RAJASTHAN TECHNICAL UNIVERSITY, KOTA

III Year-V Semester: B.Tech. Computer Science and Engineering

5CS5-11: Wireless Communication

Vision of CSE Department

To become renowned Centre of Excellence in Computer Science and Engineering and make competent engineers and professionals with high ethical values prepared for lifelong learning.

Mission of CSE Department

M1 - To impart outcome based education for emerging technologies in the field of computer science and engineering.

M2 - To provide opportunities for interaction between academia and industry.

M3 - To provide platform for lifelong learning by accepting the change in technologies

M4 - To develop aptitude of fulfilling social responsibilities.

PEOs of CSE Department

1. To provide students with the fundamentals of Engineering Sciences with more emphasis in computer science and engineering by way of analysing and exploiting engineering challenges.
2. To train students with good scientific and engineering knowledge so as to comprehend, analyse, design, and create novel products and solutions for the real life problems.
3. To inculcate professional and ethical attitude, effective communication skills, teamwork skills, multidisciplinary approach, entrepreneurial thinking and an ability to relate engineering issues with social issues.
4. To provide students with an academic environment aware of excellence, leadership, written ethical codes and guidelines, and the self-motivated life-long learning needed for a successful professional career.
5. To prepare students to excel in Industry and Higher education by Educating Students along with High moral values and Knowledge.

Course Outcome of Wireless Communication

- CO1: Able to explain the fundamentals of wireless communication techniques such as fading, Path loss models, Parameters of mobile multipath channel techniques and link budget design
- CO2: Analyse the cellular architecture and understand the methods of sharing the communication channel through various multiple access techniques, and capacity calculation and improvement
- CO3 : Analyse the link establishment in wireless communication, description of digital signalling for fading channels
- CO4: Gain an in-depth knowledge and develop an in-depth understanding multipath mitigation techniques. Equalization, diversity and error probability in fading channels. Multiple antenna techniques –MIMO system model

Program Outcome

1. **Engineering knowledge:** Apply the knowledge of mathematics, science, engineering fundamentals, and an engineering specialization to the solution of complex engineering problems.
2. **Problem analysis:** Identify, formulate, research literature, and analyze complex engineering problems reaching substantiated conclusions using first principles of mathematics, natural sciences, and engineering sciences.
3. **Design/development of solutions:** Design solutions for complex engineering problems and design system components or processes that meet the specified needs with appropriate consideration for the public health and safety, and the cultural, societal, and environmental considerations.
4. **Conduct investigations of complex problems:** Use research-based knowledge and research methods including design of experiments, analysis and interpretation of data, and synthesis of the information to provide valid conclusions.
5. **Modern tool usage:** Create, select, and apply appropriate techniques, resources, and modern engineering and IT tools including prediction and modeling to complex engineering activities with an understanding of the limitations.
6. **The engineer and society:** Apply reasoning informed by the contextual knowledge to assess societal, health, safety, legal and cultural issues and the consequent responsibilities relevant to the professional engineering practice.

To be continued….

7- **Environment and sustainability:** Understand the impact of the professional engineering solutions in societal and environmental contexts, and demonstrate the knowledge of, and need for sustainable development.

8- **Ethics:** Apply ethical principles and commit to professional ethics and responsibilities and norms of the engineering practice.

9- **Individual and team work**: Function effectively as an individual, and as a member or leader in diverse teams, and in multidisciplinary settings.

10- **Communication**: Communicate effectively on complex engineering activities with the engineering community and with society at large, such as, being able to comprehend and write effective reports and design documentation, make effective presentations, and give and receive clear instructions.

11- **Project management and finance**: Demonstrate knowledge and understanding of the engineering and management principles and apply these to one's own work, as a member and leader in a team, to manage projects and in multidisciplinary environments.

12- **Life-long learning**: Recognize the need for, and have the preparation and ability to engage in independent and life-long learning in the broadest context of technological change.

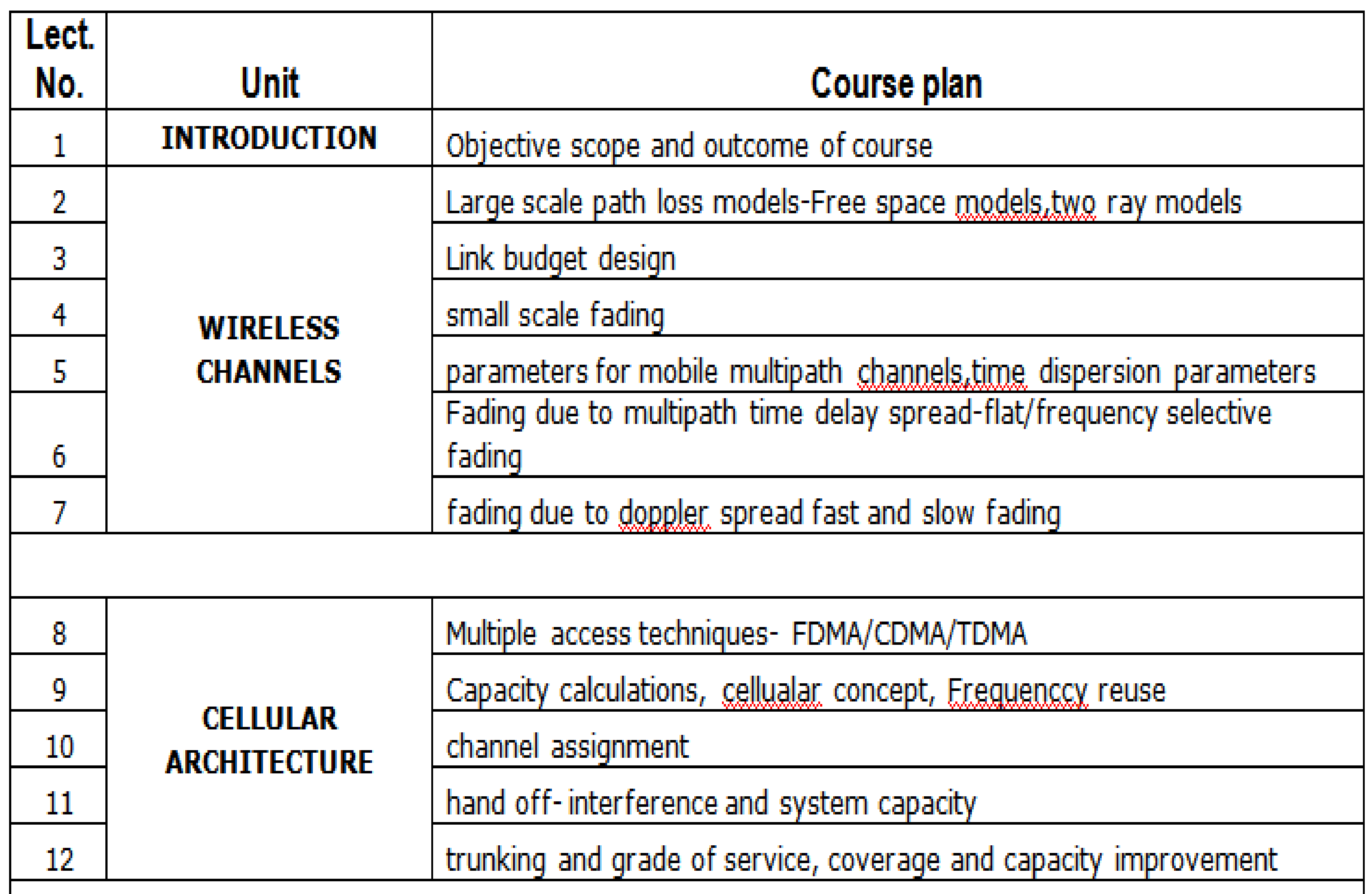
Program Specific Outcome(PSO)

- PSO1:Ability to interpret and analyse network specific and cyber security issues, automation in real word environment.
- PSO2: Ability to Design and Develop Mobile and Web-based applications under realistic constraints.

CO- PO MAPPING

COs	PO1	PO2	PO3	PO4	PO5	PO6	PO7	PO8	PO9	PO10	PO11	PO12
Able to explain the fundamentals of wireless communication techniques such as fading, Path loss models, Parameters of mobile multipath channel techniques and link budget design	3	2	1	1	2	3	2	1	3	1	2	1
Analyse the cellular architecture and understand the methods of sharing the communication channel through various multiple access techniques, and capacity calculation and improvement	3	2	1	1	2	3	2	1	3	1	2	1
Analyse the link establishment in wireless communication, description of digital signalling for fading channels	3	3	2	1	3	3	2	1	3	1	2	1
Gain an in-depth knowledge and develop an in-depth understanding multipath mitigation techniques. Equalization, diversity and error probability in fading channels. Multiple antenna techniques –MIMO system model	3	3	2	2	3	3	2	1	3	2	3	1

Course Plan



Lect. No.	Unit	Course plan
1	**INTRODUCTION**	Objective scope and outcome of course
2	**WIRELESS CHANNELS**	Large scale path loss models-Free space models,two ray models
3		Link budget design
4		small scale fading
5		parameters for mobile multipath channels,time dispersion parameters
6		Fading due to multipath time delay spread-flat/frequency selective fading
7		fading due to doppler spread fast and slow fading
8	**CELLULAR ARCHITECTURE**	Multiple access techniques- FDMA/CDMA/TDMA
9		Capacity calculations, cellualar concept, Frequenccy reuse
10		channel assignment
11		hand off- interference and system capacity
12		trunking and grade of service, coverage and capacity improvement

13	**DIGITAL SIGNALLING FOR FADING CHANNELS**	Structure of a wireless communication link
14		Principles of offset QPSK,p/4-DQPSK
15		Minimum shift keying , Gussian MSK
16		Error performance in fading channels
17		OFDM, cyclic prefix,windowing,PAPR
18	**MULTIPATH MITIGATION TECHNIQUES**	Equalisation, Adaptive Equalisation
19		Linear and Non Linear Equalisation
20		Zero forcing and LMS algorithms
21		Diversity , Micro and Macro Diversity
22		Diversity combining techiques,
23		Error probability in fading channels with diversity reception, rake receiver

24	**MULTIPLE ANTENNA TECHNIQUES**	MIMO Systems-spatial multiplexing
25		System model, pre coding
26		Beam forming transmitter diversity
27		reciever diversity-channel state information
28		capacity in fading and non fading channels

Reference books:

1. Wireless Communications, 2/e, Rappaport, PHI
2. Stallings, Data and computer communication, 8th ed. Pearson
3. Tri. T. Ha, Digital Satellite Communications, 2/e, Tata McGraw Hill
4. Alberto Leon-Garcia, Indra Widjaja, COMMUNICATION NETWORKS, 2nd ed., TMH

Syllabus

Introduction: Objective, scope and outcome of the course.

CO1: Explain the fundamentals of wireless communication techniques such as fading, Path loss models, Parameters of mobile multipath channel techniques and link budget design.

CO2: Analyze the cellular architecture and understand the methods of sharing the communication channel through various multiple access techniques, and capacity calculation and improvement.

to be continued…

CO3: Analyze the link establishment in wireless communication, description of digital signaling for fading channels.

CO4: Gain an in-depth knowledge and develop an in-depth understanding multipath mitigation techniques, equalization, diversity and error probability in fading channels. Multiple antenna techniques –MIMO system model.

WIRELESS COMMUNICATION

WHY WIRELESS COMMUNICATION?

- Freedom from wires.
- No bunch of wires running from here and there.
- “Auto Magical” instantaneous communication without physical connection setup e.g.- Bluetooth, Wi-Fi.
- Global coverage
- Communication can reach where wiring is infeasible or costly
- E.g.- rural areas,buildings,battlefield,outerspace.
- Stay connected,flexiblity to connect multiple devices.

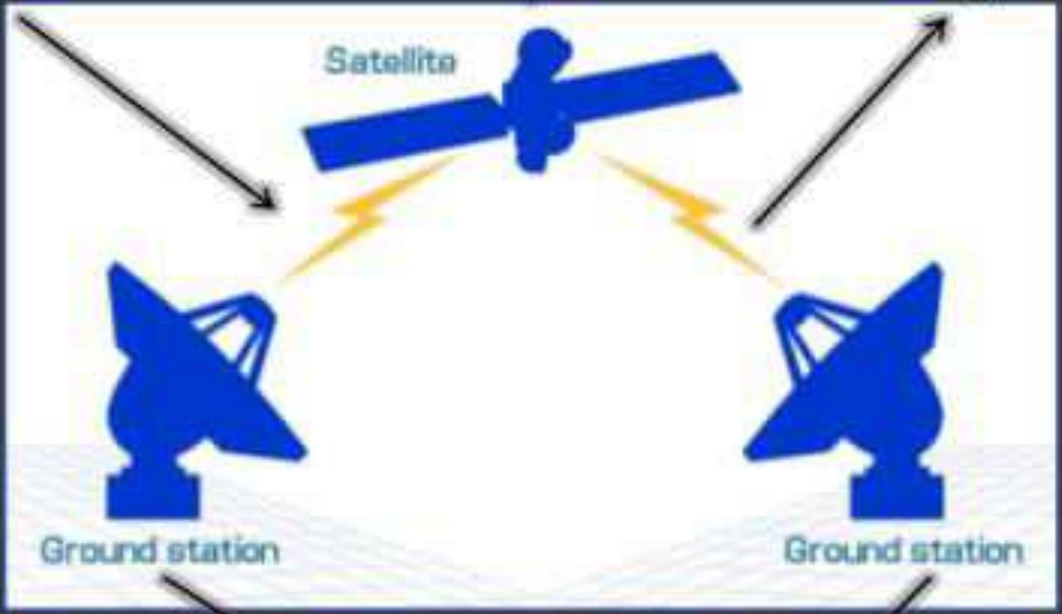
WHAT IS WIRELESS COMMUNICATION?

- Transmitting/receiving voice and data using electromagnetic waves in open space.
- The information from sender to receiver is carried over a well defined channel.
- Each channel has a fixed frequency bandwidth & capacity(bit rate).
- Different channels can be used to transmit information in parallel and independently.

TYPICAL FREQUENCIES

FM RADIO	88 MHZ
TV BROADCAST	200 MHZ
GSM PHONES	900 MHZ
GPS	1.2 GHZ
PCS PHONES	1.8 GHZ
BLUETOOTH	2.4 GHZ
Wi-Fi	2.4 GHZ

HOW COMMUNICATION TAKES PLACE?



Satellite

Transmitting Signal

Received
Signal

Transmitting
Antenna

**Receiving
Antenna**

TYPES OF WIRELESS COMMUNICATION?

RADIO TRANSMISSION:- easily generated, Omni-directional , travel long distance , easily penetrates buildings.

- PROBLEMS:- frequency dependent , relatively low bandwidth for data communication , tightly licensed by government.

MICROWAVE TRANSMISSION:- widely used for long distance communication , relatively inexpensive.

- PROBLEMS:- don't pass through buildings , weather and frequency dependent.

TYPES CONTINUED….

INFRARED AND MILIMETER WAVES:-

Widely used for short range communication , unable to pass through solid objects , used for indoor wireless LANs , not for outdoors.

LIGHT WAVE TRANSMISSION:- unguided optical signal such as laser , unidirectional , easy to install , no license required.

PROBLEMS:- unable to penetrate rain or thick fog , laser beam can be easily diverted by air.

ADVANTAGES AND DISADVANTAGES OF WIRELESS COMMUNICATION

ADVANTAGES:

- Working professionals can work and access Internet anywhere and anytime without carrying cables or wires wherever they go. This also helps to complete the work anywhere on time and improves the productivity.
- A wireless communication network is a solution in areas where cables are impossible to install (e.g. hazardous areas, long distances etc.)
- Wireless networks are cheaper to install and maintain

DISADVANTAGES:

- Has security vulnerabilities
- High costs for setting the infrastructure
- Unlike wired communication, wireless communication is influenced by physical obstructions, climatic conditions, interference from other wireless devices

CURRENT WIRELESS SYSTEMS

- CELLULAR SYSTEM

- WIRELESS LANS

- SATELLITE SYSTEM

- PAGING SYSTEM

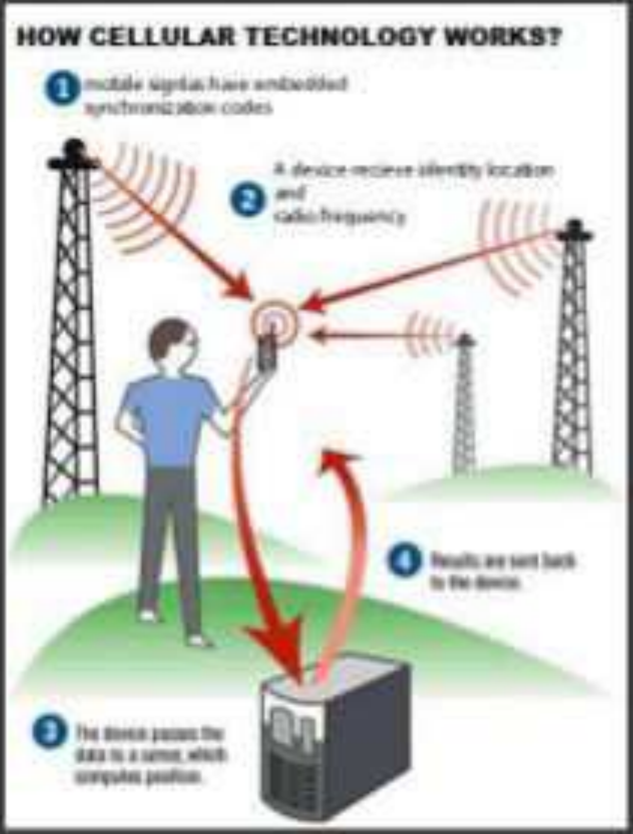
- PANS(BLUETOOTH)

WHAT IS CELLULAR SYSTEM?

Definition

Wireless communication technology in which several small exchanges (called cells) equipped with low-power radio antennas (strategically located over a wide geographical area) are interconnected through a central exchange. As a receiver (cell phone) moves from one place to the next, its identity, location, and radio frequency is handed-over by one cell to another without interrupting a call.

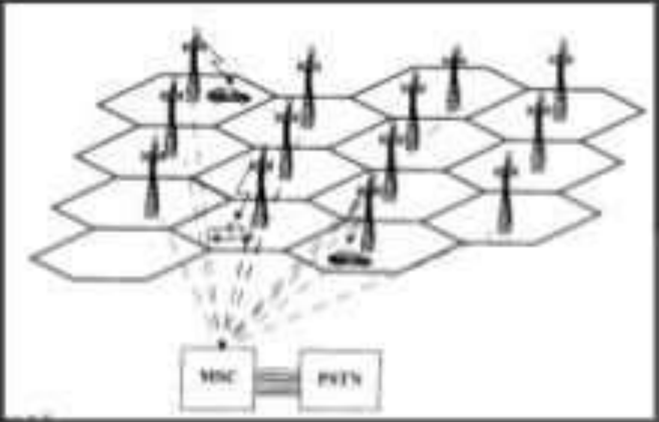
Practical



- 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

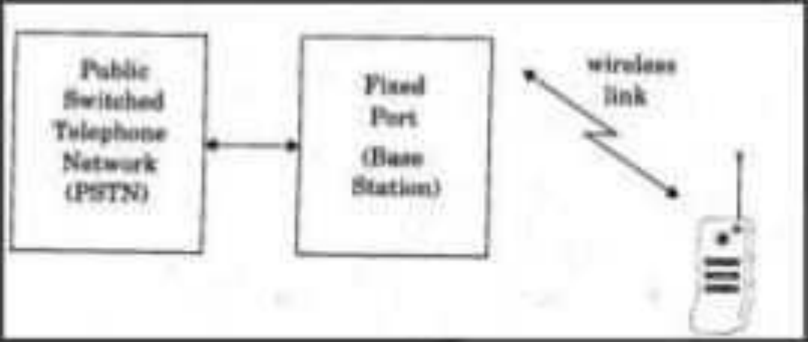
CELLULAR TELEPHONE SYSTEMS

- 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.



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



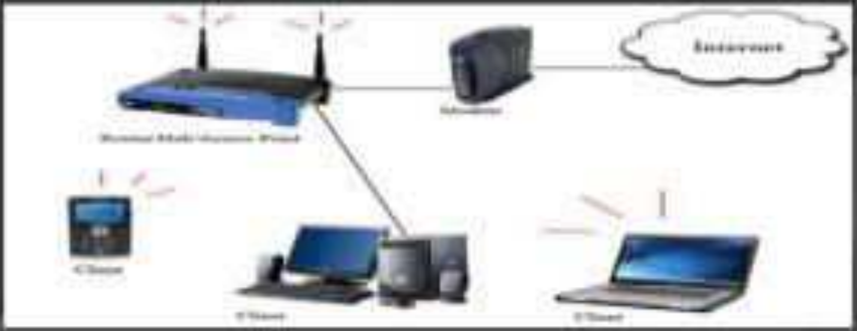
EXAMPLE OF MOBILE RADIO SYSTEMS

- 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.

WIRELESS LOCAL AREA NETWORK(WLAN)

- WLAN connect local computers
- Range (100 m) confined region
- Break data into packets
- Channel access is shared
- Backbone internet provides best service
- Poor performance in some application like videos
- Low mobility



SATELLITE SYSTEM ?

- Global coverage
- Optimized for good transmission
- Expensive base stations.
- Voice and data transmission
- Telecommunication application
- GPS , global telephone connection
- TV broadcasting , military , weather broadcasting

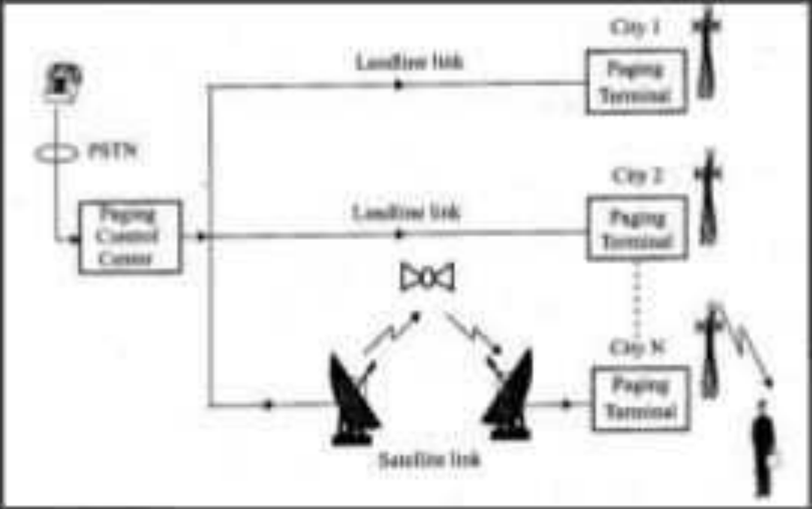
PAGING SYSTEM ?

- Broad coverage for short messages
- Message broadcast from all base stations
- Simple terminals
- Optimized for one way transmission
- Answer back hard
- Overtaken by cellular

Pager system →

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.
- Large transmission power to cover wide area.



THANK YOU

Unit 2: Wireless Channels

Section-A
By: Deepmala Kulshreshth
(EC Department)

Syllabus

Wireless Channels:

Large scale path loss – Path loss models: Free Space and Two-Ray models -Link Budget design – Small scale fading- Parameters of mobile multipath channels – Time dispersion parameters-Coherence bandwidth – Doppler spread & Coherence time, Fading due to Multipath time delay spread – flat fading – frequency selective fading – Fading due to Doppler spread – fast fading – slow fading.

PARAMETERS OF MOBİLE MULTİPATH CHANNELS

- Time Dispersion Parameters
- Coherence Bandwidth
- Doppler Spread and Coherence Time

TIME DISPERSION PARAMETERS

Parameters which grossly quatifies the multipath channel are :

- The mean excess delay,
- rms delay spread, and
- excess delay spread (X dB)

- These can be determined from a power delay profile.
- The mean excess delay is the first moment of the power delay profile and is defined as

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

TIME DISPERSION PARAMETERS (CONTD.)

- The rms delay spread is the square root of the second central moment of the power delay profile, where

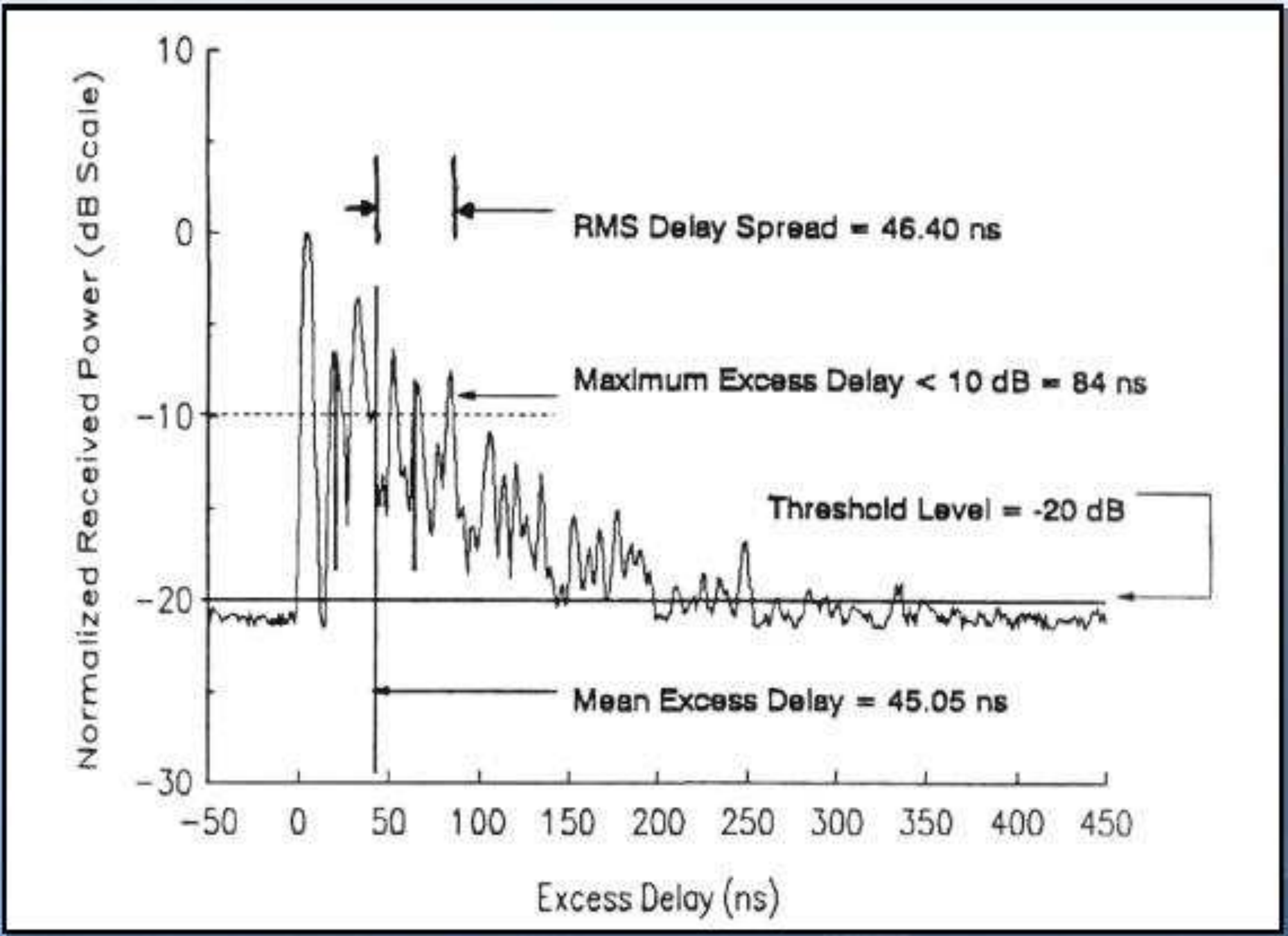
$$\sigma_\tau = \sqrt{\overline{\tau^2} - (\bar{\tau})^2} \qquad \overline{\tau^2} = \frac{\sum_k a_k^2 \tau_k^2}{\sum_k a_k^2} = \frac{\sum_k P(\tau_k)\tau_k^2}{\sum_k P(\tau_k)}$$

- Typical values of rms delay spread are on the order of microseconds in outdoor mobile radio channel and on the order of nanoseconds in indoor radio channel

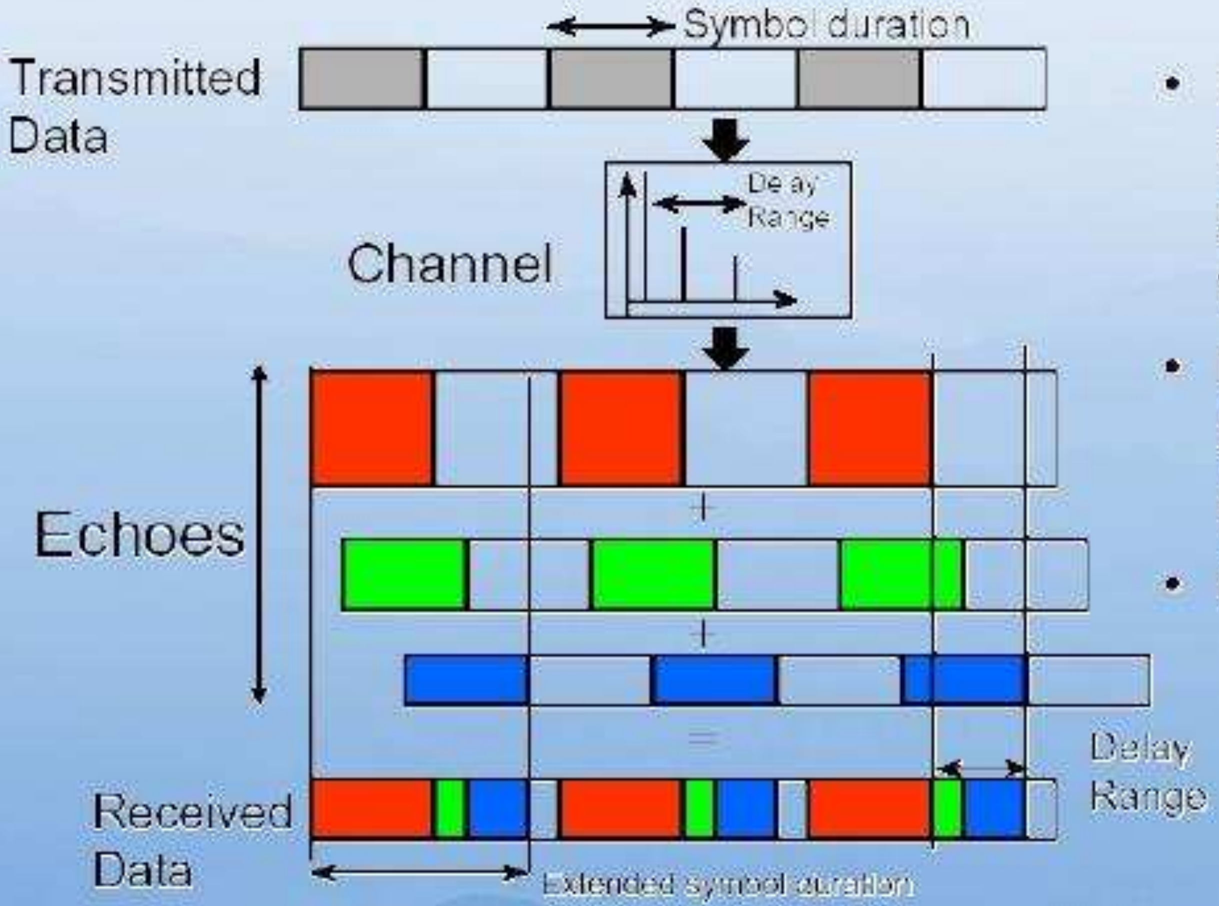
MAXİMUM EXCESS DELAY (X DB)

- **Maximum Excess Delay (X dB):** Defined as the time delay value after which the multipath energy falls to X dB below the maximum multipath energy. It is also called *excess delay spread*.
- It is defined as (τ_x - τ_0), where τ_0 is the first arriving signal and τ_x is the maximum delay at which a multipath component is within X dB of the strongest arriving multipath signal.
  - The values of time dispersion parameters also depend on the noise threshold (the level of power below which the signal is considered as noise).
  - If noise threshold is set too low, then the noise will be processed as multipath and thus causing the parameters to be higher.

RMS DELAY SPREAD



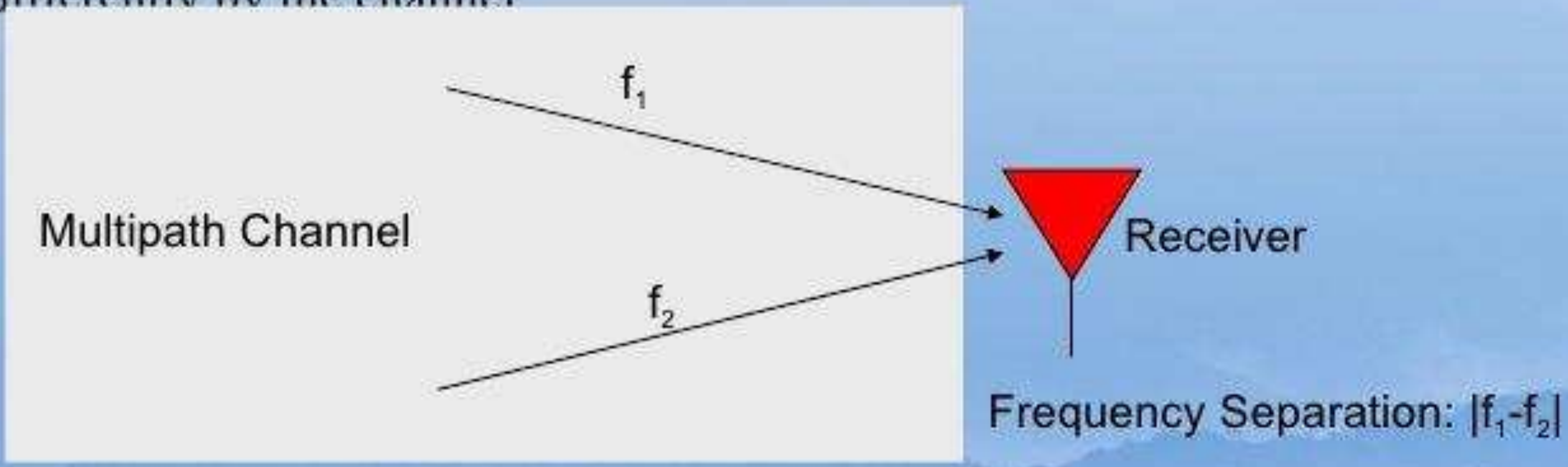
EFFECT OF DELAY SPREAD



- Received Symbols smeared in time
- Inter symbol interference (ISI)
- Ghosting

COHERENT BANDWIDTH

- Coherence bandwidth is used to characterize the channel in the frequency domain.
- It is a statistical measure of the range of frequencies over which the channel can be considered flat.
- Two sinusoids with frequency separation greater than B_c are affected quite differently by the channel



COHERENCE BANDWIDTH

- Frequency correlation between two sinusoids: $0 <= C_{r1, r2} <= 1$.
- Coherence bandwidth is the range of frequencies over which two frequency components have a strong potential for amplitude correlation.
  - σ is rms delay spread

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

  - If correlation is above 0.9, then

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

  - If correlation is above 0.5, then
    - This is called 50% coherence bandwidth.

DOPPLER SPREAD

- Delay spread and Coherence bandwidth describe the time dispersive nature of the channel in a local area.
  - They don’t offer information about the time varying nature of the channel caused by relative motion of transmitter and receiver.
- It is measure of spectral broadening caused by motion, the time rate of change of the mobile radio channel, and is defined as the range of frequencies over which the received Doppler spectrum is essentially non-zero.

DOPPLER SPREAD (CONTD.)

- We know how to compute Doppler shift: f_d
- Doppler spectrum have components in the range of f_c-f_d to f_c+f_d
- Doppler spread, B_D, is defined as the maximum Doppler shift: $f_m = v/l$
- If the baseband signal bandwidth is much less than B_D then effect of Doppler spread is negligible at the receiver. This is slow fading channel characteristics.

COHERENCE TIME

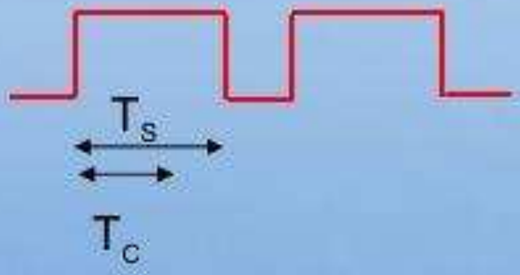
- Coherence time is also defined as: $T_C \approx \sqrt{\frac{9}{16\pi f_m^2}} = \frac{0.423}{f_m}$
- The time domain dual of B_D
- Coherence time definition implies that two signals arriving with a time separation greater than Tc are affected differently by the channel.
- If the coherence time is defined as the time over which the time correlation function is above 0.5, then the coherence time is approximately, $T_c \approx \frac{9}{16\pi f_m}$ where $f_m = \frac{v}{\lambda}$

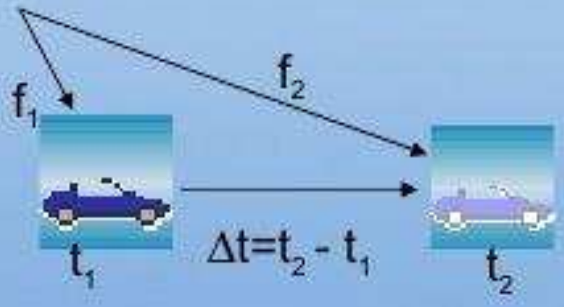
COHERENCE TIME

- If the symbol period of the baseband signal (reciprocal of the baseband signal bandwidth) is greater the coherence time, than the signal will distort, since channel will change during the transmission of the signal .

Coherence time (T_C) is defined as:

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

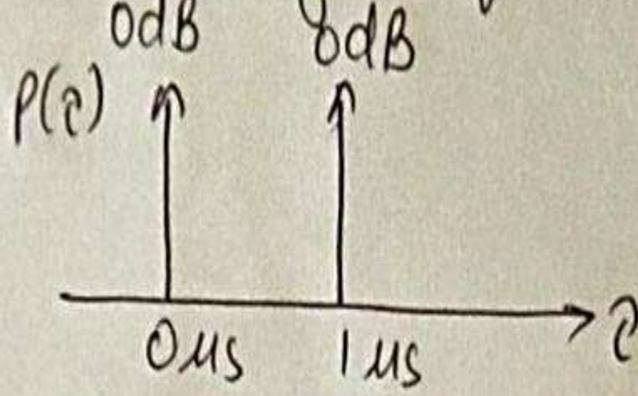




IMPORTANT QUESTIONS

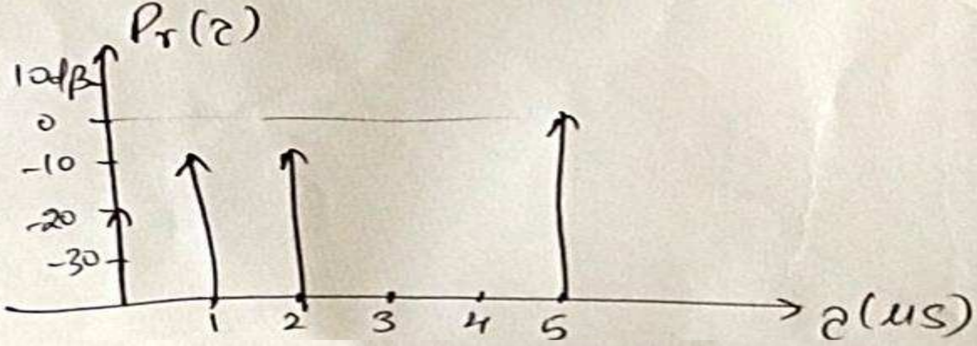
Ques 1: Compute the RMS Delay Spread for the following Power Delay Profile.

(a)



(b) If BPSK modulation is used what is the maximum bit rate that can be sent through the channel without needing an equalizer?

Ques2: Calculate the mean excess delay, rms delay spread and the maximum excess delay (10dB) for the multipath profile given in figure below. Estimate 50% coherence bandwidth of the channel. Would this channel be suitable for AMPS or GSM service without the use of an equalizer?



Ques3: Determine the proper spatial sampling interval required to make small scale propagation measurements which assume that consecutive samples are highly correlated in time. How many samples will be required over 10 m travel distance of $f_c = 1900$ MHz and $v = 50$ m/s. How long would it take to make these

measurements, assuming they could be made in real time from a moving vehicle? What is the doppler spread B_D for the channel?

Ans 1: (a) $\bar{\tau} = \dfrac{(1)(0)+(1)(1)}{1+1} = \dfrac{1}{2} = 0.5\,\mu s$

(0 dB = 1)

$\overline{\tau^2} = \dfrac{(1)(0)^2+(1)(1)^2}{1+1} = \dfrac{1}{2} = 0.5\,\mu s^2$

RMS delay spread $\sigma_\tau = \sqrt{\overline{\tau^2}-(\bar{\tau})^2} = \sqrt{0.5-(0.5)^2}$

$= \sqrt{0.25} = 0.5\,\mu s.$

(b) for BPSK

$\dfrac{\sigma_\tau}{T_s} \leq 0.1$

$T_s \geq \dfrac{\sigma_\tau}{0.1}$

$T_s \geq \dfrac{0.5\,\mu s}{0.1}$

$T_s \geq 5\,\mu s$

$R_s = \dfrac{1}{T_s} = 0.2 \times 10^6$ sps $= 200$ ksps

$R_b = 200$ kbps

Ans 2: By the definition of maximum excess delay it can be seen that $\tau_{10dB} = 5 \mu s$.

Mean excess delay for given profile

$$\bar{\tau} = \frac{\sum_k P(\tau_k)\,\tau_k}{\sum_k P(\tau_k)}$$

$$\bar{\tau} = \frac{(1)(5) + (0.1)(1) + (0.1)(2) + (0.01)(0)}{[0.01 + 0.1 + 0.1 + 1]} = 4.38 \mu s$$

second moment

$$\overline{\tau^2} = \frac{(1)(5)^2 + (0.1)(1)^2 + (0.1)(2)^2 + (0.01)(0)^2}{1.21} = 21.07 \mu s^2$$

Therefore RMS delay spread

$$\sigma_\tau = \sqrt{21.07 - (4.38)^2} = 1.37 \mu s$$

Coherence Bandwidth (50%)

$$B_c = \frac{1}{5\sigma_\tau} = \frac{1}{5 \times 1.37} = 146 \text{ KHz}$$

Since B_c is greater than 30 KHz, AMPS will work without an equalizer. However GSM requires 200 KHz BW which exceeds B_c, thus an equalizer would be needed for this channel.

Ans 3: for correlation, ensure that time between sample is equal to $T_c/2$ and we will use smallest value of T_c for conservative design

$$T_c \simeq \frac{9}{16\pi f_m} = \frac{9\lambda}{16\pi v} \qquad f_m = v/\lambda$$

$$T_c = \frac{9c}{16\pi v f_c} = \frac{9\times3\times10^8}{16\times3.14\times50\times1900\times10^6}$$

$$\boxed{T_c = 565\,\mu s}$$

Taking time samples at less than half T_c, at $282.5\,\mu s$ corresponds to a spatial sampling interval of

$$\Delta x = \frac{vT_c}{2} = \frac{50\times565\,\mu s}{2} = 0.014125\,m$$

$$= 1.41\,cm$$

Therefore, the number of samples required over a 10m travel distance is

$$N_x = \frac{10}{\Delta x} = \frac{10}{0.014125} = 708 \text{ samples}$$

Time taken to make this measurement is equal to $\frac{10\,m}{50\,m/s} = 0.2\,s$

Doppler spread $B_D = f_m = \frac{vf_c}{c} = \frac{50\times1900\times10^6}{3\times10^8}$

$$B_D = 316.66\,Hz$$

Important formulae

1. Mean Excess Delay $\bar{\tau} = \dfrac{\sum_k P(\tau_k)\,\tau_k}{\sum_k P(\tau_k)}$

~~2~~ Second moment of PDP

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

2. RMS Delay Spread

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

3. Coherence Bandwidth

a. When correlation f^n is above 0.9

$$B_c \simeq \frac{1}{50\,\sigma_\tau}$$

b. When correlation f^n is above 0.5

$$B_c \simeq \frac{1}{5\,\sigma_\tau}$$

4. Coherence Time

(when correlation f^n is above 0.5)

$$T_c \simeq \frac{9}{16\pi f_m}$$

Unit-3: Cellular Architecture

Part- I

By: Deepmala Kulshreshth
(EC Department)

Syllabus

Cellular Architecture:

Multiple Access techniques - FDMA,TDMA, CDMA – Capacity calculations–Cellular concept- Frequency reuse – channel assignment- hand off- interference & system capacity- trunking & grade of service – Coverage and capacity improvement.

Multiple Access Techniques

There are mainly four kinds of multiple access techniques through which radio resources can be shared among many users simultaneously. These are given as:

1- Frequency Division Multiple Access (FDMA)

2- Time Division Multiple Access (TDMA)

3- Code Division Multiple Access (CDMA)

4- Space Division Multiple Access (SDMA)

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 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

reverse channel

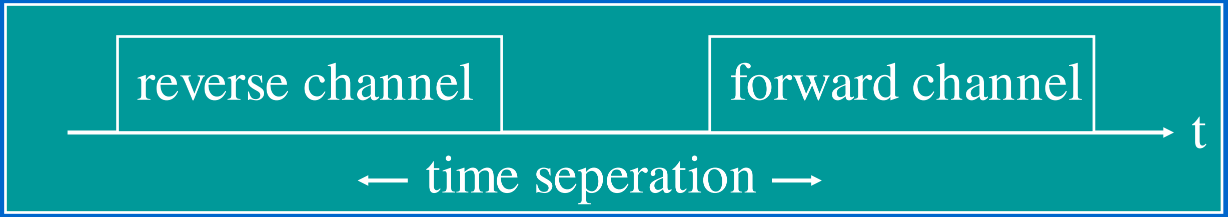
forward channel

← frequency seperation →

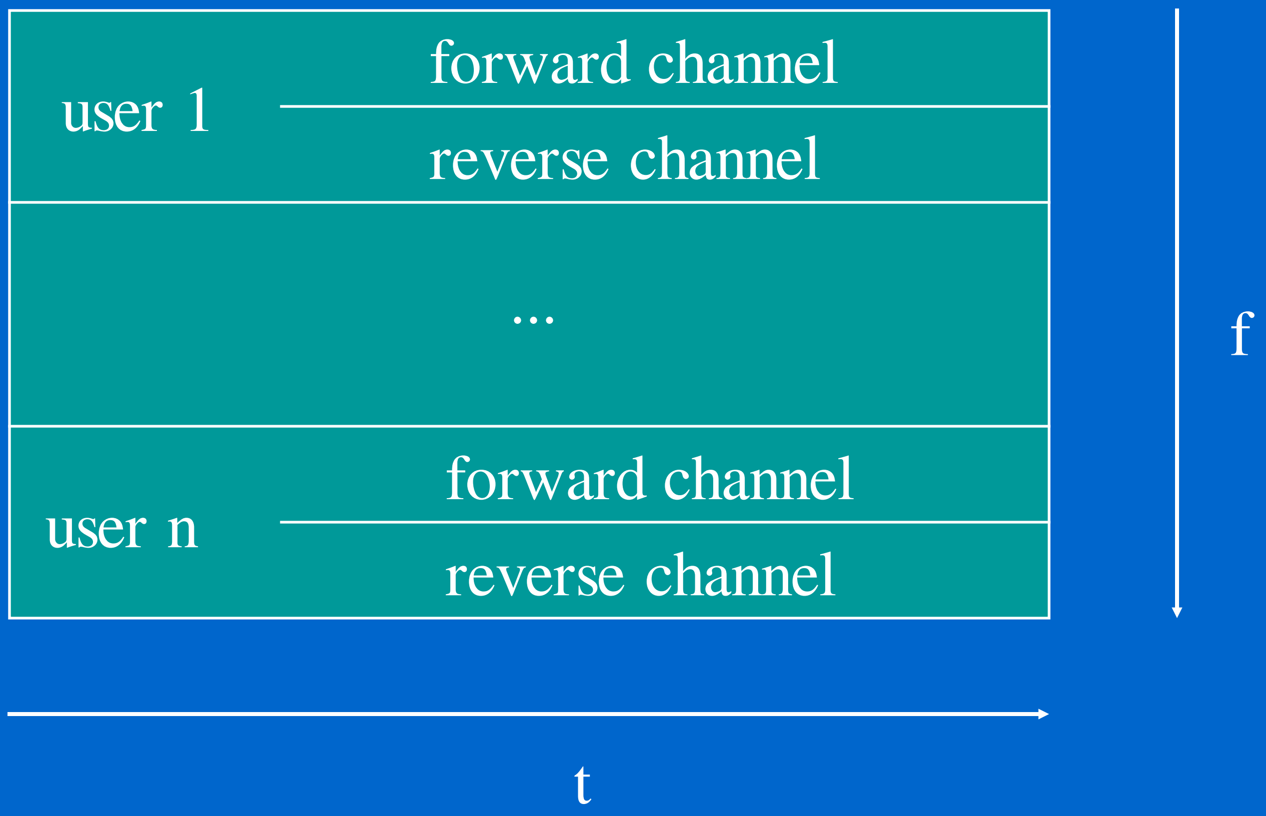
f

Time division duplexing (TDD)

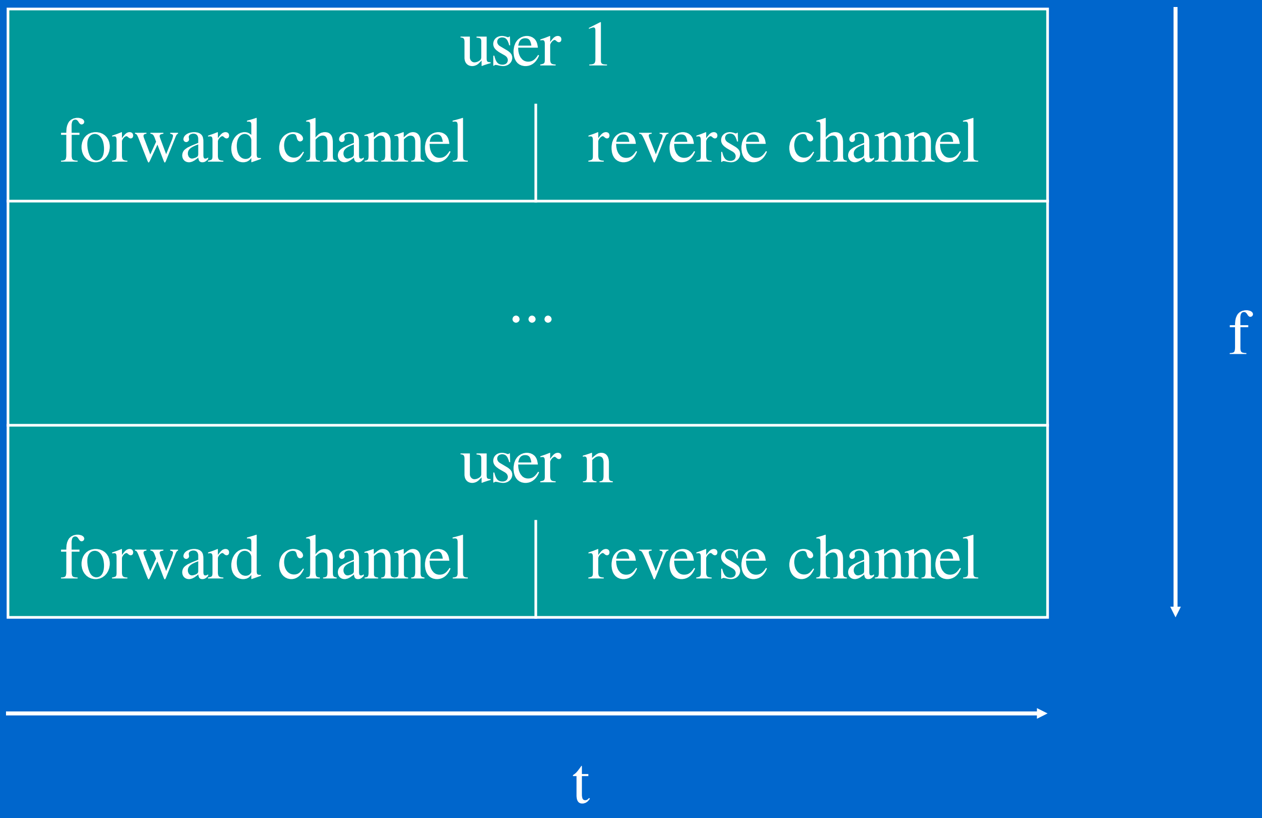
- uses time for forward and reverse link
- multiple users share a single radio channel
- forward time slot
- reverse time slot
- no duplexer is required



Logical separation FDMA/FDD



Logical separation FDMA/TDD



user 1

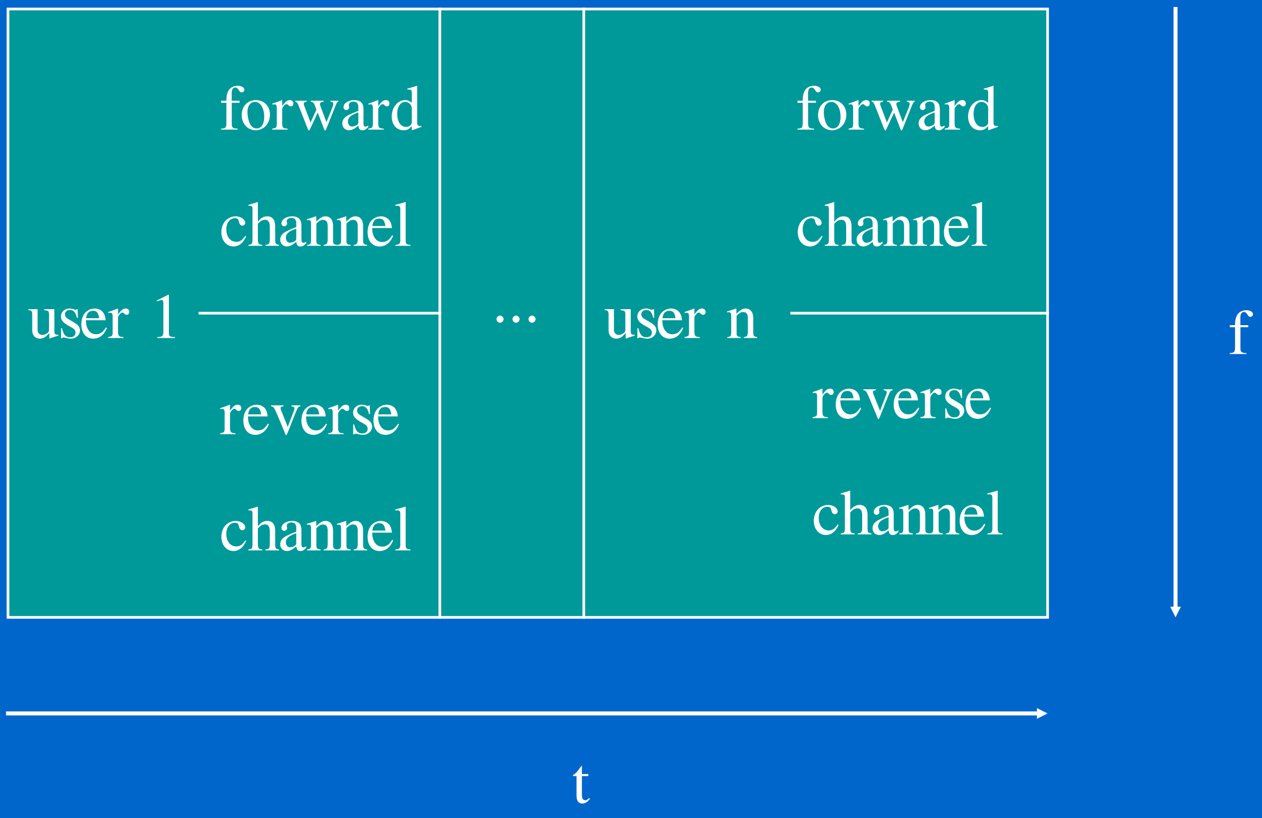
forward channel | reverse channel

…

user n

forward channel | reverse channel

Logical separation TDMA/FDD


forward channel

user 1

reverse channel

…

forward channel

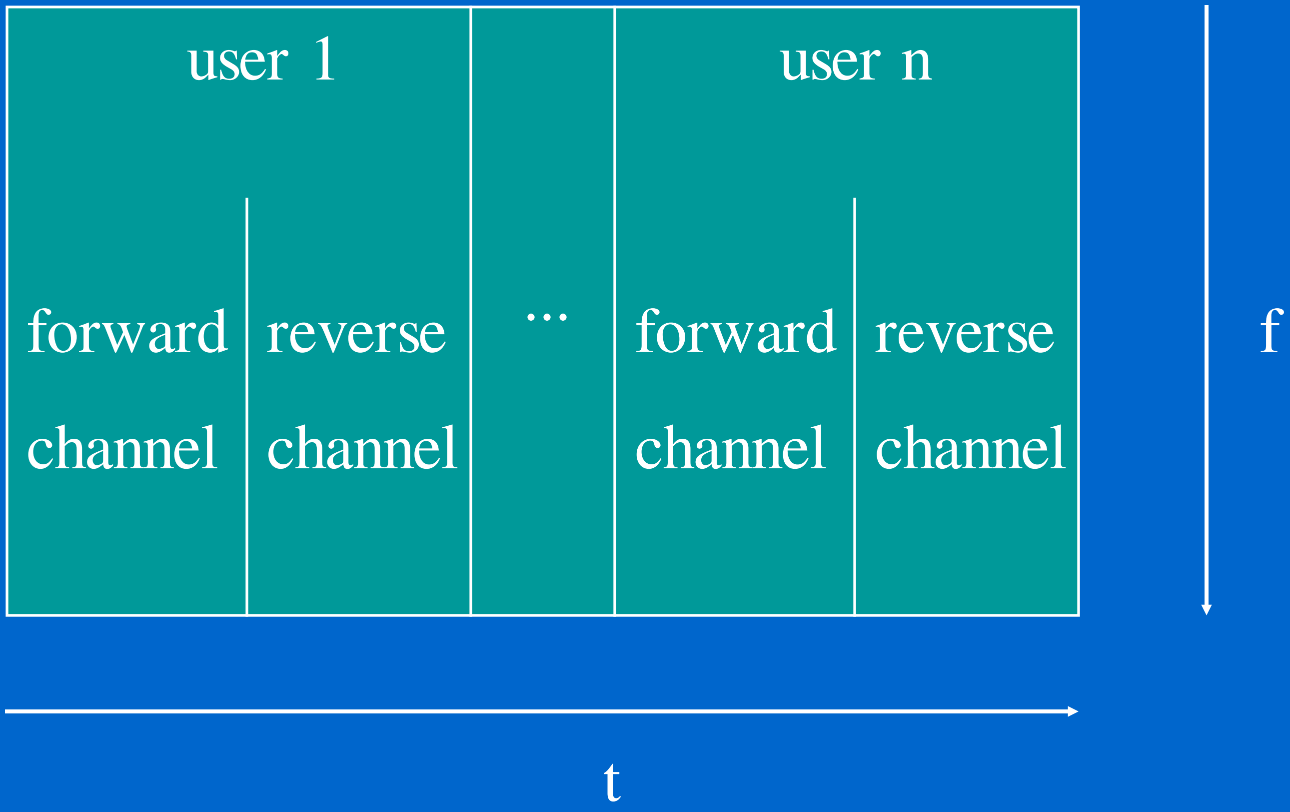
user n

reverse channel

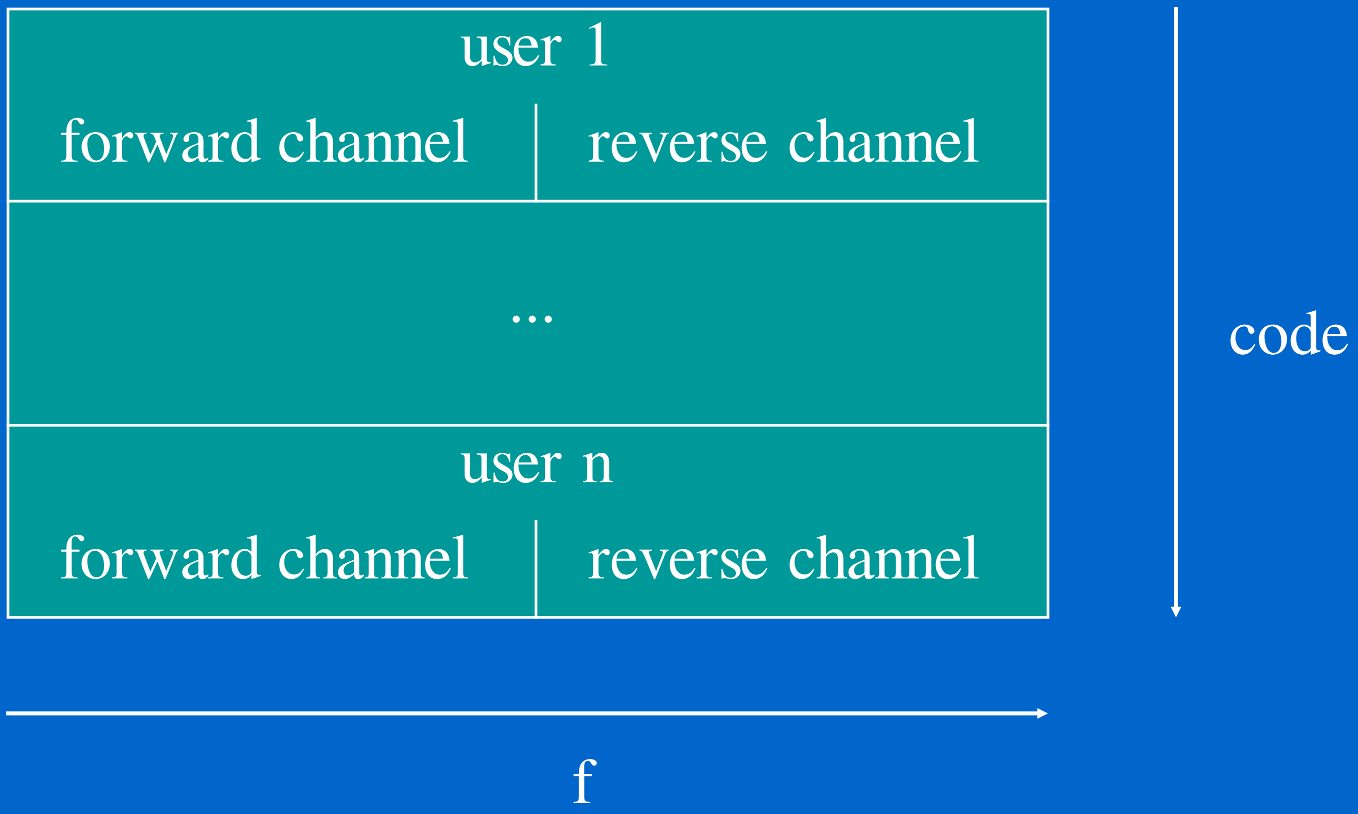
f

t

Logical separation TDMA/TDD



Logical separation CDMA/FDD



user 1

forward channel | reverse channel

...

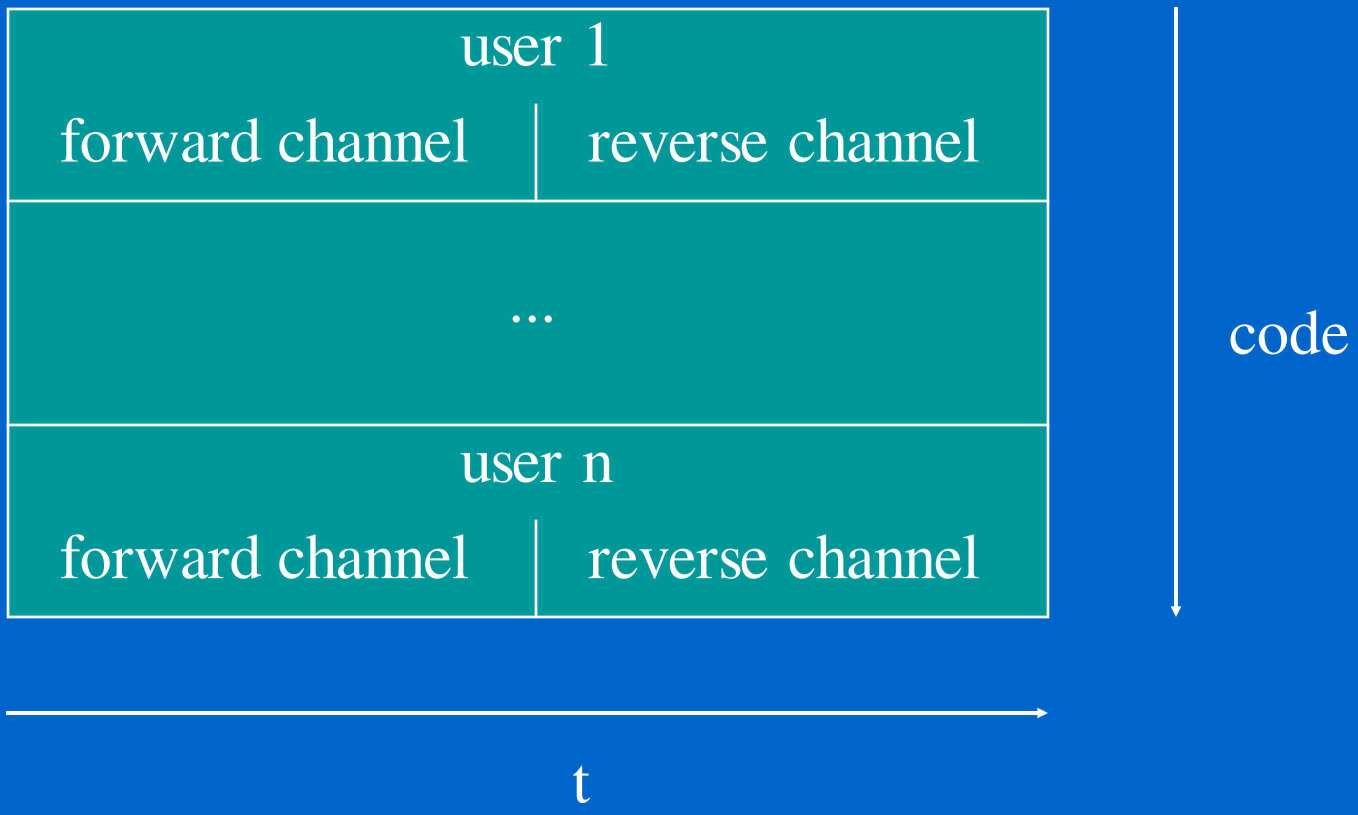
user n

forward channel | reverse channel

code

f

Logical separation CDMA/TDD



user 1

forward channel | reverse channel

…

user n

forward channel | reverse channel

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

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

- N … number of channels
- B_t … total spectrum allocation
- B_{guard} … guard band
- B_c … channel bandwidth

Example: Advanced Mobile Phone System

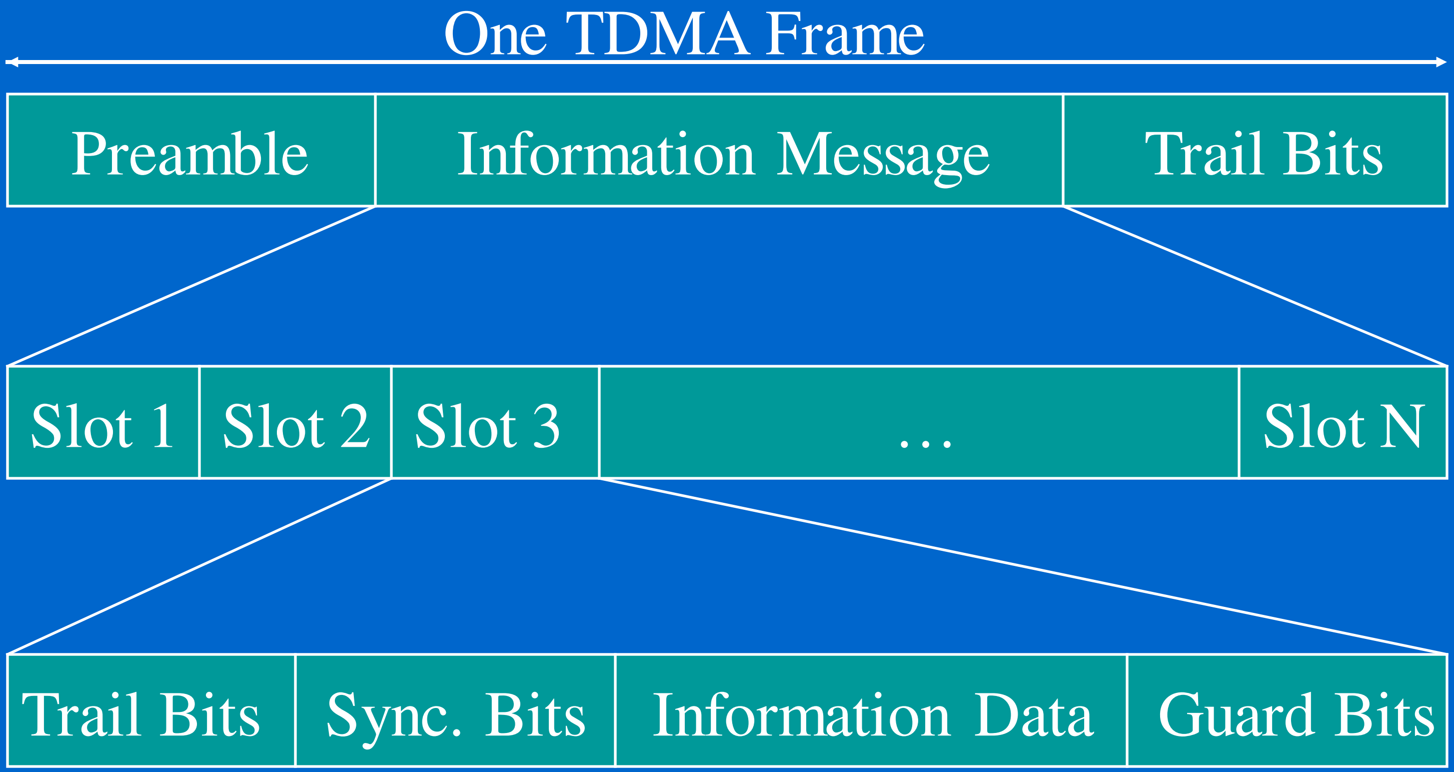
- AMPS
- FDMA/FDD
- analog cellular system
- 12.5 MHz per simplex band - B_t
- $B_{guard} = 10$ kHz ; $B_c = 30$ kHz

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

Time Division Multiple Access

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

Repeating Frame Structure



One TDMA Frame

Preamble | Information Message | Trail Bits

Slot 1 | Slot 2 | Slot 3 | … | Slot N

Trail Bits | Sync. Bits | Information Data | Guard Bits

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
- B_{tot} … total spectrum allocation
- B_{guard} … Guard Band
- B_c … channel bandwidth

Example: Global System for Mobile (GSM)

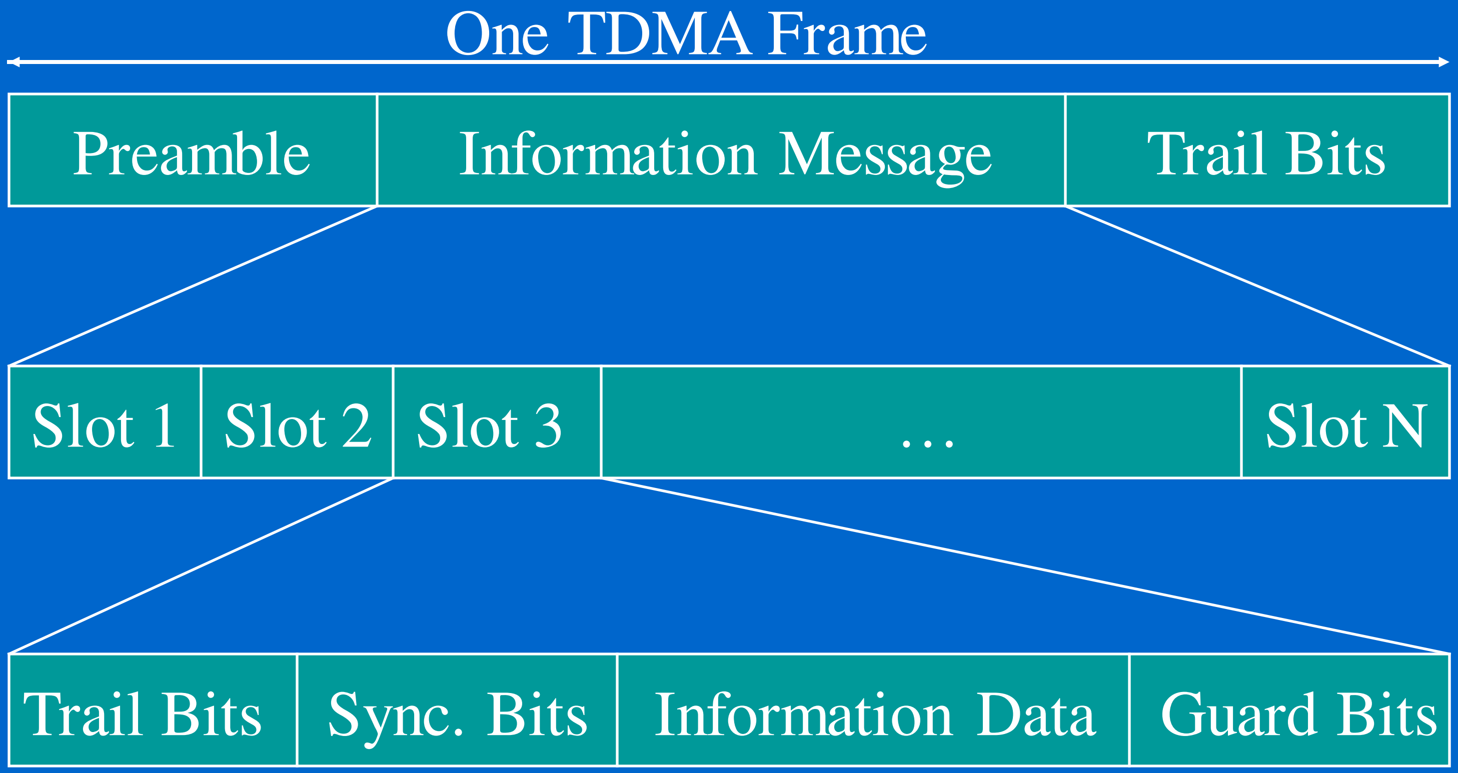
- TDMA/FDD
- forward link at $B_{tot} = 25$ MHz
- radio channels of $B_c = 200$ kHz
- if $m = 8$ speech channels supported, and
- if no guard band is assumed :

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

Efficiency of TDMA

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

Repeating Frame Structure



One TDMA Frame

Preamble | Information Message | Trail Bits

Slot 1 | Slot 2 | Slot 3 | … | Slot N

Trail Bits | Sync. Bits | Information Data | Guard Bits

The frame is cyclically repeated over time.

Efficiency of TDMA

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

- b_{OH} … number of overhead bits
- N_r … number of reference bursts per frame
- b_r … reference bits per reference burst
- N_t … number of traffic bursts per frame
- b_p … overhead bits per preamble in each slot
- b_g … 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

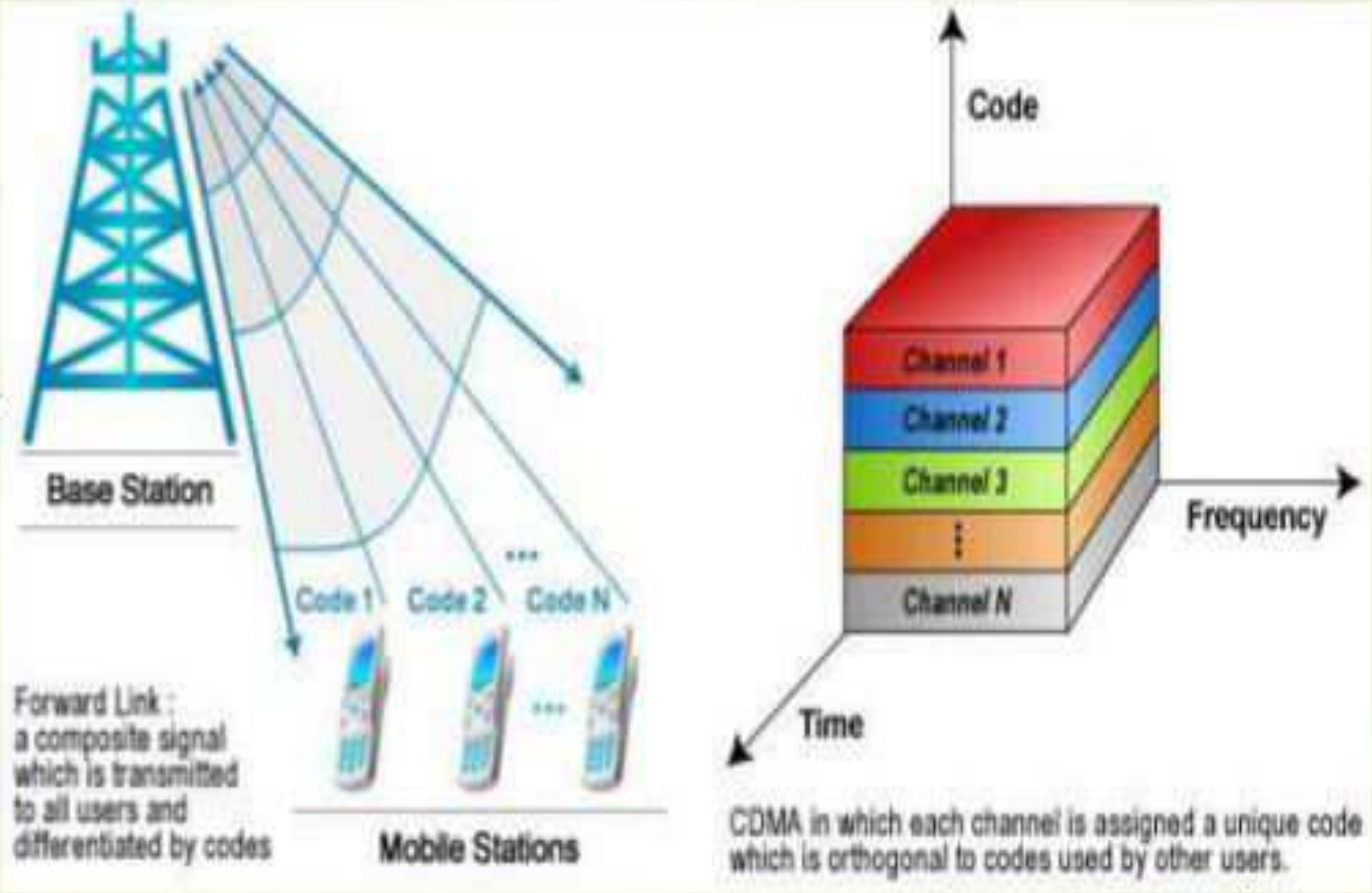
CDMA

- In CDMA systems, narrow band message signal is multiplied with large BW signal called the spreading system.
- These spreading signals are PN sequences whose chip rate is larger than data rate of message.
- CDMA uses same carrier frequency to modulate all the users and also it allows all the users to transmit simultaneously.
- Each user has its pseudorandom codeword which is orthogonal to all other codewords.

Continued….

- To ensure minimal mutual interference spreading codes must be orthogonal.
- The receiver performs time correlation function so that all other signal appears uncorrelated. However receiver should know the codeword to decrypt the message signal.
- In CDMA systems, power of users determine noise floor of entire system. Failing to incorporate the proper power control leads to near far problem.
- It refers that users with low power will not get a chance to connect with base station thereby left unserved.

CONT...



Forward Link : a composite signal which is transmitted to all users and differentiated by codes

CDMA in which each channel is assigned a unique code which is orthogonal to codes used by other users.

Advantages

- Improvement in capacity and security
- Improvement in handover/ handoff
- Use of wide bandwidth is possible
- More number of users can share same bandwidth
- It is well matched with other cellular technologies

Disadvantages

- System is more complicated
- Guard band and guard time both are required to be provided
- As the number of users increases, overall quality decreases.

Spread Spectrum Technique

- There are two types of techniques in which message signal is mixed with PN sequence before transmission. These techniques are :

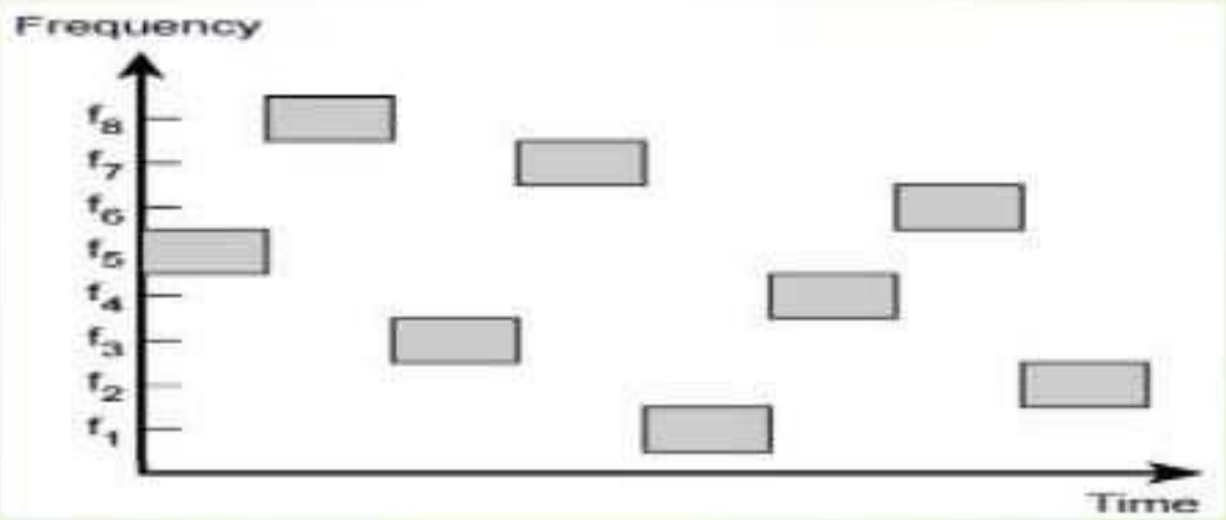
1. Frequency Hopping
2. Direct Sequence

Frequency Hopping

- It is very easy spread spectrum modulation technique.
- Main idea behind this technique is to transmit data across a broad spectrum and frequency can be switched rapidly from one to another.
- Transmitter and receiver are synchronised every time with an accurate clocking system.

Cont…

- Following diagram shows that frequency is changing after each interval of time
- So that, It would be difficult for any third party to know about which frequency is being used



Direct Sequence Technique

- It is quite popular technique in which data signal is directly multiplied by PN code.
- PN code is a sequence of chips having values -1 and1. Here -1 represents 0 zero.
- Data encodes at the transmitter side and decodes at the receiver side by using same spreading code.

Application

- It is used in military and some commercial applications.
- It is used in used in mobile communication.
- It is used in radar and navigation systems.
- CDMA is considered as highest of wireless communication and is used for fast and safe mode of data exchange such as 3G.

Space Division Multiple Access

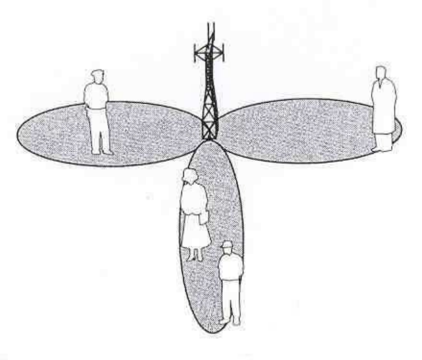
- All users can communicate at the same time using the same channel.
- It is completely free from interference.
- A single satellite can communicate with more satellite receivers of same frequency
- Directional spot beam antennas are used hence base station in SDMA can track moving user

Space Division Multiple Access

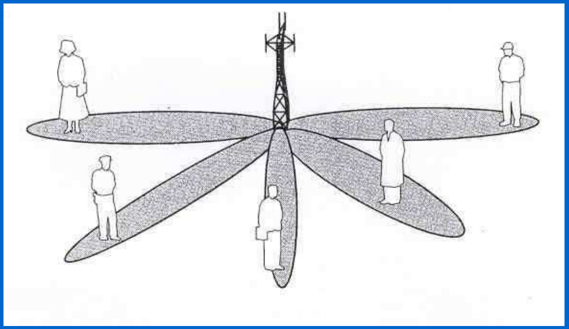
- Controls radiated energy for each user in space
- using spot beam antennas
- base station tracks user when moving
- cover areas with same frequency:
- TDMA or CDMA systems
- cover areas with same frequency:
- FDMA systems

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

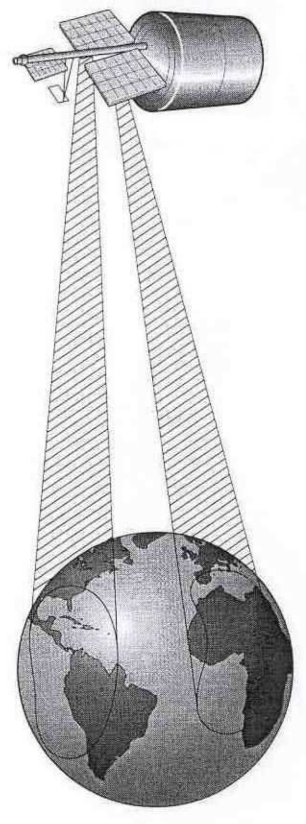
- adaptive antennas promise to mitigate reverse link problems
- limiting case of infinitesimal beamwidth
- limiting case of infinitely fast track ability
- thereby unique channel that is free from interference
- all user communicate at same time using the same channel

Disadvantage of SDMA

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

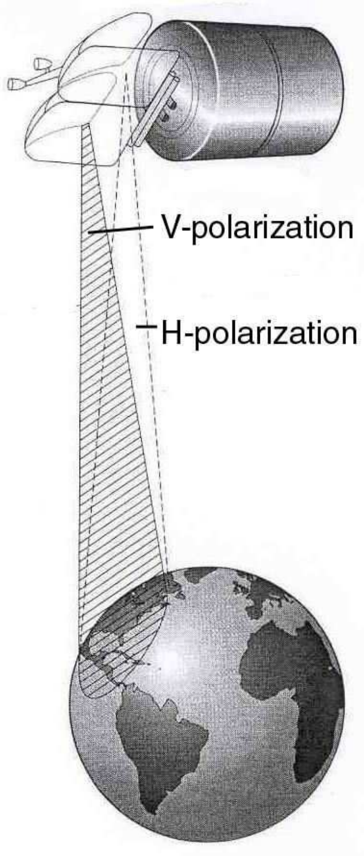
SDMA and PDMA in satellites

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



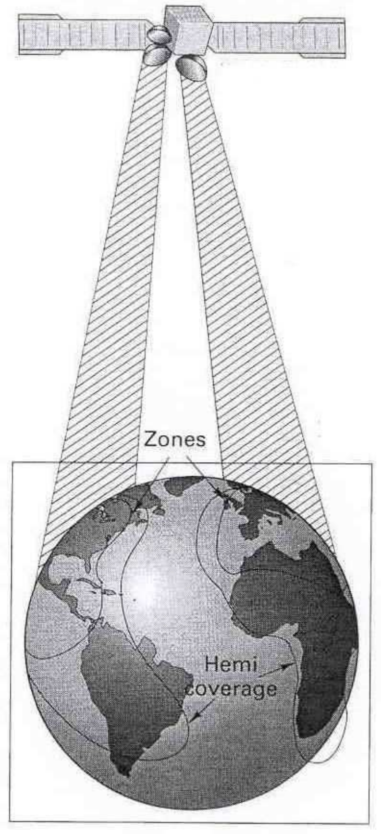
SDMA and PDMA in satellites

- 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?

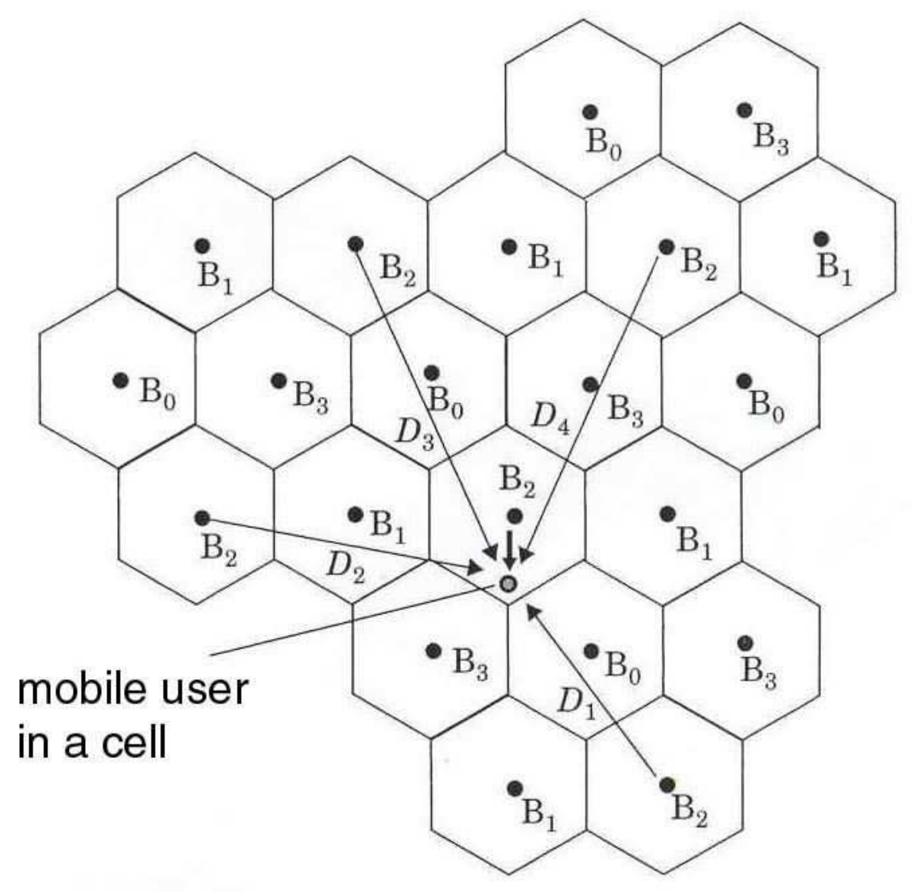
Co-Channel Reuse Ratio Q

$$Q = D/R$$

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

Forward channel interference

- cluster size of 4
- D_0 … 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 $D_0 = R$
- $(C/I)_{min}$ for acceptable signal quality
- following equation must hold:

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

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

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

- Bt … total allocated spectrum for the system
- Bc … 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 B_t and number of radio channels per cell m constant to get $(C/I)_{eq}$:

Compare different Systems

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

- B_c … bandwidth of a particular system
- $(C/I)_{min}$ … tolerable value for the same system
- B_c' … 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 R_c and B_c is always linear ($R_c/R_c' = B_c/B_c'$)
- assume that level I is the same for two different systems ($I' = I$) :

$$\boxed{\frac{E_c}{E_c'} = \left(\frac{B_c'}{B_c}\right)^3}$$

Compare C/I between FDMA and TDMA

- Assume that multichannel FDMA system occupies same spectrum as a TDMA system
- FDMA : $C = E_b * R_b$; $I = I_0 * B_c$
- TDMA : $C' = E_b * R_b'$; $I' = I_0 * B_c'$
- E_b … Energy per bit
- I_0 … interference power per Hertz
- R_b … channel bit rate
- B_c … 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

$$\underline{C'} = Eb*Rb' = 1/3*(Eb*10\text{E}4\ \text{bits}) = 3*Rb*Eb = \underline{3*C}$$

$$\underline{I'} = I0*Bc' = I0*30\text{kHz} = \underline{3*I}$$

- 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

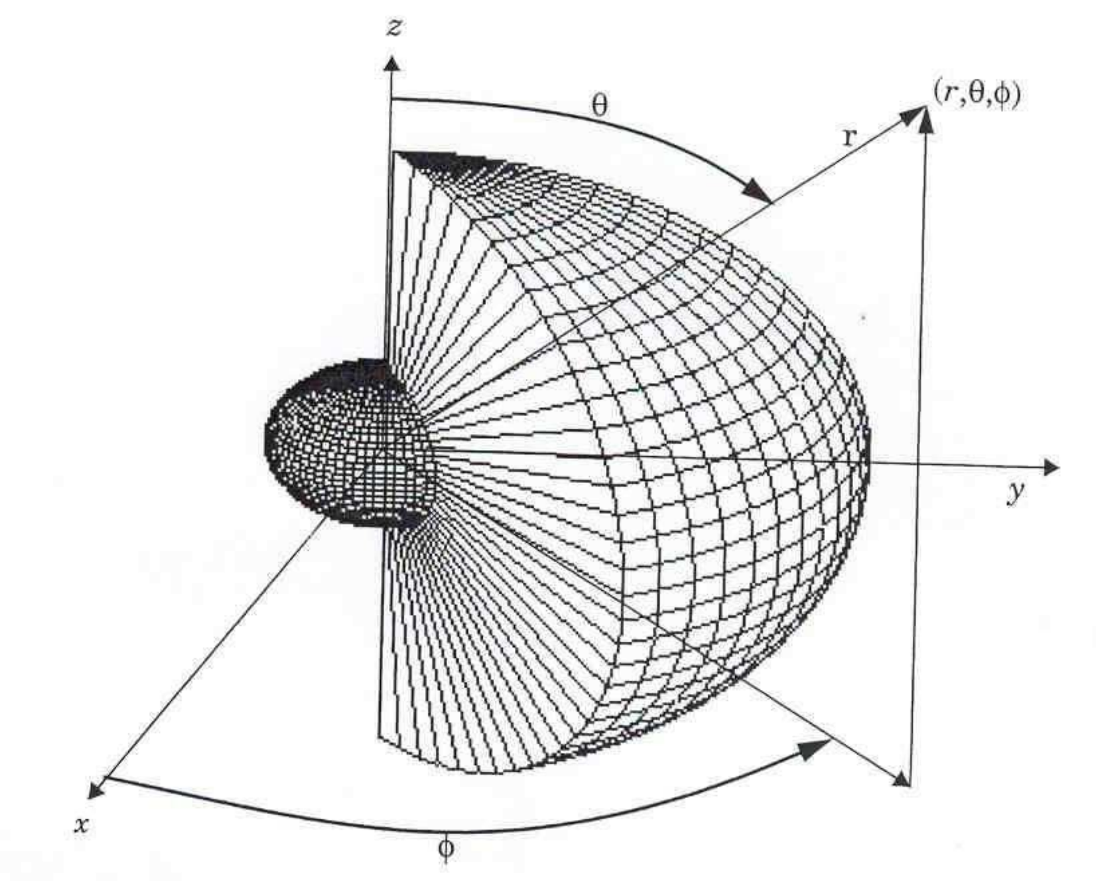
Capacity of SDMA systems

- 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 $P_{r;0}$
- interfering users i = 1,…,k-1 have received power $P_{r;I}$
- 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:

$$I = P_c\ E\ \{\ \overset{K-1}{\underset{i=1}{\text{💧}}}\ G(\text{☞}i)\ \}$$

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

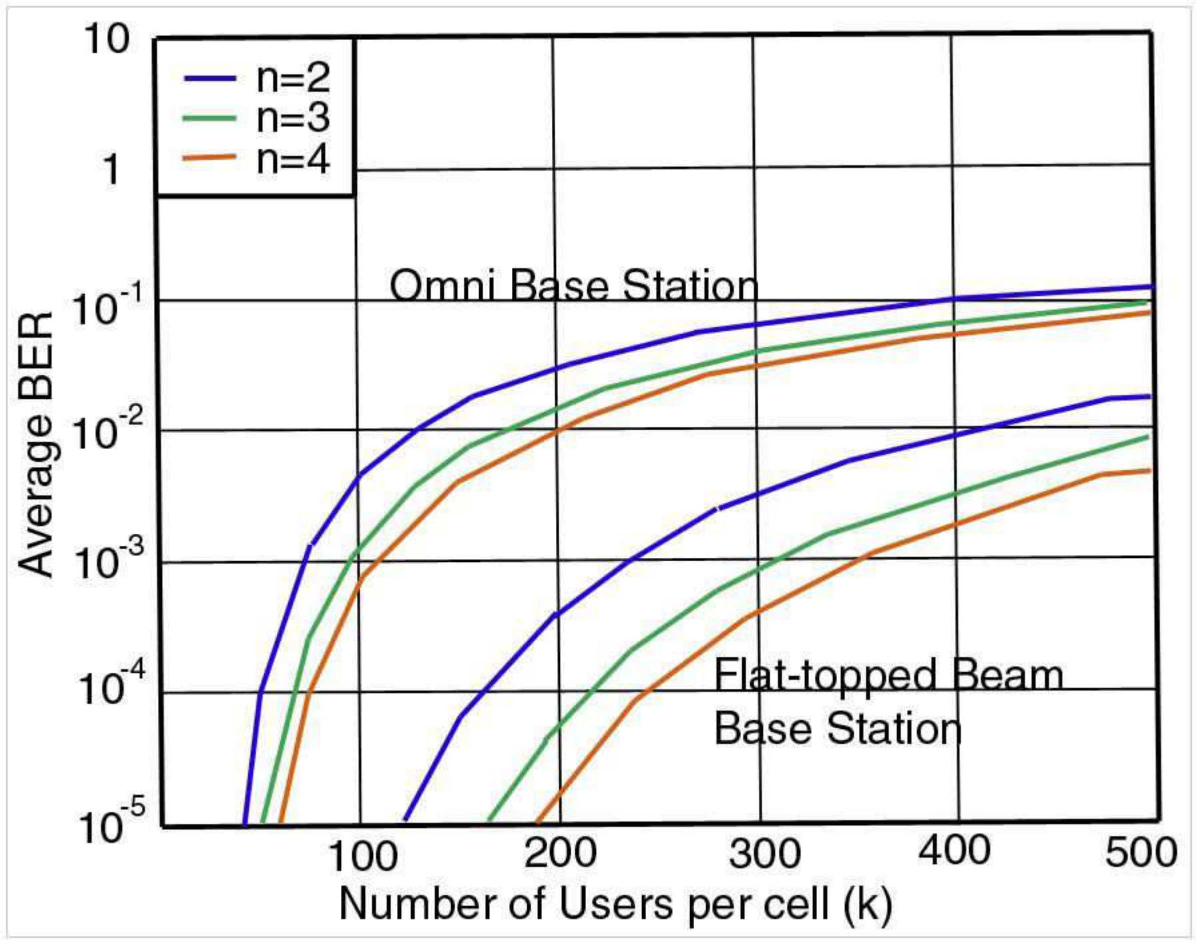
Capacity of SDMA systems

- Average bit error rate P_b 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



Syllabus

Cellular Architecture:

Multiple Access techniques - FDMA, TDMA, CDMA – Capacity calculations–Cellular concept- Frequency reuse – channel assignment- hand off- interference & system capacity- trunking & grade of service – Coverage and capacity improvement.

Cellular Systems-Basic Concepts

- Cellular system solves the problem of spectral congestion.
- Offers high capacity in limited spectrum.
- High capacity is achieved by limiting the coverage area of each BS to a small geographical area called cell.
- Replaces high powered transmitter with several low power transmitters.
- Each BS is allocated a portion of total channels and nearby cells are allocated completely different channels.
- All available channels are allocated to small no of neighboring BS.
- Interference between neighboring BSs is minimized by allocating different channels.

Cellular Systems-Basic Concepts

- Same frequencies are reused by spatially separated BSs.
- Interference between co-channels stations is kept below acceptable level.
- Additional radio capacity is achieved.
- Frequency Reuse-Fix no of channels serve an arbitrarily large no of subscribers

Frequency Reuse

- used by service providers to improve the efficiency of a cellular network and to serve millions of subscribers using a **limited radio spectrum**
- After covering a certain distance a radio wave gets attenuated and the signal falls below a point where it can no longer be used or cause any interference
- A transmitter transmitting in a specific frequency range will have only a limited coverage area
- Beyond this coverage area, that frequency can be reused by another transmitter.
- The entire network coverage area is divided into cells based on the principle of frequency reuse

Frequency Reuse

- A <u>cell</u> = basic geographical unit of a cellular network; is the area around an antenna where a specific frequency range is used.
- when a subscriber moves to another cell, the antenna of the new cell takes over the signal transmission
- a <u>cluster</u> is a group of adjacent cells, usually 7 cells; no frequency reuse is done within a cluster
- the frequency spectrum is divided into sub-bands and each sub-band is used within one cell of the cluster
- in heavy traffic zones cells are smaller, while in isolated zones cells are larger

Frequency Reuse

- The design process of selecting and allocating channel groups for all of the cellular base stations within a system is called frequency reuse or frequency planning.
- Cell labeled with same letter use the same set of frequencies.
- Cell Shapes:
- Circle, Square, Triangle and Hexagon.
- Hexagonal cell shape is conceptual , in reality it is irregular in shape

Frequency Reuse

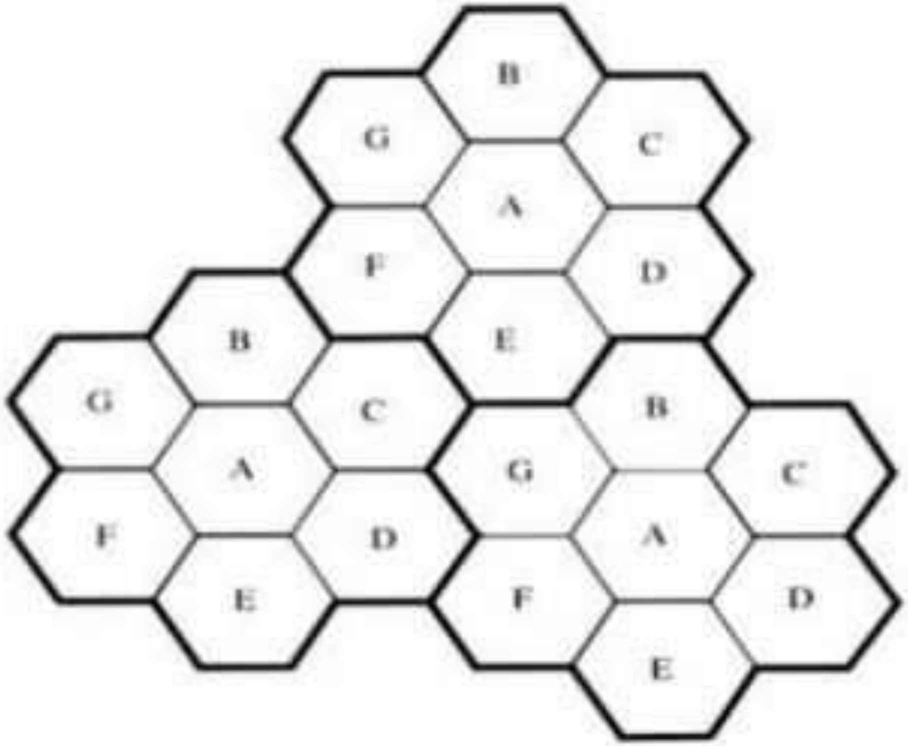


Figure 3.1 Illustration of the cellular frequency reuse concept. Cells with the same letter use the same set of frequencies. A cell cluster is outlined in bold and replicated over the coverage area. In this example, the cluster size, *N*, is equal to seven, and the frequency reuse factor is 1/7 since each cell contains one-seventh of the total number of available channels.

Frequency Reuse

- In hexagonal cell model, BS transmitter can be in centre of cell or on its 3 vertices.
- Centered excited cells use omni directional whereas edge excited cells use directional antennas.
- A cellular system having ‘S’ duplex channels, each cell is allocated ‘k’ channels(k<S).
- If S channels are allocated to N cells into unique and disjoint channels, the total no of available channel is S=kN.

Frequency Reuse

- N cells collectively using all the channels is called a cluster, is a group of adjacent cells.
- If cluster if repeated M times, the capacity C of system is given as

$$C=MkN=MS$$

- Capacity of system is directly proportional to the no of times cluster is repeated.
- Reducing the cluster size N while keeping the cell size constant, more clusters are required to cover the given area and hence more capacity.
- Co-channel interference is dependent on cluster size, large cluster size less interference and vice versa.

Frequency Reuse

- The Frequency Reuse factor is given as 1/N, each cell is assigned 1/N of total channels.
- Lines joining a cell and each of its neighbor are separated by multiple of 60^0,certain cluster sizes and cell layout possible
- Geometery of hexagon is such that no of cells per cluster i.e N, can only have values which satisfy the equation

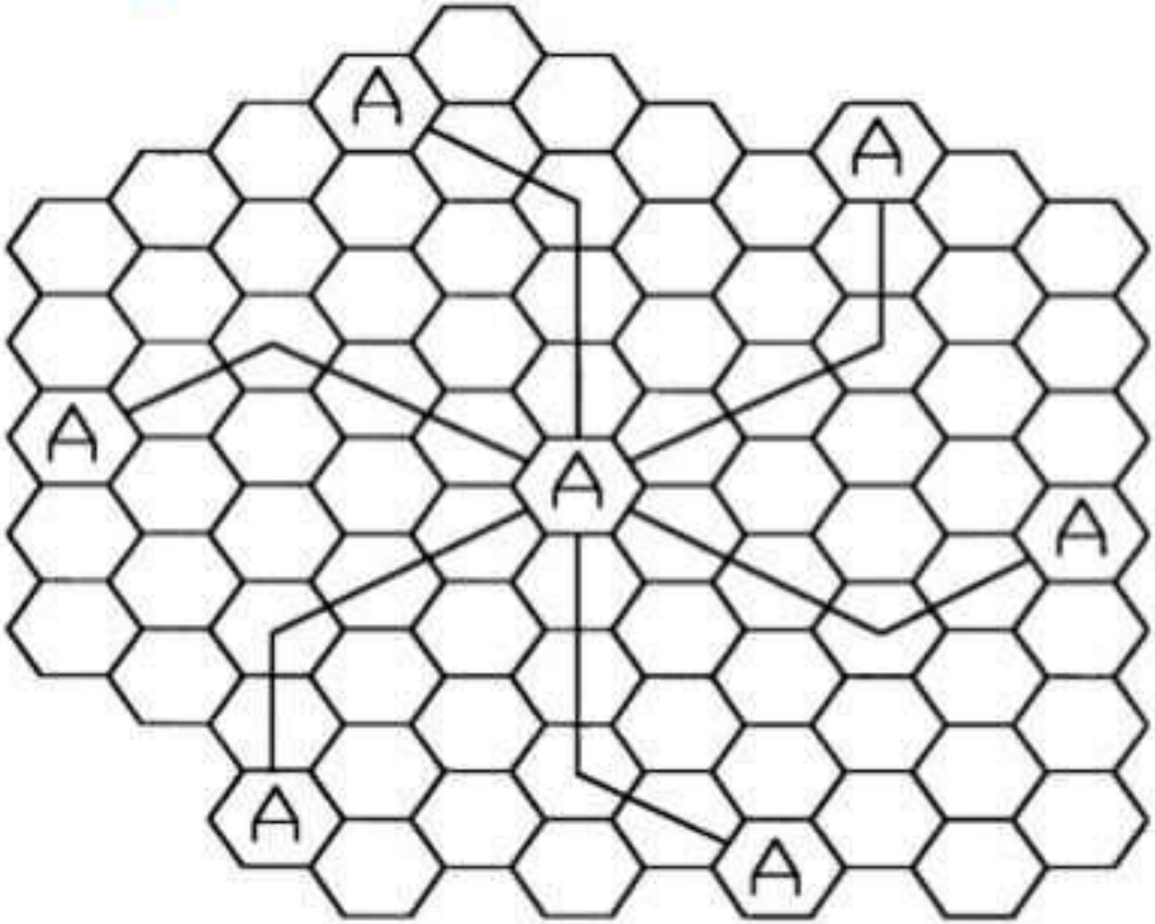
$$N=i^2+ij+j^2$$

N, the cluster size is typically 4, 7 or 12.

In GSM normally N =7 is used.

- i and j are integers, for i=3 and j=2 N=19.
- Example from Book

Locating co-channel Cell



Channel Assignment Strategies

- A scheme for increasing capacity and minimizing interference is required.
- CAS can be classified as either fixed or dynamic
- Choice of CAS impacts the performance of system.
- In Fixed CA each cell is assigned a *predetermined* set of voice channels
- Any call attempt within the cell can only be served by the *unused* channel in that particular cell
- If all the channels in the cell are occupied, the call is *blocked*. The user does not get service.
- In variation of FCA, a cell can *borrow channels* from its neighboring cell if its own channels are full.

Dynamic Channel Assignment

- Voice channels are not allocated to different cells *permanently*.
- Each time a call request is made, the *BS request* a channel from the MSC.
- MSC allocates a channel to the requesting cell using an algorithm that takes into account
  - likelihood of future blocking
  - The reuse distance of the channel (should not cause interference)
  - Other parameters like cost
- To ensure min QoS, MSC only allocates a given frequency if that frequency is not currently in use in the cell or any other cell which falls within the *limiting reuse distance*.
- DCA reduce the likelihood of blocking and increases capacity
- Requires the MSC to collect realtime data on channel occupancy and traffic distribution on continous basis.

Hand-off

- Mobile *moves into a different cell during* a conversation, MSC transfers the call to new channel belonging to new BS
- Handoff operation involves *identifying the new BS* and *allocation of voice and control signal* to channels associated with new BS
- Must be performed *successfully, infrequently* and *impercitble* to user
- To meet these requirements an *optimum signal level* must be defined to initiate a handoff.
- Min usuable signal for acceptable voice qualtiy -90 to -100 dBm
- A slight higher value is used as *threshold*

Hand-off strategies

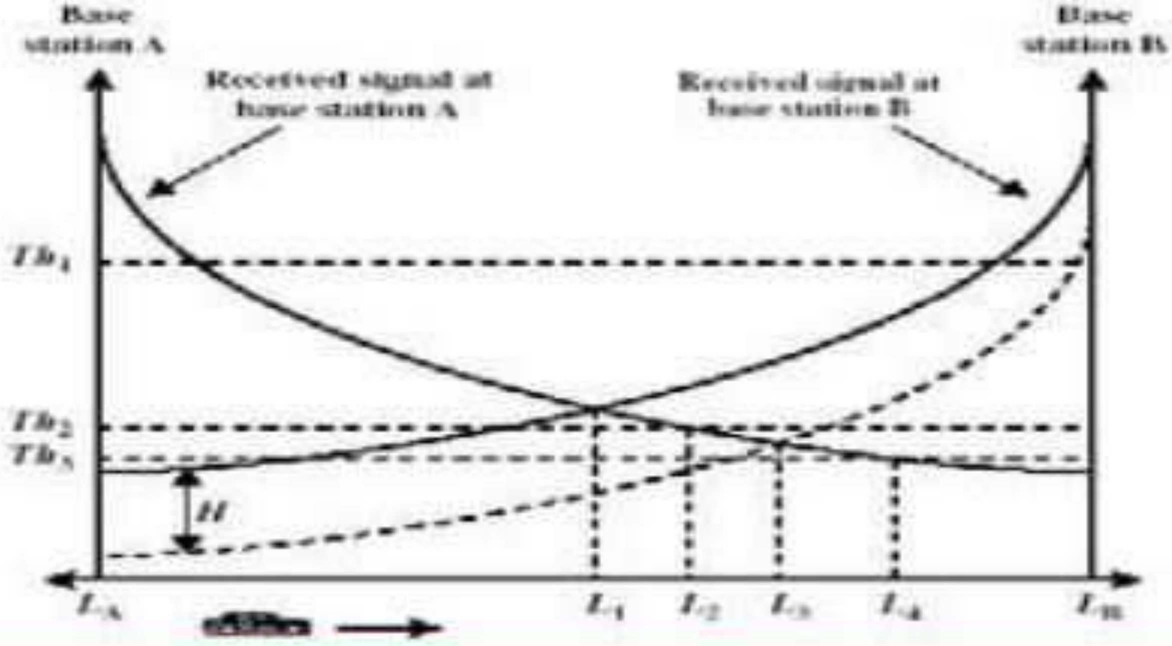
- Handoff is made when received signal at the BS *falls below* a certain threshold
- During handoff: to avoid call termination, *safety margin should exist* and should not be too large or small

$$\Delta = \text{Power}_{\text{handoff}} - \text{Power}_{\text{min usable}}$$

- Large Δ results in unecesarry handoff and for small Δ unsufficient time to complete handoff, so carefully chosen to meet the requirements.
- Fig a, handoff not made and signal falls below min acceptable level to keep the channel active.
- Can happen due to excessive delay by MSC in assigning handoff, or when threshold Δ is set to small.
- Excessive delay may occur during high traffic conditions due to computional loading or non avialablilty of channels in nearby cells

Handoff

By looking at the variations of signal strength from either BS it is possible to decide on the optimum area where handoff can take place



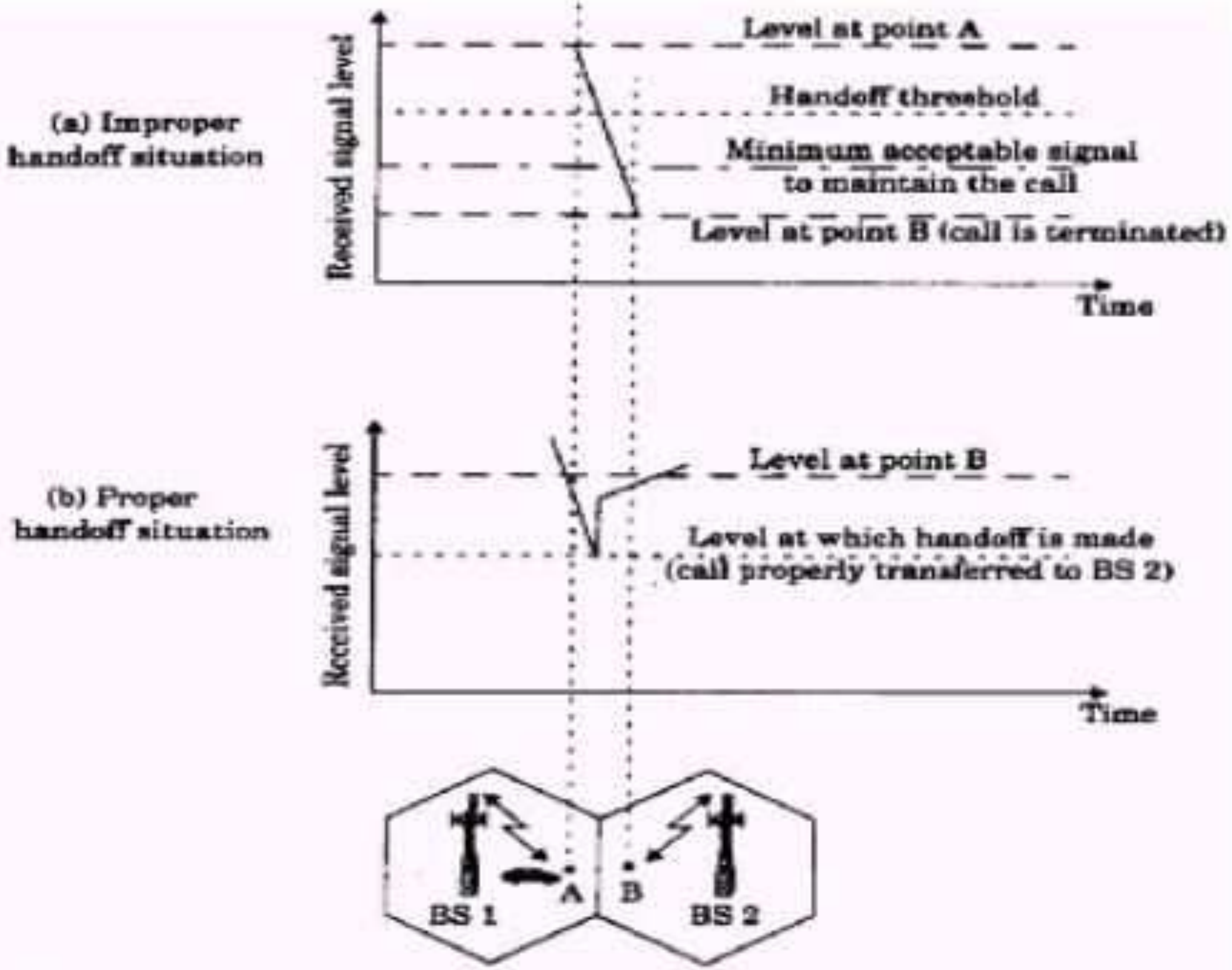


Figure 2.3
Illustration of a handoff scenario at cell boundary.

Hand-off

- In deciding when to handoff , it is important to ensure that the drop in signal level is not due to momentary fading.

- In order to ensure this the BS monitors the signal for a certain period of time before initiating a handoff

- The length of time needed to decide if handoff is necessary depends on the speed at which the mobile is moving

Hand-off strategies

- In 1st generation analog cellular systems, the signal strength measurements are made by the BS and are supervised by the MSC.
- A spare Rx in base station (locator Rx) monitors RSS of RVC's in neighboring cells
    - Tells Mobile Switching Center about these mobiles and their channels
    - Locator Rx can see if signal to this base station is significantly better than to the host base station
  - ☐ MSC monitors RSS from all base stations & decides on handoff

Hand-off strategies

- In 2nd generation systems Mobile Assisted Handoffs (MAHO)are used
- In MAHO, every MS measures the received power from the surrounding BS and continually reports these values to the corresponding BS.
- Handoff is initiated if the signal strength of a neighboring BS exceeds that of current BS
- MSC no longer monitors RSS of all channels
  - reduces computational load considerably
  - enables much more rapid and efficient handoffs
  - imperceptible to user

Soft Handoff

- CDMA spread spectrum cellular systems provides a unique handoff capability
- Unlike channelized wireless systems that assigns different radio channel during handoff (called hard handoff), the spread spectrum MS share the same channel in every cell
- The term handoff here implies that a different BS handles the radio communication task
- The ability to select between the instantaneous received signals from different BSs is called soft handoff

Inter system Handoff

- If a mobile moves from one cellular system to a different system controlled by a different MSC, an inter-system handoff is necessary
- MSC engages in intersystem handoff when signal becomes weak in a given cell and MSC cannot find another cell within its system to transfer the on-going call
- Many issues must be resolved
  - ☐ Local call may become long distance call
  - ☐ Compatibility between the two MSCs

Prioritizing Handoffs

- Issue: Perceived Grade of Service (GOS) – service quality as viewed by users
  - "quality" in terms of dropped or blocked calls (not voice quality)
  - assign higher priority to handoff vs. new call request
  - a dropped call is more aggravating than an occasional blocked call
- Guard Channels
  - % of total available **cell** channels exclusively set aside for handoff requests
  - makes fewer channels available for new call requests
  - a good strategy is dynamic channel allocation (not fixed)
    - adjust number of guard channels as needed by demand
    - so channels are not wasted in cells with low traffic

Prioritizing Handoffs

- *Queuing* of Handoff Requests
  - use time delay between handoff threshold and minimum useable signal level to place a blocked handoff request in queue
  - a handoff request can "*keep trying*" during that time period, instead of having a single block/no block decision
  - prioritize requests (based on mobile speed) and handoff as needed
  - calls will still be dropped if time period expires

Practical Handoff Considerations

- Problems occur because of a *large range of mobile velocities*
    - pedestrian vs. vehicle user
- Small cell sizes and/or micro-cells → *larger # handoffs*
- MSC load is *heavy* when high speed users are passed between very small cells
- **Umbrella Cells**
    - use *different antenna heights* and *Tx power levels* to provide large **and** small cell coverage
    - multiple antennas & Tx can be co-located at single location if necessary (saves on obtaining new tower licenses)
    - large cell → high speed traffic → fewer handoffs
    - small cell → low speed traffic
    - example areas: interstate highway passing through urban center, office park, or nearby shopping mall

Umbrella Cells

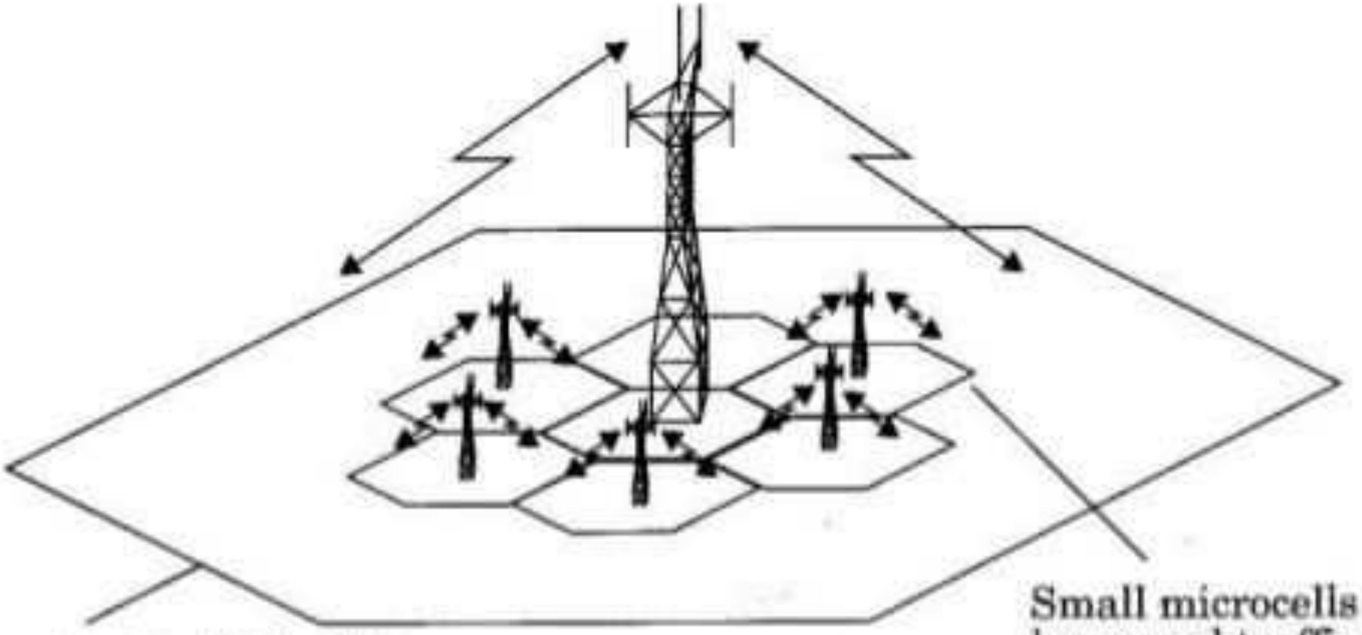


Figure 3.4 The umbrella cell approach.

Typical handoff parameters

- Analog cellular (1st generation)
  - threshold margin Δ ≈ 6 to 12 dB
  - total time to complete handoff ≈ 8 to 10 sec

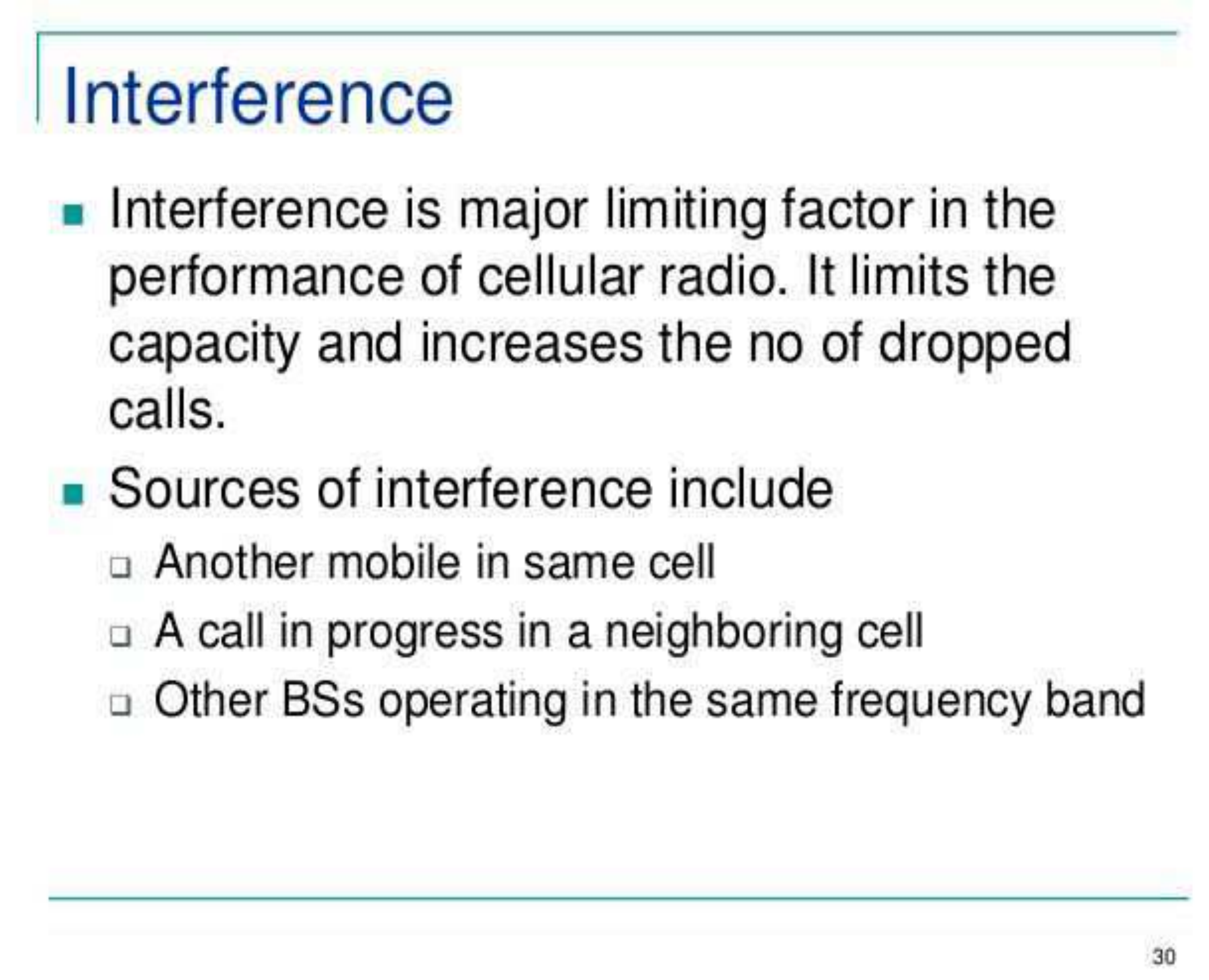
- Digital cellular (2nd generation)
  - total time to complete handoff ≈ 1 to 2 sec
  - lower necessary threshold margin Δ ≈ 0 to 6 dB
  - enabled by mobile assisted handoff

Reuse Ratio:

- For hexagonal cell reuse distance is given by
  $D=R(\sqrt{3N})$
- Where R is cell size or cell radius and N is cluster size
- D increases as we increase N
- Reuse factor is given by $Q=D/R=(\sqrt{3N})$

Interference

- Goals for this section
  - Co-Channel
  - Adjacent Channel
- How to calculate signal to interference ratio



Interference

- Interference is major limiting factor in the performance of cellular radio. It limits the capacity and increases the no of dropped calls.
- Sources of interference include
  - Another mobile in same cell
  - A call in progress in a neighboring cell
  - Other BSs operating in the same frequency band

Effects of Interference

- Interference in voice channels causes
    - Crosstalk
    - Noise in background
- Interference in control channels causes
    - Error in digital signaling, which causes
        - Missed calls
        - Blocked calls
        - Dropped calls

Interference

- Two major types of Interferences
  - Co-channel Interference (CCI)
  - Adjacent channel Interference (ACI)
- CCI is caused due to the cells that reuse the same frequency set. These cells using the same frequency set are called Co-channel cells
- ACI is caused due to the signals that are adjacent in frequency

Co-channel Interference

- Increase base station Tx power to improve radio signal reception?
  - will also increase interference into other co-channel cells by the same amount
  - no net improvement
- Separate co-channel cells by some minimum distance to provide sufficient isolation from propagation of radio signals?
  - if all cell sizes, transmit powers, and coverage patterns ≈ same → co-channel interference is independent of Tx power

Co-channel Interference

- co-channel interference depends on:
  - *R* : cell radius
  - *D* : distance to base station of nearest co-channel cell where $D=R(\sqrt{3N})$

- if *D/R* ↑ then spatial separation relative to cell coverage area ↑
  - improved isolation from co-channel RF energy

- $Q = D / R$: co-channel reuse ratio
  - hexagonal cells → $Q = D/R = \sqrt{3N}$
- Smaller value of Q provides larger capacity, but higher CCI
- Hence there is tradeoff between capacity and interference.
  - small Q → small cluster size → more frequency reuse → larger system capacity
  - small Q → small cell separation → increased CCI

Signal to Interference ratio S/I

- The Signal-to-Interference (S/I) for a mobile is

$$\text{Eq. (3.5)}: \quad \frac{S}{I} = \frac{S}{\sum_{i=1}^{i_o} I_i} \quad \text{where}$$

  - S is desired signal power , I_i : interference power from i^{th} co-channel cell
- The average received power at distance d is

$$P_r = Po\,(d/d_o)^{-n}$$

- The RSS decays as a power law of the distance of separation between transmitter and receiver
- Where P_o is received power at reference distance d_o and n is the path loss exponent and ranges between 2-4
- If D_i is the distance of i^{th} interferer, the received power is proportional to $(D_i)^{-n}$

Signal to Interference ratio S/I

- The S/I for mobile is given by

$$\frac{S}{I} = \frac{\text{signal from intended base station when at edge of cell (R away)}}{\text{signals from other base stations (D away)}}$$

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

$$\frac{S}{I} = \frac{R^{-n}}{\sum_{i=1}^{i_0=6} (D_i)^{-n}} = \frac{(D/R)^n}{6} = \frac{(\sqrt{3N})^n}{6} = \frac{Q^4}{6}$$

- With only the first tier(layer of) equidistant interferers.
- For a hexagonal cluster size, which always have 6 CC cell in first tier

Signal to Interference ratio S/I

- The MS is at cell boundary

The aproximate S/I is given by, both in terms of R and D, along with channel reuse ratio Q

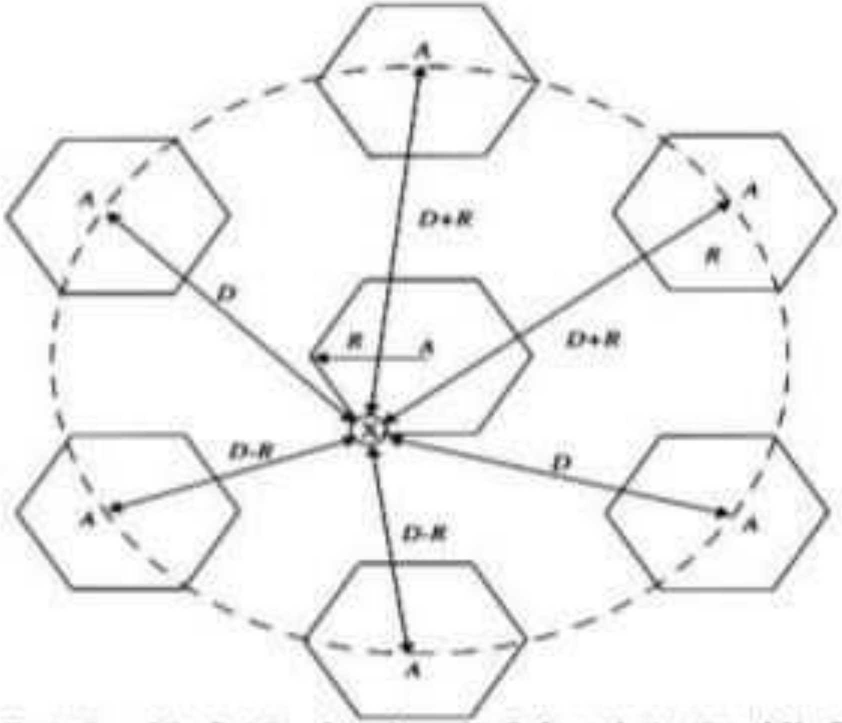


Figure 3.5 Illustration of the first tier of co-channel cells for a cluster size of $N = 7$. An approximation of the exact geometry is shown here, whereas the exact geometry is given in [Lee86]. When the mobile is at the cell boundary (point X), it experiences worst case co-channel interference on the forward channel. The marked distances between the mobile and different co-channel cells are based on approximations made for easy analysis.

$$\frac{S}{I} = \frac{R^{-4}}{2(D-R)^{-4} + 2(D+R)^{-4} + 2D^{-4}} \qquad \frac{S}{I} = \frac{1}{2(Q-1)^{-4} + 2(Q+1)^{-4} + 2Q^{-4}}$$

Numerical Problem

If a signal to interference ratio of 15 dB is required for Satisfactory forward channel performance of a cellular system, what is the frequency reuse factor and cluster size that should be used for maximum capacity, if path loss exponent is

(a) n=4 (b) n=3

Example S/I

- Examples for Problem 2.3
- TDMA can tolerate S/I = 15 dB
- What is the optimal value of N for omni-directional antennas? Path loss = 4. **Co-channel Interference**

- cluster size N =7 (choices 4,7,12)
- path loss exponent (means)n=4
- co-channel reuse ratio Q=sqrt(3N)=4.582576
- Ratio of distance to radius Q=D/R=4.582576
- number of neighboring cells i_o=6 # of sides of hexagon
- signal to interference ratio S/I= $(D/R)^{\wedge n} / i_o$ =73.5
- convert to dB, S/I=10log(S/I) =18.66287dB

- S/I is greater than required, it will work.

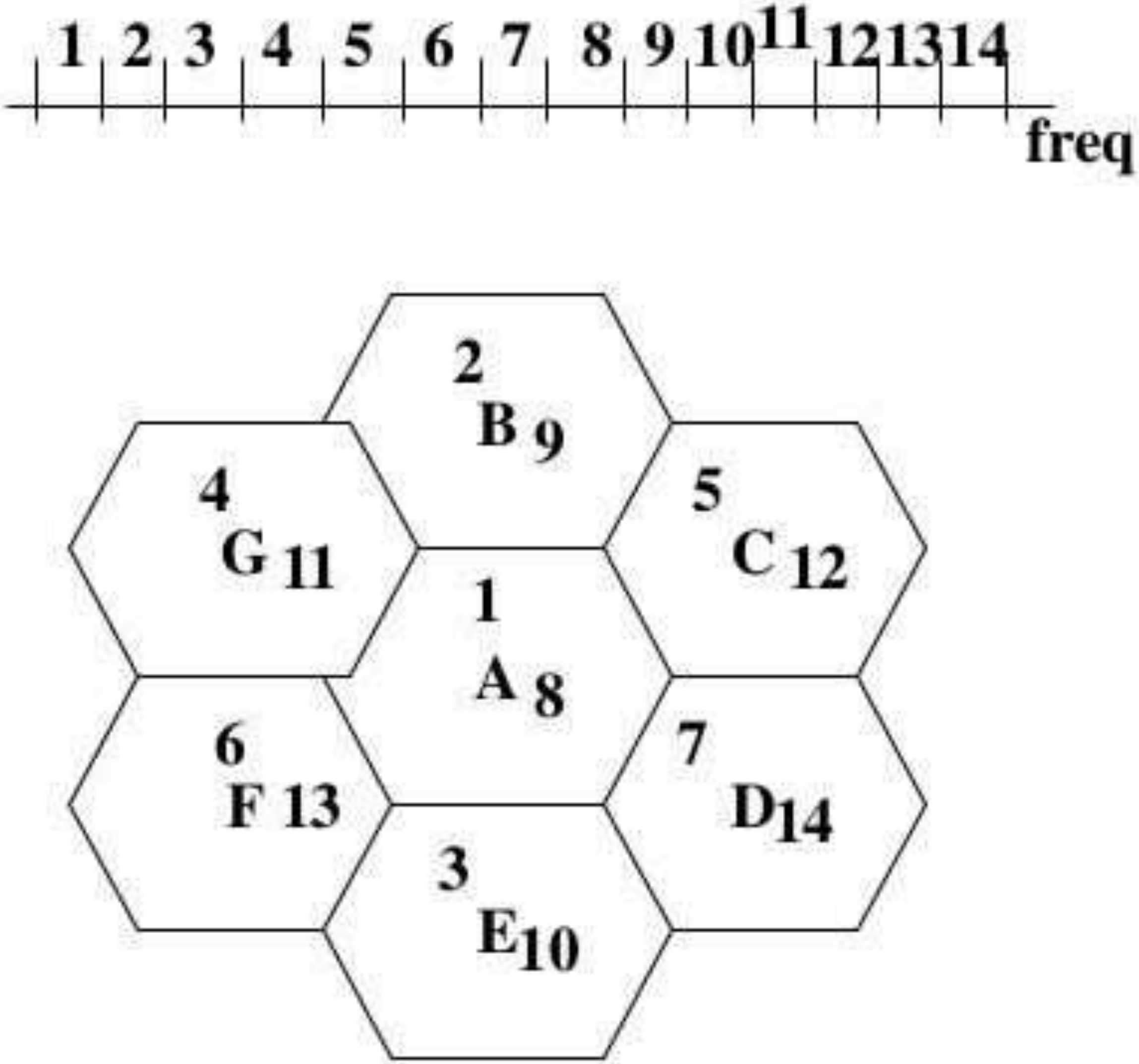
Example S/I

- cluster size N=4 (choices 4,7,12)
- path loss exponent (means) n=4
- co-channel reuse ratio Q= sqrt(3N)=3.464102
- Ratio of distance to radius Q=D/R=3.464102
- number of neighboring cells io=6 ,# of sides of hexagon
- signal to interference ratio S/I= $(D/R)^{\wedge n} / i_o$ =24
- convert to dB, S/I= 10log(S/I)=13.80211dB
- S/I is less than required, it will not work!

- cluster size N=7
- path loss exponent n=3
- Q=sqrt(3N)=4.582576
- number of neighboring cells io= 6, # of sides of hexagon
- signal to interference ratio=S/I= $(D/R)^{\wedge n} / i_o$ =16.03901
- convert to dB, S/I=10log(S/I)=12.05178dB
- S/I is less than required, it will not work!

Adjacent Channel Interference

- Results from imperfect receiver filters, allowing nearby frequencies to leak into pass-band.
- Can be minimized by careful filtering and channel assignments.
- Channels are assigned such that frequency separations between channels are maximized.
- For example, by sequentially assigning adjacent bands to different cells
- Total 832 channels, divided into two groups with 416 channels each.
- Out of 416, 395 are voice and 21 are control channels.
- 395 channels are divided into 21 subsets, each containing almost 19 channels, with closet channel 21 channels away
- If N=7 is used, each cell uses 3 subsets, assigned in such a way that each channel in a cell is 7 channels away.



Frequency Planning/Channel Assignment

Learning Objectives

- Concept of Trunking
- Key definitions in Trunking /Traffic Theory
- Erlang-(unit of traffic)
- Grade of Service
- Two Types of Trunked Systems
- Trunking Efficiency

Trunking & Grade of Service

- Cellular radio systems rely on *trunking to accommodate a large number of users in a limited radio spectrum.*

- Trunking allows a large no of users to share a relatively small number of channels in a cell by providing access to each user, on demand, from a pool of available channels.

- In a trunked radio system (TRS) each user is allocated a channel on a per call basis, upon termination of the call, the previously occupied channel is immediately returned to the pool of available channels.

Key Definitions

- Setup Time: Time required to allocate a radio channel to a requesting user
- Blocked Call: Call which cannot be completed at the time of request, due to congestion(*lost call)*
- Holding Time: Average duration of a typical call. Denoted by *H(in seconds)*
- Request Rate: The average number of calls requests per unit time(λ)
- Traffic Intensity: Measure of channel time utilization or the average channel occupancy measured in Erlangs. Dimensionless quantity. Denoted by A
- Load: Traffic intensity across the entire TRS (Erlangs)

Erlang-a unit of traffic

- The fundamentals of trunking theory were developed by Erlang, a Danish mathematician, the unit bears his name.
- An Erlang is a unit of telecommunications traffic measurement.
- Erlang represents the continuous use of one voice path.
- It is used to describe the total traffic volume of one hour
- A channel kept busy for one hour is defined as having a load of one Erlang
- For example, a radio channel that is occupied for thirty minutes during an hour carries 0.5 Erlangs of traffic
- For 1 channel
  - Min load=0 Erlang (0% time utilization)
  - Max load=1 Erlang (100% time utilization)

Erlang-a unit of traffic

- For example, if a group of 100 users made 30 calls in one hour, and each call had an average call duration(holding time) of 5 minutes, then the number of Erlangs this represents is worked out as follows:

- Minutes of traffic in the hour = number of calls x duration
- Minutes of traffic in the hour = 30 x 5 = 150
- Hours of traffic in the hour = 150 / 60 = 2.5
- **Traffic Intensity= 2.5 Erlangs**

Traffic Concepts

- Traffic Intensity offered by each user(Au): Equals average call arrival rate multiplied by the holding time(service time)

  Au=λ*H(Erlangs)*

- Total Offered Traffic Intensity for a system of U users (A):

  A =U*Au(Erlangs)

- Traffic Intensity per channel, in a C channel trunked system

  Ac=U*Au/C(Erlangs)

Trunking & Grade of Service

- In a TRS, when a particular user requests service and all the available radio channels are already in use , the user is *blocked or denied access to the system. In some systems a queue may be used to hold the requesting users until a channel becomes available.*
- Trunking systems must be designed carefully in order to ensure that there is a low likelihood that a user will be blocked or denied access.
- The likelihood that a call is blocked, or the likelihood that a call experiences a delay greater than a certain queuing time is called "**Grade of Service" (GOS)''.**

Trunking & Grade of Service

- **Grade of Service (GOS): Measure of ability of a user to access a trunked system during the busiest hour. Measure of the congestion which is specified as a probability.**

- The probability of a call being blocked
- **Blocked calls cleared(BCC) or Lost Call Cleared(LCC) or Erlang B systems**

- The probability of a call being delayed beyond a certain amount of time before being granted access
- **Blocked call delayed or Lost Call Delayed(LCD) or Erlang C systems**

Blocked Call Cleared Systems

- When a user requests service, there is a minimal call set-up time and the user is given immediate access to a channel if one is available
- If channels are already in use and no new channels are available, call is blocked without access to the system
- The user does not receive service, but is free to try again later
- All blocked calls are instantly returned to the user pool

Modeling of BCC Systems

- The Erlang B model is based on following assumptions :
  - Calls are assumed to arrive with a Poisson distribution
  - There are nearly an infinite number of users
  - Call requests are memory less ,implying that all users, including blocked users, may request a channel at any time
  - All free channels are fully available for servicing calls until all channels are occupied
  - The probability of a user occupying a channel(called service time) is exponentially distributed. Longer calls are less likely to happen
  - There are a finite number of channels available in the trunking pool.
  - Inter-arrival times of call requests are independent of each other

Modeling of BCC Systems

- **Erlang B formula is given by**

$$\mathrm{Pr[blocking]} = \frac{(A^C/C\,!)}{\sum_{k=0}^{C} \frac{A^k}{k\,!}}$$

- where ***C*** *is the number of trunked channels offered by a trunked radio system and* ***A*** *is the total offered traffic.*

Example 3.4

- How many users can be supported for 0.5% blocking probability for the following number of trunked channels in a BCC system? (a) 5, (b) 10,(c)=20. Assumed that each user generates 0.1 Erlangs of traffic.
- Solution
- Given C=5, GOS=0.005, Au=0.1,
- From graph/Table using C=5 and GOS=0.005,A=1.13
- Total Number of users U=A/Au=1.13/0.1=11 users
- Given C=10, GOS=0.005, Au=0.1,
- From graph/Table using C=5 and GOS=0.005,A=3.96
- Total Number of users U=A/Au=3.96/0.1=39 users
- Given C=20, GOS=0.005, Au=0.1,
- From graph/Table using C=20 and GOS=0.005,A=11.10
- Total Number of users U=A/Au=11.10/0.1=110 users

Erlang B Trunking GOS

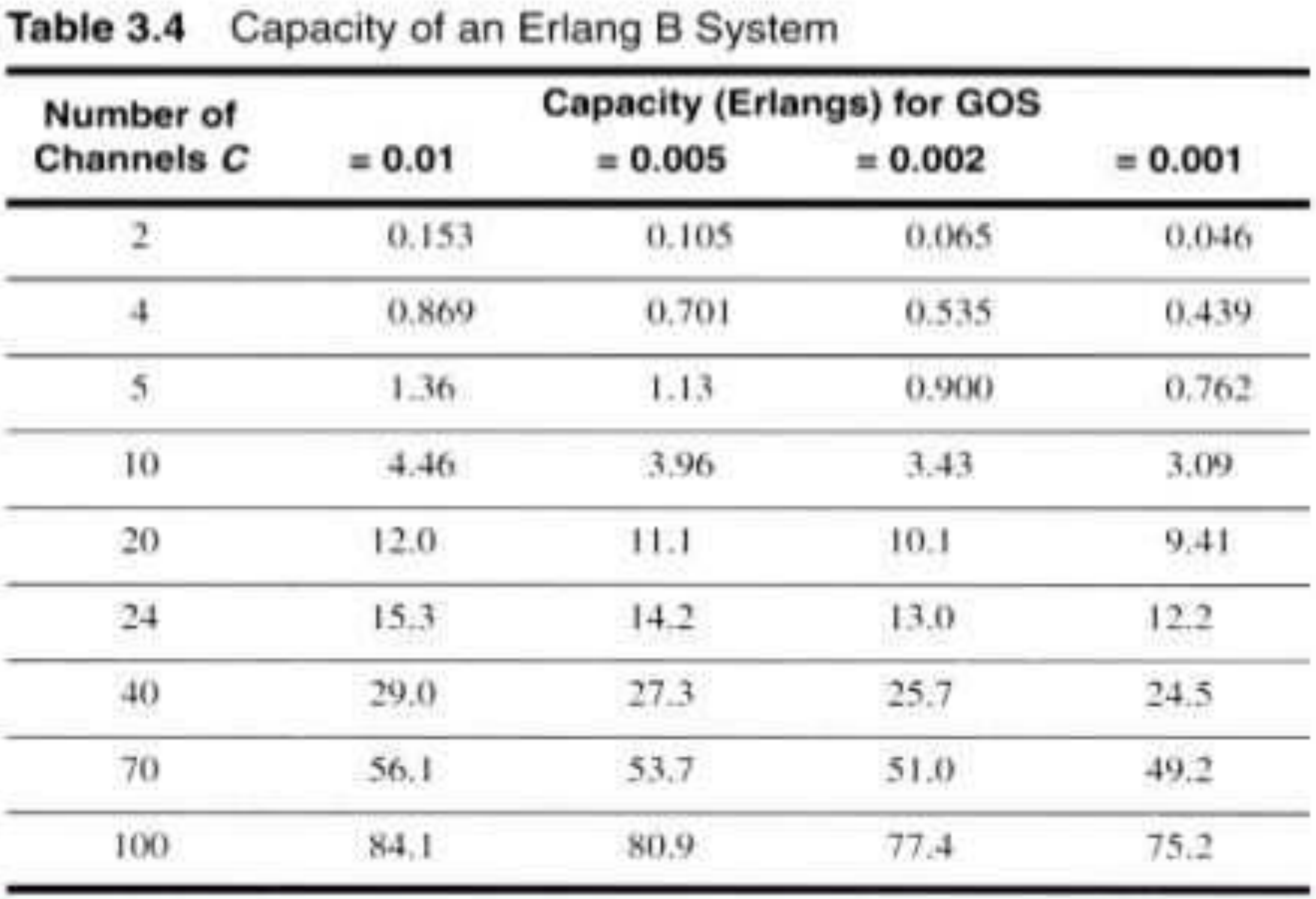


Table 3.4 Capacity of an Erlang B System

Number of Channels *C*	Capacity (Erlangs) for GOS = 0.01	= 0.005	= 0.002	= 0.001
2	0.153	0.105	0.065	0.046
4	0.869	0.701	0.535	0.439
5	1.36	1.13	0.900	0.762
10	4.46	3.96	3.43	3.09
20	12.0	11.1	10.1	9.41
24	15.3	14.2	13.0	12.2
40	29.0	27.3	25.7	24.5
70	56.1	53.7	51.0	49.2
100	84.1	80.9	77.4	75.2

BCC System Example

- Assuming that each user in a system generates a traffic intensity of 0.2 Erlangs, how many users can be supported for 0.1% probability of blocking in an Erlang B system for a number of trunked channels equal to 60.
- **Solution 1:**
- System is an Erlang B
- *Au* = 0.2 Erlangs
- Pr [Blocking] = 0.001
- *C = 60 Channels*
- From the Erlang B figure, we see that
- *A ≈ 40 Erlangs*
- *Therefore U=A/Au=40/0.02=2000users.*

Blocked Call Delayed(BCD) Systems

- Queues are used to hold call requests that are initially blocked
- When a user attempts a call and a channel is not immediately available, the call request may be delayed until a channel becomes available
- Mathematical modeling of such systems is done by Erlang C formula
- The Erlang C model is based on following assumptions :
- Similar to those of Erlang B
- Additionally, if offered call cannot be assigned a channel, it is placed in a queue of infinite length
- Each call is then serviced in the order of its arrival

Blocked Call Delayed Systems

- Erlang C formula which gives likelihood of a call not having immediate access to a channel (all channels are already in use)

$$\Pr(delay > 0) = \frac{A^C}{A^C + C!\left(1 - \frac{A}{C}\right)\sum_{k=0}^{C-1}\frac{A^k}{k!}}$$

Modeling of BCD Systems

- Probability that any caller is delayed in queue for a wait time greater than **t seconds is given as GOS of a BCD System**
- The probability of a call getting delayed for any period of time greater than zero is

  P[delayed call is forced to wait > t sec]=P[delayed] x Conditional P[delay is >t sec]

- Mathematically;

$$\Pr[\text{delay}>t] = \Pr[\text{delay}>0]\ \Pr[\text{delay}>t \mid \text{delay}>0]$$

- Where $P[\text{delay}>t \mid \text{delay}>0] = e^{(-(C-A)t/H)}$

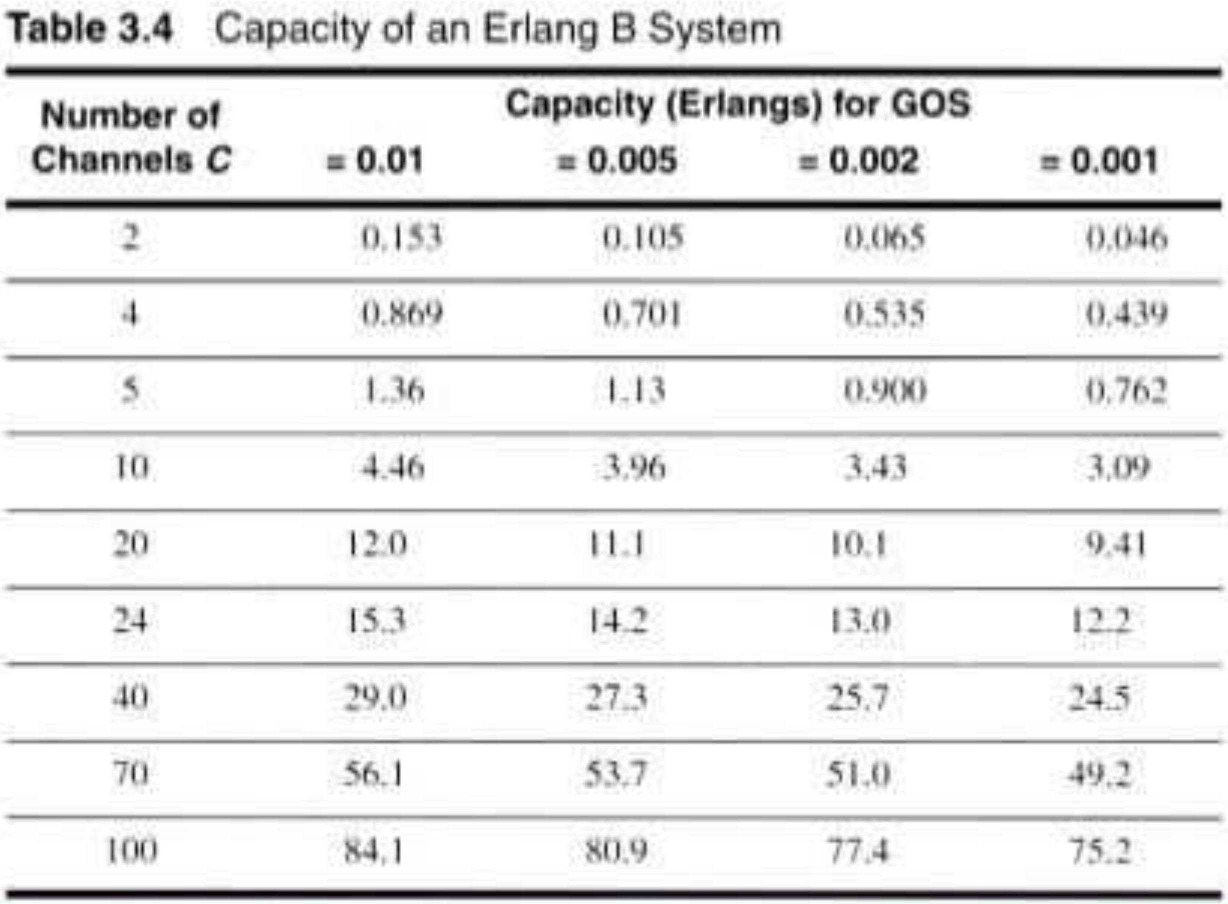
$$\Pr[\text{delay}>t] = \Pr[\text{delay}>0]\ e(-(C-A)t/H)$$

  - where C = total number of channels, *t =delay time of interest*, *H=average duration of call*

Trunking Efficiency

- Trunking efficiency is a measure of the number of users which can be offered a particular GOS with a particular configuration of fixed channels.
- The way in which channels are grouped can substantially alter the number of users handled by a trunked system.
- **Example:**
- 10 trunked channels at a GOS of 0.01 can support 4.46 Erlangs, where as two groups of 5 trunked channels can support 2x1.36=2.72 Erlangs of traffic
- 10 trunked channels can offer 60% more traffic at a specific GOS than two 5 channel trunks.
- Therefore, if in a certain situation we sub-divide the total channels in a cell into smaller channel groups then the total carried traffic will reduce with increasing number of groups

Erlang B Trunking GOS



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70	56.1	53.7	51.0	49.2
100	84.1	80.9	77.4	75.2

Improving Capacity

- As demand for service increases, system designers have to provide more channel per unit coverage area
- Common Techniques are: Cell Splitting, Sectoring and Microcell Zoning
- Cell Splitting increases the number of BS deployed and allows an orderly growth of the cellular system
- Sectoring uses directional antennas to further control interference
- Micro cell Zoning distributes the coverage of cell and extends the cell boundary to hard-to-reach areas

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- **Grade of Service (GOS): Measure of ability of a user to access a trunked system during the busiest hour. Measure of the congestion which is specified as a probability.**

- The probability of a call being blocked
- **Blocked calls cleared(BCC) or Lost Call Cleared(LCC) or Erlang B systems**

- The probability of a call being delayed beyond a certain amount of time before being granted access
- **Blocked call delayed or Lost Call Delayed(LCD) or Erlang C systems**

Blocked Call Cleared Systems

- When a user requests service, there is a minimal call set-up time and the user is given immediate access to a channel if one is available

- If channels are already in use and no new channels are available, call is blocked without access to the system

- The user does not receive service, but is free to try again later

- All blocked calls are instantly returned to the user pool

Modeling of BCC Systems

- The Erlang B model is based on following assumptions :
  - Calls are assumed to arrive with a Poisson distribution
  - There are nearly an infinite number of users
  - Call requests are memory less ,implying that all users, including blocked users, may request a channel at any time
  - All free channels are fully available for servicing calls until all channels are occupied
  - The probability of a user occupying a channel(called service time) is exponentially distributed. Longer calls are less likely to happen
  - There are a finite number of channels available in the trunking pool.
  - Inter-arrival times of call requests are independent of each other

Modeling of BCC Systems

- **Erlang B formula is given by**

$$\Pr[\text{blocking}] = \frac{(A^C/C!)}{\sum_{k=0}^{C} \frac{A^k}{k!}}$$

- where ***C*** *is the number of trunked channels offered by a trunked radio system and* ***A*** *is the total offered traffic.*

Example 3.4

- How many users can be supported for 0.5% blocking probability for the following number of trunked channels in a BCC system? (a) 5, (b) 10,(c)=20. Assumed that each user generates 0.1 Erlangs of traffic.
- Solution
- Given C=5, GOS=0.005, Au=0.1,
- From graph/Table using C=5 and GOS=0.005,A=1.13
- Total Number of users U=A/Au=1.13/0.1=11 users
- Given C=10, GOS=0.005, Au=0.1,
- From graph/Table using C=5 and GOS=0.005,A=3.96
- Total Number of users U=A/Au=3.96/0.1=39 users
- Given C=20, GOS=0.005, Au=0.1,
- From graph/Table using C=20 and GOS=0.005,A=11.10
- Total Number of users U=A/Au=11.10/0.1=110 users

Erlang B Trunking GOS

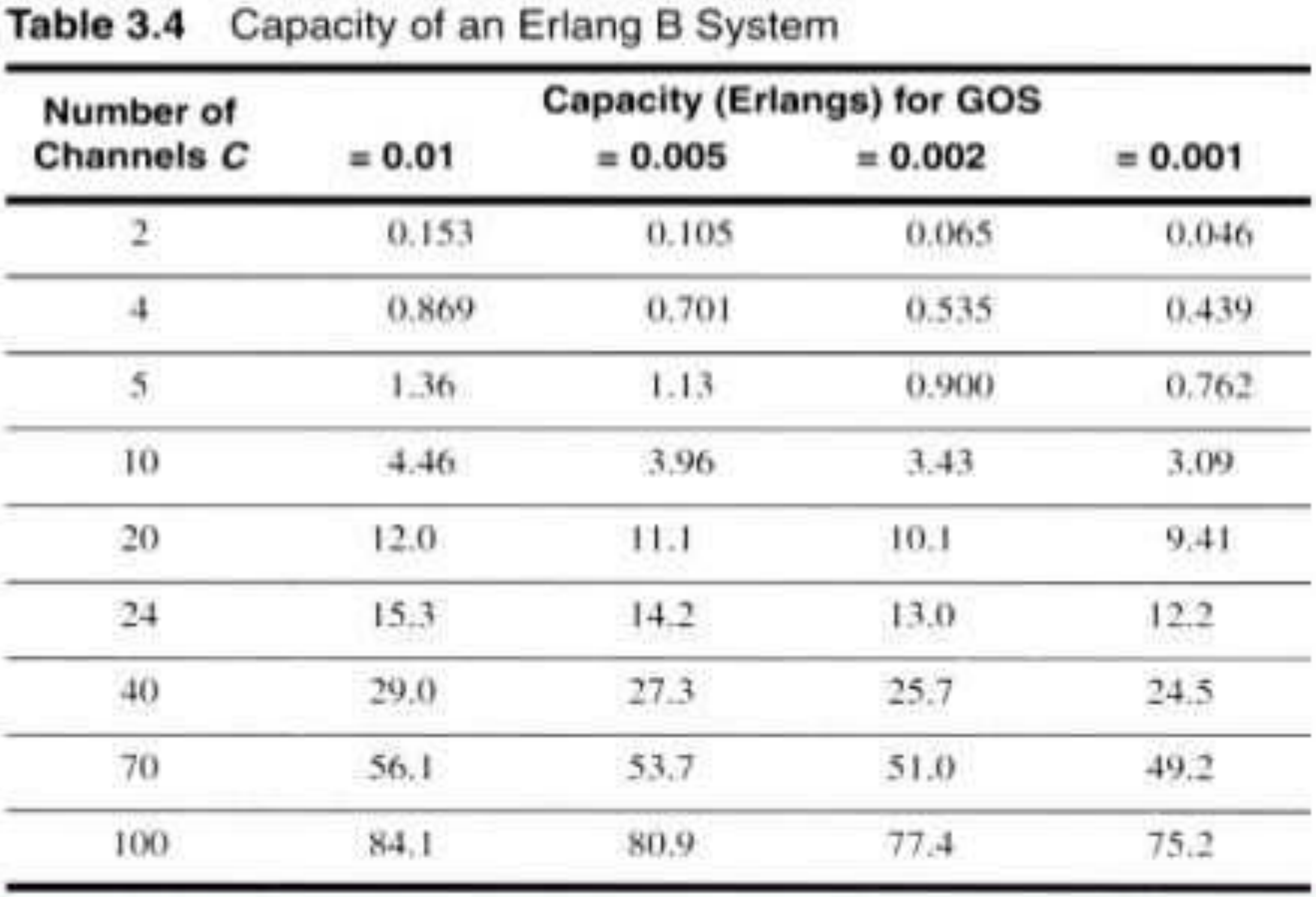


Table 3.4 Capacity of an Erlang B System

Number of Channels *C*	Capacity (Erlangs) for GOS = 0.01	= 0.005	= 0.002	= 0.001
2	0.153	0.105	0.065	0.046
4	0.869	0.701	0.535	0.439
5	1.36	1.13	0.900	0.762
10	4.46	3.96	3.43	3.09
20	12.0	11.1	10.1	9.41
24	15.3	14.2	13.0	12.2
40	29.0	27.3	25.7	24.5
70	56.1	53.7	51.0	49.2
100	84.1	80.9	77.4	75.2

BCC System Example

- Assuming that each user in a system generates a traffic intensity of 0.2 Erlangs, how many users can be supported for 0.1% probability of blocking in an Erlang B system for a number of trunked channels equal to 60.
- **Solution 1:**
- System is an Erlang B
- *Au* = 0.2 Erlangs
- Pr [Blocking] = 0.001
- *C = 60 Channels*
- From the Erlang B figure, we see that
- *A ≈ 40 Erlangs*
- *Therefore U=A/Au=40/0.02=2000users.*

Blocked Call Delayed(BCD) Systems

- Queues are used to hold call requests that are initially blocked
- When a user attempts a call and a channel is not immediately available, the call request may be delayed until a channel becomes available
- Mathematical modeling of such systems is done by Erlang C formula
- The Erlang C model is based on following assumptions :
- Similar to those of Erlang B
- Additionally, if offered call cannot be assigned a channel, it is placed in a queue of infinite length
- Each call is then serviced in the order of its arrival

Blocked Call Delayed Systems

- Erlang C formula which gives likelihood of a call not having immediate access to a channel (all channels are already in use)

$$\Pr(delay > 0) = \frac{A^C}{A^C + C!\left(1 - \frac{A}{C}\right)\sum_{k=0}^{C-1}\frac{A^k}{k!}}$$

Modeling of BCD Systems

- Probability that any caller is delayed in queue for a wait time greater than **t seconds is given as GOS of a BCD System**
- The probability of a call getting delayed for any period of time greater than zero is

  P[delayed call is forced to wait > t sec]=P[delayed] x Conditional P[delay is >t sec]

- Mathematically;

$$\Pr[\text{delay}>t] = \Pr[\text{delay}>0]\Pr[\text{delay}>t \mid \text{delay}>0]$$

- Where $P[\text{delay}>t \mid \text{delay}>0] = e^{(-(C-A)t/H)}$

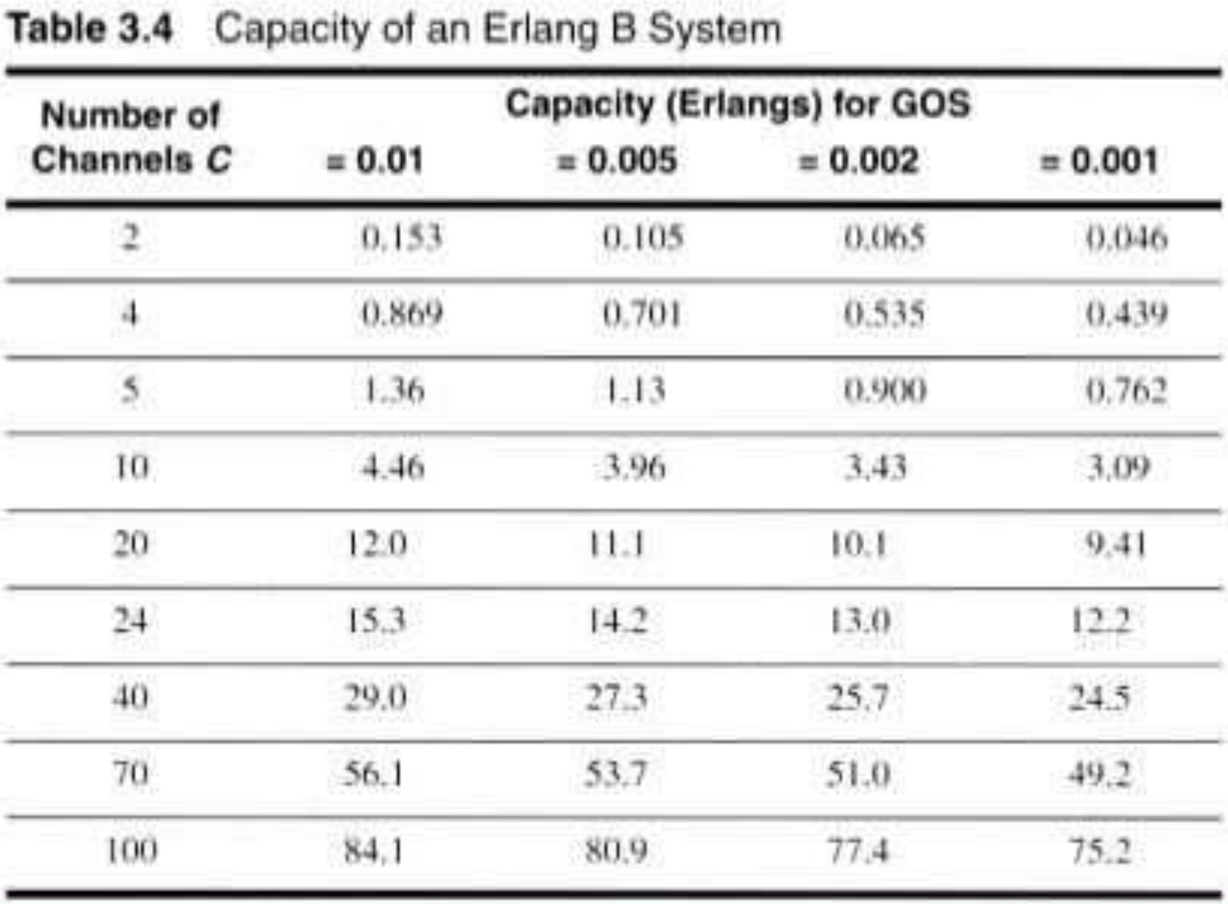
$$\Pr[\text{delay}>t] = \Pr[\text{delay}>0]\, e(-(C-A)t/H)$$

  - where C = total number of channels, *t =delay time of interest*, *H=average duration of call*

Trunking Efficiency

- Trunking efficiency is a measure of the number of users which can be offered a particular GOS with a particular configuration of fixed channels.
- The way in which channels are grouped can substantially alter the number of users handled by a trunked system.
- **Example:**
- 10 trunked channels at a GOS of 0.01 can support 4.46 Erlangs, where as two groups of 5 trunked channels can support 2x1.36=2.72 Erlangs of traffic
- 10 trunked channels can offer 60% more traffic at a specific GOS than two 5 channel trunks.
- Therefore, if in a certain situation we sub-divide the total channels in a cell into smaller channel groups then the total carried traffic will reduce with increasing number of groups

Erlang B Trunking GOS



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40	29.0	27.3	25.7	24.5
70	56.1	53.7	51.0	49.2
100	84.1	80.9	77.4	75.2

Improving Capacity

- As demand for service increases, system designers have to provide more channel per unit coverage area
- Common Techniques are: Cell Splitting, Sectoring and Microcell Zoning
- Cell Splitting increases the number of BS deployed and allows an orderly growth of the cellular system
- Sectoring uses directional antennas to further control interference
- Micro cell Zoning distributes the coverage of cell and extends the cell boundary to hard-to-reach areas

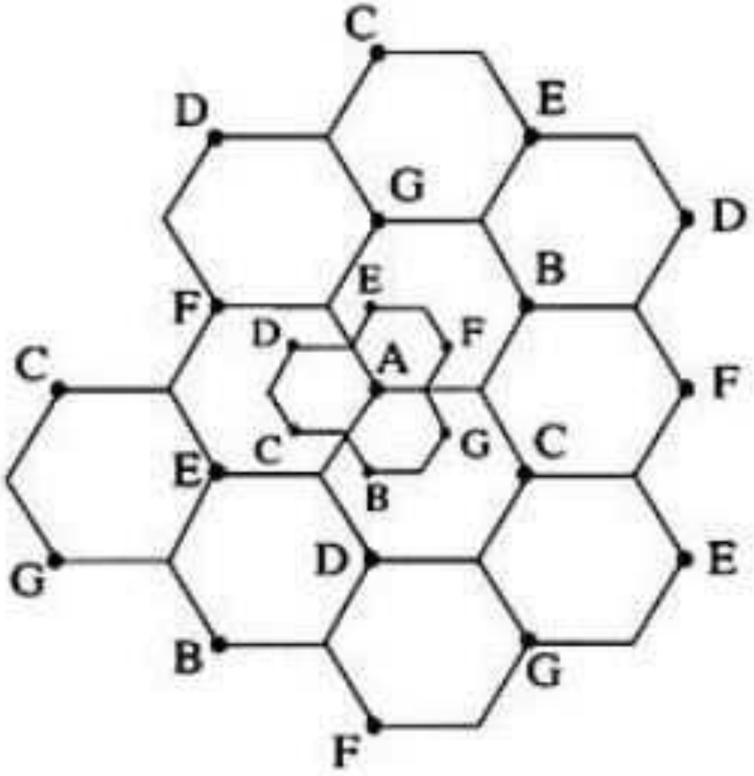
Cell Splitting

- Cell splitting is the process of subdividing a congested cell into smaller cells with
  - their own BS
  - a corresponding reduction in antenna height
  - a corresponding reduction in transmit power

- Splitting the cell reduces the cell size and thus more number of cells have to be used
- For the new cells to be smaller in size the transmit power of these cells must be reduced.
- Idea is to keep Q=D/R constant while decreasing R

- More number of cells ► more number of clusters ► more channels ►high capacity

Cells are split to add channels with no new spectrum usage



Cell Splitting-Power Issues

- Suppose the cell radius of new cells is reduced by half
- What is the required transmit power for these new cells??

$$\text{Pr[at old cell boundary]} = Pt1R^{-n}$$

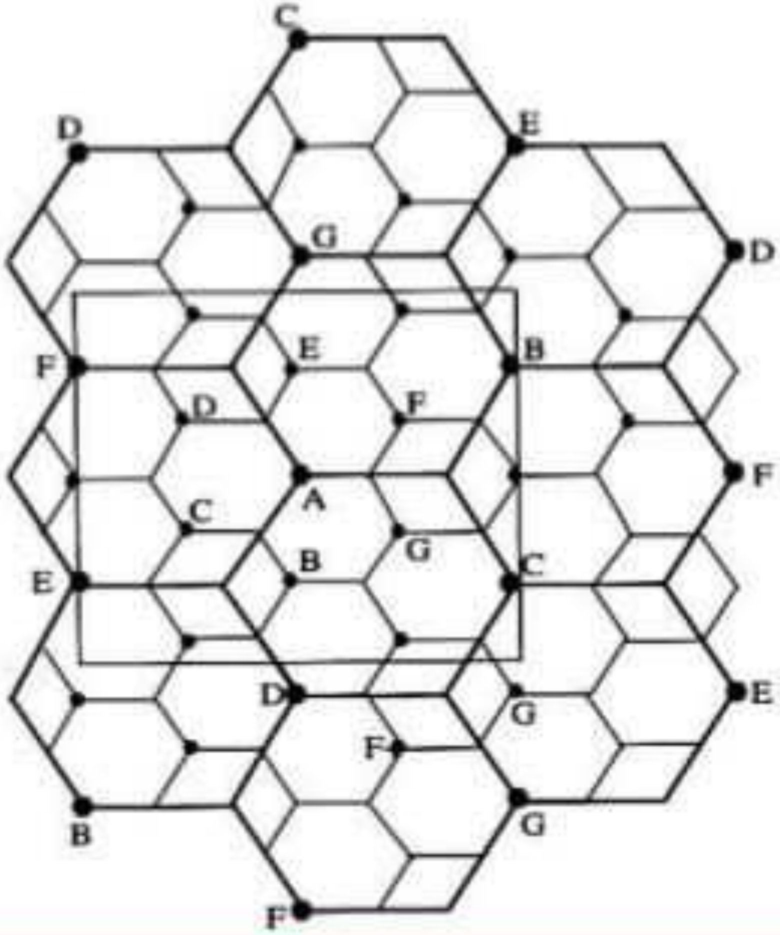
$$\text{Pr[at new cell boundary]} = Pt2(R/2)^{-n}$$

- where Pt1and Pt2are the transmit powers of the larger and smaller cell base stations respectively, and n is the path loss exponent.
- So, $Pt2= Pt1/2^n$
- If we take *n=3 and the received powers equal to each other, then*

$$Pt2=Pt1/8$$

- In other words, the transmit power must be reduced by 9dB in order to fill in the original coverage area while maintaining the S/I requirement

Illustration of cell splitting in 3x3 square centered around base station A



Cell Splitting

- In practice not all the cells are split at the same time hence different size cells will exist simultaneously.

- In such situations, special care needs to be taken to keep the distance between co-channel cells at the required minimum, and hence channel assignments become more complicated.

- To overcome handoff problem:
  - Channels in the old cell must be broken down into two channel groups, one for smaller cell and other for larger cell
  - The larger cell is usually dedicated to high speed traffic so that handoffs occur less frequently
  - At start small power group has less channels and large power group has large no of channels, at maturity of the system large power group does not have any channel

Umbrella Cells

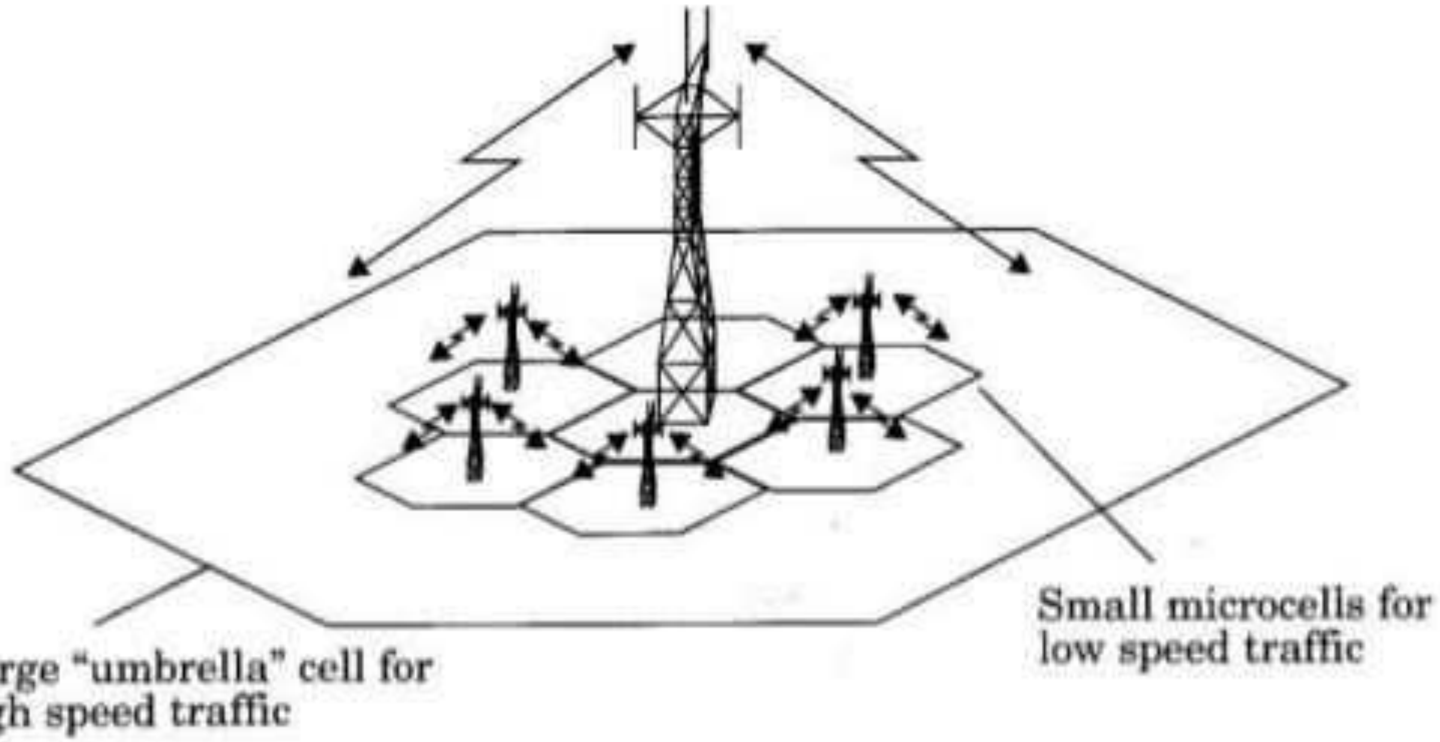
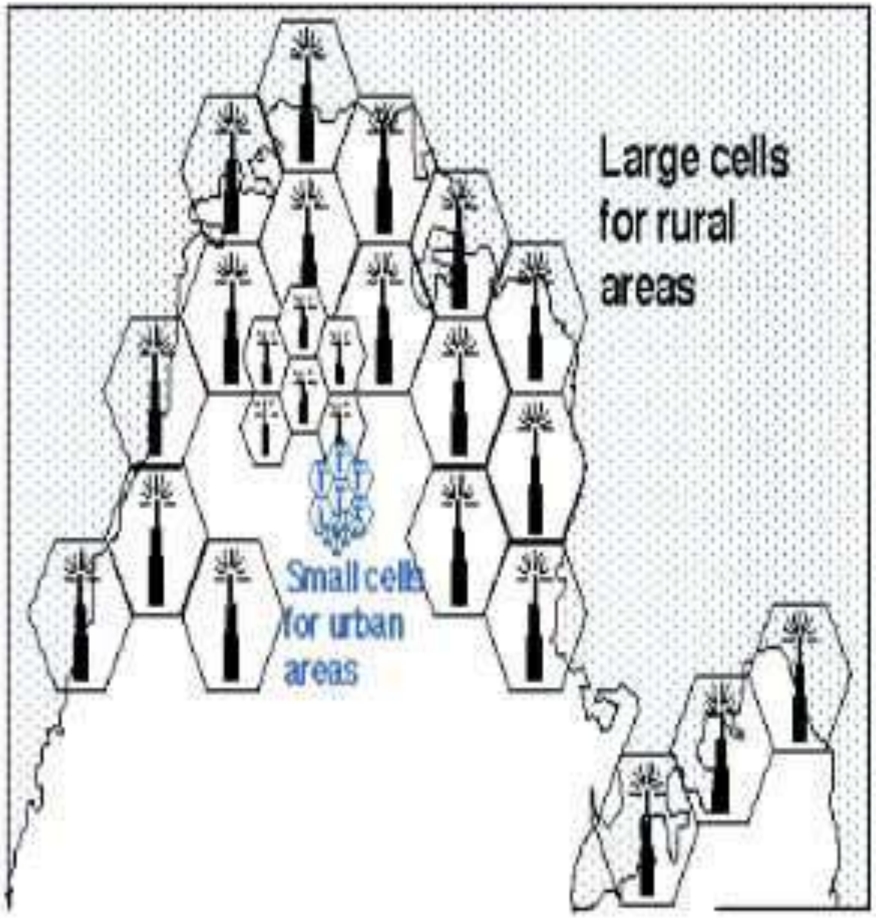
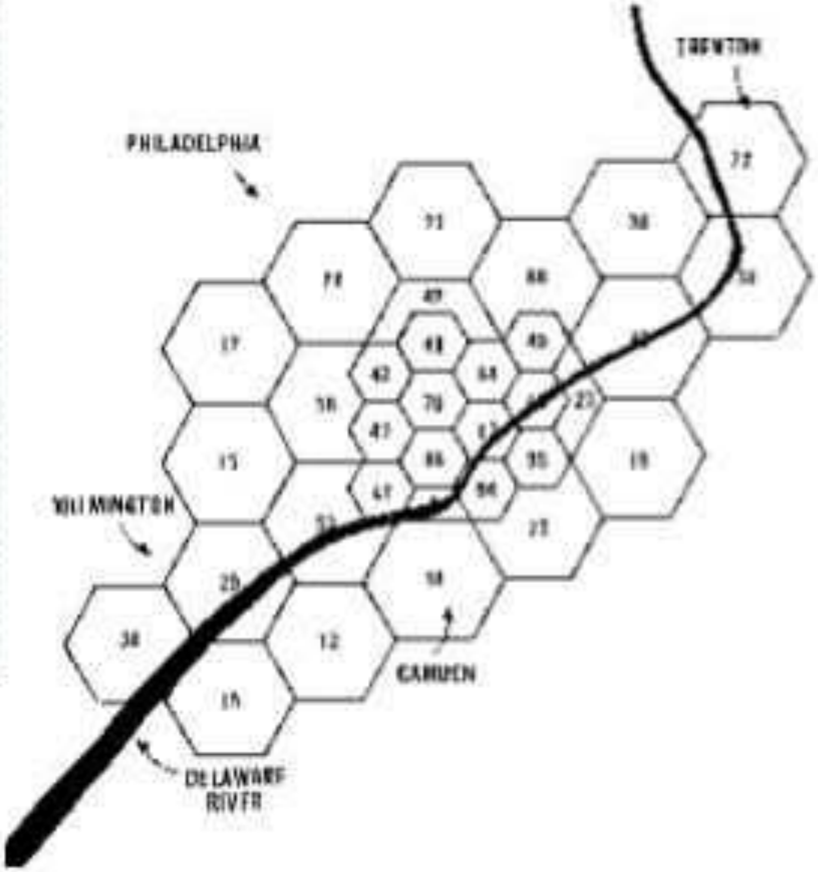


Figure 3.4 The umbrella cell approach.

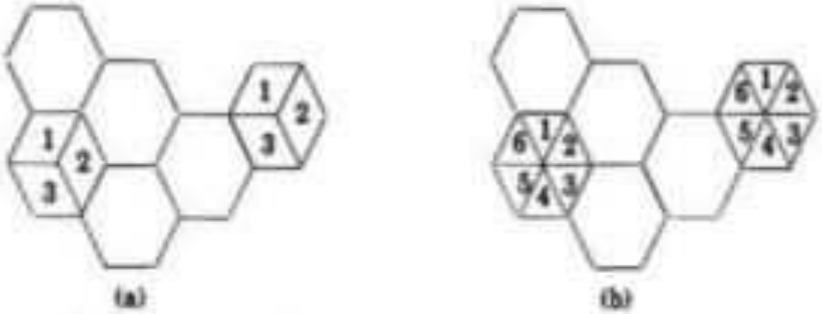

Large cells for rural areas
Small cells for urban areas


TRENTON
PHILADELPHIA
WILMINGTON
CAMDEN
DELAWARE RIVER
72
38
25
12
42
19
23

Sectoring

- In this approach
  - first SIR is improved using directional antennas,
  - capacity improvement is achieved by reducing the number of cells in a cluster thus increasing frequency reuse

- The CCI decreased by replacing the single omni-directional antenna by several directional antennas, each radiating within a specified sector



(a)

(b)

Figure 3.10 (a) 120° sectoring; (b) 60° sectoring.

Sectoring

A directional antenna transmits to and receives from only a fraction of total of the co-channel cells. Thus CCI is reduced

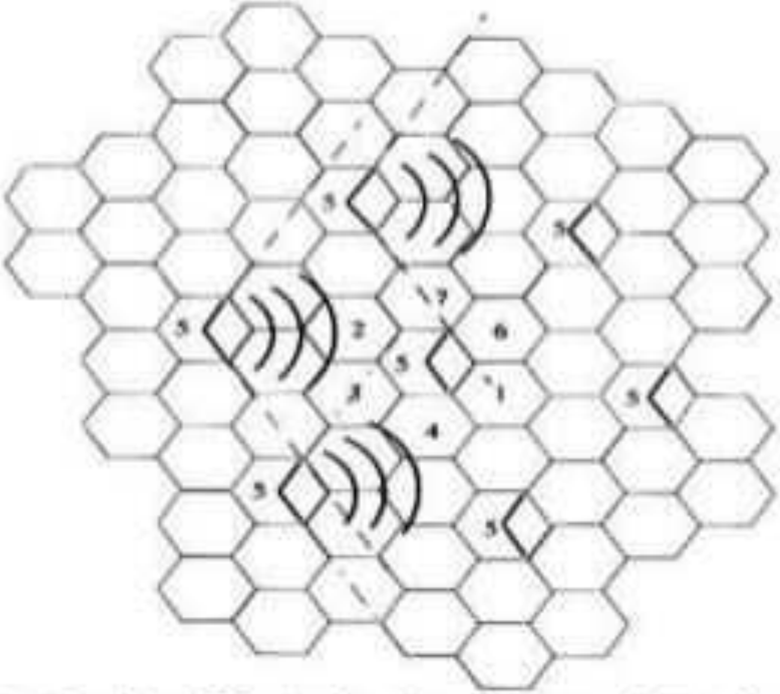


Figure 3.11 Illustration of how 120° sectoring reduces interference from co-channel cells. Out of the 6 co-channel cells in the first tier, only two of them interfere with the center cell. If omnidirectional antennas were used at each base station, all six co-channel cells would interfere with the center cell.

Problems with Sectoring

- Increases the number of antennas at each BS
- Decrease in trunking efficiency due to sectoring(dividing the bigger pool of channels into smaller groups)
- Increase number of handoffs(sector-to sector)
- Good news:Many modern BS support sectoring and related handoff without help of MSC

Microcell Zone Concept

- The Problems of sectoring can be addressed by Microcell Zone Concept
- A cell is conceptually divided into microcells or zones
- Each microcell(zone) is connected to the same base station(fiber/microwave link)
- Doing something in middle of cell splitting and sectoring by extracting good points of both
- Each zone uses a directional antenna
- Each zone radiates power into the cell.
- MS is served by strongest zone
- As mobile travels from one zone to another, it retains the same channel, i.e. no hand off
- The BS simply switches the channel to the next zone site

Micro Zone Cell Concept

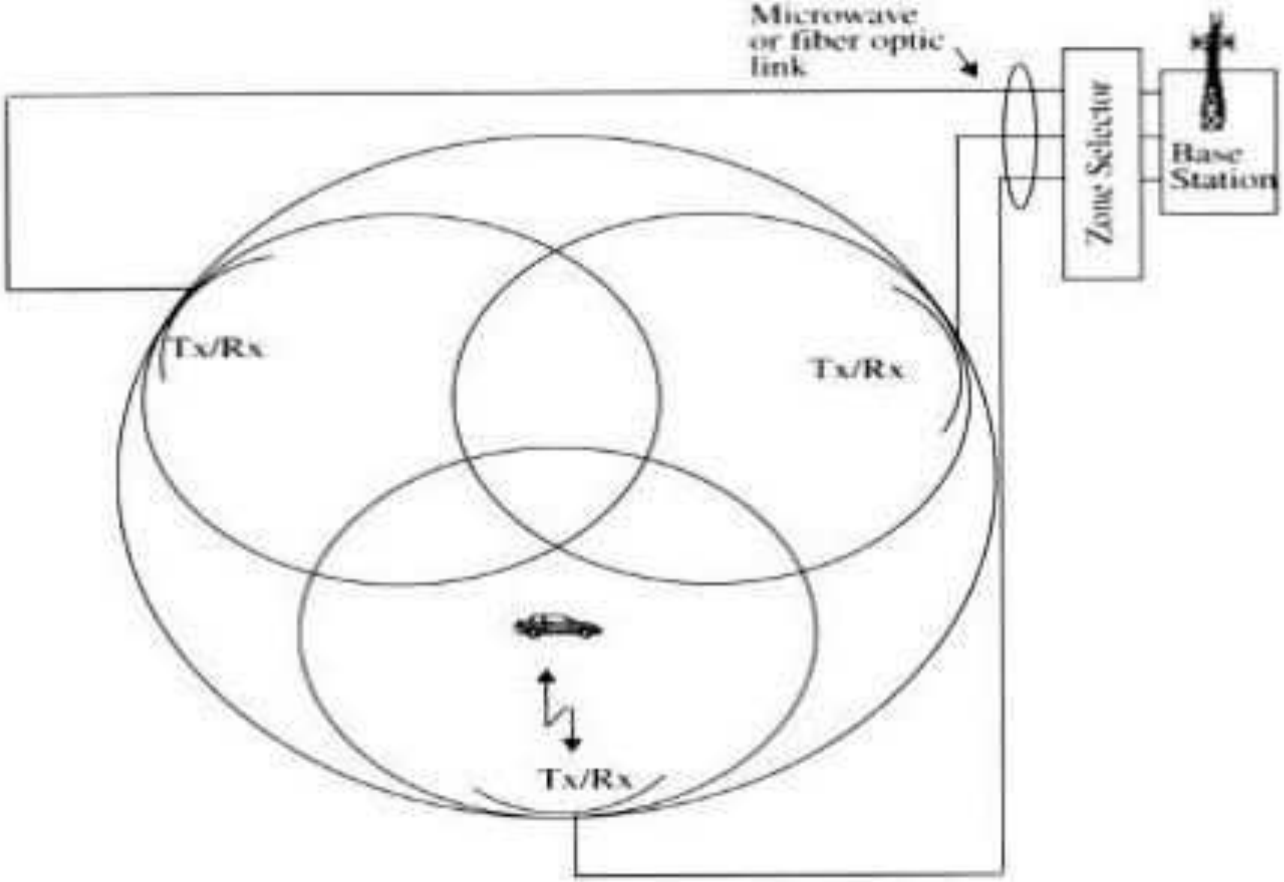


Figure 3.13 The microcell concept [adapted from [Lee91b] © IEEE].

Microcell Zone Concept

- Reduced Interference (Zone radius is small so small and directional antennas are used).
- Decrease in CCI improves the signal quality and capacity.
- No loss in trunking efficiency (all channels are used by all cells).
- No extra handoffs.
- Increase in capacity (since smaller cluster size can be used).

Microcell Zone Concept

- Reduced Interference (Zone radius is small so small and directional antennas are used).
- Decrease in CCI improves the signal quality and capacity.
- No loss in trunking efficiency (all channels are used by all cells).
- No extra handoffs.
- Increase in capacity (since smaller cluster size can be used).

Repeaters for Range Extension

- Useful for hard to reach areas
  - Buildings
  - Tunnels
  - Valleys

- Radio transmitters called Repeaters can be used to provide coverage in these area
- Repeaters are **bi-directional**
- Rx signals from BS
- Amplify the signals
- Re-radiate the signals
- Received noise and interference is also re-radiated

Digital Signalling for Fading Channels

Unit-4

By: Deepmala Kulshreshth

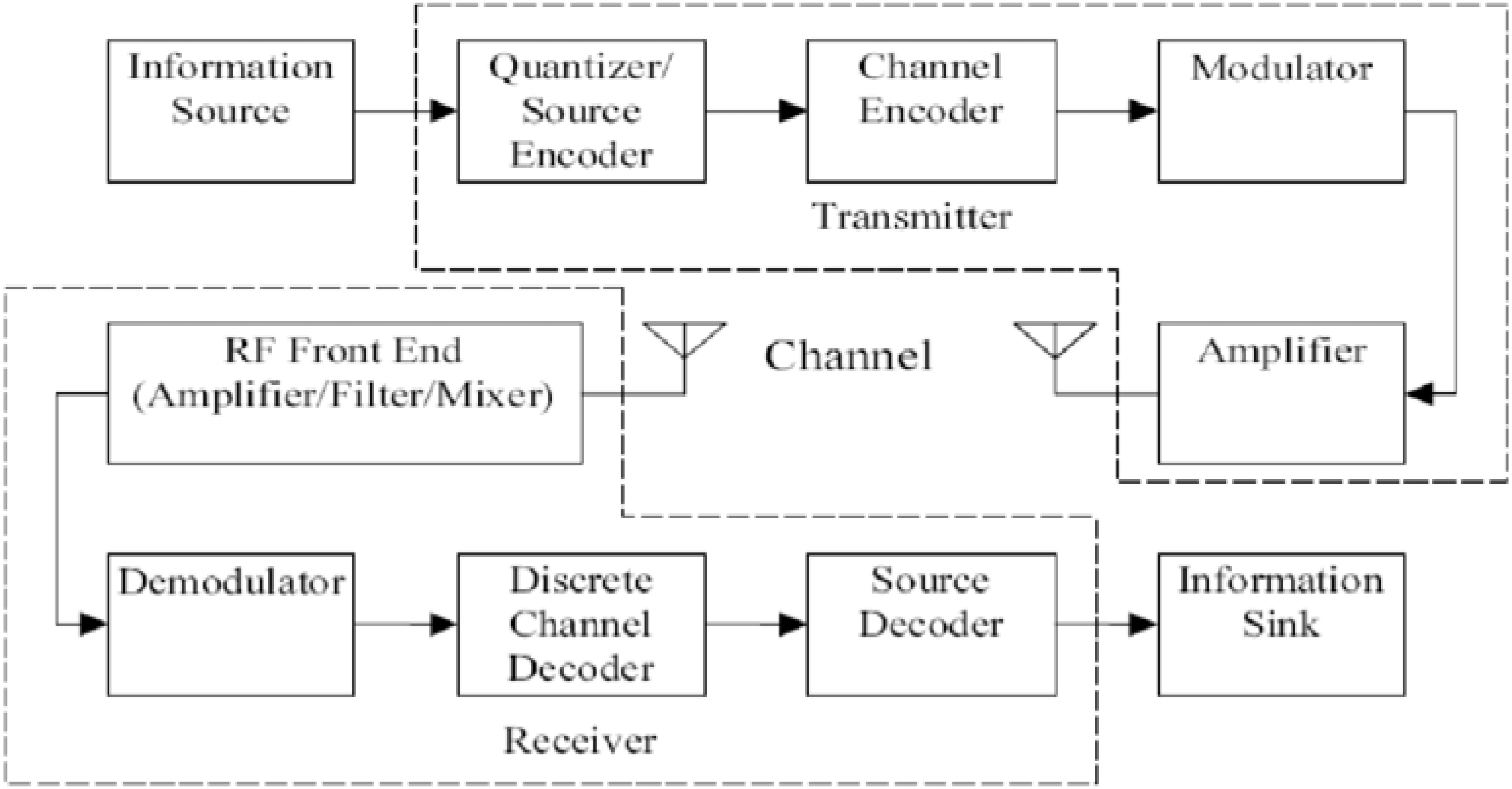
EC Department, JECRC

Syllabus

Digital Signaling For Fading Channels:

Structure of a wireless communication link, Principles of Offset-QPSK, p/4-DQPSK, Minimum Shift Keying, Gaussian Minimum Shift Keying, Error performance in fading channels, OFDM principle – Cyclic prefix, Windowing, PAPR.

Structure of a wireless communication link



Block Explanation

- Information source:
  - Provides the source signal
  - Can be either analog or digital
- Source coder
  - They are used to reduce the redundancy of the source messages. In order to improve the bit rate.
  - Original message bits are converted to symbols
  - Ex. Zero padding

- Channel coder
  - This process adds the additional bits in order to protect data against transmission errors.
  - Ex. Error detection codes, header and trailer bits, Reed Solomon codes, CRC Codes etc.,
- Modulator
  - This converts the input bit stream suitable for transmission.
  - Converts the low frequency signals to high frequency signals
- Channel
  - Provides the electrical connection between the transmitter and receiver.
  - The various channels used are pairs of wires, co axial cables, optical fibers or radio channels

- Diversity Combiner:
  - A normal receiver will receive multiple signals from various antennas. All signals will be combined here.
- Equalizers
  - Mainly they are used to reduce the ISI and dispersion in the signal caused by the channels
- Demodulator
  - They are the reverse process of the modulation.
  - They extracts the message signal from the modulated signal.

- Channel decoder
  - Used to reconstruct the original wave form from the encoded signal .
  - Inverse algorithm of the encoder is used to reconstruct the original message bits
- Source decoder
  - They convert the symbols to message bits
- Data sink
  - These devices converts the waveform to analog signals and they are fed to the respective devices.

MODULATION AND DEMODULATION SCHEMES

Types of Modulation formats

- Binary Phase Shift Keying **[BPSK]**
- Differential Phase Shift Keying **[DPSK]**
- Quadrature Phase Shift Keying **[QPSK]**
- Offset – Quadratrure Phase Shift Keying **[OQPSK]**
- Pi / 4 Quatrature Phase Shift Keying **[pi / 4 - QPSK]**
- Binary Frequency Shift Keying **[BFSK]**
- Minimum Shift Keying **[MSK]**
- Gaussian Minimum Shift Keying **[GMSK]**

BPSK

- In bpsk , the phase of the constant amplitude carrier is shifted between 2 values according to the possible signals
- Since it is binary we have only 2 symbols “1” and “0”
- The transmitted signal is given by

$$s_{\mathrm{BPSK}}(t) = \sqrt{\frac{2E_b}{T_b}}\cos(2\pi f_c t + \theta_c) \qquad 0 \le t \le T_b \text{ (binary 1)}$$

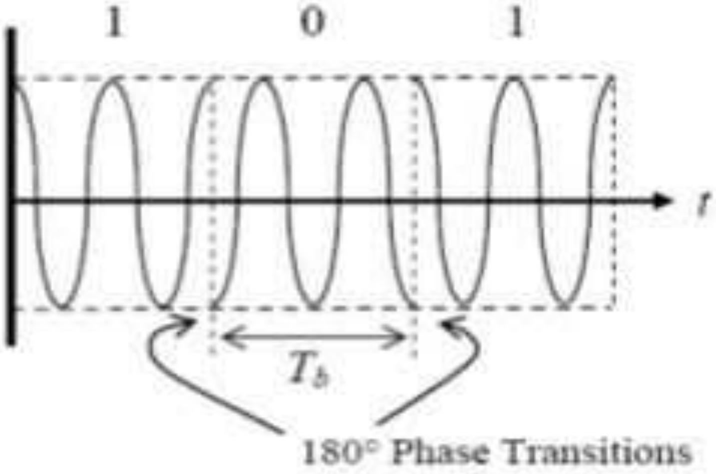
$$s_{\mathrm{BPSK}}(t) = \sqrt{\frac{2E_b}{T_b}}\cos(2\pi f_c t + \pi + \theta_c)$$

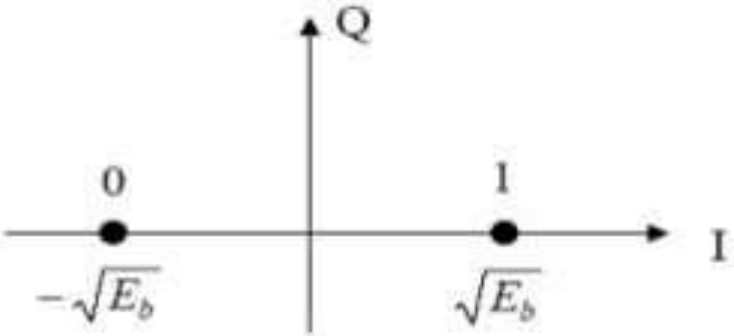
$$= -\sqrt{\frac{2E_b}{T_b}}\cos(2\pi f_c t + \theta_c) \quad 0 \le t \le T_b \text{ (binary 0)}$$

- In general the BPSK message signal is given by

$$s_{\mathrm{BPSK}}(t) = m(t)\sqrt{\frac{2E_b}{T_b}}\cos(2\pi f_c t + \theta_c)$$

- Constellation diagram of BPSK:
  - It is the graphical representation to compute the bit error probabilities

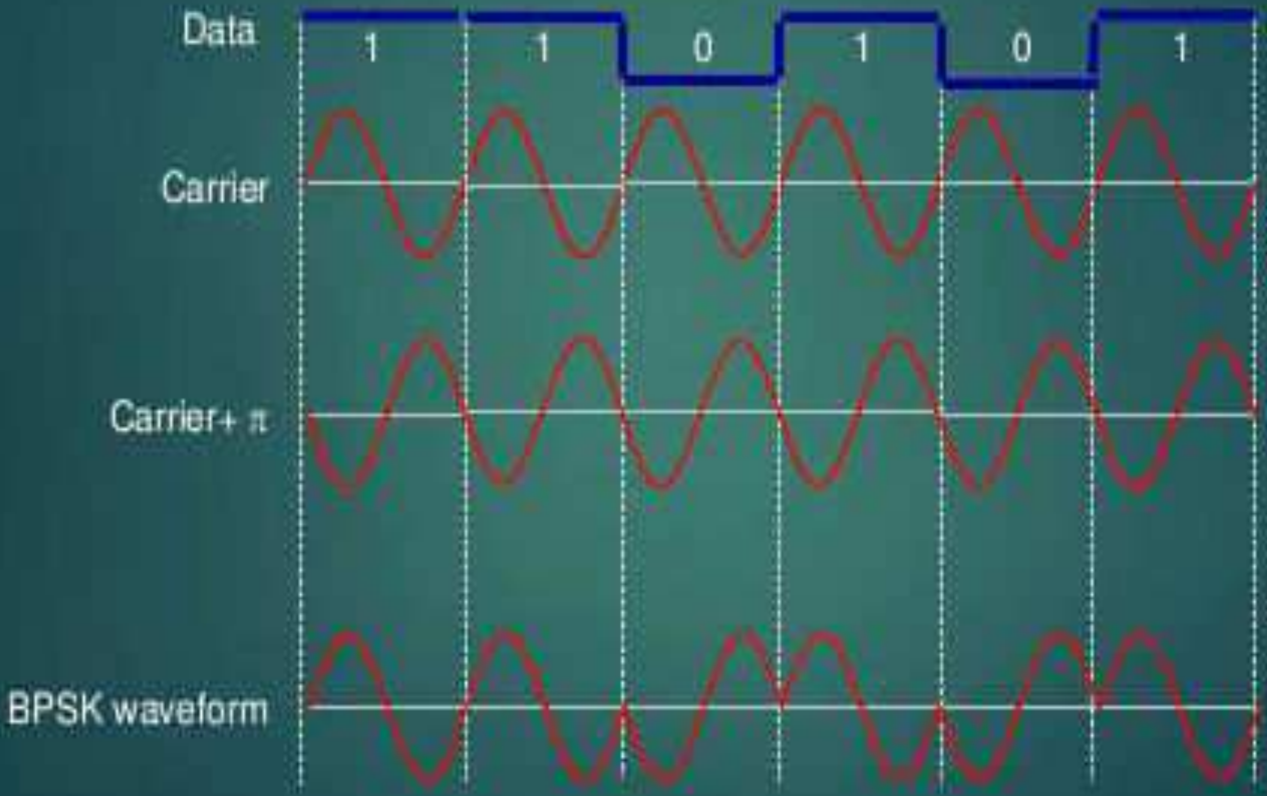




Generation of BPSK

http://techtonicsa.blogspot.com/2015/04/what-is-semiconductor.html

Generation of BPSK contd.



PSD of BPSK

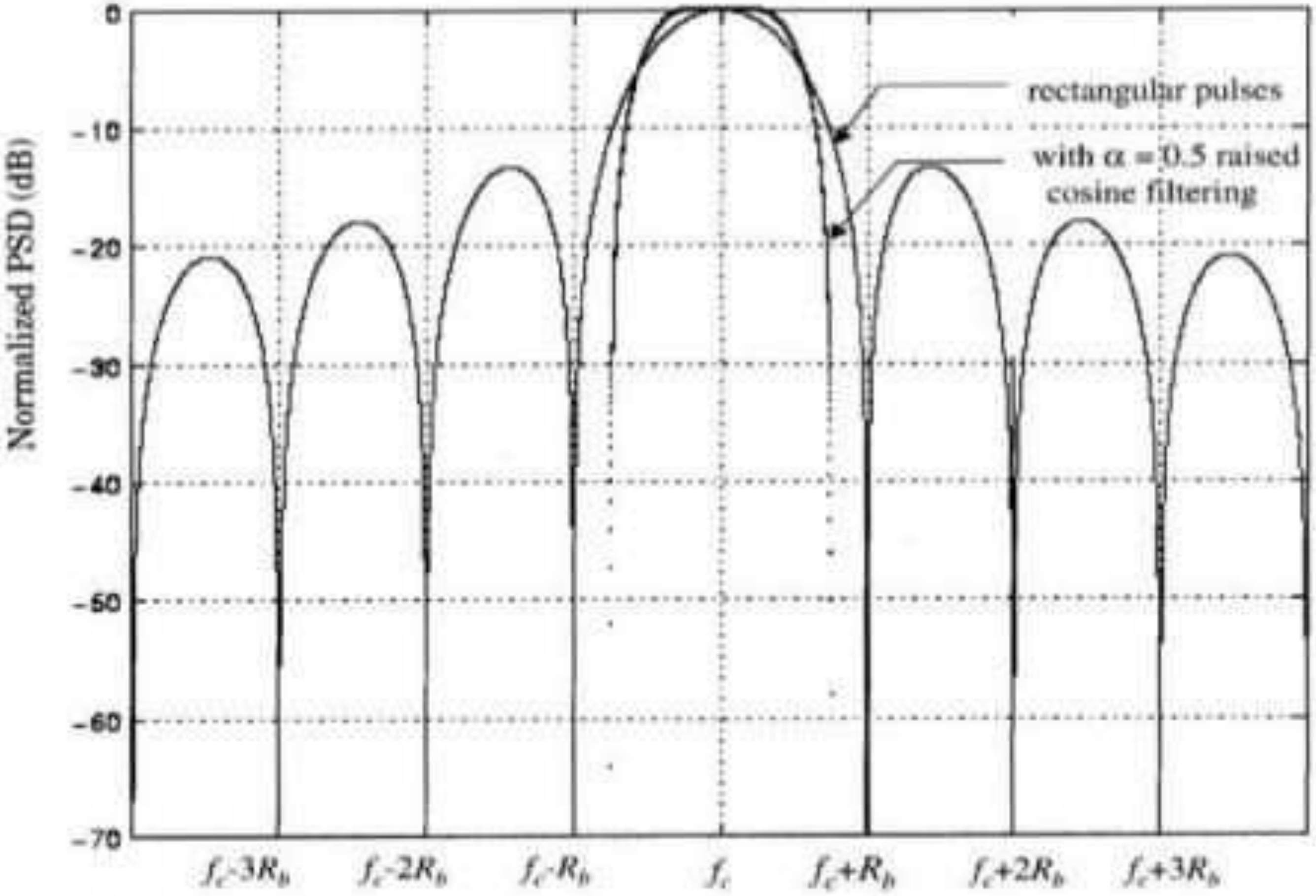


Figure 6.22 Power spectral density (PSD) of a BPSK signal.

Demodulation in BPSK

- Demodulation in Rx
  - Requires reference of Tx signal in order to properly determine phase
    - carrier must be transmitted along with signal
  - Called Synchronous or "**Coherent**" detection
    - complex & costly Rx circuitry
    - good BER performance for low *SNR* → **power efficient**

BPSK Receiver

$$s_{\text{BPSK}}(t) = m(t)\sqrt{\frac{2E_b}{T_b}}\cos(2\pi f_c t + \theta_c + \theta_{ch})$$

$$= m(t)\sqrt{\frac{2E_b}{T_b}}\cos(2\pi f_c t + \theta)$$

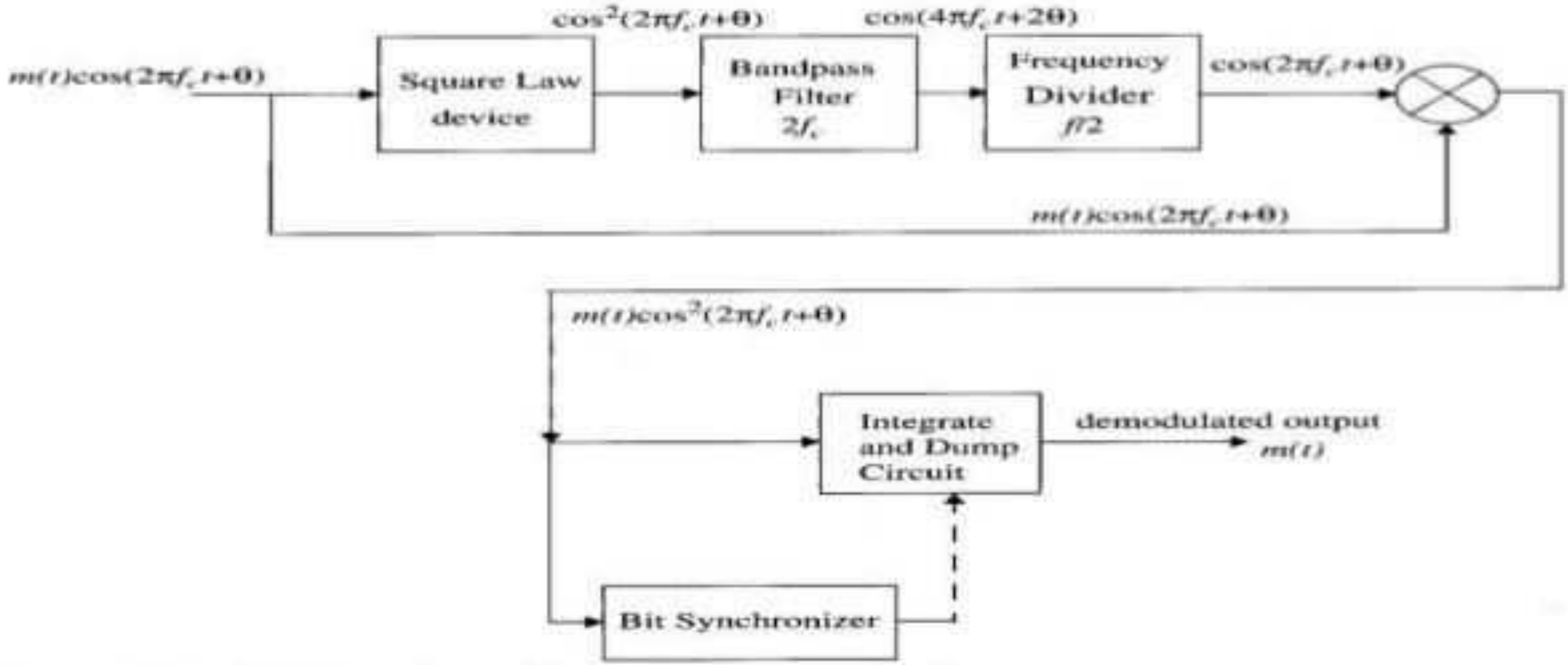
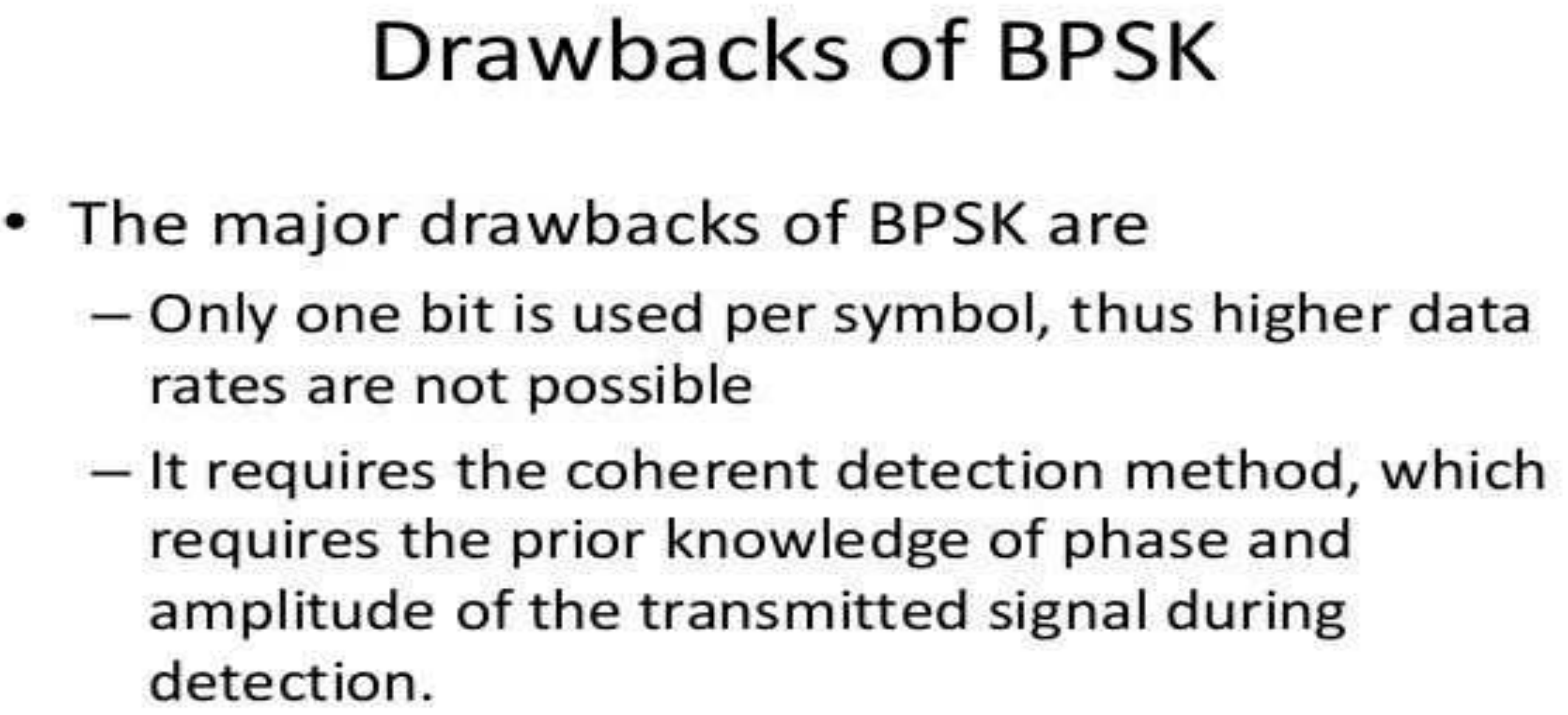
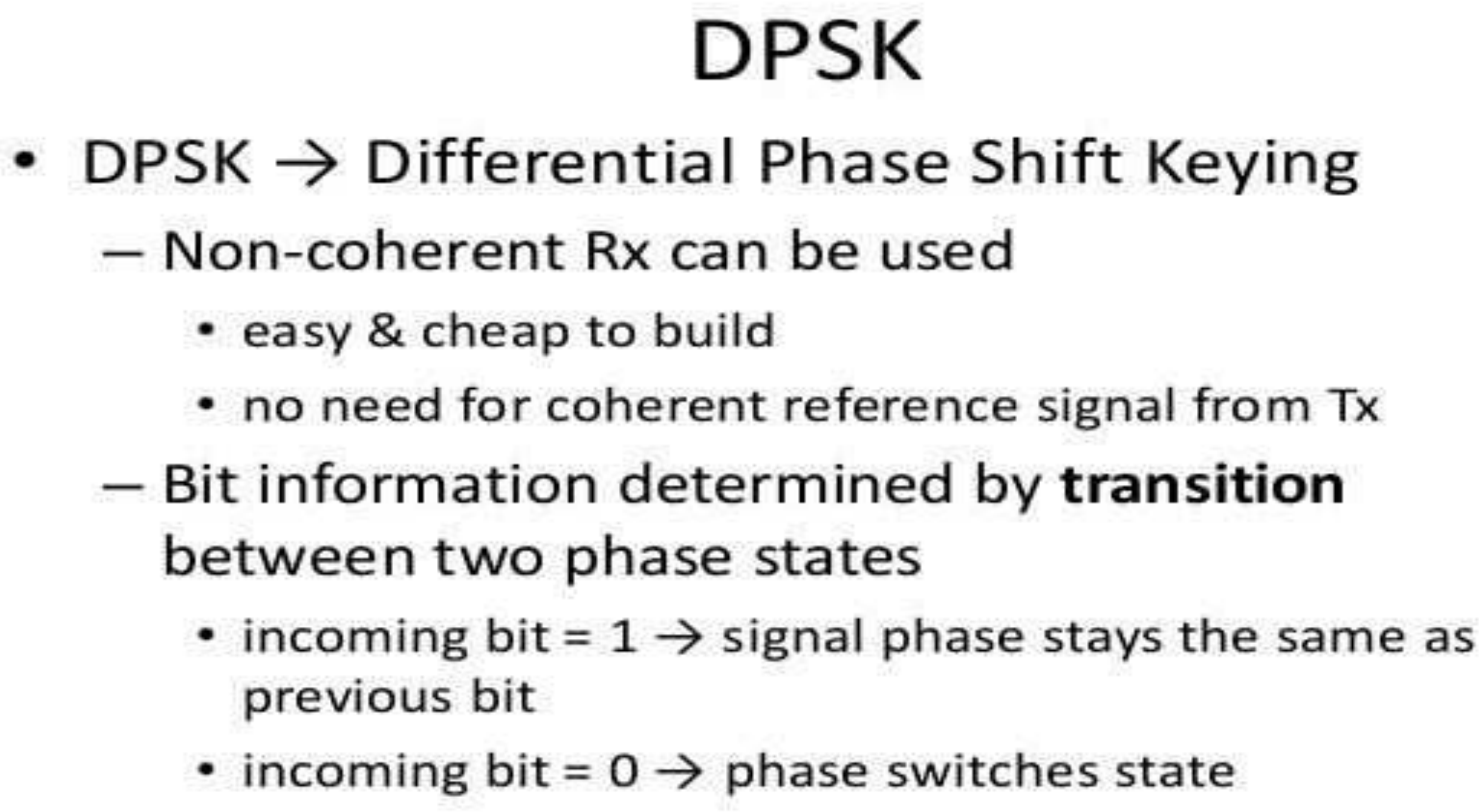


Figure 6.23 BPSK receiver with carrier recovery circuits.



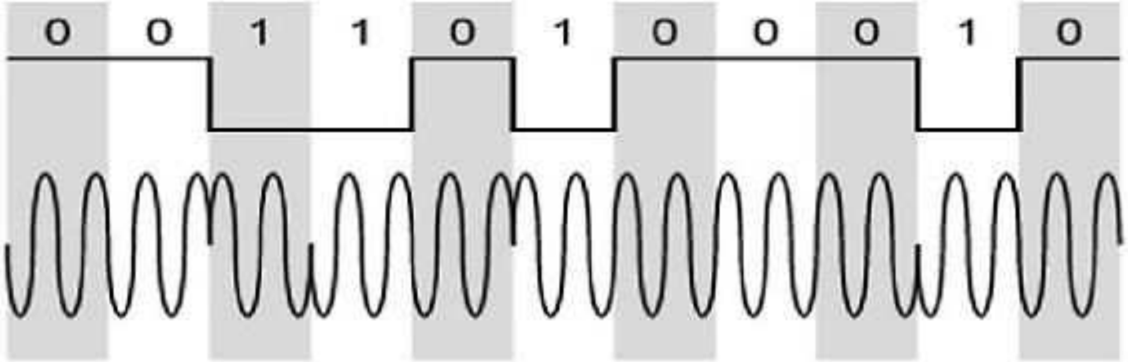
Drawbacks of BPSK

- The major drawbacks of BPSK are
  - Only one bit is used per symbol, thus higher data rates are not possible
  - It requires the coherent detection method, which requires the prior knowledge of phase and amplitude of the transmitted signal during detection.



DPSK

- DPSK → Differential Phase Shift Keying
  - – Non-coherent Rx can be used
    - easy & cheap to build
    - no need for coherent reference signal from Tx
  - – Bit information determined by **transition** between two phase states
    - incoming bit = 1 → signal phase stays the same as previous bit
    - incoming bit = 0 → phase switches state


0
0
1
1
0
1
0
0
0
1
0

Transmitter - DPSK

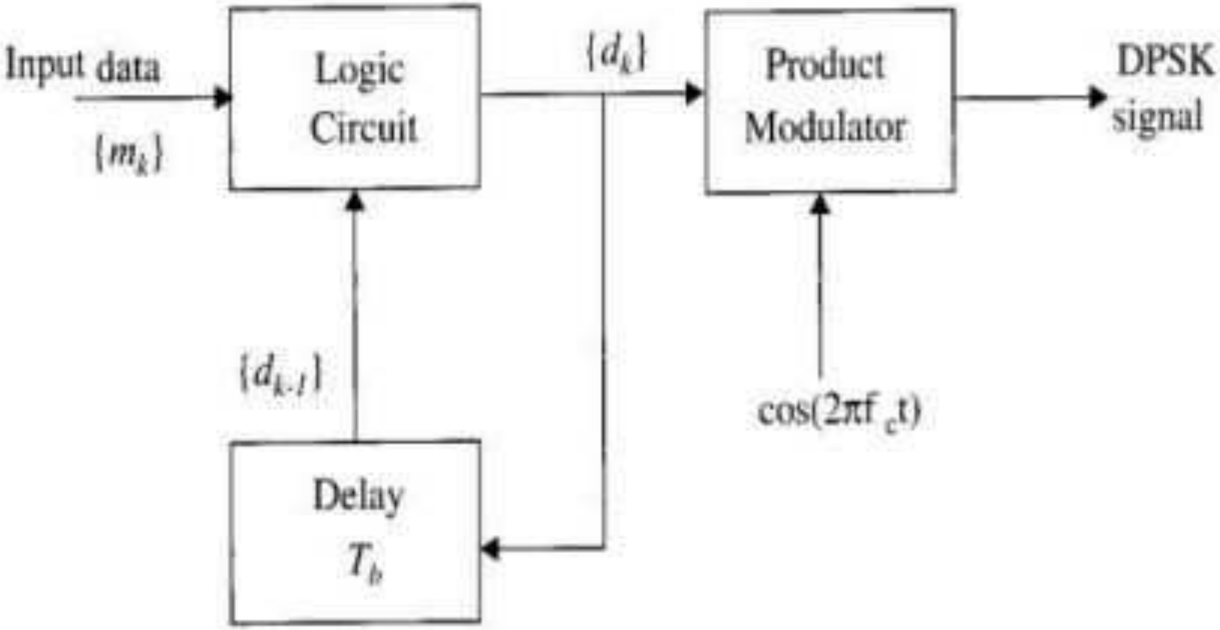


Figure 6.24 Block diagram of a DPSK transmitter.

Receiver - DPSK

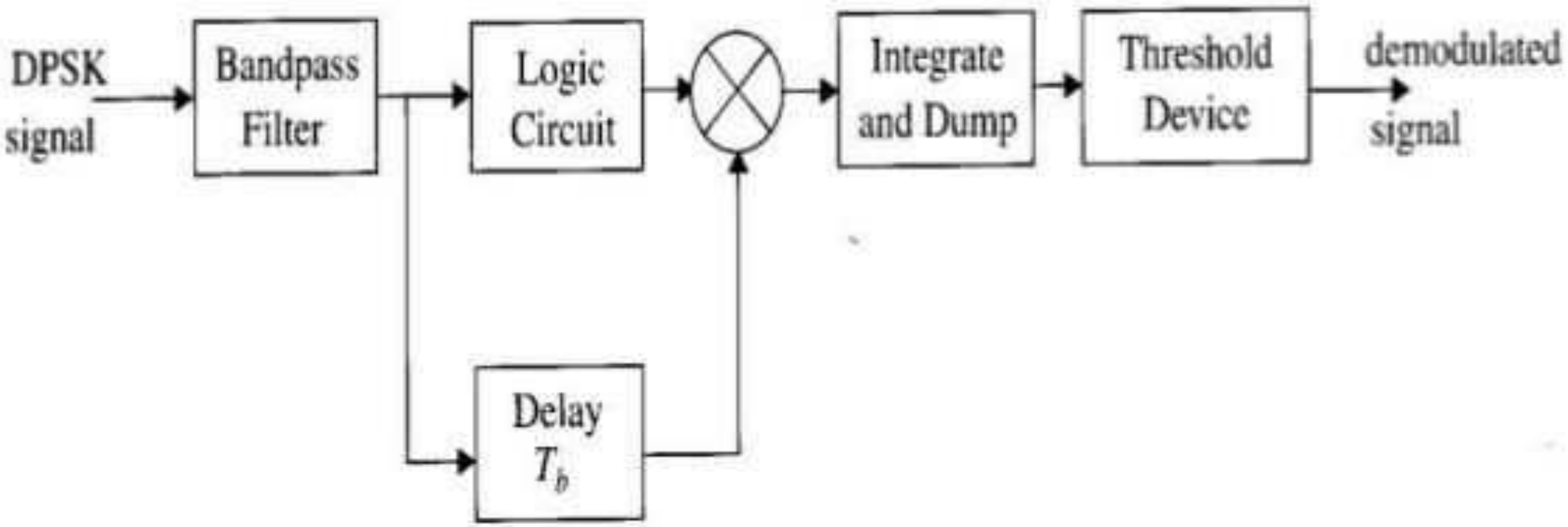
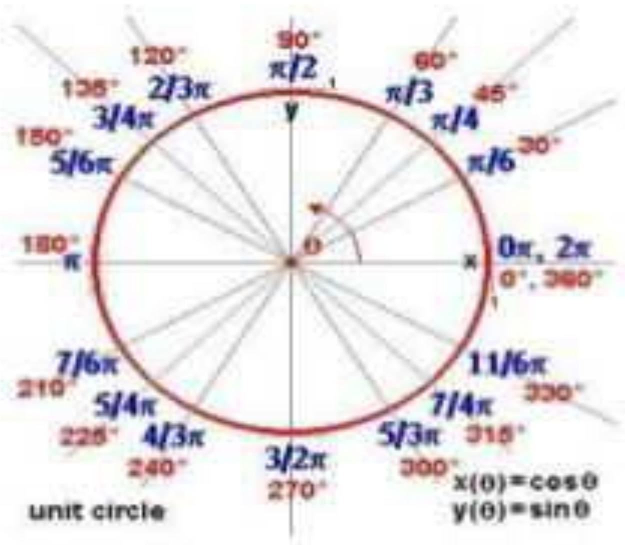


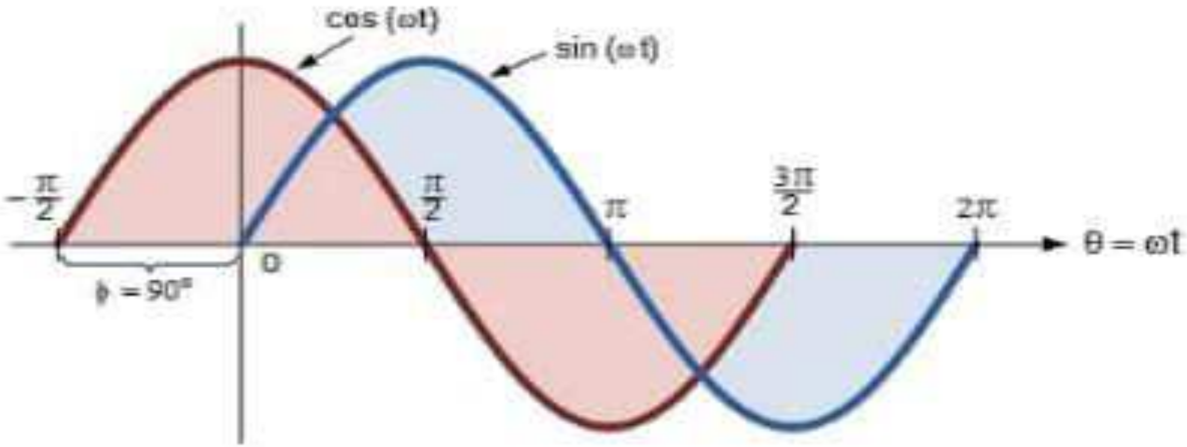
Figure 6.25 Block diagram of DPSK receiver.

Quadrature Phase Shift Keying - QPSK

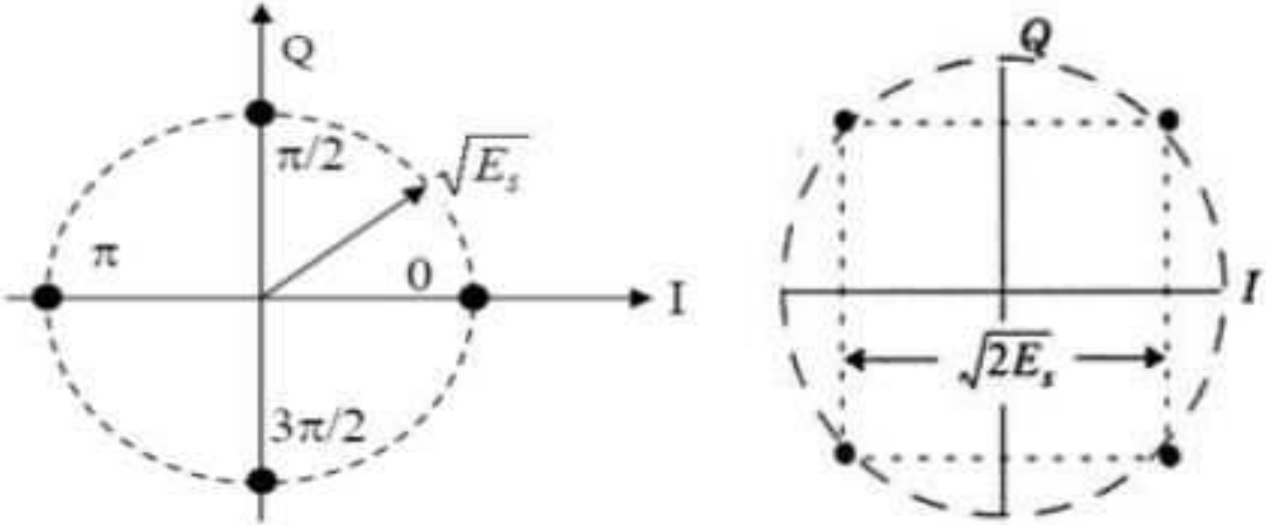
- It has twice the bandwidth efficiency of the BPSK, since two bits are transferred in a single symbol.
- The phase of the signal will take one of the four equally spaced values such as 0,pi/2, pi, 3pi/2 [or] pi/4, 3pi/4, 5pi/4, 7pi/4.
- The QPSK symbol is given by:

$$S_{QPSK} = \sqrt{\frac{2E_S}{T_s}} \cos\left(2\pi f_c t + (i-1)\frac{\pi}{2}\right) \quad \text{for } i = 1, 2, 3, 4$$


90°
π/2
120°
2/3π
60°
π/3
135°
3/4π
45°
π/4
150°
5/6π
30°
π/6
y
θ
180°
π
0π, 2π
0°, 360°
x
7/6π
210°
11/6π
330°
5/4π
225°
7/4π
315°
4/3π
240°
5/3π
300°
3/2π
270°
unit circle
x(θ)=cosθ
y(θ)=sinθ


cos (ωt)
sin (ωt)
$-\frac{\pi}{2}$
$\frac{\pi}{2}$
π
$\frac{3\pi}{2}$
2π
0
ϕ = 90°
θ = ωt

Constellation Diagram



(a) (b)

Figure 6.26 (a) QPSK constellation where the carrier phases are 0, $\pi/2$, π, $3\pi/2$; (b) QPSK constellation where the carrier phases are $\pi/4$, $3\pi/4$, $5\pi/4$, $7\pi/4$.

Power Spectral Density

$$
\begin{aligned}
P_{\mathrm{QPSK}}(f) &= \frac{E_s}{2}\left[\left(\frac{\sin \pi(f-f_c)T_s}{\pi(f-f_c)T_s}\right)^2 + \left(\frac{\sin \pi(-f-f_c)T_s}{\pi(-f-f_c)T_s}\right)^2\right] \\
&= E_b\left[\left(\frac{\sin 2\pi(f-f_c)T_b}{2\pi(f-f_c)T_b}\right)^2 + \left(\frac{\sin 2\pi(-f-f_c)T_b}{2\pi(-f-f_c)T_b}\right)^2\right]
\end{aligned}
$$

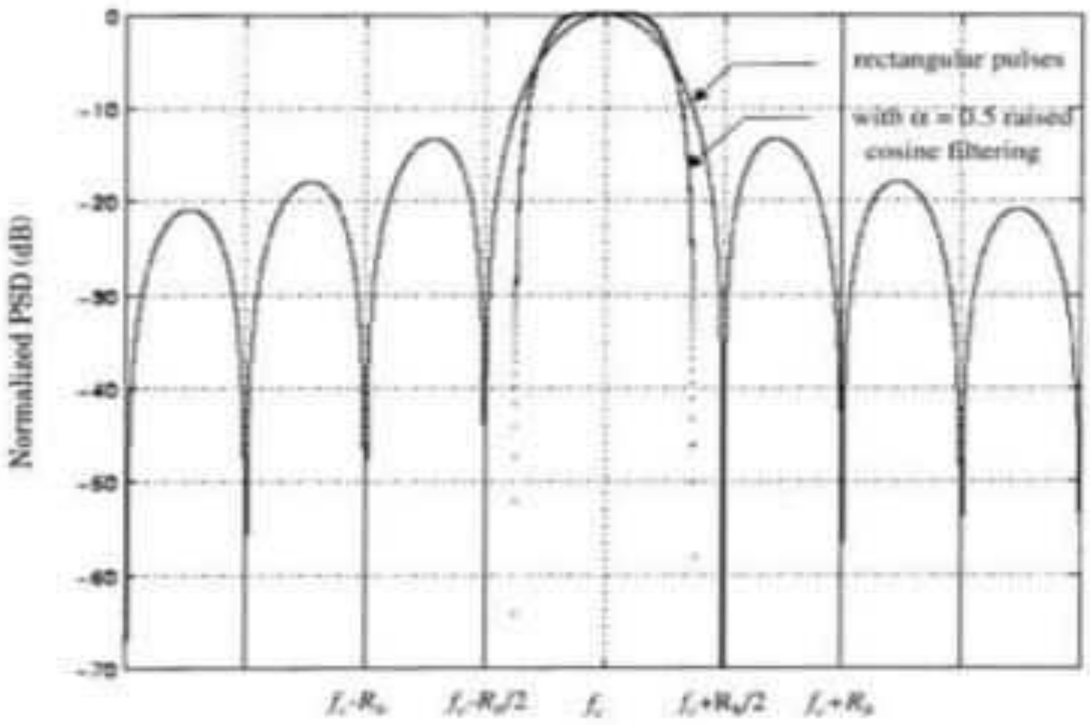


Figure 6.27 Power spectral density of a QPSK signal.

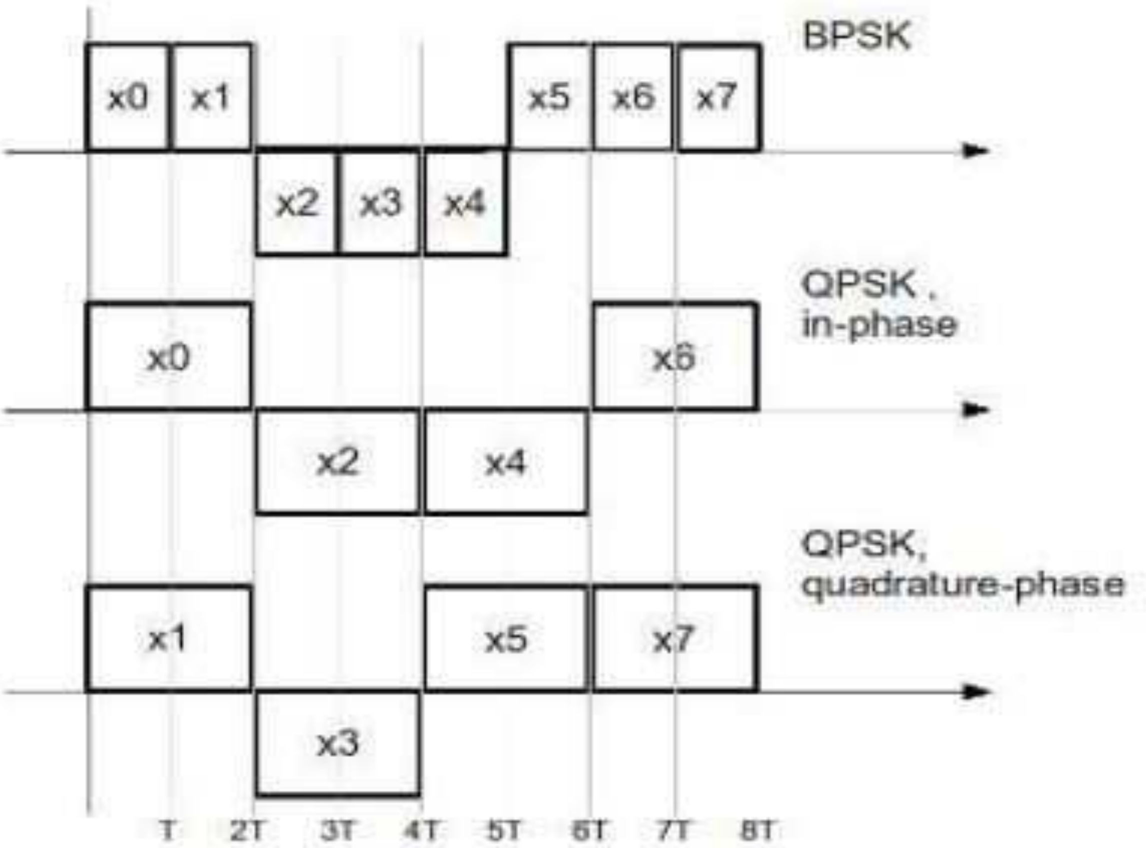
Modulation Steps

- Unipolar binary sequence are converted to bi polar NRZ sequence
- The bit stream $M(t)$ is split in to two bit streams $M_I(t)$ and $M_Q(t)$
  - $M_I(t)$ → In phase streams (or) Even Stream
  - $M_Q(t)$ → Quadrature streams (or) Odd Stream

  The binary sequences are modulated separately using $\varnothing_1(t)$ and $\varnothing_2(t)$.

  These 2 signals are now considered as the BPSK Signals and they are BPSK Modulated.

Splitting up of input binary sequence



QPSK Demodulator

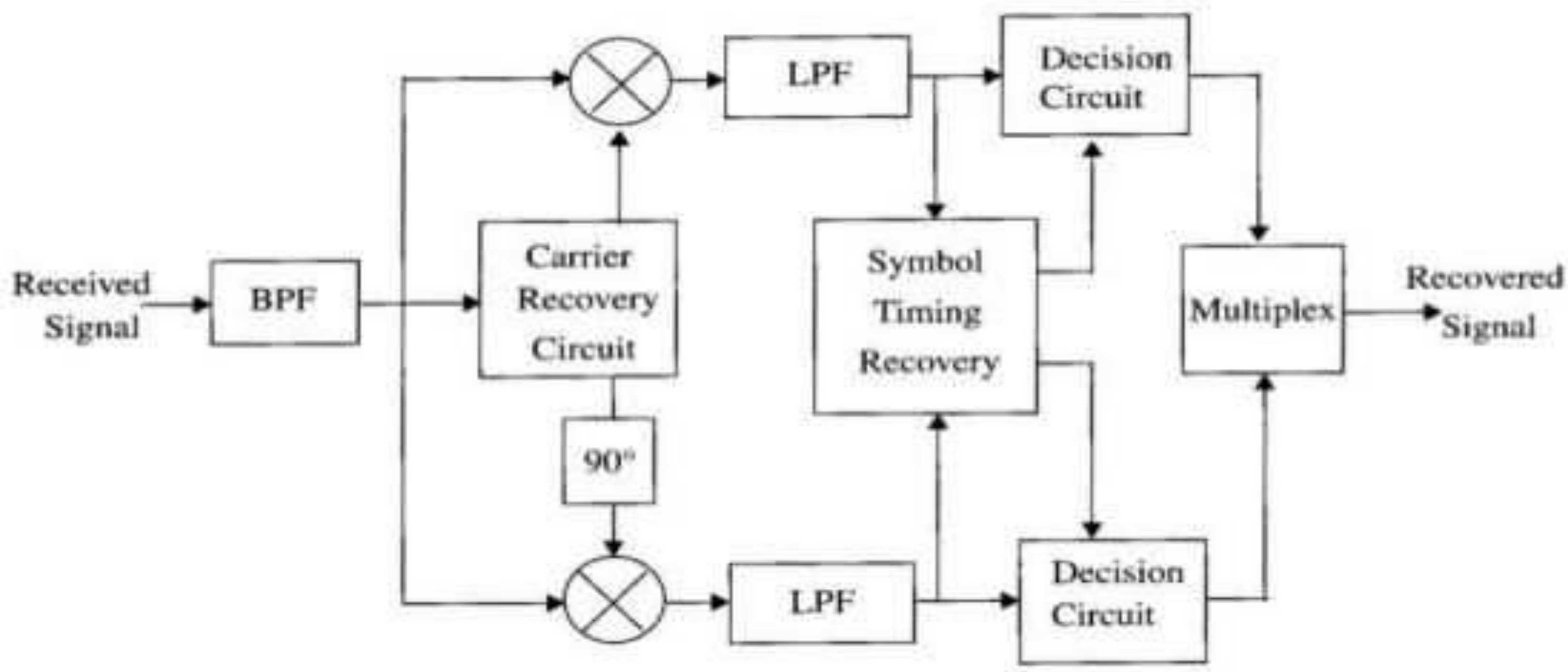


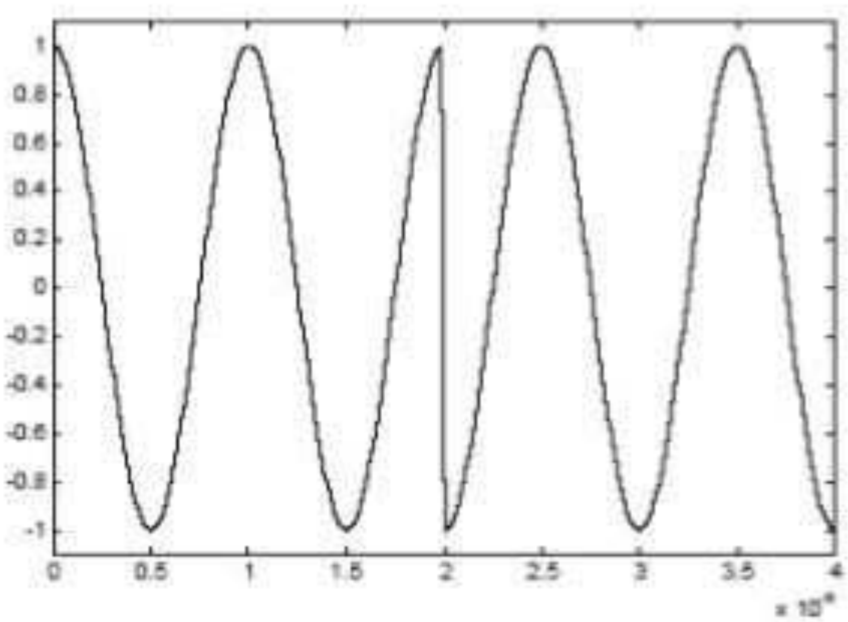
Figure 6.29 Block diagram of a QPSK receiver.

Drawbacks Of QPSK

- For QPSK modulated stream, whenever there is a 2 bit change in the input sequence transition in the state crosses the origin of constellation diagram for a particular period of time.
- This causes nonlinearity effects in the system.
- System attracts filtered side lobes
- Also linear amplifiers can not amplify the signals to optimal levels.

OFFSET Quadrature Phase Shift Keying - OQPSK

- Offset QPSK
  - The occasional phase shift of π radians can cause the signal envelope to pass through zero for just in instant.
  - Any kind of hard limiting or nonlinear amplification of the zero-crossings brings back the filtered sidelobes
    - since the fidelity of the signal at small voltage levels is lost in transmission.
  - OQPSK ensures there are fewer baseband signal transitions applied to the RF amplifier,
    - helps eliminate spectrum regrowth after amplification.

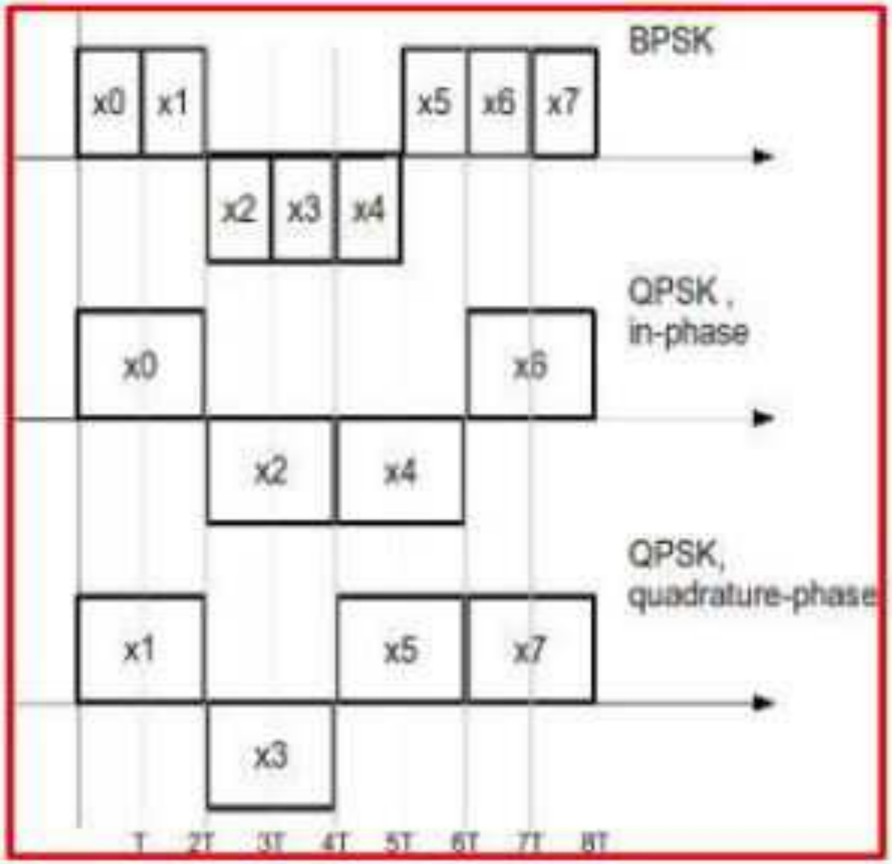


- Example above: First symbol (00) at 0°, and the next symbol (11) is at 180°. Notice the signal going through zero at 2 microseconds.
  - This causes problems.

Offset QPSK (OQPSK)

- It is a modified form of QPSK, which is less susceptible to deleterious effects and supports more efficient amplification.
- It is similar to QPSK except for time alignment of the even and odd bit streams.
- In QPSK signalling, bit transitions of even and odd bit streams occur at the same time instants, but in OQPSK signalling, even and odd bit streams are offset in their relative alignment by one period(half symbol period).

QPSK Vs OQPSK



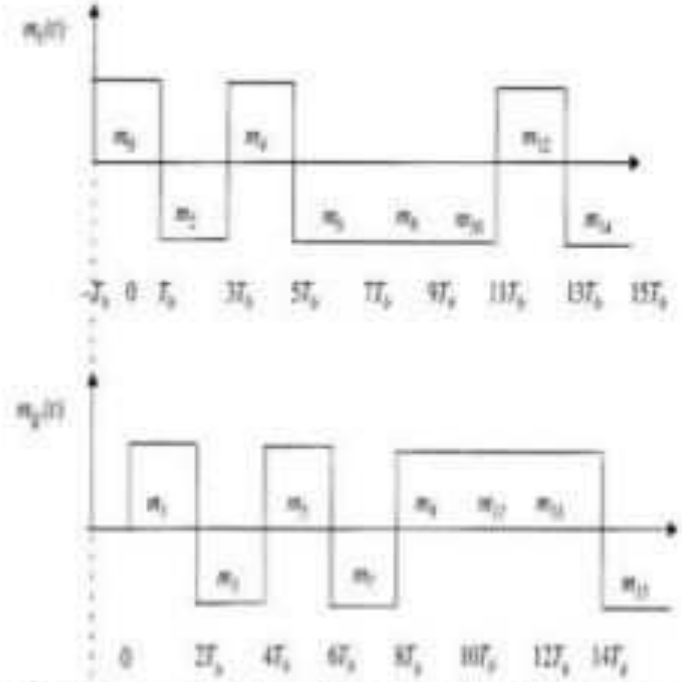
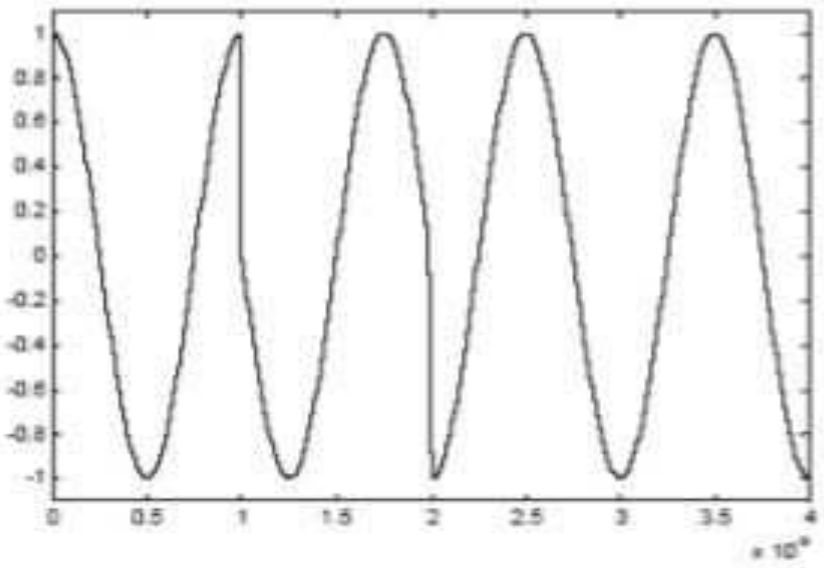


Figure 6.30 The time offset waveforms that are applied to the in-phase and quadrature arms of an OQPSK modulator. Notice that a half-symbol offset is used.

To be continued..

- Due to the time alignment in QPSK, phase transition occur only once every $T_s = 2T_b$ s, and a maximum phase shift of 180 degrees if there is a change in the values of both bit streams.
- In OQPSK, bit transition occur every Tb s. Due to an offset between transition instants of both bit streams, at any given instant only one of the two bit streams can change values.
- In this way maximum phase shift for OQPSK signals is +90 or -90.
- IS 95 uses OQPSK , hence it is a popular modulation scheme used in communication system.


1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
-1
0
0.5
1
1.5
2
2.5
3
3.5
4
x 10

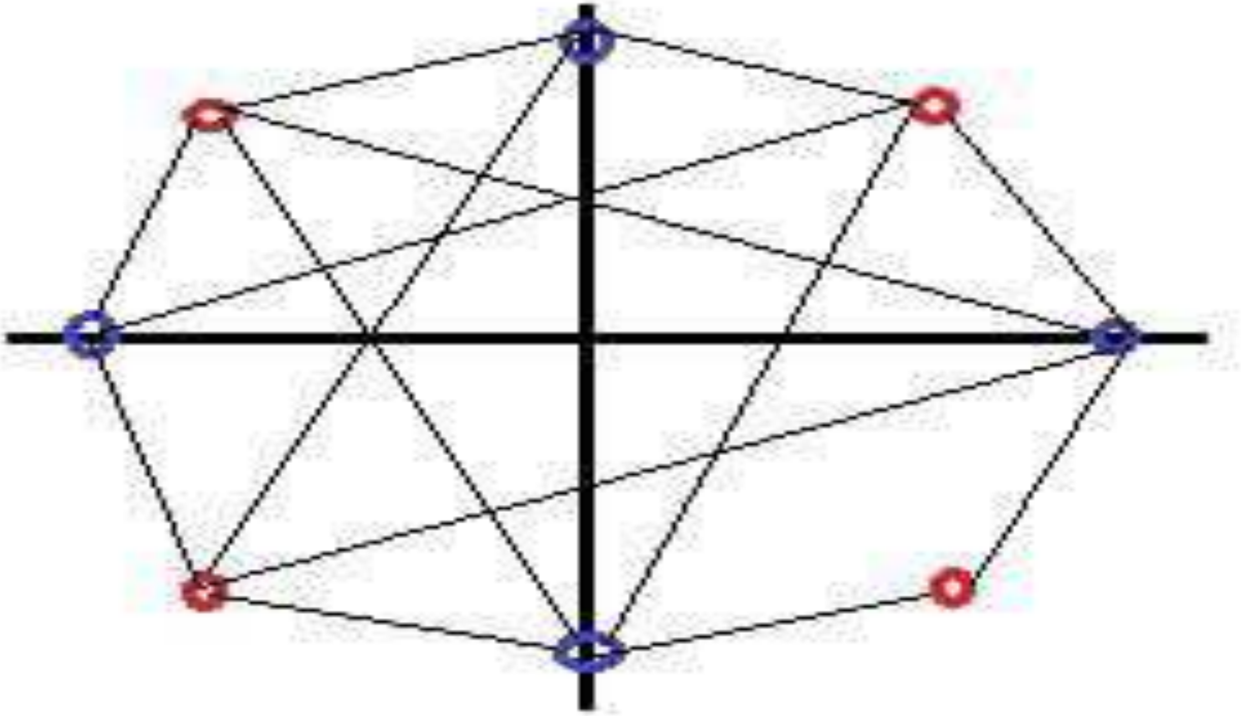
π/4 QPSK

- π/4 QPSK
  - The π/4 shifted QPSK modulation is a quadrature phase shift keying technique
    - offers a compromise between OQPSK and QPSK in terms of the allowed maximum phase transitions.
  - It may be demodulated in a coherent or non coherent fashion.
    - greatly simplifies receiver design.
  - In π/4 QPSK, the maximum phase change is limited to ± 135°
  - in the presence of multipath spread and fading, π/4 QPSK performs better than OQPSK

Constellation Diagram

- Signalling points of the modulated signal are selected from two QPSK constellations which are shifted by pi/4 with respect to each other.
- Every successive bit ensures that there is atleast a phase shift of integer multiple of pi/4.

Constellation Diagram



All the possible states of pi/4 QPSK Constellation

Pi/4 DQPSK

- When message bits are differentially encoded in pi/4 QPSK then it becomes pi/4 DQPSK.
- It is preferred over pi/4 QPSK because it provides easy implementation of differential detection or coherent demodulation with phase ambiguity in recovered carrier.
- All the characteristics and generation method are used similar to pi/4 QPSK.

Pi/4 QPSK transmitter

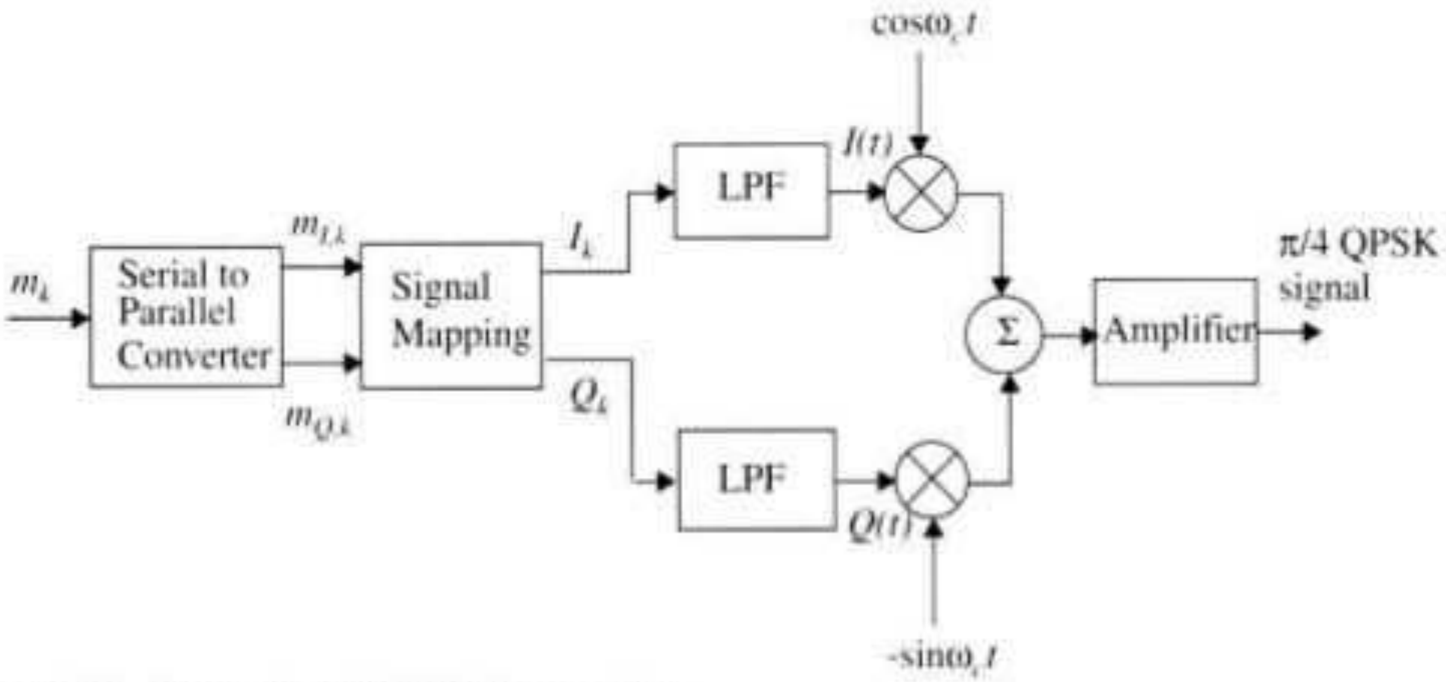
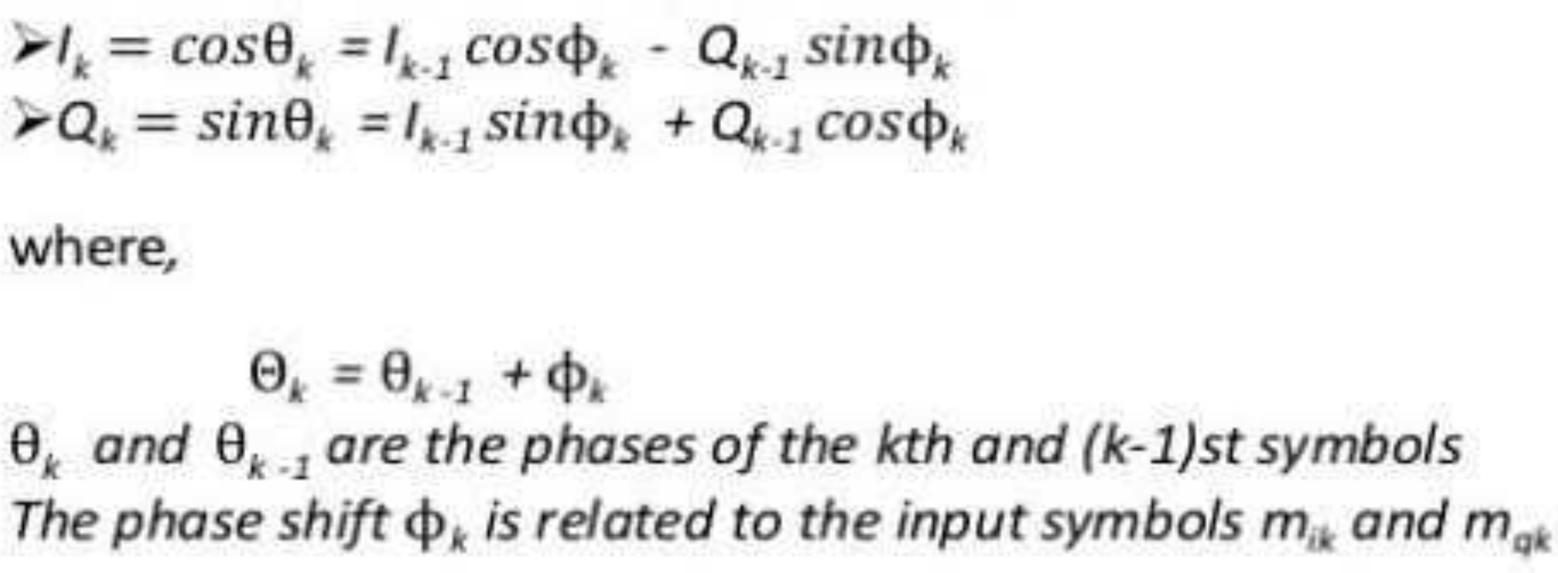


Figure 6.32 Generic π/4 QPSK transmitter.

Pi/4 QPSK Transmitter

- The input bit stream is partitioned by serial to parallel converter into two data streams, each with a symbol rate which is half of incoming bit rate.
- The k th in phase and quadrature pulses I_k and Q_k are produced at the output of signal mapping circuit.



- $I_k = \cos\theta_k = I_{k-1}\cos\phi_k - Q_{k-1}\sin\phi_k$
- $Q_k = \sin\theta_k = I_{k-1}\sin\phi_k + Q_{k-1}\cos\phi_k$

where,

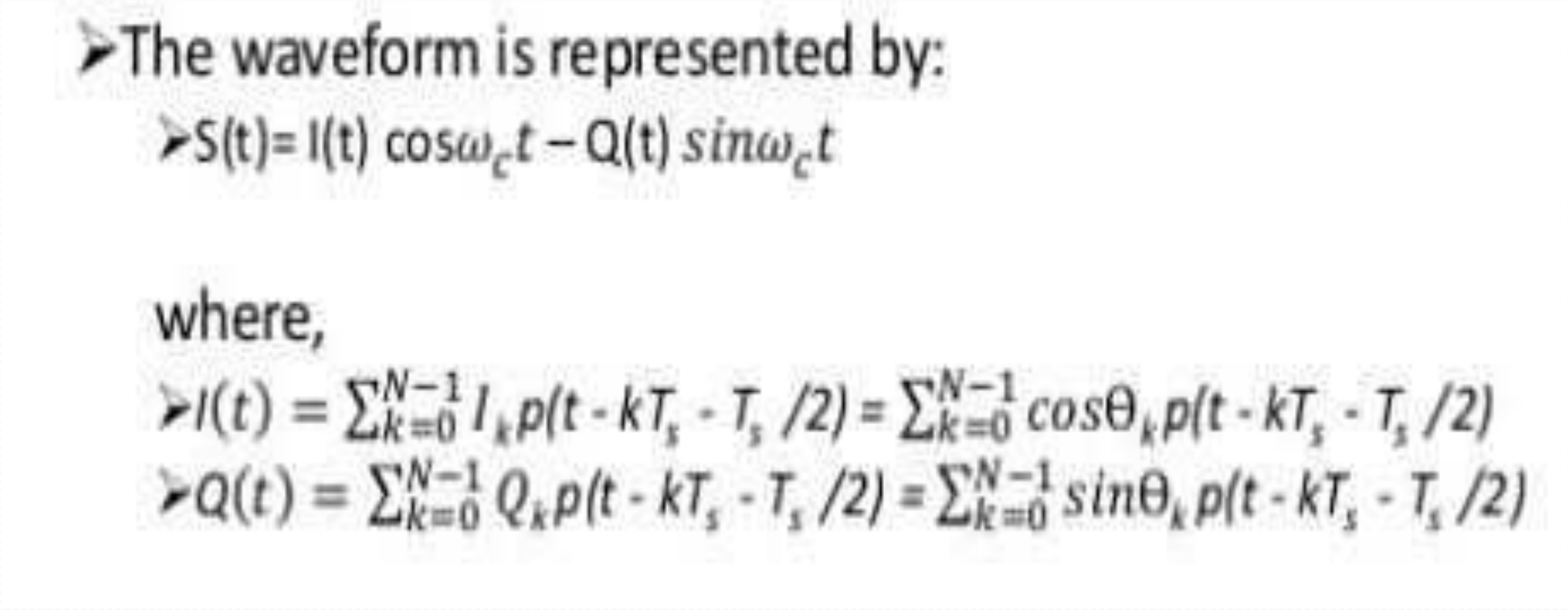
$$\Theta_k = \theta_{k-1} + \phi_k$$

θ_k and θ_{k-1} are the phases of the kth and (k-1)st symbols

The phase shift ϕ_k is related to the input symbols m_{ik} and m_{qk}

To be continued….

- Just as in QPSK modulator, in phase and quadrature bit streams are then separately modulated by two carriers which are in quadrature with each other.



- The waveform is represented by:
  - $S(t) = I(t)\cos\omega_c t - Q(t)\sin\omega_c t$

where,

- $I(t) = \sum_{k=0}^{N-1} I_k p(t - kT_s - T_s/2) = \sum_{k=0}^{N-1} \cos\Theta_k p(t - kT_s - T_s/2)$
- $Q(t) = \sum_{k=0}^{N-1} Q_k p(t - kT_s - T_s/2) = \sum_{k=0}^{N-1} \sin\Theta_k p(t - kT_s - T_s/2)$

Pi/4 Detection Techniques

- There are various types of detection processes that can be used for efficient detection. It includes baseband differential detection, IF differential detection and FM discrimination detection.
- Baseband and IF differential detector determines cosine and sine functions of the phase difference and then decides on phase difference accordingly.
- FM discriminator detects the phase difference directly in a noncoherent manner.
- Bit error rate performance is same for three tech.

I. Differential detection of pi/4 QPSK

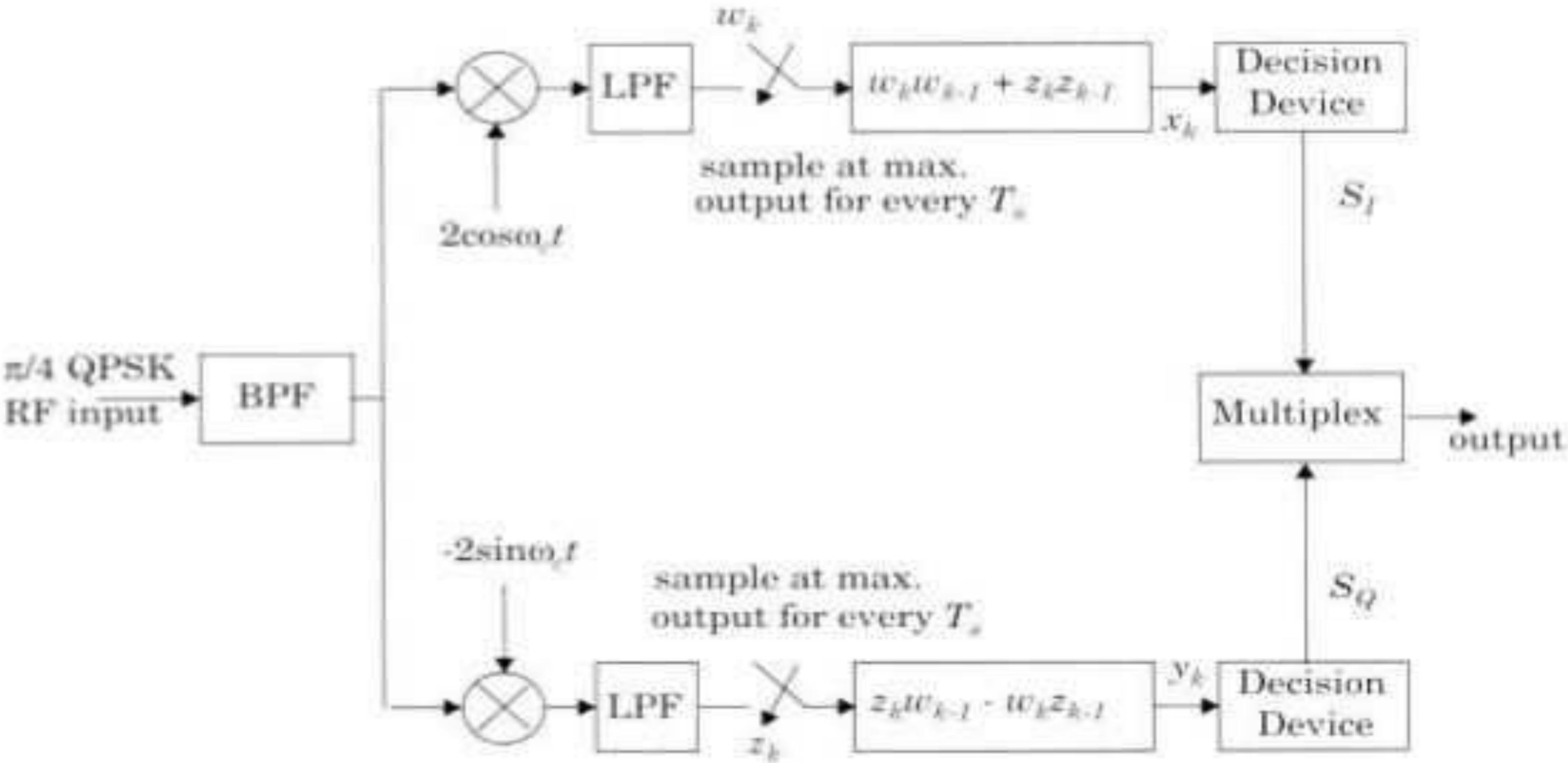


Figure 6.33 Block diagram of a baseband differential detector [from [Feh91] © IEEE].

II. IF Differential Detection

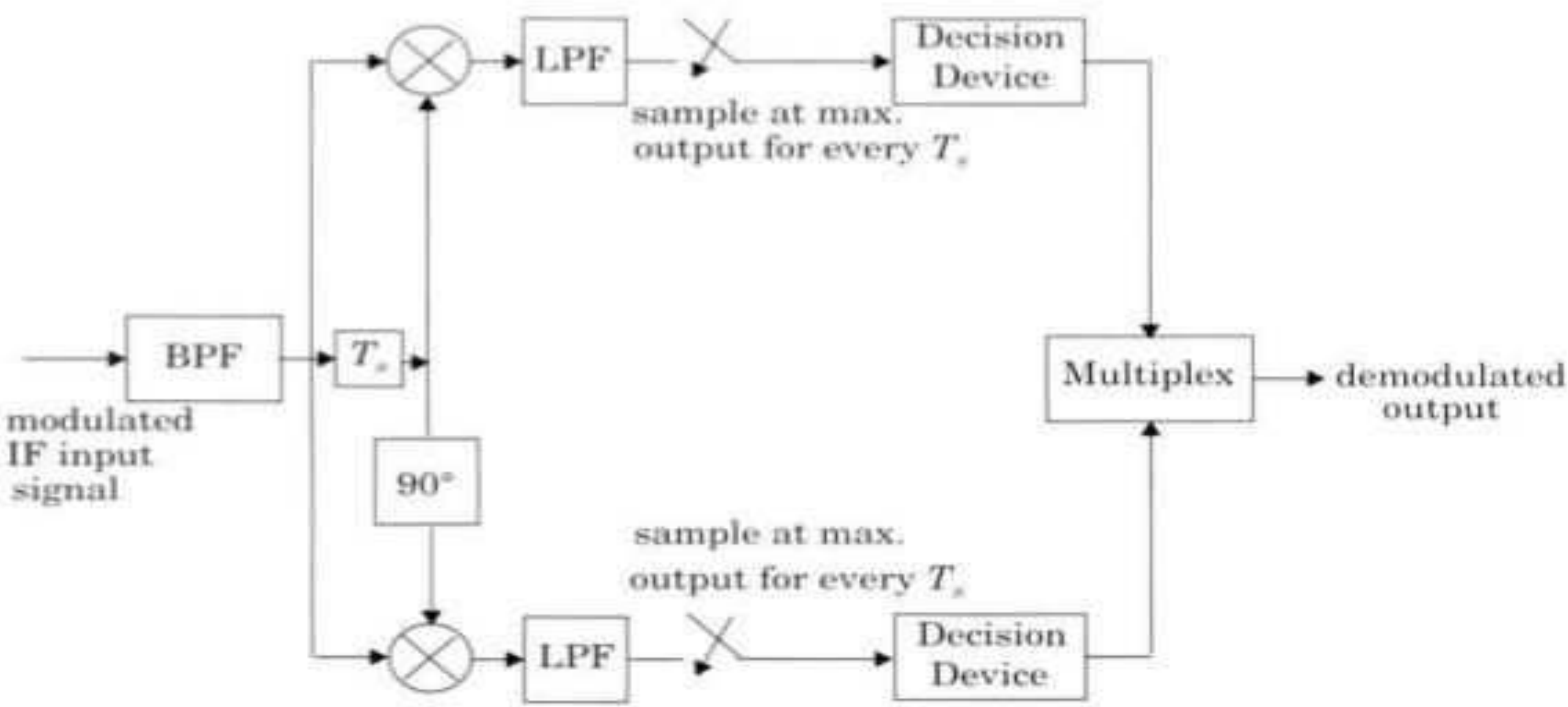


Figure 6.34 Block diagram of an IF differential detector for π/4 QPSK.

III. FM Discriminator detector

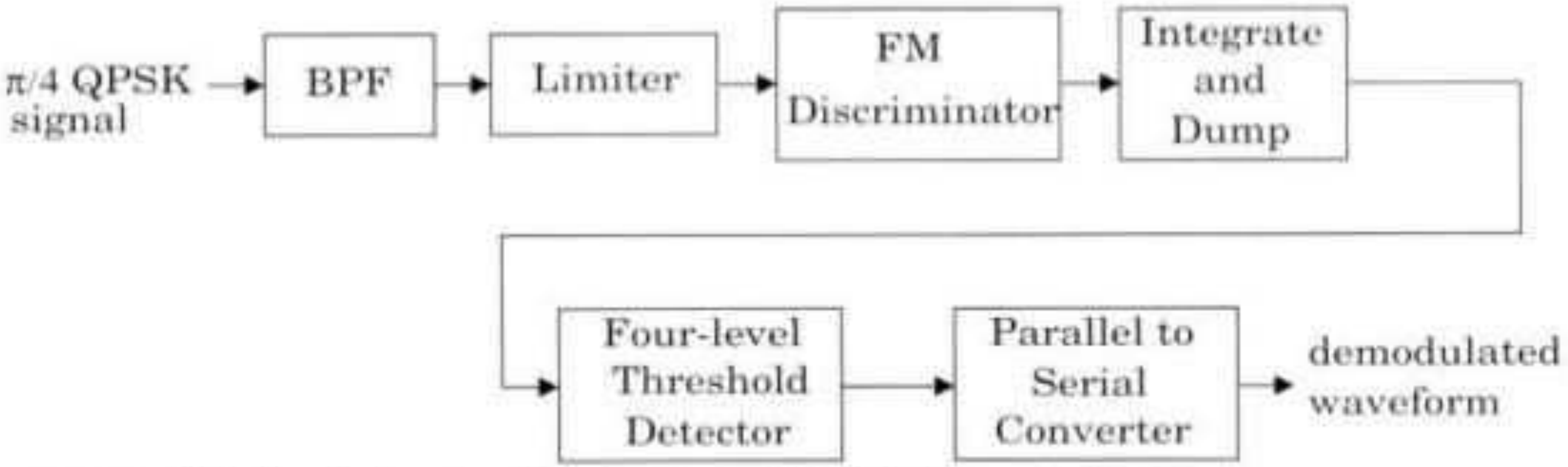


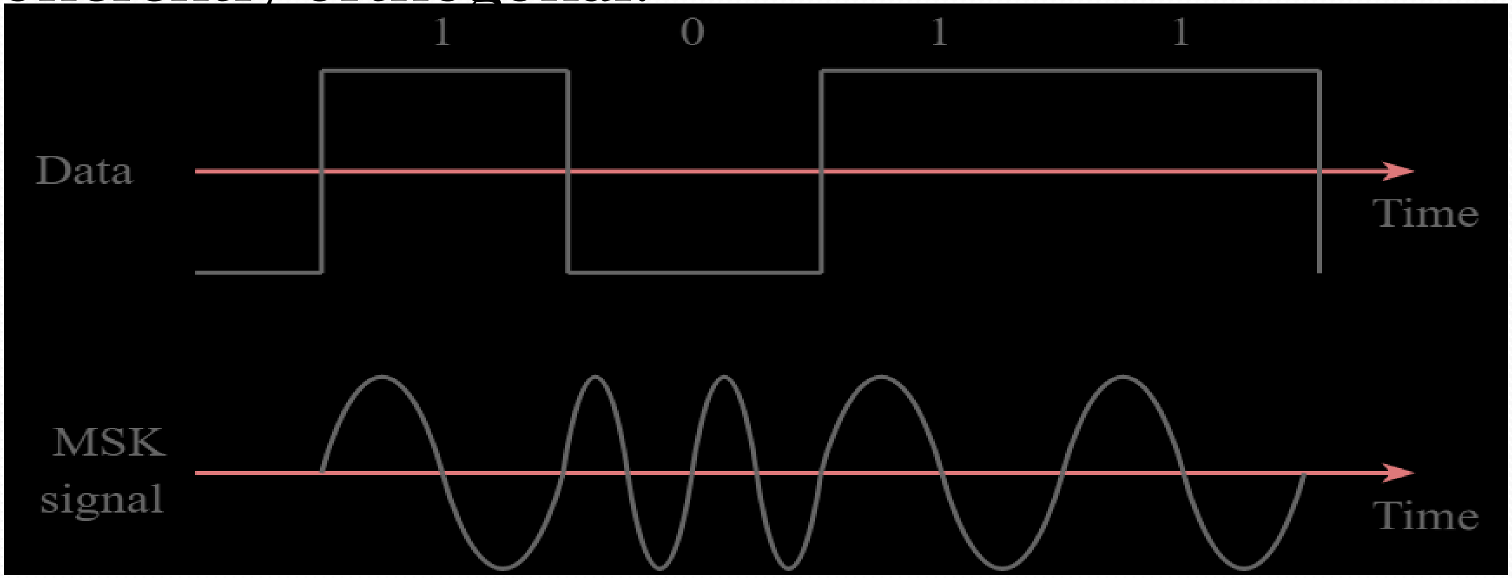
Figure 6.35 FM discriminator detector for π/4 DQPSK demodulation.

Minimum Shift Keying

- It is a special type of continuous phase frequency shift keying wherein peak frequency deviation is equal to 1/4th bit rate.
- It is spectrally efficient modulation scheme attractive for use in mobile radio communication system.
- Main properties associated with MSK includes constant envelope, spectral efficiency, good BER performance and self synchronizing capability.

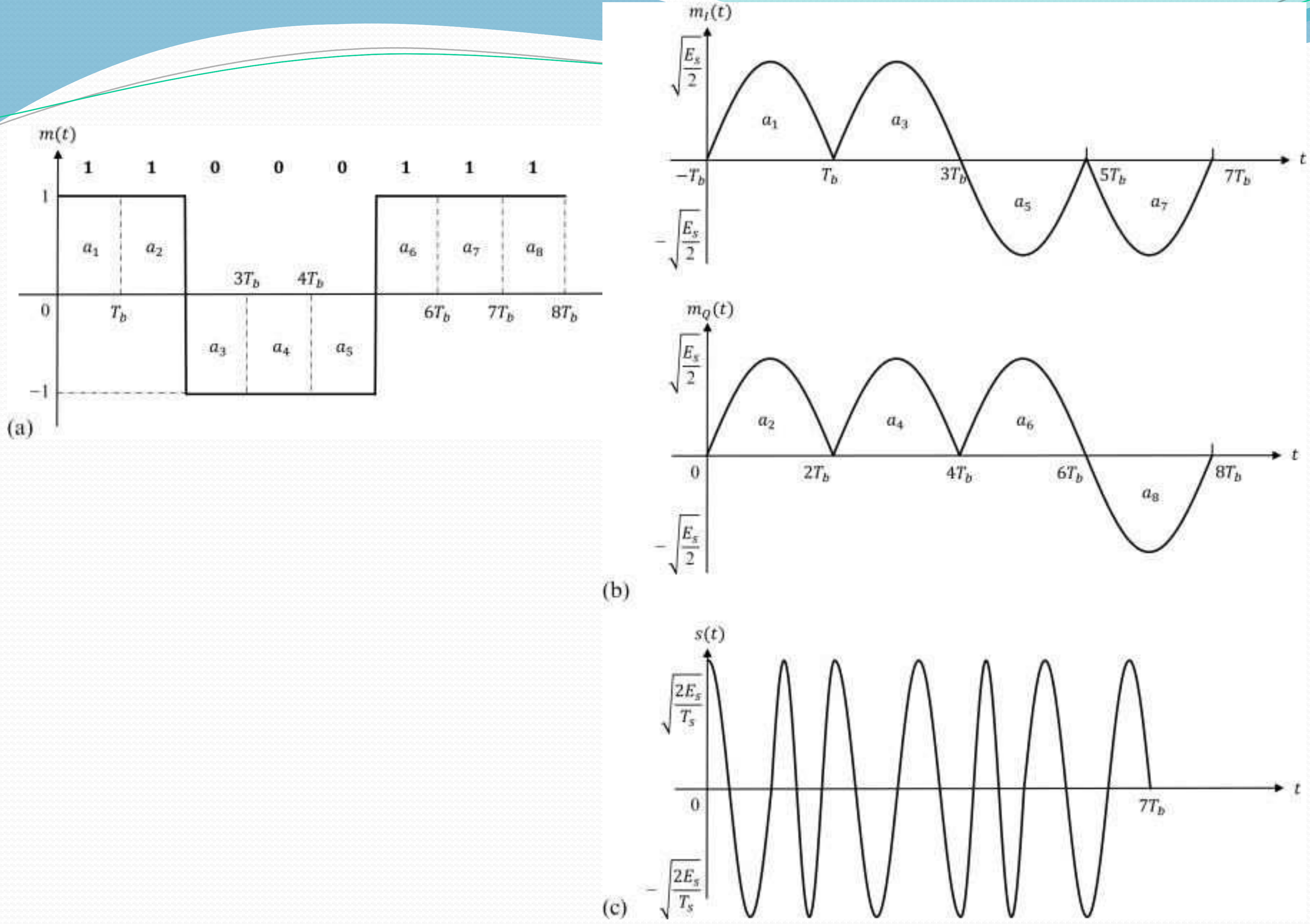
To be continued….

- Modulation index, similar to FM modulation is 0.5.
- A modulation index of 0.5 corresponds to minimum frequency spacing that allows two FSK signals to be coherently orthogonal.



To be continued….

- "MSK" implies minimum frequency separation that allows orthogonal detection.
- Orthogonality make the signal more uncorrelated so that easy to separate at the receiver end.
- MSK is also referred as fast FSK as it has half frequency separation as compared to conventional noncoherent FSK.
- It is a special form of OQPSK where baseband rectangular pulses are replaced with half sinusoidal pulses.

$m(t)$
1 1 0 0 0 1 1 1
1
0
−1
a_1 a_2 a_3 a_4 a_5 a_6 a_7 a_8
T_b $3T_b$ $4T_b$ $6T_b$ $7T_b$ $8T_b$
(a)
$m_I(t)$
$\sqrt{\frac{E_s}{2}}$
$-\sqrt{\frac{E_s}{2}}$
a_1 a_3 a_5 a_7
$-T_b$ T_b $3T_b$ $5T_b$ $7T_b$
t
$m_Q(t)$
$\sqrt{\frac{E_s}{2}}$
$-\sqrt{\frac{E_s}{2}}$
a_2 a_4 a_6 a_8
0 $2T_b$ $4T_b$ $6T_b$ $8T_b$
t
(b)
$s(t)$
$\sqrt{\frac{2E_s}{T_s}}$
$-\sqrt{\frac{2E_s}{T_s}}$
0 $7T_b$
t
(c)

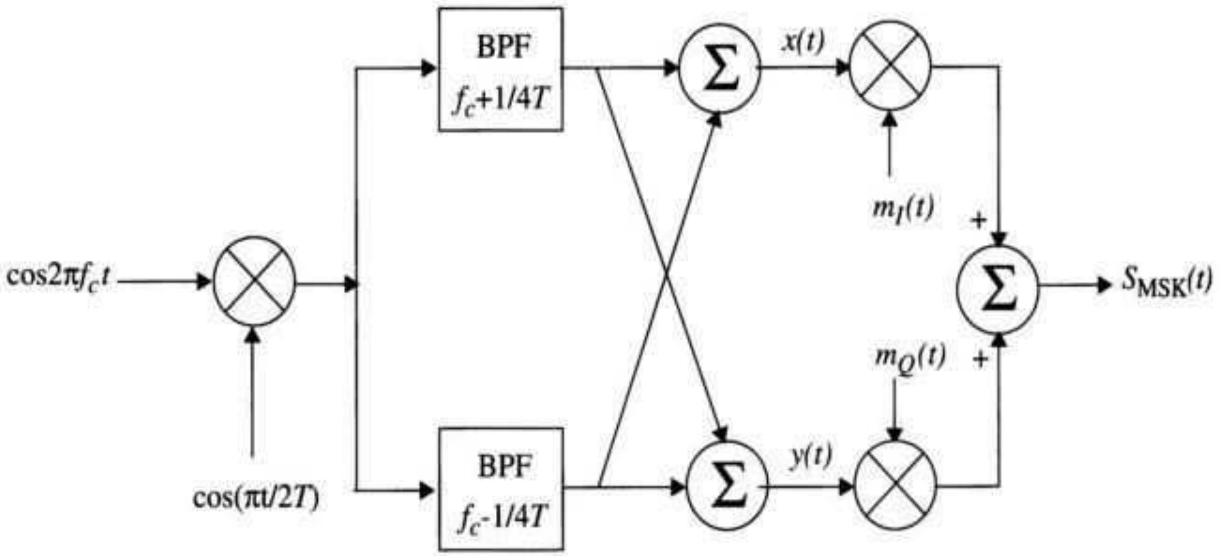


Figure 28
Block diagram of an MSK transmitter.

$$S_{MSK}(t)=m_I(t)\cos(\frac{\pi t}{2T_b})\cos(2\pi f_c t)+m_Q(t)\sin(\frac{\pi t}{2T_b})\sin(2\pi f_c t)$$

MSK Transmitter

- The carrier signal is multiplied with cos (pi*t/2T) produces two phase coherent signals at f_c + 1/4T and f_c- 1/4T.
- These two signals are separated by two narrow BPFs and appropriately combine to form in phase and quadrature phase componenets x(t) and y(t).
- These carriers are multiplied with the odd and even bit streams, upon addition produces MSK signal.

Block diagram of an MSK receiver

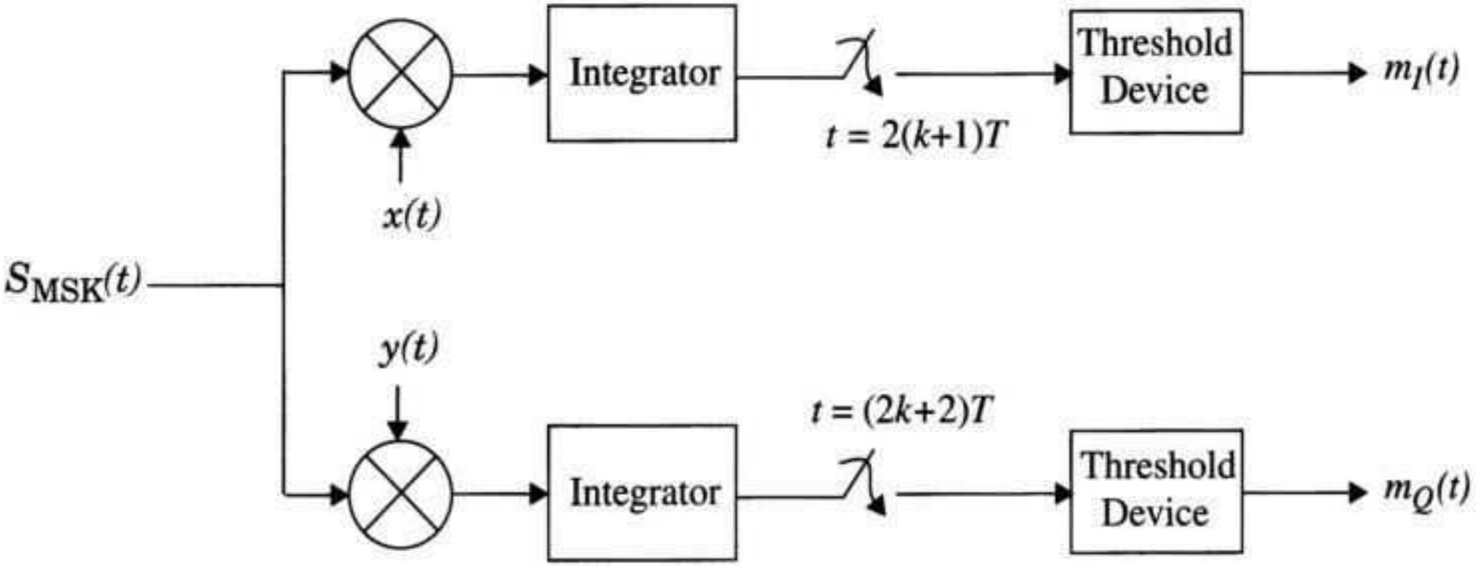


Figure 29
Block diagram of an MSK receiver.

MSK Receiver

- The received signal is multiplied by respective in phase and quadrature carrier components x(t) and y(t).
- The outputs of multiplier is integrated over two bit periods and dumped to a decision circuit at the end of each two bit periods.
- Based on the level of signals at the output of integrator, threshold detector decides whether the signal is 0 or a 1.

To be continued….

- The output data streams corresponds to $m_I(t)$ and $m_Q(t)$, which are offset combined to obtain the demodulated signal.

Gaussian Minimum Shift Keying(GMSK)

- GMSK is advanced derivative of MSK.
- It is obtained by introducing a Gaussian filter before FM modulation.
- In GMSK, sidelobe levels of the spectrum are reduced by passing the modulating NRZ data waveform through a premodulation Gaussian pulse shaping filter .
- It helps to smooth the phase trajectory of MSK signal and hence stabilizes the instantaneous frequency variations over time.

Gaussian Filter

The requirements for the filter are:

- It should have a sharp cutoff
- Narrow bandwidth
- Impulse response should show no overshoot
- Gaussian shaped response to an impulse and no ringing

Reliability of gmsk data message

The reliability of a data message produced by a GMSK system is highly dependent on the following:

- **Receiver thermal noise**: this is produced partly by the receive antenna and mostly by the radio receiver.
- **Channel fading:** this is caused by the multipath propagation nature of the radio channel
- **Band limiting:** This is mostly associated with the receiver
- **DC drifts:** may be caused by a number of factors such as temperature variations, asymmetry of the frequency response of the receiver, frequency drifts of the receiver local oscillator

Bit error rate

- GMSK bit rate offers better performance within one decibel of optimum MSK when the 3dB bandwidth bit duration product BT is equal to 0.25

- Bit error probability for GMSK is

$$P_e = Q\left\{\sqrt{\frac{2\gamma E_b}{N_o}}\right\}$$

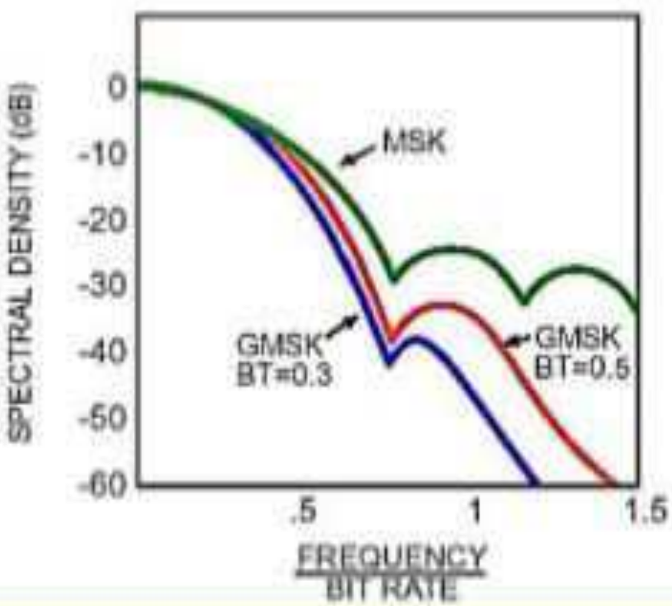
Where γ is constant related to BT.

$$\gamma = \begin{cases} 0.85 \ for\ MSK\ (BT = \infty) \\ 0.68\ for\ GMSK\ (BT = 0.25) \end{cases}$$

- **Bandwidth-time product BT.**
  - Describes the amount of the symbols overlap
  - BT = 0.3 for GSM networks
  - Good spectral efficiency

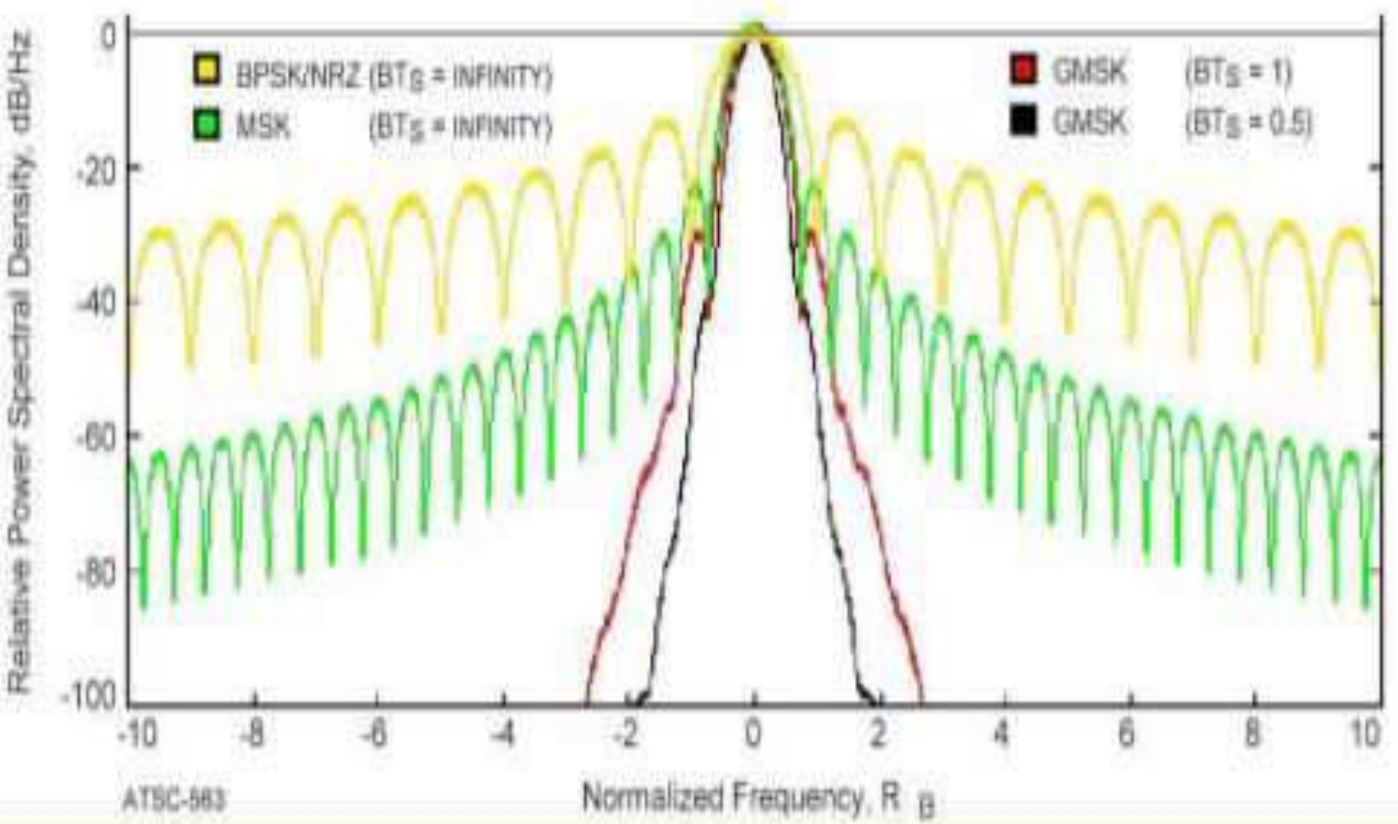
Frequency Response

- GMSKs power spectrum drops much quicker than MSK's. Furthermore, as BT is decreased, the roll-off is much quicker



Gmsk spectral shaping

- Generally achieves a bandwidth efficiency less than 0.7 b/s/Hz , QPSK can be as high as 1.6 b/s/Hz



GMSK transmitter using direct FM generation

- The impulse response of the GMSK premodulation filter

$$h_G(t)=\frac{\sqrt{\pi}}{\alpha}\exp\left(-\frac{\pi^2}{\alpha^2}t^2\right),\quad \alpha=\frac{\sqrt{2\ln 2}}{B}$$

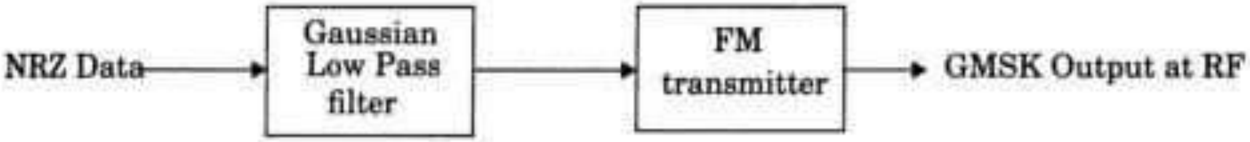


Figure 30
Block diagram of a GMSK transmitter using direct FM generation.

Block Diagram of a GMSK receiver

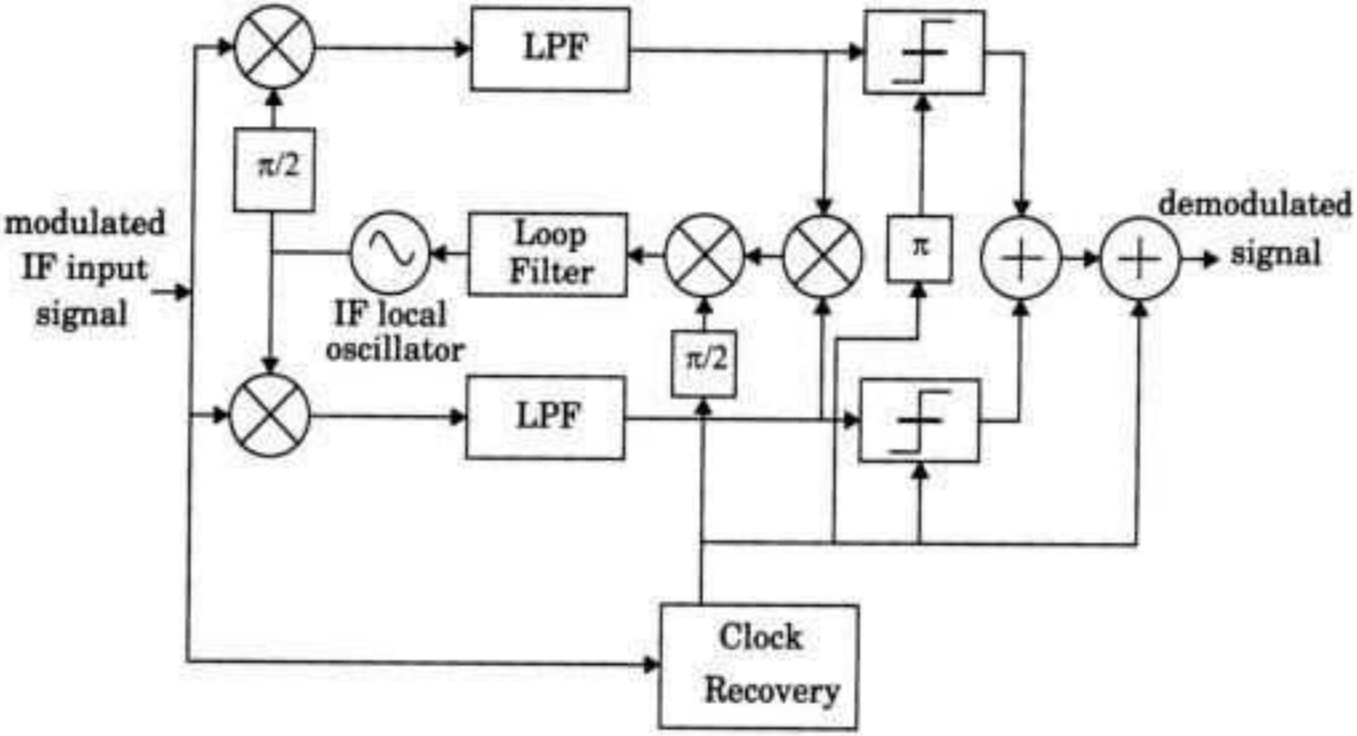


Figure 31
Block diagram of a GMSK receiver.

Advantages

- High spectral efficiency
- Reducing sideband power
- Excellent power efficiency due to constant envelope
- Good choice for voice modulation
- ISI is tolerable
- GMSK is highly useful in wireless communication
- Good BER performance
- Self synchronizing capability

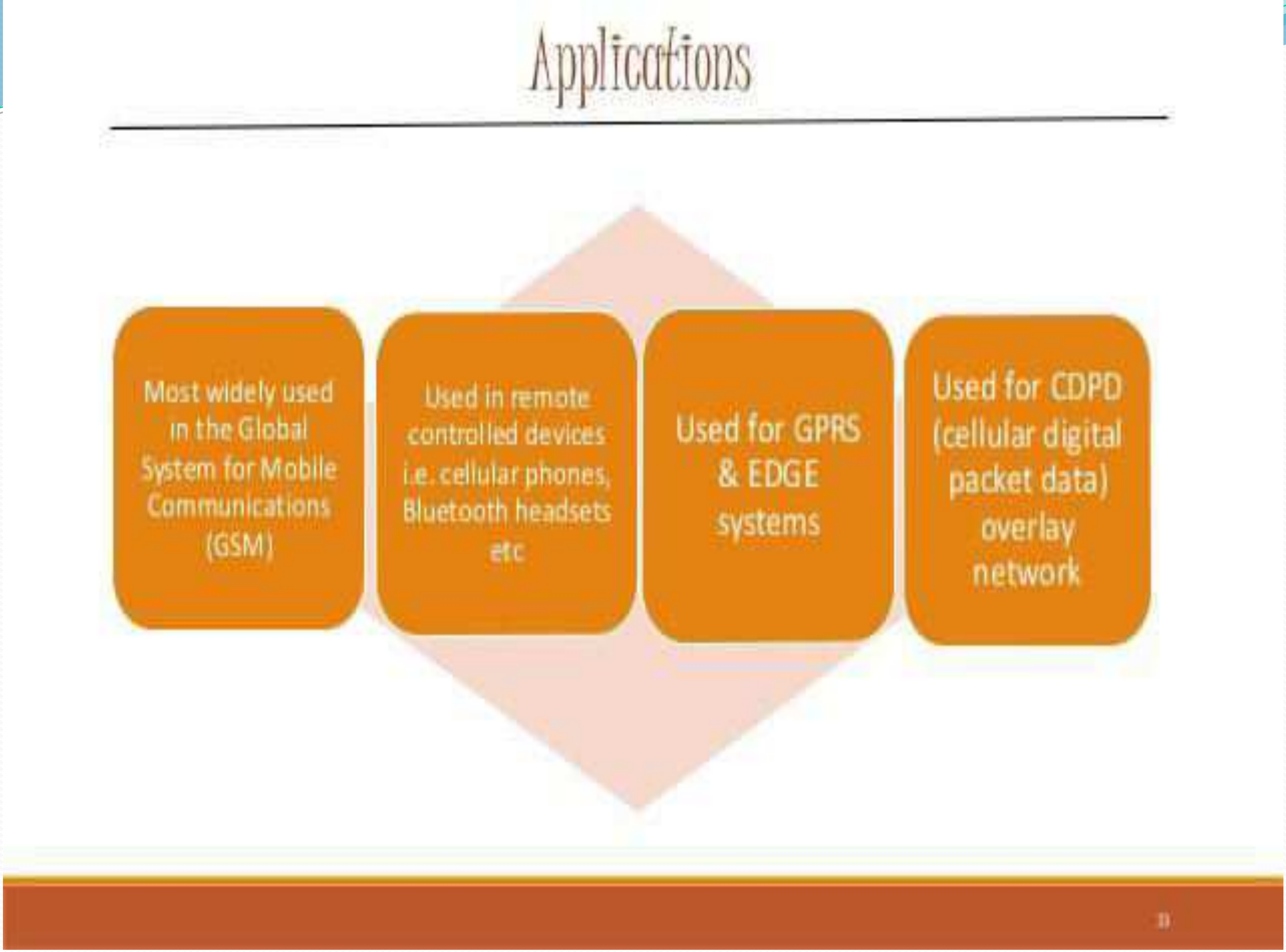
disadvantages

- Higher power level than QPSK
- Requiring more complex channel equalization algorithms such as an adaptive equalizer at the receiver
- Probability of error is higher then MSK.

$$p_e \leq (M-1)Q\left(\sqrt{\frac{E_b \log_2 M}{N_o}}\right)$$

Where;

Q → Q-function
Eb → energy of bit
No → Noise



Applications

Most widely used in the Global System for Mobile Communications (GSM)

Used in remote controlled devices i.e. cellular phones, Bluetooth headsets etc

Used for GPRS & EDGE systems

Used for CDPD (cellular digital packet data) overlay network

conclusion

GMSK spectrally efficient modulation method for wireless data transmission system.

GMSK modulation technique is implemented in GSM and CDPD methods.

Improved spectral efficiency.

Reduced main lobe over MSK

Requires more power to transmit data than many comparable modulation schemes.

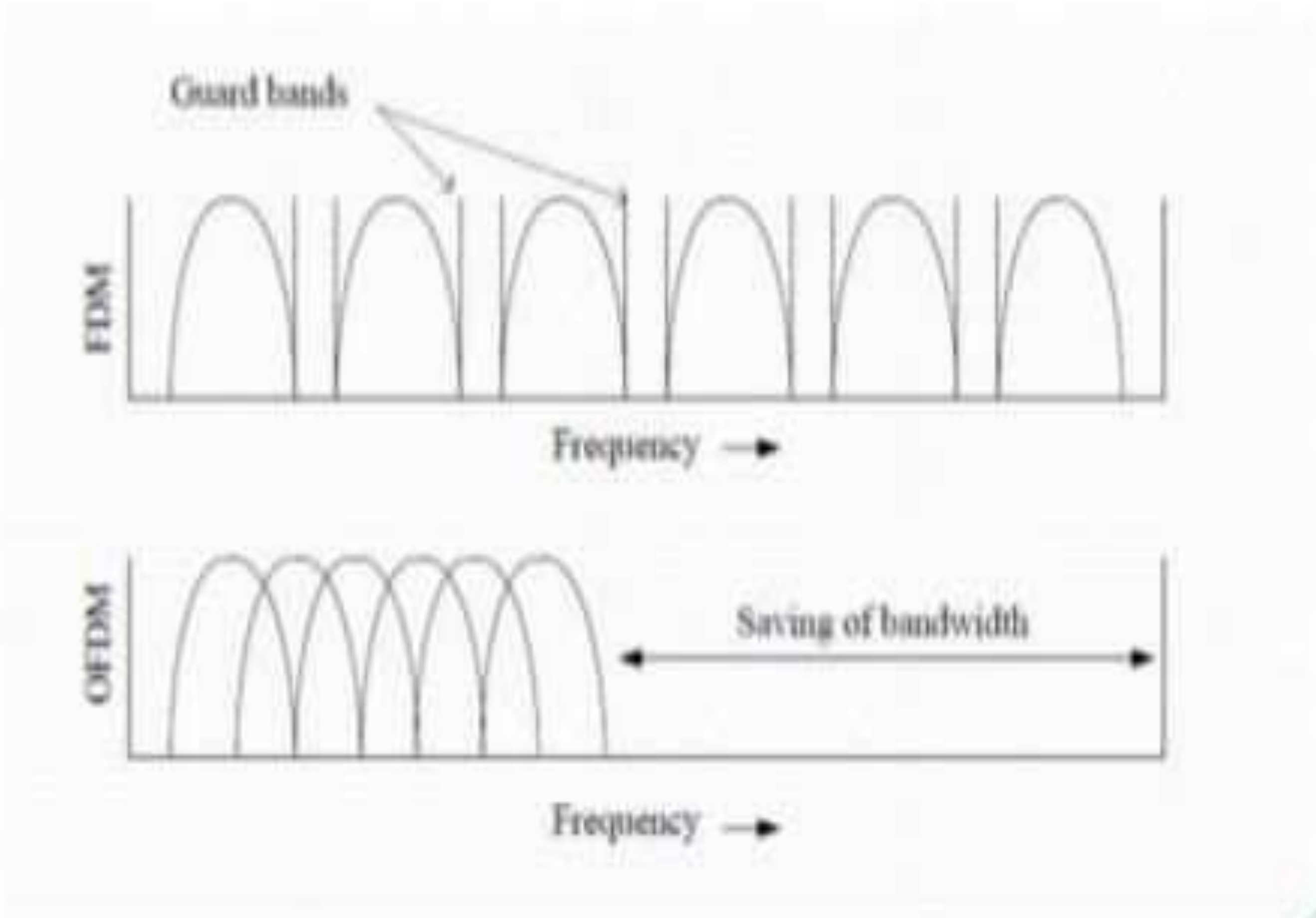
ORTHOGONAL FREQUENCY DIVISION MULTIPLEXING

(OFDM)

INTRODUCTION

- **Orthogonal frequency-division multiplexing** (**OFDM**) is a frequency-division multiplexing (FDM) scheme used as a digital multi-carrier modulation method.
- A large number of closely-spaced orthogonal sub-carriers are used to carry data.
- The data is divided into several parallel data streams or channels, one for each sub-carrier.
- Each sub-carrier is modulated with a conventional modulation scheme (such as QAM or PSK) at a low symbol rate, maintaining total data rates similar to conventional *single-carrier* modulation schemes in the same bandwidth.
- OFDM has developed into a popular scheme used in applications such as digital video and audio broadcasting, wireless networking and WiMAX.

FDM vs OFDM


Guard bands
FDM
Frequency →
OFDM
Saving of bandwidth
Frequency →

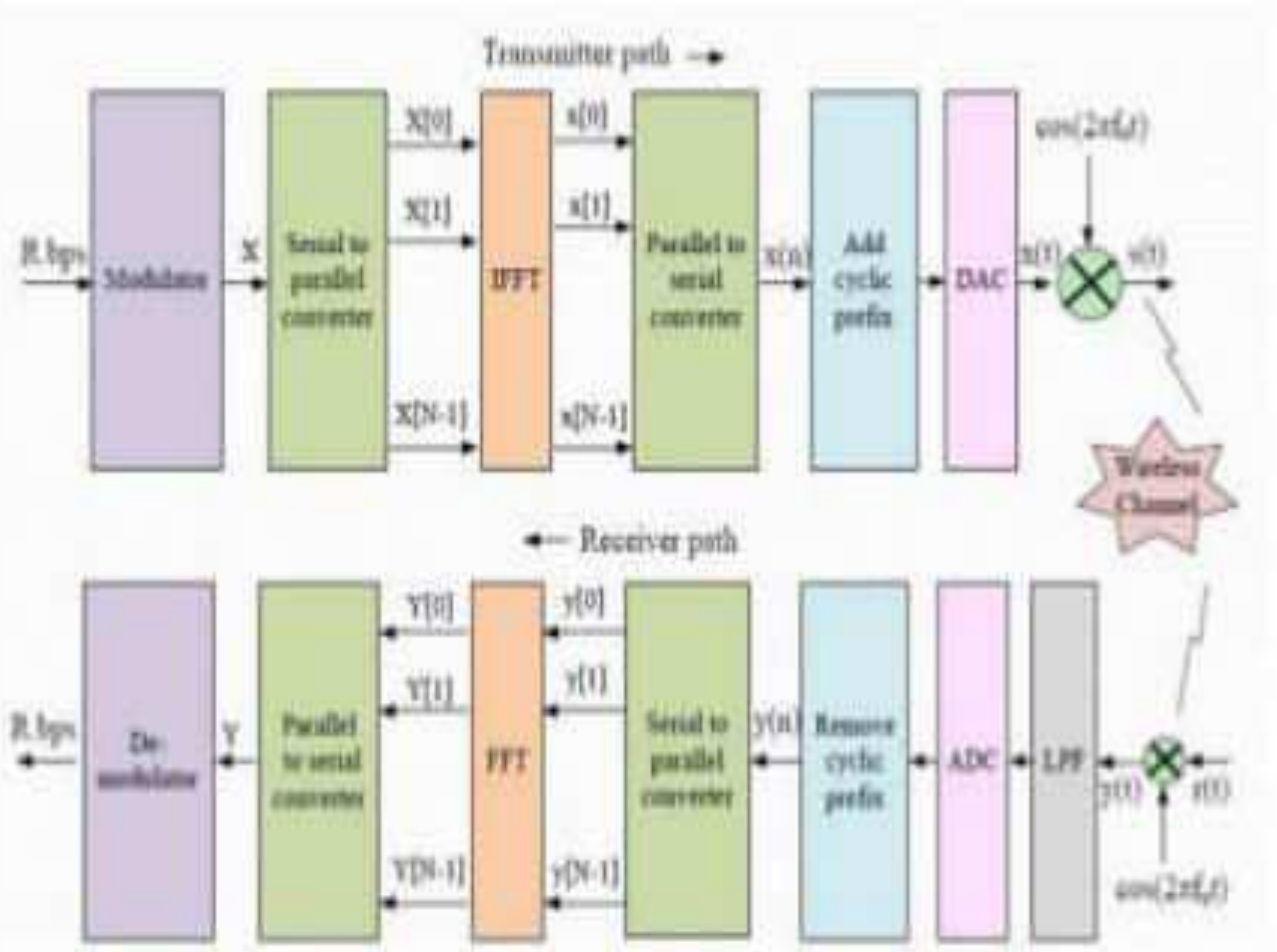
WHY OFDM?

- Can easily adapt to severe channel conditions without complex time-domain equalization.
- Robust against narrow-band co-channel interference.
- Robust against inter-symbol interference (ISI) and fading caused by multipath propagation.
- High spectral efficiency as compared to conventional modulation schemes, spread spectrum, etc.
- Efficient implementation using Fast Fourier Transform (FFT).
- Low sensitivity to time synchronization errors.

Principle of OFDM

- ❑ Data to be transmitted is spreaded over a large number of carriers.
- ❑ Each carrier modulated at a low rate.
- ❑ Carriers are orthogonal to each other.
- ❑ Divides the total available bandwidth in the spectrum into sub-bands for multiple carriers to transmit in parallel.
- ❑ Combines a large number of low data rate carriers to construct a composite high data rate communication system.

Basic OFDM system



Features of OFDM

- Symbols are modulated onto orthogonal sub-carriers.
- Modulation is done by using IFFT.
- Orthogonality is maintained during channel transmission by adding a cyclic prefix to the OFDM frame.
- Synchronization: Cyclic prefix can be used to detect the start of each frame.
- Demodulation of the received signal by using FFT.
- Channel equalization: By using a training sequence or sending pilot symbols at predefined sub-carriers.
- Decoding and de-interleaving.

ISSUES WITH OFDM

- ☐ Inter-carrier Interference between the subcarriers.
- ☐ High Peak to average power ratio (PAPR).
- ☐ Sensitivity to Doppler Effect.
- ☐ Distortion problem due to Large peak-to-mean power ratio.
- ☐ Very sensitive to frequency errors.
- ☐ Sensitive to carrier frequency offsets.

Inter-carrier Interference

❑ Factors Inducing ICI:

- Doppler Effect
- Synchronization Error
- Multipath Fading

❑ Solutions for ICI:

- CFO Estimation
- Windowing
- Inter-carrier Interference Self-cancellation

CFO Estimation

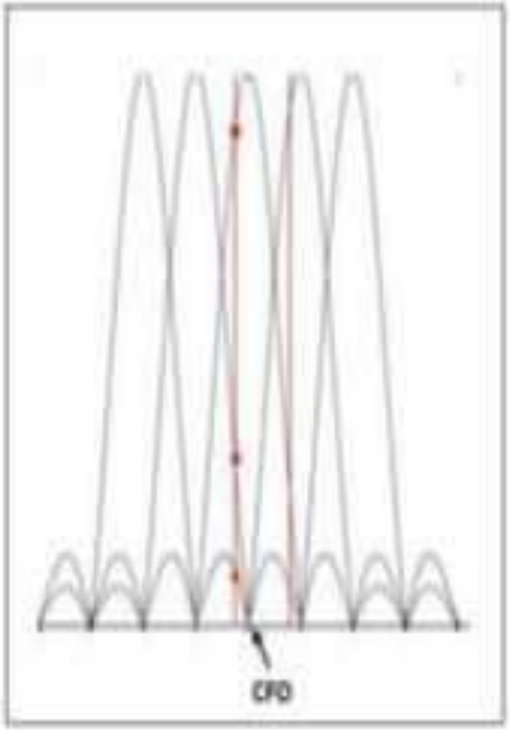
☐ Firstly CFO must be estimated.

☐ Then a perfect equalizer then can be designed to eliminate ICI.

☐ Signal processing methods are applied.

☐ Liu's & Tureli's MUSIC-based and ESPRIT-based algorithms estimate CFO.

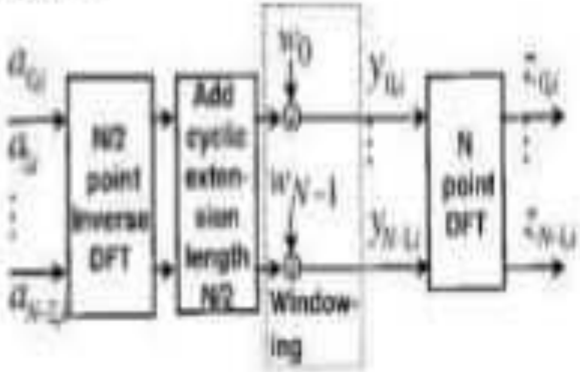
☐ Other CFO estimation methods involve with training sequences.



Relationship of CFO and ICI

WINDOWING

- Receiver remains the same as the principal OFDM receiver.
- Multiplication operation in the frequency domain is equivalent to the circular convolution in the time domain.
- Many kinds of windowing schemes:
  - Hanning window
  - Nyquist window
  - Kaiser window
- MMSE Nyquist window is used to mitigate the white noise.



Windowing in the transmitter

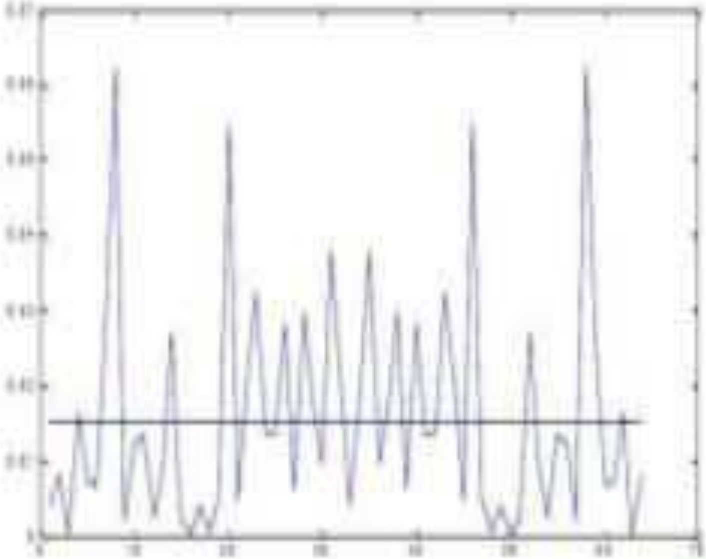
PAPR Problem

- Input symbol stream of the IFFT should possess a uniform power spectrum.
- Output of the IFFT may result in a non-uniform or spiky power spectrum.
- Transmission energy would be allocated for a few instead of the majority subcarriers.
- Mathematically PAPR is given as:

$$PAPR = \frac{Max\{|X_i|^2\}}{E\{|X_i|^2\}},$$

PAPR Reduction Techniques

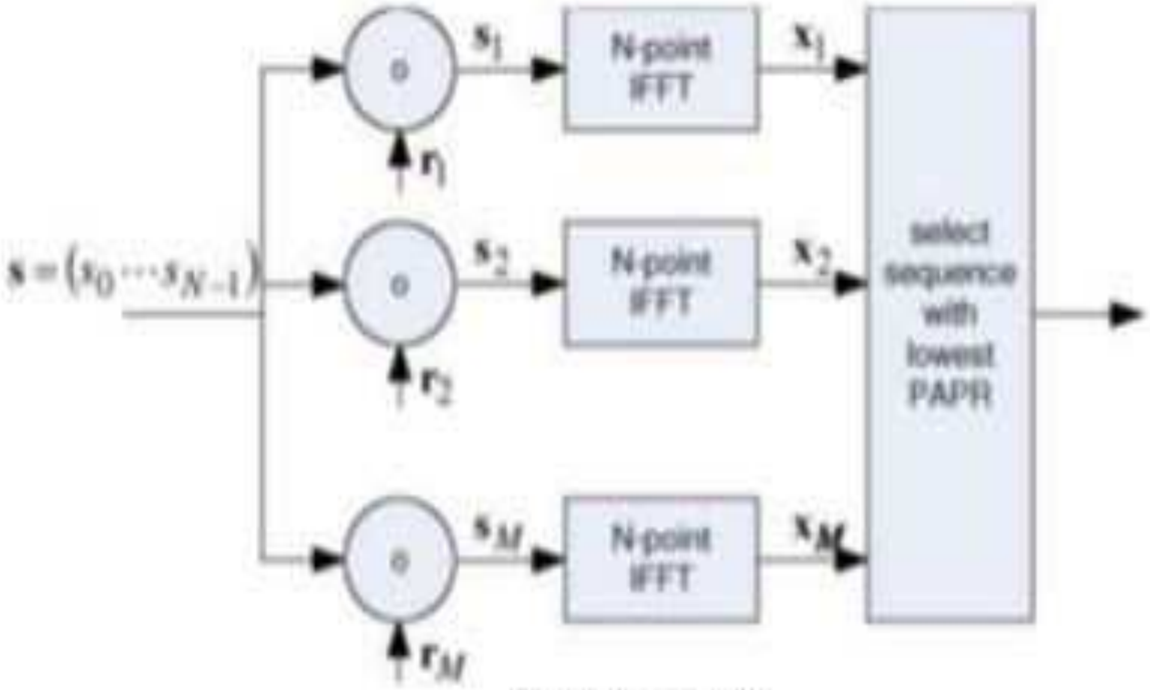
- ❑ Clipping and Filtering
- ❑ Selected Mapping (SLM)
- ❑ Partial Transmit Sequence (PTS)
- ❑ Tone Reservation
- ❑ Active Set Extension
- ❑ Tone Injection
- ❑ Coding And Companding Approaches



A PAPR example

Selective mapping approach

- Transmitted symbols multiplied by predetermined sequence.
- Obtained signal converted into OFDM signals by inverse FFTs.
- Signal with a minimum PAPR transmitted.



SLM approach

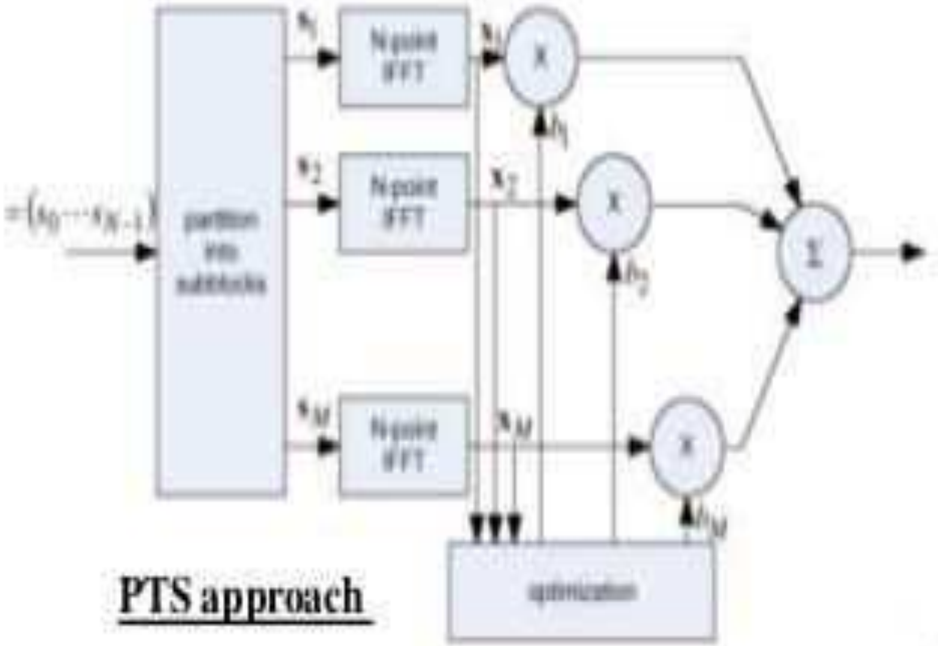
CONTD.

- Predetermined sequences are known to the transmitter and the receiver.
- Only the index of the predetermined sequence sent to the receiver for each OFDM signal.
- A modified SLM scheme is also proposed to reduce the complexity of the original SLM scheme.

Partial transmit sequence approach

❑ Transmitted symbols for an OFDM block partitioned into M disjoint sub-blocks.

❑ PTS approach finds $b_m \in \{-1, 1\}$ such that the PAPR for $n = 0, \ldots, N-1$ is minimized.



PTS approach

CONTD.

❑ Similar to the SLM approach.

❑ Sequence to optimize the PAPR needs to be sent to the receiver for the receiver to detect the transmitted symbols.

❑ At the cost of a minor performance degradation the computational complexity of the PTS is reduced.

ADVANTAGES OF OFDM

☐ Multipath delay spread tolerance

☐ Immunity to frequency selective fading channels

☐ Efficient modulation and demodulation

☐ High transmission bitrates

☐ Flexibility

☐ Easy equalization

☐ High spectral efficiency

☐ Resiliency to RF interference

☐ Lower multi-path distortion

DISADVANTAGES OF OFDM

- Peak to average power ratio (PAPR) is high.
- Inter-carrier Interference (ICI) between the subcarriers.
- Very sensitive to frequency errors.
- High power transmitter amplifiers need linearization.
- Sensitive to carrier frequency offsets.
- More complex than single-carrier Modulation.
- High synchronism accuracy.
- Distortion problem due to Large peak-to-mean power ratio.

APPLICATIONS OF OFDM

- Digital Audio Broadcasting (DAB)
- Digital Video Broadcasting (DVB)
- HDTV
- Wireless LAN Networks
- HIPERLAN/2
- IEEE 802.16 Broadband Wireless Access System (WiMAX)
- Wireless ATM transmission system
- Evolved UMTS Terrestrial Radio Access

UNIT V

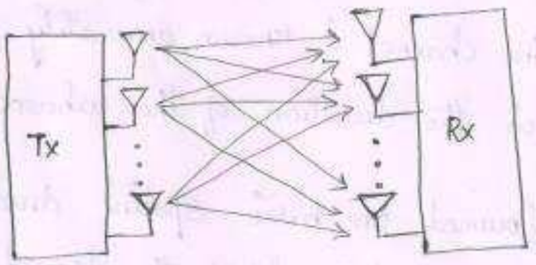
Multiple Antenna Techniques

MIMO Systems :-

- Multiple input multiple output or MIMO is a radio communication technalogy or RF technology that is being mentioned and used in many new technalogies these days.

- The wireless MIMO channel is assumed to consist of a system with multiple transmit antennas and multiple receive antennas which are connected by means of fading channels

MIMO Model



- The antennas are placed in order to ensure that the channels across antennas are independent.

- placement Separation in units of $\lambda/2$ is one means to ensure independences. Conventionally for a MIMO system with M transmit antennas is N receive antennas the number of channels counting each link from a transmitter to a receiver separately is MN much like in conventional Wireless Communication.

- These channels must be known at least the receiver or transmitter or both in order to communicate information successfully during the coherence interval.

- This is done by means of estimation of the channel coefficients using an appropriate techniques

- An M transmitter N receiver MIMO System represented as an NxM matrix denoted by H.

- A flat fading model for simplicity of analysis since transform techniques such as OFDM Can be used to convert frequency selective channels into flat fading Ones.

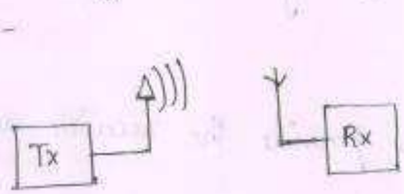
- Assume that the channel is known accurately to the receiver & does not change in the duration of this coherence interval.

- MIMO system foursed on basic spatial diversity here the MIMO System was used to limit the degradation Caused by multipath Propagation.

- The first step as system then started to utilise the multipath propagation to advantage turning the additional signal paths into what might effectively be considered as additional channels to carry additional data.

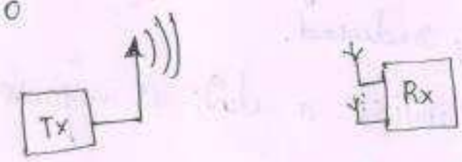
Multi antenna types

SISO:-



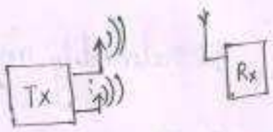
Single i/p single o/p means that the transmitter and receiver of the radio system have only One antenna.

SIMO



Single input multiple output means that the receiver has multiple antennas while the transmitter has One antenna.

MISO



Multiple input single output means that the transmitter has multiple antennas while the receiver has One antenna.

MIMO

Multiple i/p multiple o/p means that the both the transmitter & receiver have multiple antennas.

- The channel may be affected by fading & this will impact the signal to noise ratio.

- The principle of diversity is to provide the receiver with multiple version of the same signal.

- If these can be made to be affected in different ways by the signal path, the probability that they will be affected at the same time is considerably reduced.

- The diversity helps to stabilise a link & improve proformance reducing error rate.

- Multiple data streams transmitted in a single channel at the same time

- Multiple radios collect multipath signals

- Delivers simultaneous speed, covererage, & reliability improvements

Several different diversity modes are available & provide a number of

Time diversity :-

Using time diversity a message may be transmitted at different times e.g. Using different time slots & channel coding

FREQUENCY Diversity -

This form of diversity uses different frequencies. It may be in the form of using different channels or technologies Suchas spread Spectrum/OFDM

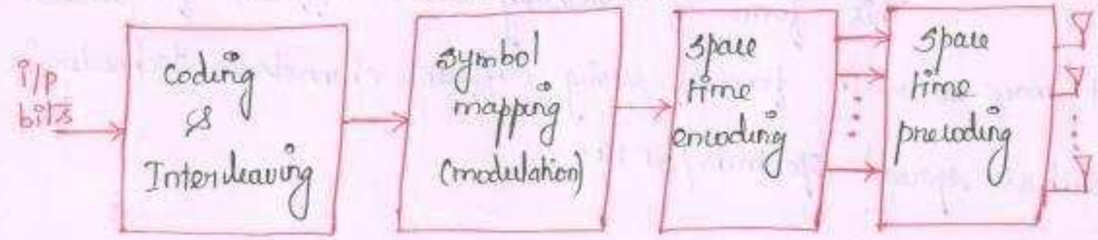
Space diversity :

Space diversity used in the broadest sense of the definition is used as the basis for MIMO. It uses antennas located in different postions to take advantage of the different radio paths that exist in a typical terrestrial envronment.

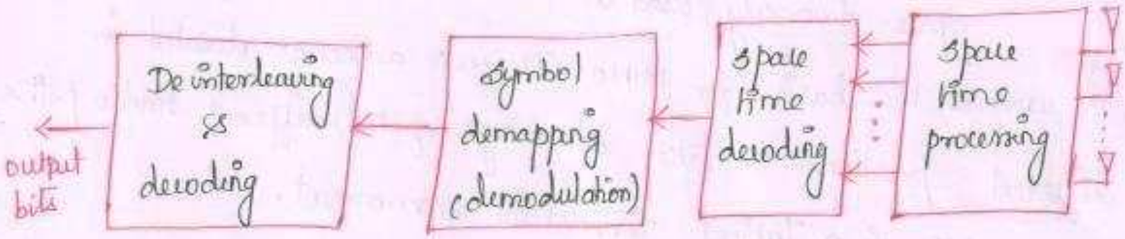
- MIMO uses multiple antennas On both the Transmitter and receiver. They have dual capability of Combining the SIMO & MISO technologies.
- They can also ↑ Capacity by using spatial Multiplexing.
- The MIMO method has some clear advantages over SISO methods
- The fading is greatly eliminated by spatial diversity low power is required compared to other techniques in MIMO.
- The number of antenna element ↑ the channel Capacity is ↑
- The improving of MIMO from MISO channel Capacity as antenna ↑.

Building Blocks of MIMO

Transmitter



Receiver



- The space dimensions to improve wireless systems capacity range & reliability

- It offers significant ↑ in data throughput & link range without additional bandwidth or increased transmit power.

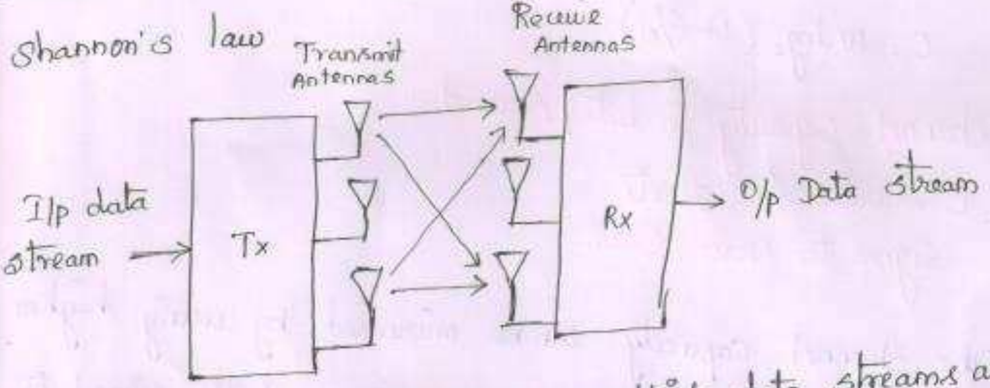
- MIMO achieves this goal by spreading the same total transmit power over the antenna to achieve an array gain that improves the spectral efficiency or to achieve a diversity gain that improves the link reliability.

Spatial Multiplexing

One of the key advantages of MIMO Spatial multiplexing is the fact that it is able to provide additional data capacity.

- MIMO spatial multiplexing achieves this by utilising the multiple paths is effectively using them as additional channels to carry data.

- The maximum amount of data that can be carried by a radio channel is limited by the physical boundaries defined order Shannon's law



- The spatial multiplexing, multiple data streams are transmitted at the same time.

- They are transmitted On the same Channel but by different antenna. They are recombined at the receiver using MIMO signal Processing.

Shannon's law :-

- The amount of data that can be passed along a specific channel in the presence of noise.

- The law that governs that is called shannon's law named after the formulated it.

Shannon's law defines the maximum rate at which error free data can be transmitted over a given bandwidth in the presence of noise. It is usually expressed in the form

$$C = W \log_2 (1 + S/N)$$

C - channel capacity in bits/second
W - Bandwidth in Hertz
S/N - Signal to Noise Ratio

- The channel capacity can be increased by using higher Order modulation scheme but these require a better signal to noise ratio then the lower Order modulation schemes. but these require a better signal to noise ratio then the lower order modulation schemes

- Thus a balance exists b/w the data rate & the allowable error rate signal to noise ratio & power that can be transmitted .

- spatial Multiplexing is a transmission technique in MIMO spatial multiplexing is a wireless communication to transmit independent & separately encoded data signals so called streams for each of the multiple transmit antennas.

- If the transmitter is equipped with N_t antennas & the receiver has N_R antennas the maximum spatial multiplexing Order is $N_S = MIN(N_T, N_r)$

N_s - streams can be transmitted in parallel, ideally leading to an N_s ↑ of the spectral efficiency.

- The multiplexing gain can be limited by spatial correlation which means some of the parallel stream may have very weak channel gains.

BEAM FORMING:-

- Antenna technologies are the key in increasing network capacity. It started with sectorized antennas.

- These antenna illuminate 60° or 120° operate as one cell.

- Adaptive antenna arrays intensify spatial multiplexing

- Smart antennas belong to adaptive antenna arrays but differ in their smart direction of arrival estimation

- Smart antennas can form a user specific beam. optional feed back can reduce complexity of the array system

Beam forming is the method used to create the radiation pattern of an antenna array. It Can be applied in all antenna array systems as well as MIMO systems.

Smart antennas are divided into 2 groups.

* phased array system
* Adaptive array system with an infinite number of patterns adjusted to the Scenario in real time

Switched Beam former

Adaptive Beam former

- Switched beam formers eletrically calulate the DOA'S Switch on the fixed beam. The user only has the optimum signal strength along the center of the beam.

- The adaptive beam former deals with that problem'S adjusts the beam in realtime to the moving UE. The complexity & the cost of such a system is higher than It first Type

Pre coding

- It is a generalization of beam forming to support multilayer transmission in multi antenna wireless communications.

- In conventional single layer beam forming the same signal is emitted from each of the transmit antennas with appropriate weighting such that the single power is maximized at the receiver o/p.

Pre coding can be separated by two classifications

- precoding for single user MIMO
- precoding for Multi user MIMO

Pre coding for single user MIMO

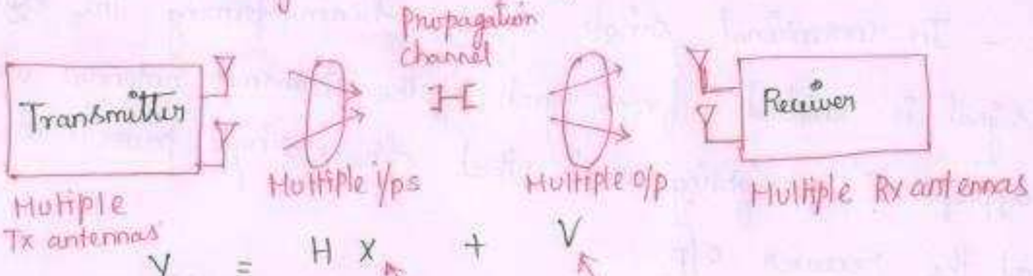
- In single user MIMO systems a transmitter equipped with multiple antennas communicate with a receiver that has multiple antennas.

- Most classic precoding assume narrowband, slowly fading channels meaning that the channel for a certain period of time can be described by a single channel matrix which does not change faster.

- The precoding strategy that maximize the through put called channel capacity depends on the channel state information available in

- Single user MIMO communication systems exploit multiple transmit and receive antennas to improve capacity, reliability & resistance to interference.

Single User MIMO system



$$\underset{\text{Receiver vetor}}{Y} = \underset{\text{Matrix channel}}{H}\ \underset{\text{Transmit vector}}{X} + \underset{\text{noise vector}}{V}$$

Pre coding for Multi User MIMO

- In multi User MIMO a multi antenna transmitter Communicates Simultaneously with multiple receivers. This is known as Space division multiple access.

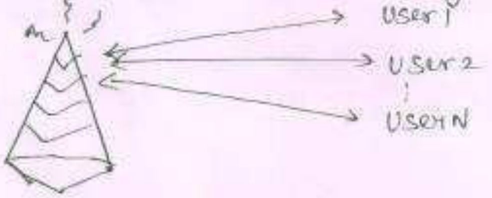
- precoding algorithm for SDMA System can be sub-divided into linear & non linear pre coding types.

- The capacity achieving algorithms are nonlinear but linear pre coding approaches usually achieve resonable performance with much lower Complexity.

- Linear precoding strategies include MMSE pre coding & the Simplified zero forcing precoding.

- There are also precoding strategies tailored for low-rate feedback of channel state information for ex random beam forming.

- Non linear precoding is designed based on the cocept of dirty paper coding which shows that any known interference at the transmitter can be subtraited without the penalty of radio resources if the optimal pre coding scheme can be applied on the trammit signal.



Diversity coding :-

- It is used when there is no channel knowledge at the transmitter.

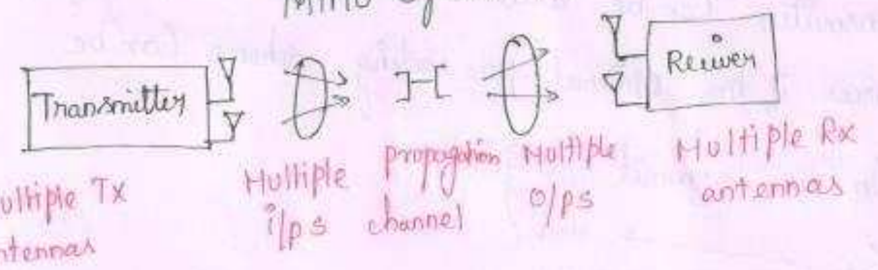
- In diversity methods a single stream is transmitted but the signal is coded using techniques called space time coding.

- The signal is emitted from each of the transmit antennas with full or near orthogonal coding.

CHANNEL MODEL (SYSTEM MODEL)

- The transmitter & receiver are equipped with multiple antenna elements.
- The transmit stream go through a matrix channel which consists of multiple receive antennas at the receiver.
- Then the receiver gets the received signal vector by the multiple receive antennas & decodes the received signal vectors into the Original information.

MIMO System Model



$$\underset{\text{Receive vector}}{r} = \underset{\text{matrix channel}}{H} . \underset{\text{transmit vector}}{s} + n \leftarrow \text{Noise vector}$$

- r is the Mx1 received signal vector as there are M antennas in receiver
- H represented channel Matrix
- S is the Nx1 Transmitted Signal Vector as there are N antennas in Transmitter
- n is an Mx1 Vector of additive noise term

Let Q denote the covariance matrix of x then the capacity of the system described by information ⑧

$$C = \log_2 \left[\det \left(I_M + HQH^* \right) \right] \; b/s/Hz$$

- This is optimal when is known at the transmitter & the information is the Gaussian i/p distribution maximizing the mutual information is the Gaussian distribution

- channel feedback may be known at the transmitter & the optimal is not proportional to the identity matrix but is constructed from a water filling argument.

- The effect of $Q = (P/N)$. Q based on perfect channel estimation & feedback then we can evaluate a maximum capacity gain due to feedback.

- The effect of H matrix has wide range of channel models including for ex. correlated fading & specular components,

$$C_{EP} = \sum_{L=1}^{M} \log_2 \left(1 + \frac{P}{N} \lambda_i \right) \; b/s/Hz$$

where $\lambda_1, \lambda_2 \ldots \lambda$ the non zero eigen values of W

$m = \min(M, N)$

$$W = \begin{cases} HH^*, & M \leq N \\ H^*H, & N \leq M \end{cases}$$

The singular Value Decomposition given by

$$H = UDV^*$$

U & V are unitary

$$D = \mathrm{diag}(\sqrt{\lambda_1}, \sqrt{\lambda_2}, \sqrt{\lambda_3}, \dots \sqrt{\lambda_m}, 0, \dots 0)$$

The MIMO signal model

$$\hat{r} = D\tilde{s} + \tilde{n}$$

where $\tilde{r} = u+r$, $\tilde{s} = V*s$ & $\tilde{n} = U*n$

When the channel is known at the transmitter then H is known at above eqn

Capacity over Q subject to the power constraint $tr(Q) \leq P$

The optimal Q in this case is well known & is called a water filling solutions.

Capacity

$$C_{wp} = \sum_{i=1}^{M} \log_2(\mu\lambda_i)^* \text{ b/s/Hz}$$

where μ is chosen to satisfy

$$P = \sum_{i=1}^{M} (\mu - \lambda_i^{-1})^*$$

MIMO Diversity Techniques

- Diversity can be implemented at the transmit end at the receive end or at both ends of the wireless link.

- Generally MIMO diversity techniques can provide higher SNR and improve transmission reliability.

Transmit diversity :-

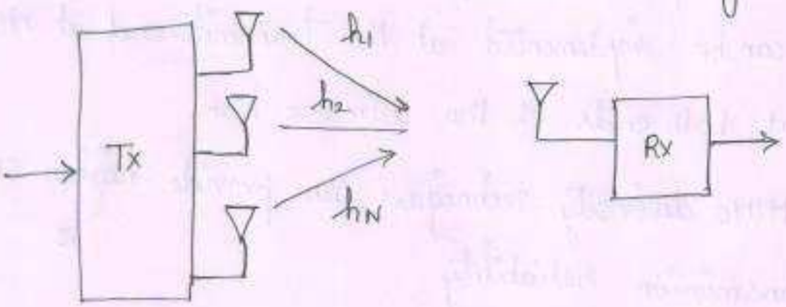
- It improves the signal quality and achieves a higher SNR ratio at the receiver side; it involves transmitting data stream through multiple antennas & receiving by single antenna or more.

- Transmit diversity can effectively mitigate multipath fading effects as multiple antennas afford a receiver several observations of the same data stream.

- Each antenna will experience a different interference environment & if one antenna experienced a deep fade, Than it is likely that another has a sufficient signal.

- Ex: The transmit diversity techniques include Alamaiti code & orthogonal ∫ codes proposed by whole system Nt transmit antenna system.

Transmit Diversity



Receive Diversity

- It is widely Used in wireless communication systems
it can be achived by receiving redundant copies of the same signal.

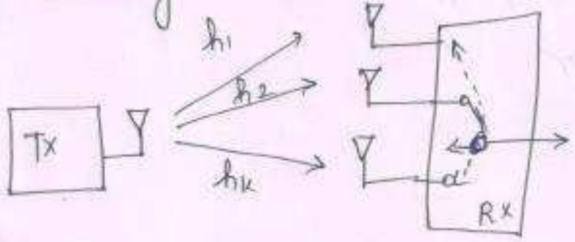
- The idea behind receive diversity is that each antenna at the receive end can observe an independent copy of the same signal.

- The probability that all signals are in deep fade simultaneously is significantly reduced.

- This type of diversity hasn't particular settings or requirements on the transmit end but requires a receiver that could simultaneously process all received signals & combines them by a proper combining method.

- There are several classical methods for combining the different diversity branches at the receiver most important of which is most widely used are selection combining, Maximal Ratio Combining & equal gain Combining

Selection combining



- The selection diversity improve SNR.

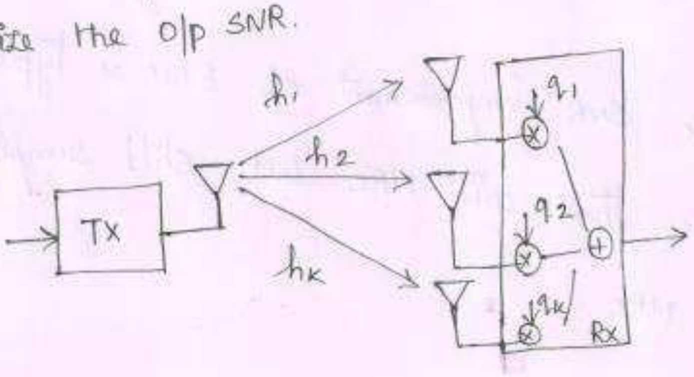
Let $\tilde{\gamma}$ is new average signal SNR. Γ_{avg}. SNR in each branch

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

Maximal Ratio Combining

- The Selection combining technique ignores information from all diversity branches except the particular branch that has highest SNR. This drawbacks is mitigated by using Maximal Ratio combining.

- The information from all branch is combined in order to maximize the O/p SNR.



The resulting signal envelop applied to detector

$$r_m = \sum_{i=1}^{n} G_i r$$

Total Noise power

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

SNR applied to detector

$$r_m = r_m^2 / 2N_t$$

Equal gain Combining:

- Equal gain Combining is similar to Maximal Ratio Combining without weighting the signals before summation.

- In EGC co-phasing is needed to avoid signal cancellation.

- The average SNR improvement of EGC is typically about 1 dB worse than with MRC but still simpler to implement than MRC.

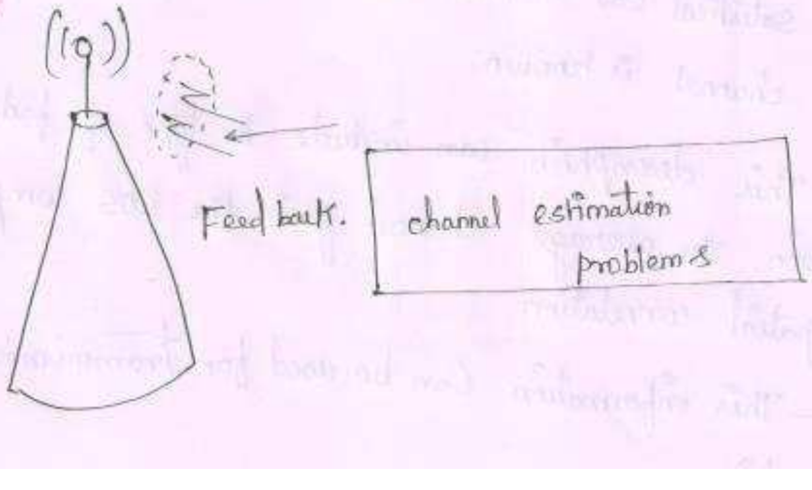
channel state information

- In wireless Communication channel state information simply represents the properties of a Communication link b/w the transmitter and receiver.

- The CSI describes how a signal propagates from the transmitter to the receiver & represents the combined effect of for ex scattering, fading & power delay with distance.

- The CSI makes it possible to adapt transmission to current channel conditions which is cruicible for achieving reliable communication with high data rates in multiantenna systems.

- The CSI at the transmitter is vital in MIMO systems in Order to increase the transmission rate, to enhance coverage, to improve spectral efficiency and to reduce receiver complexity.



- The CSI is usually estimated at the receiving end & then quantized & fed back to transmitting side.

Instaneous CSI

- It is also known as short term CSI.

- CSI means that the current conditions of the channel are known which can be viewed as knowing the impulse response of a digital filter.

- This gives an opportunity to adapt the transmitted signal to the impulse response & thereby optimize the received signal for spatial multiplexing or to achieve low bit error rates.

Statistical CSI

- It is known as long-term CSI.

- Satistical CSI means that a statistical characterization of the channel is known.

- This description can include the type of fading distribution the average channel gain the LOS component & the spatial correlation.

- This information can be used for transmission

- The capacity of a MIMO channel is influenced by the degree of CSI available of both transmitter & receiver. ⑫

- In most instances of multi antenna communication the receiver can accurately track the instantaneous state of the channel from pilot signals that are typically embedded within the transmission.

Capacity in fading & Non fading channel

MIMO capacity: channel Unknown at the transmitter

- The generalized capacity equation for time space architecture.

knows the channel satistics such

- The transmitter only distribution parameters.

as distributions of the channel

$$C = \log_2 \left[I_N + \left(\rho/M \right)^{HH} (+) \right] \text{ b/s/Hz}$$

where $(+)$, H, I_N & ρ represents transpose conjugate, $N \times M$ channel Matrix, $N \times N$ identity matrix & SNR.

The capacity of a MIMO system improves linearly with m fold where $m = \min(M, N)$

MIMO capacity channel Known at the transmitter

- The additional performance gain can be achieved in MIMO systems with the CSI at the transmitter

- This Scenario Considers that the transmitter knows the random channel Outcomes & adjust the transmit signal.

$$C = \log_2 [I_N + HQH(\dagger)] \text{ b/s/Hz}$$

If Q denotes the covariance matrix of the transmitted M-D vector Gaussian signal of total radiated power P then the shannon's capacity for a fading MIMO channel with AWGN is given as.

where $(\dagger)$, H & I_N represents the determinant transpose Conjugate, N×M channel Matrix & N×N identity Matrix

$$Q = (P/M) I_N$$