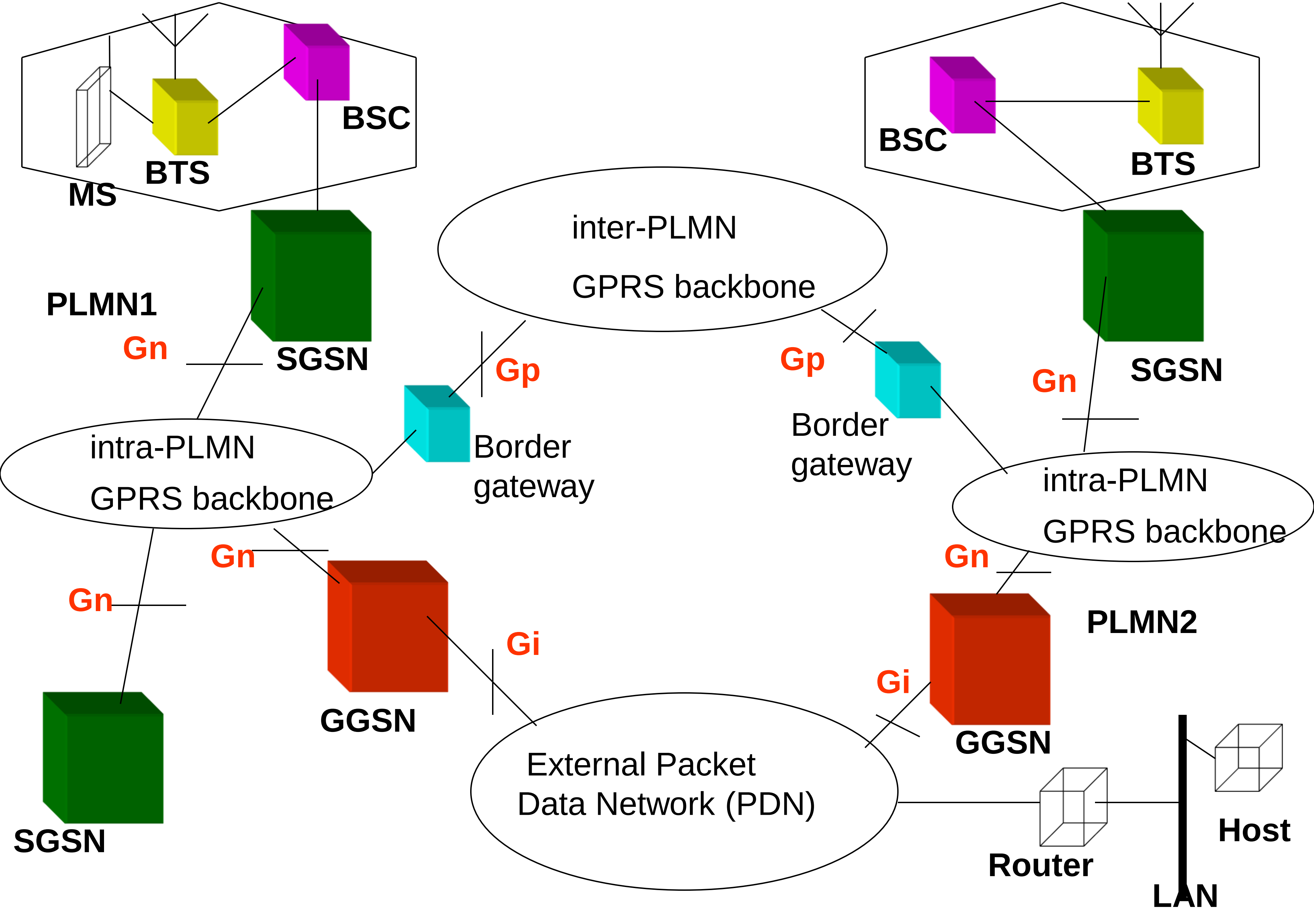
GPRS Register

- GPRS Register is integrated with GSM-HLR.
- Maintains the GPRS subscriber data and Routing information.
- Stores current SGSN address

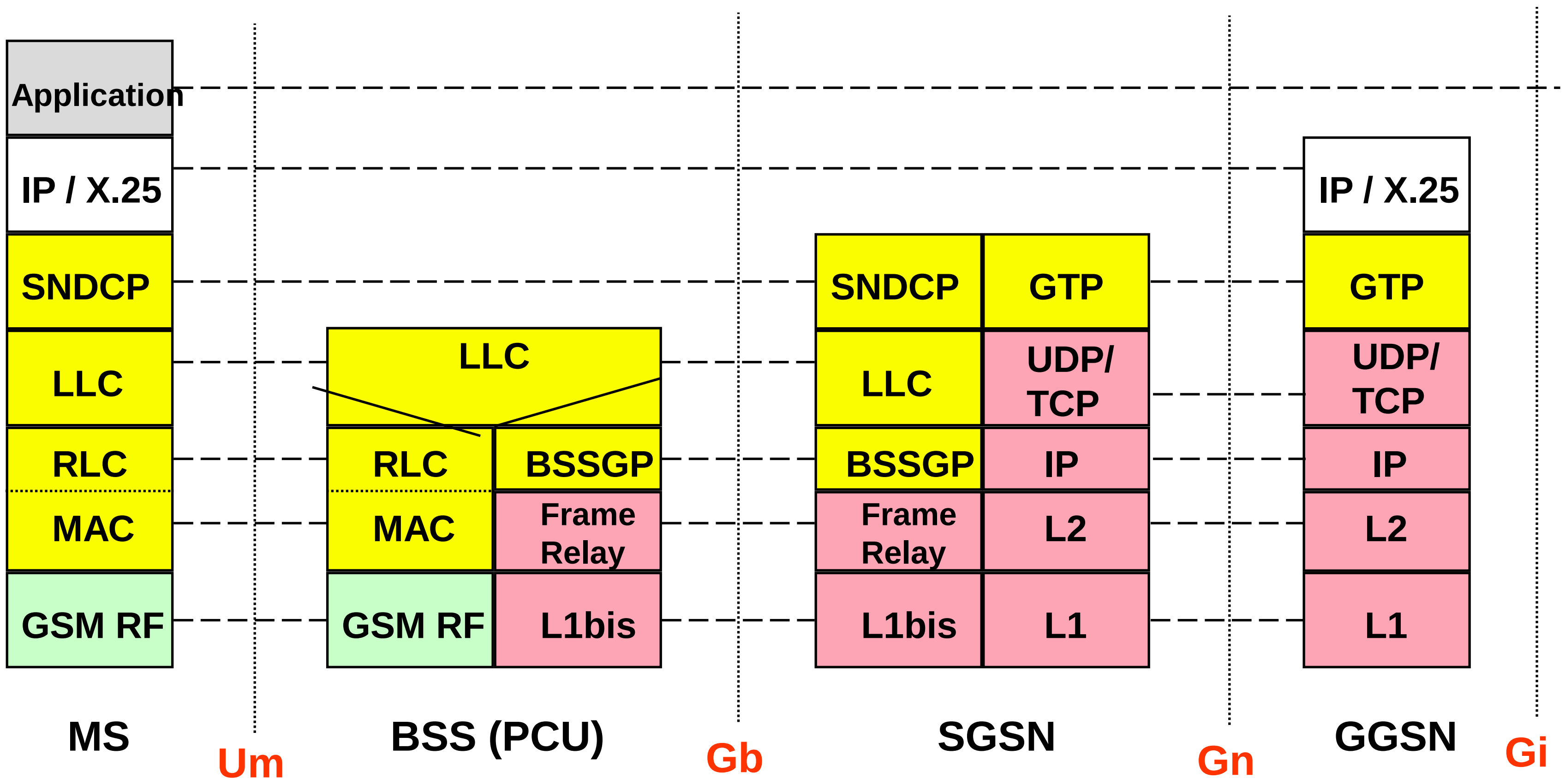
GPRS Backbone Network

- GSNs are connected through IP based backbone
- Two Backbones:
  - Intra PLMN backbone networks that connects GSNs of the same PLMN & are private IP networks
  - Inter PLMN backbone networks that connects GSNs of the different PLMN. Roaming agreement is necessary
- GPRS Tunneling protocol (GTP)
- PLMN- Inter PLMN interconnect are called Border gateways (performs security functions to protect Intra- PLMN backbone against unauthorized users and attacks).

GPRS BACKBONE NETWORK



Protocol Stack



SNDCP - Sub Network Dependent Convergence Protocol

- Used to transfer data packets between SGSN and MS
- Multiplexing of several connections of network layer onto one logical connection of underlying LLC layer
- Compression and decompression of user data and header information

Data Link layer

- Divided into two sub layers :
  - LLC layer (between MS-SGSN)
  - RLC/MAC (between MS-BSS)

LLC-Logical Link Control

- Establishes highly reliable logical link between MS & its assigned SGSN

- Works either in acknowledged or unacknowledged modes

- Data confidentiality is ensured by ciphering functions

RLC/MAC Layer

- Radio Link Control(RLC)
  - Establish a reliable link between MS & BSS
  - Segmentation and reassembly of LLC frames into RLC data blocks

- Medium Access Control(MAC)
  - Controls access attempts of an MS on radio channels shared by several MSs
  - Employs algos. for contention resolution, multiuser multiplexing on PDTCH

- Both ack and unack. Modes of operation are supported in RLC/MAC layer

Physical Layer

- Divided into two sub layers :
  - Physical Link Layer (PLL)
  - Physical RF Layer (RFL)
- PLL – Provides a physical channel between MS and BSS
  - Channel coding, interleaving, detection of physical link congestion
- RFL - Operates below PLL

BSSGP-(BSS GPRS Application Protocol)

- Delivers routing & Quality of Service related information between BSS and SGSN

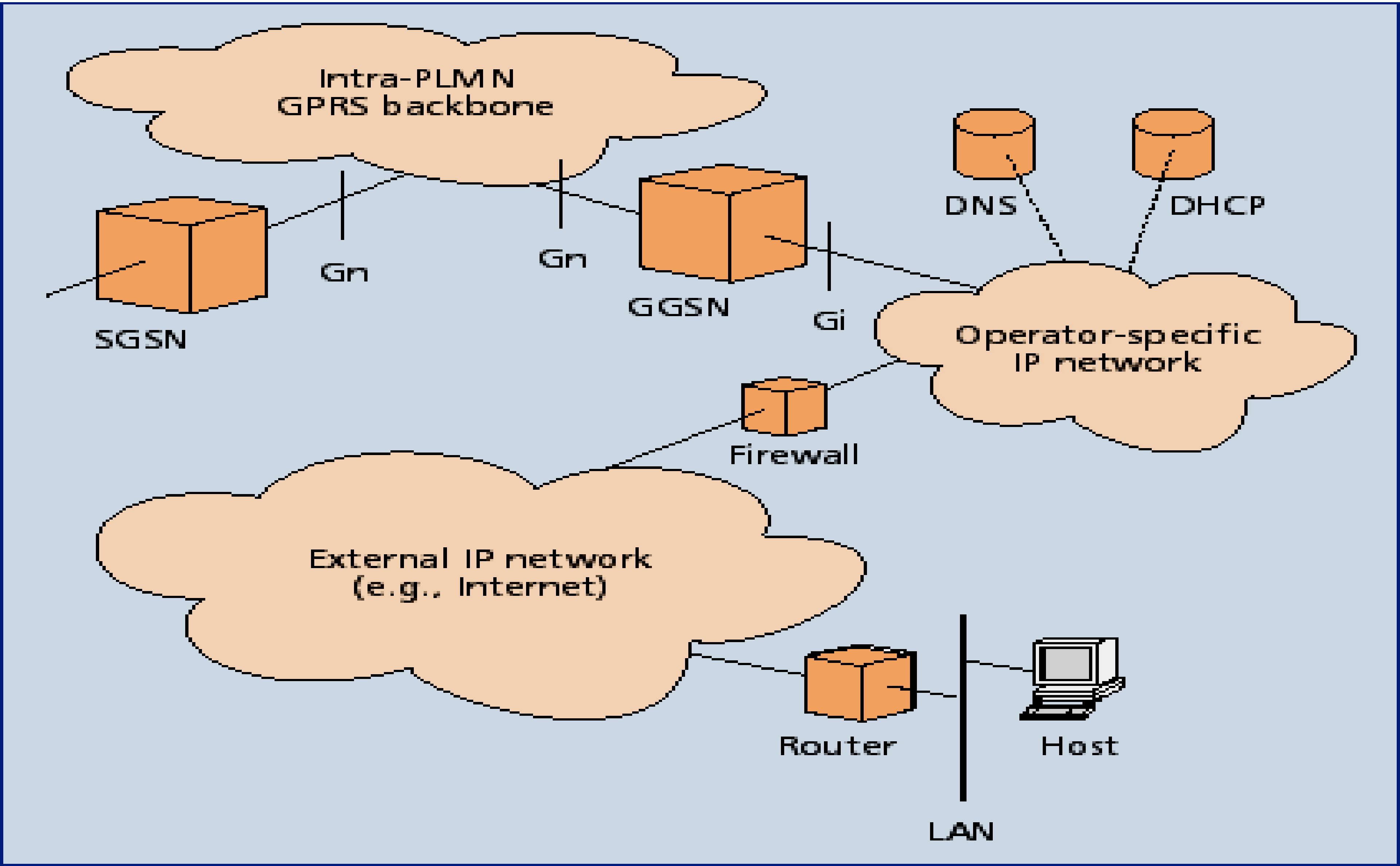
GTP – GPRS Tunneling Protocol

- GTP tunnels user data packets and related signaling information between GSNs
- Signaling is used to create, modify and delete tunnels
- Defined both at Gn and Gp interface
- Below GTP, TCP or UDP are employed to transport the GTP Packets within backbone network

Inter working with IP networks

- GPRS n/w can be interconnected with an IP-based packet data network
- GPRS supports both IPv4 and IPv6
- GPRS n/w looks like IP sub network and GGSN looks like a IP router
- DHCP, DNS servers are installed

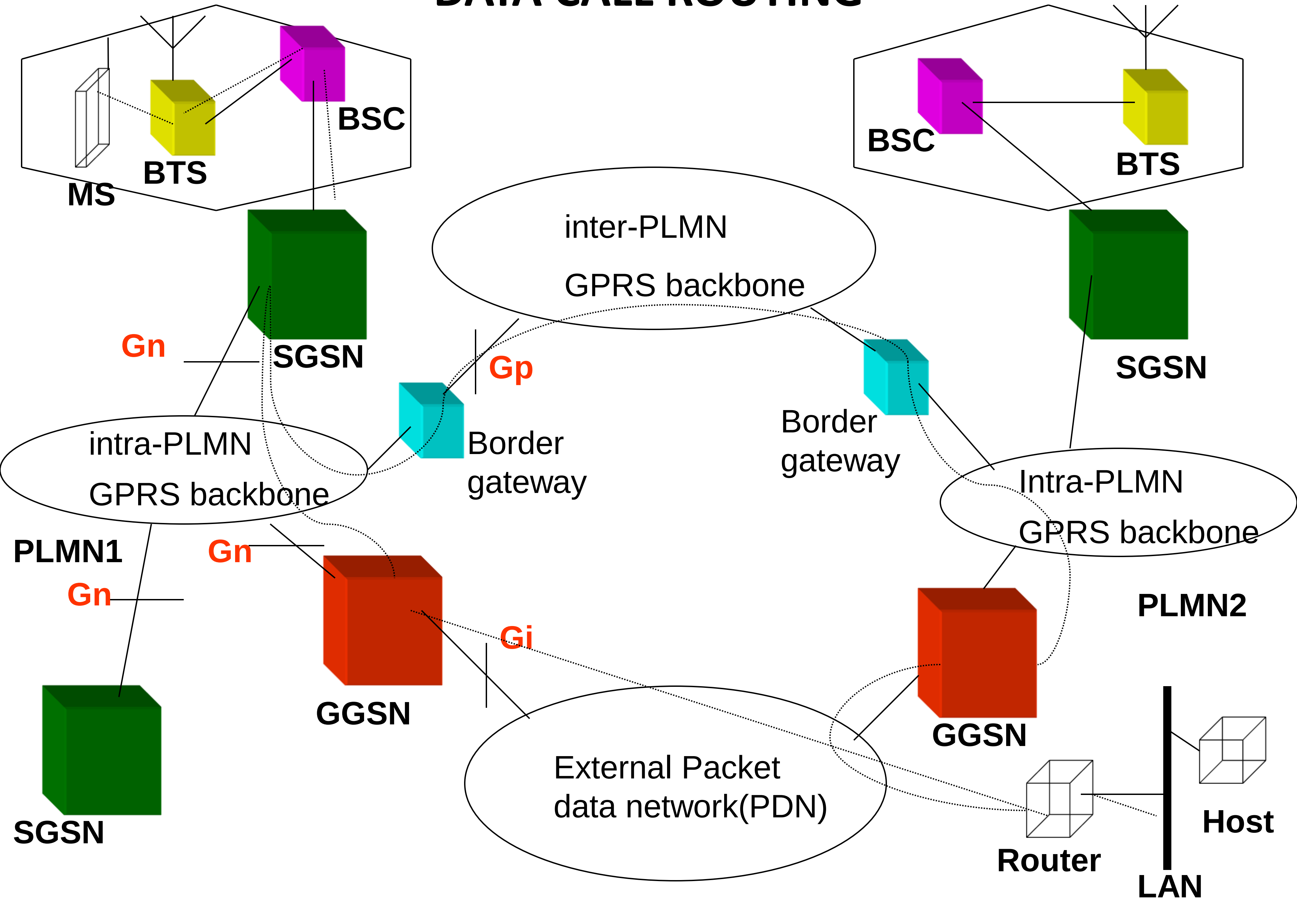
GPRS –Internet Connection



CALL ROUTING

- DATA CALL ORGINATING
- DATA CALL TERMINATING

DATA CALL ROUTING



SESSION MANAGEMENT IN GPRS

Attachment & Detachment Procedure

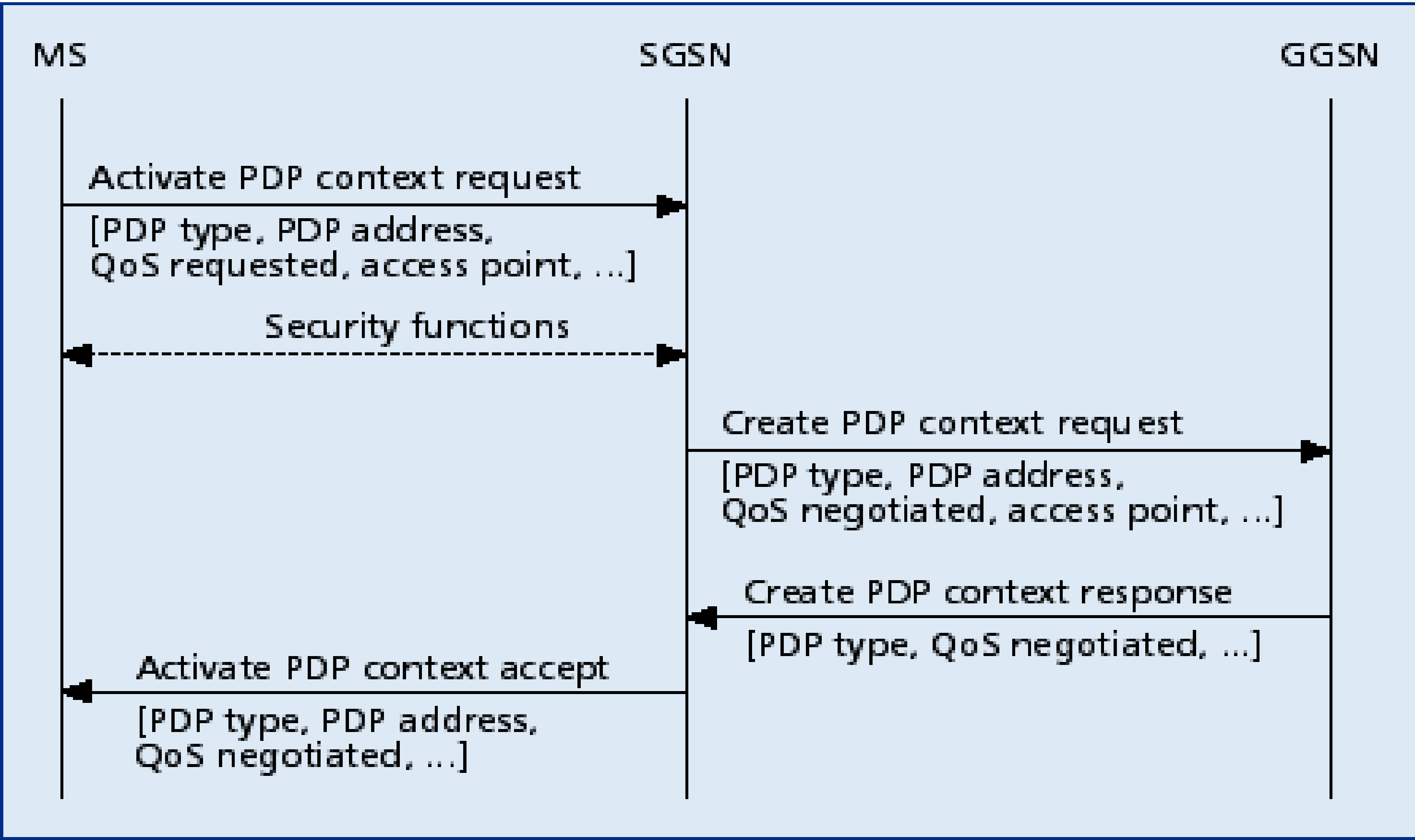
- **GPRS attach**
  - User is registered in SGSN, after authentication check from HLR
  - SGSN assigns P-TMSI to MS

- **GPRS detach**
  - Disconnection of MS from GPRS network is called GPRS detach
  - It can be initiated by MS or by network(SGSN or HLR)

Session Management

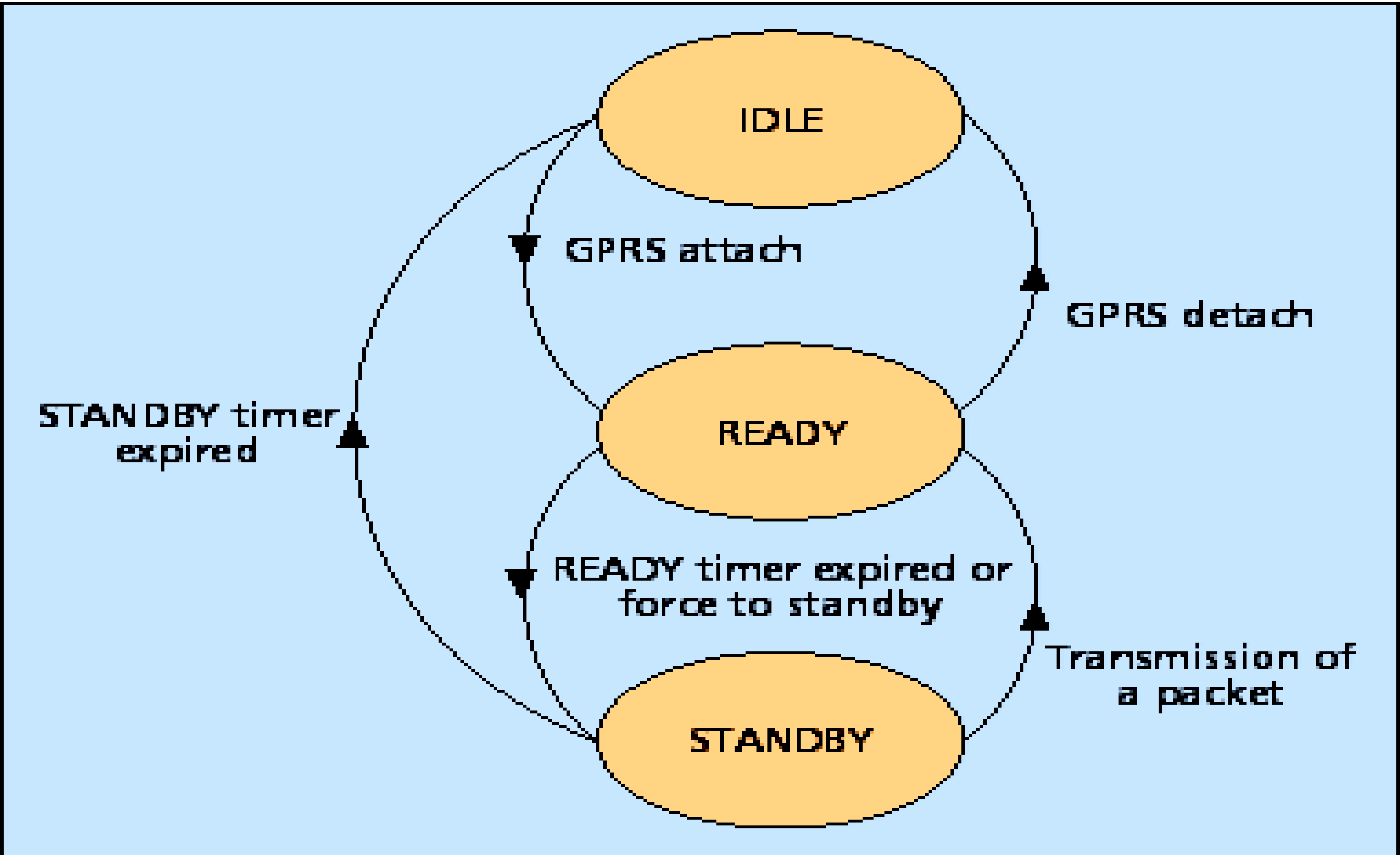
- Mobile Station applies for PDP address
- For each session **PDP context** is created & it contains
  - PDP type
  - PDP addressed assigned to MS
  - Address of GGSN that servers access point to PDN
- With active PDP context MS able to send or receive data packets
- Allocation of PDP address can be static or dynamic

PDP Context Activation



LOCATION MANAGEMENT IN GPRS

State Model of GPRS MS



Location Management

Mobile station can be in 1 of the 3 states depending on traffic amount

- **Idle** : MS is not using GPRS service
- **Ready** : Performing GPRS Attach, MS gets into READY State
- **Standby** : When MS does not send any packets for longer period of time, Ready timer Expires

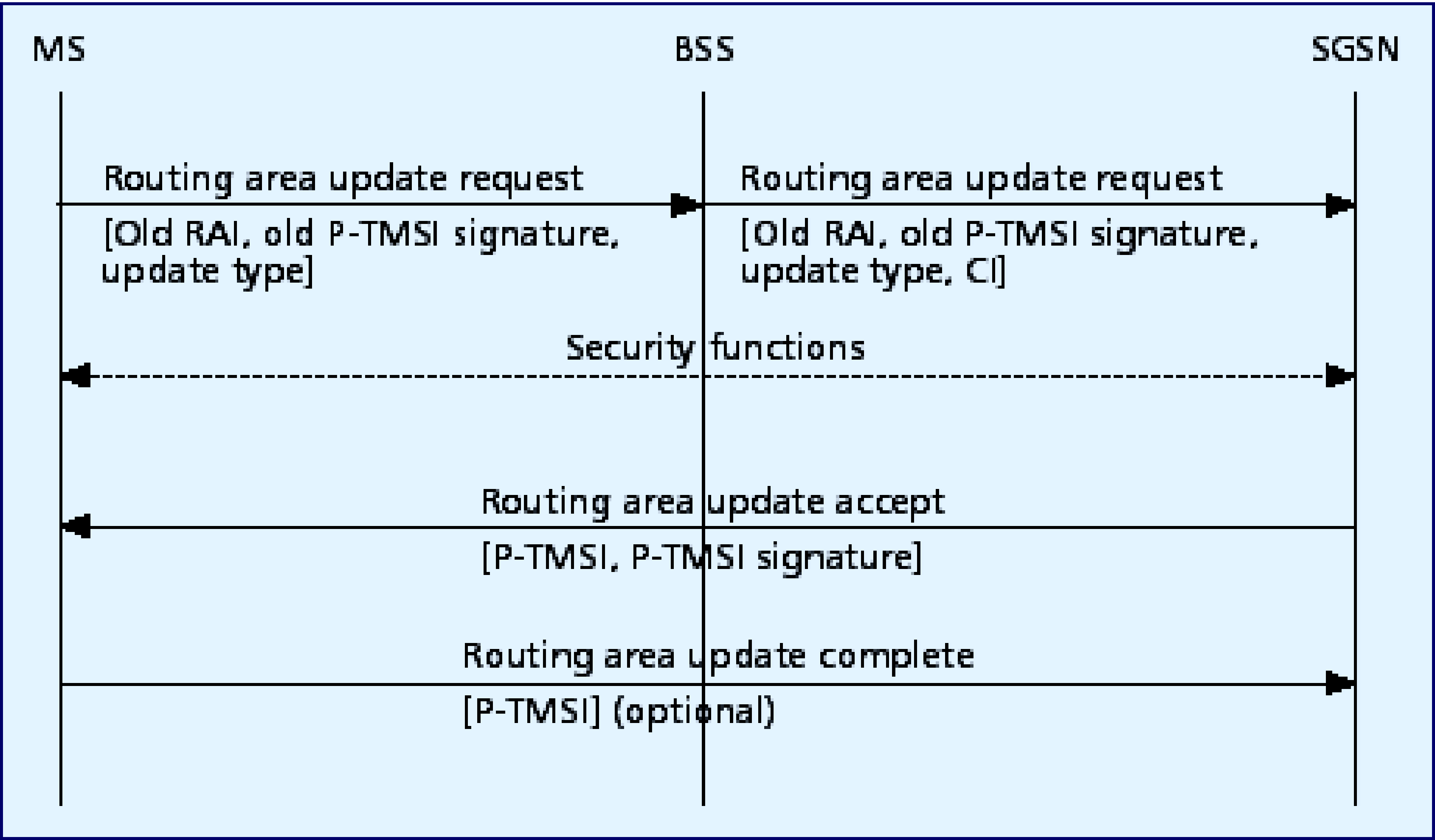
Routing Area Update

- GSM Location Area(LA) is divided into several Routing Areas(RA)
- RA consists of several cells
- SGSN is informed when MS moves to a new RA
- MS sends a “Routing Area Update Request” to its assigned SGSN

Types of Routing Area Update

- Intra SGSN Routing Area Update
- Inter SGSN Routing Area Update

Routing Area Update



Mobility Management

Consists of two levels:

- Micro mobility management :
  - Tracks the current RA or cell of MS
  - It is performed by SGSN
- Macro mobility management :
  - Keep tracks of MS's current SGSN
  - Stores it in HLR, VLR, and GGSN

Channels in GPRS

- Logical Channel
  - Traffic Channels
  - Signaling Channels (Control Channels)
- Physical Channels

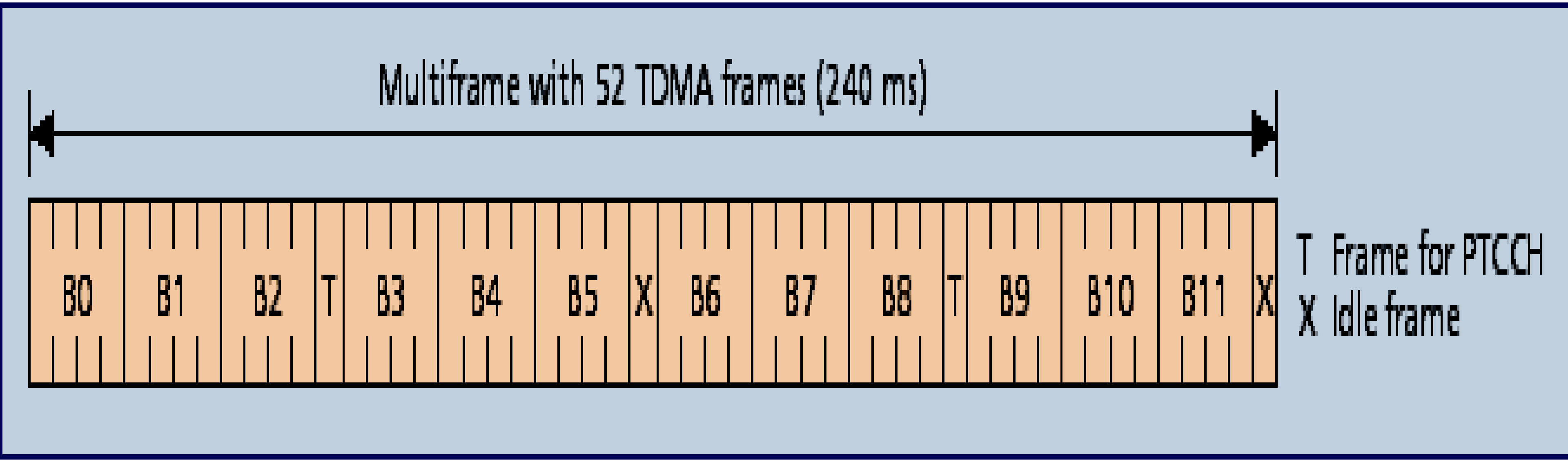
Logical Channels

Group	Channel	Function	Direction
Packet data traffic channel	PDTCH	Data traffic	MS↔BSS
Packet broadcast control channel	PBCCH	Broadcast control	MS←BSS
Packet common control channel (PCCCH)	PRACH	Random access	MS→BSS
	PAGCH	Access grant	MS←BSS
	PPCH	Paging	MS←BSS
	PNCH	Notification	MS←BSS
Packet dedicated control channels	PACCH	Associated control	MS↔BSS
	PTCCH	Timing advance control	MS↔BSS

Packet Data Channel(PDCH)

- Physical Channel for GPRS Traffic
- PDCH are taken from all channels available in the cell
- Depending on current traffic load and priority of service, the physical channel are allocated to either GPRS or GSM services.
- Physical channels not currently used by GSM can be allocated as PDCH to increase the QOS for GPRS

Multiframe Structure of PDCH

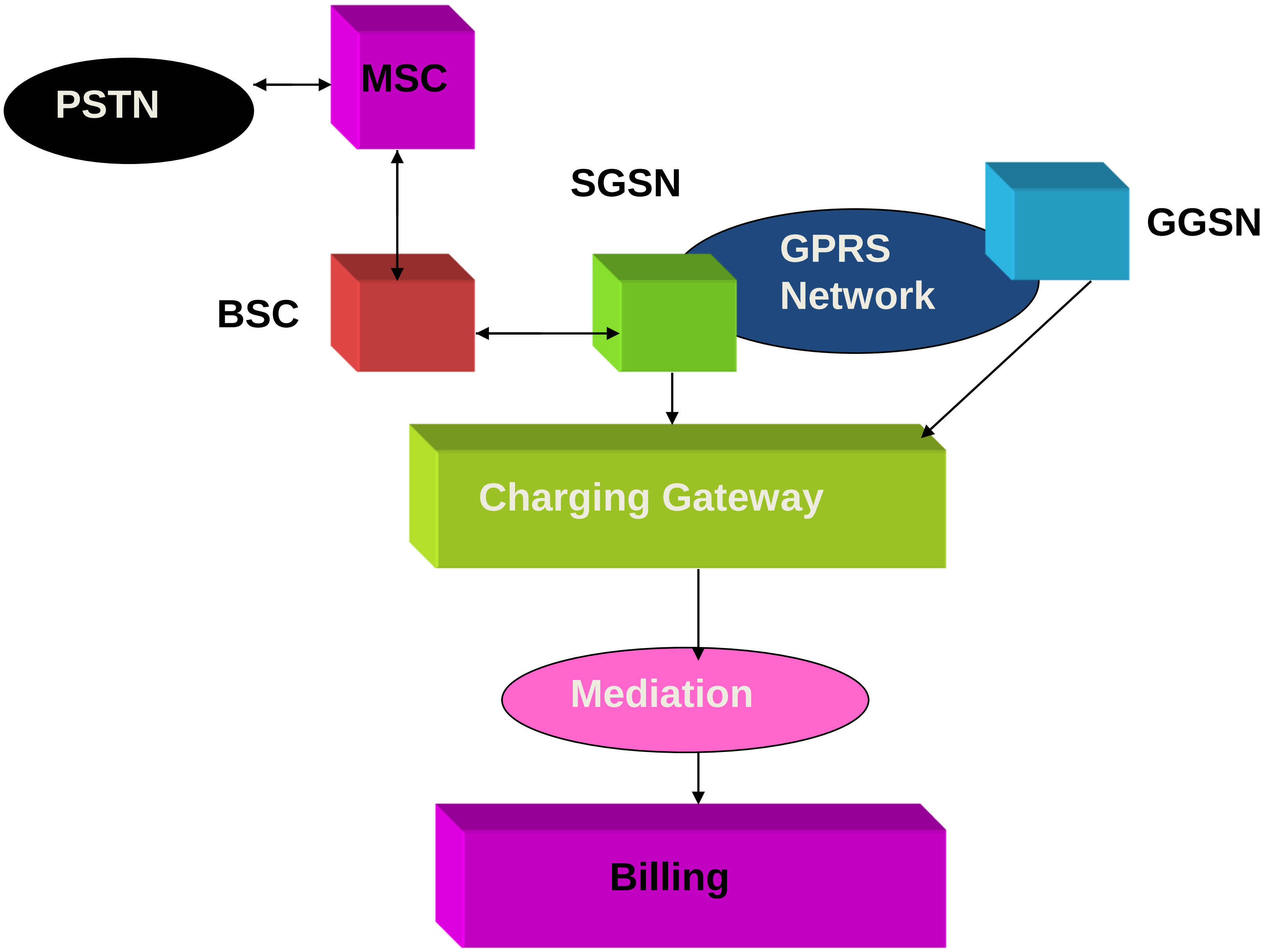


Four consecutive TDMA frame forms one block - B0 – B11

Two TDMA frames for transmission of PTCCH - T

Two Idle frames - X

Billing



PSTN
MSC
SGSN
GGSN
GPRS Network
BSC
Charging Gateway
Mediation
Billing

Applications of GPRS

- Web browsing
- Corporate & Internet Email
- Vehicle Positioning
- Remote LAN Access
- Home Automation
- Document Sharing/Collaborative working