Subject Name: Mobile Communication

Unit name: Cellular Concepts

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Pre-requisite

- Basic knowledge of Digital Communication,
- Antennas and Applied Random Processes

Aim and Objectives

- To understand the issues involved in mobile communication system design and analysis
- To understand the characteristics of wireless channels.
- To acquire knowledge in different modulation schemes and its error probability in wireless system
- To make students familiar with fundamentals of mobile communication systems
- To know the fundamental limits on the capacity of wireless channels.
- To understand the concept of frequency reuse
- To identify the limitations of 2G and 2.5G wireless mobile communication and use design of 3G and beyond mobile communication systems
- To understand the diversity concepts.
- To understanding the basic principles of mobile communication systems

MOBILE COMMUNICATION VII-Semester

Pre-requisite: Basic knowledge of Digital Communication, Antennas and Applied Random Processes

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- To understand the diversity concepts.

UNIT I THE WIRELESS CHANNEL

Overview of wireless systems – Physical modelling for wireless channels – Time and Frequency coherence – Statistical channel models – Capacity of wireless Channel- Capacity of Flat Fading Channel — Channel Distribution Information known – Channel Side Information at Receiver –Channel Side Information at Transmitter and Receiver – Capacity with Receiver diversity – Capacity comparisons – Capacity of Frequency Selective Fading channels.

UNIT II PERFORMANCE OF DIGITAL MODULATION OVER WIRELESS CHANNELS

Fading– Outage Probability– Average Probability of Error — Combined Outage and Average Error Probability – Doppler Spread – Inter-symbol Interference.

UNIT III MULTIANTENNA COMMUNICATION

Realization of Independent Fading Paths – Receiver Diversity – Selection Combing – Threshold Combing – Maximal-Ratio Combing – Equal - Gain Combing – Transmitter Diversity – Channel known at Transmitter – Channel unknown at Transmitter – The Alamouti Scheme– Transmit & Receive Diversity-MIMO Systems.

UNIT IV MULTICARRIER MODULATION

Data Transmission using Multiple Carriers – Multicarrier Modulation with Overlapping Sub channels – Mitigation of Subcarrier Fading – Discrete Implementation of Multicarrier Modulation – Peak to average Power Ratio- Frequency and Timing offset – Case study IEEE 802.11a

UNIT V CELLULAR CONCEPTS

Frequency Reuse – Channel Assignment Strategies – Hand off Strategies – Interference and system capacity- Co-Channel Interference- Adjacent Channel Interference – Trunking and Grade of service – Improving coverage & capacity in cellular systems-Cell Splitting- Sectoring-Repeaters for Range Extension-Microcell Zone Concept.

OUTCOMES:

At the end of the course, the students should be able to:

- Apply diversity techniques in wireless systems.
- Design cellular systems to achieve a given GoS (Grade of Service) in coverage and blocking probability.

TEXT BOOKS:

1. Andrea Goldsmith, "Wireless Communications", Cambridge University Press, 2005.

REFERENCES:

1. David Tse and Pramod Viswanath, "Fundamentals of Wireless Communication", Wiley Series in Telecommunications, Cambridge University Press, 2005.
2. Theodore. S. Rappaport, "Wireless Communications: Principles and Practice", 2nd Edition, Pearson Education, India, 2009.
3. Arogyaswami Paulraj, Rokit Nabar, Dhananjay Gore, "Introduction to Space-Time Wireless Communication", 1st Edition, Cambridge University Press, 2008.

Mobile Communication

Unit – I / The Wireless Channel

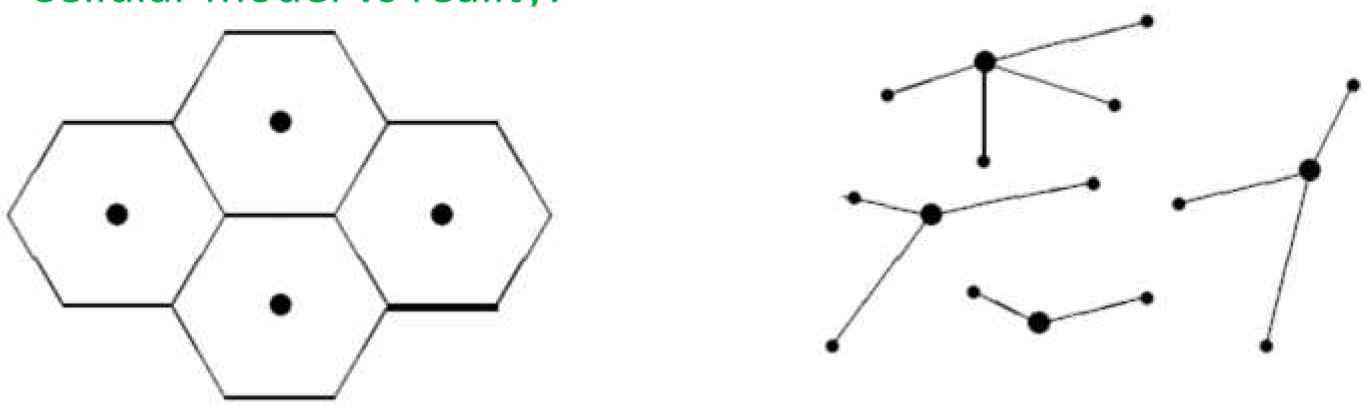
Syllabus

- Overview of wireless systems – Physical modelling for wireless channels – Time and Frequency coherence – Statistical channel models – Capacity of wireless Channel- Capacity of Flat Fading Channel —— Channel Distribution Information known – Channel Side Information at Receiver – Channel Side Information at Transmitter and Receiver – Capacity with Receiver diversity – Capacity comparisons – Capacity of Frequency Selective Fading channels.

Introduction to Wireless Channel

Wireless Channel is Very Different!

- Wireless channel “feels” very different from a wired channel.
  - Not a point-to-point link
  - Variable capacity, errors, delays
  - Capacity is shared with interferers
- Characteristics of the channel appear to change randomly with time, which makes it difficult to design reliable systems with guaranteed performance.
- Cellular model vs reality:



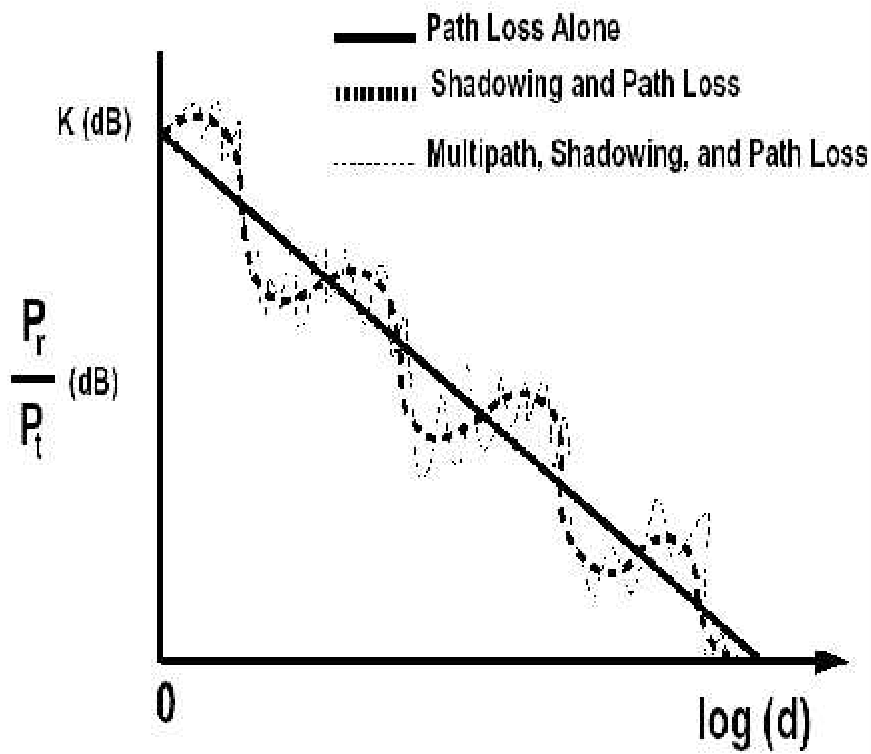
(a) (b)

Part (a): an oversimplified view in which each cell is hexagonal.

Part (b): a more realistic case where base stations are irregularly placed and cell phones choose the best base station

Basic Ideas: Path Loss, Shadowing, Fading

- Variable decay of signal due to environment, multi-paths, mobility



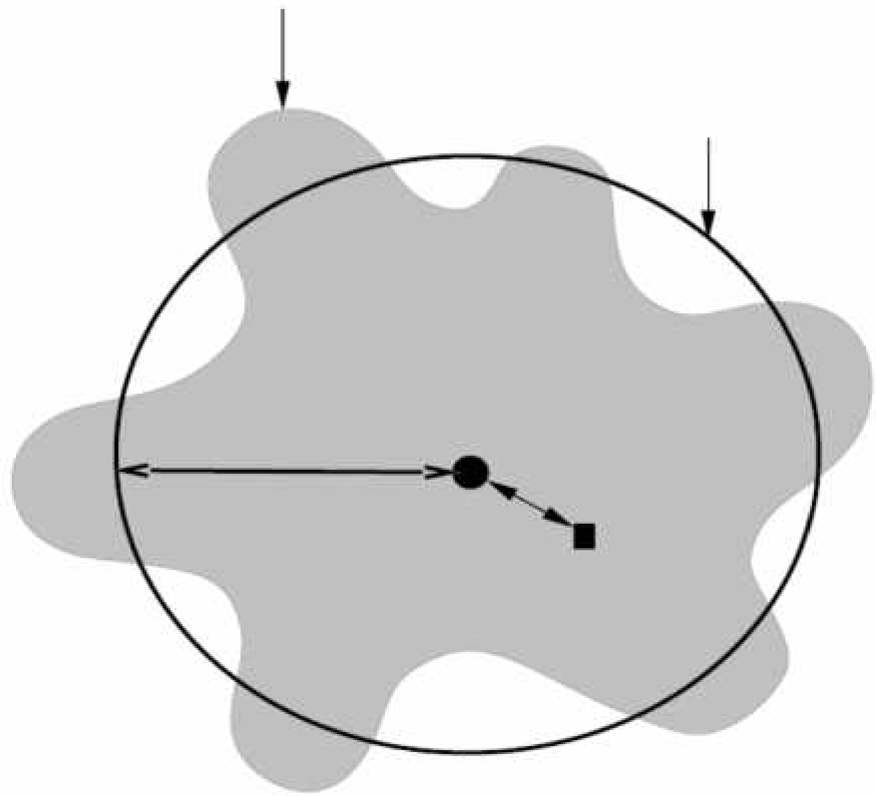
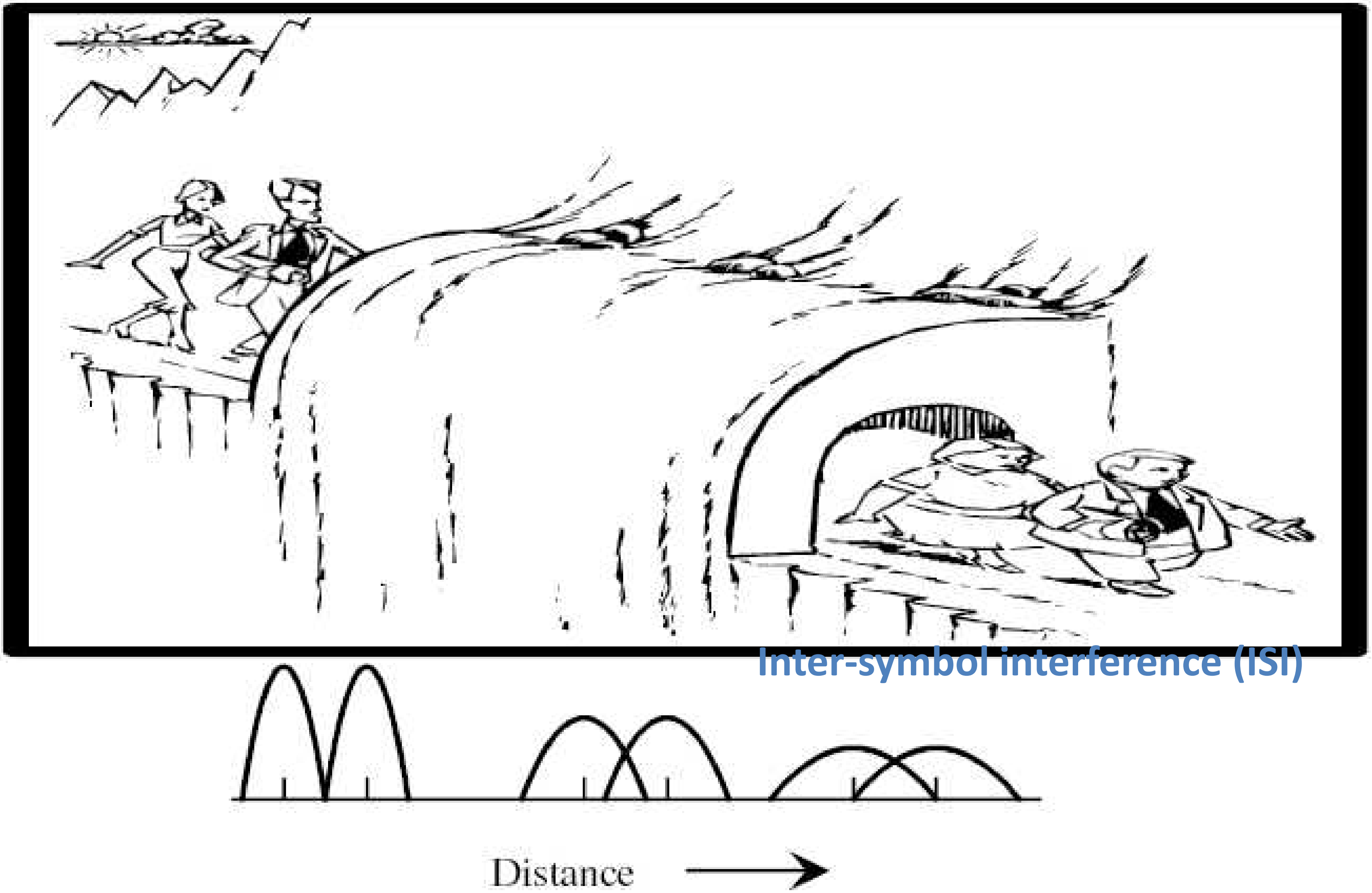
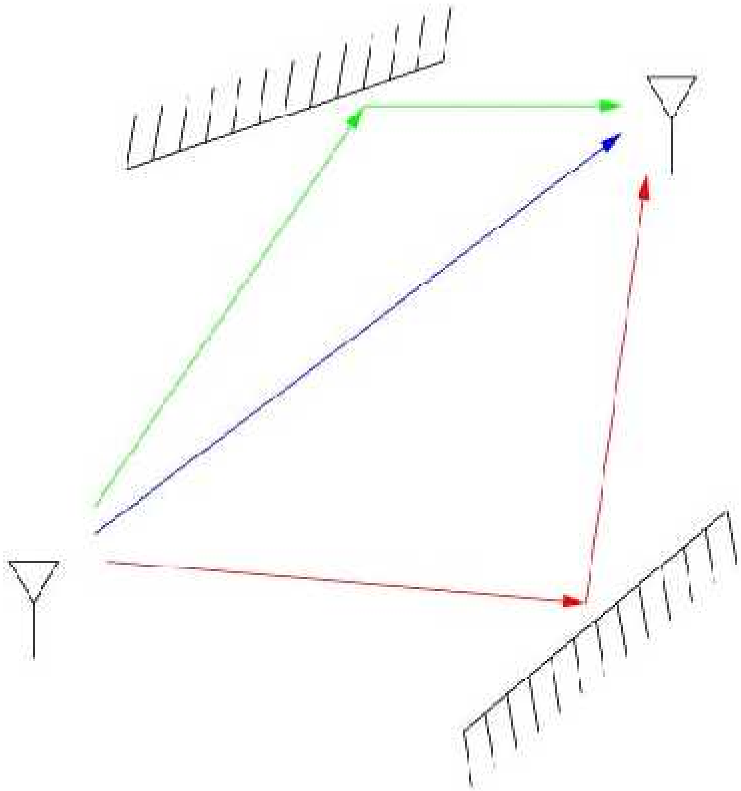


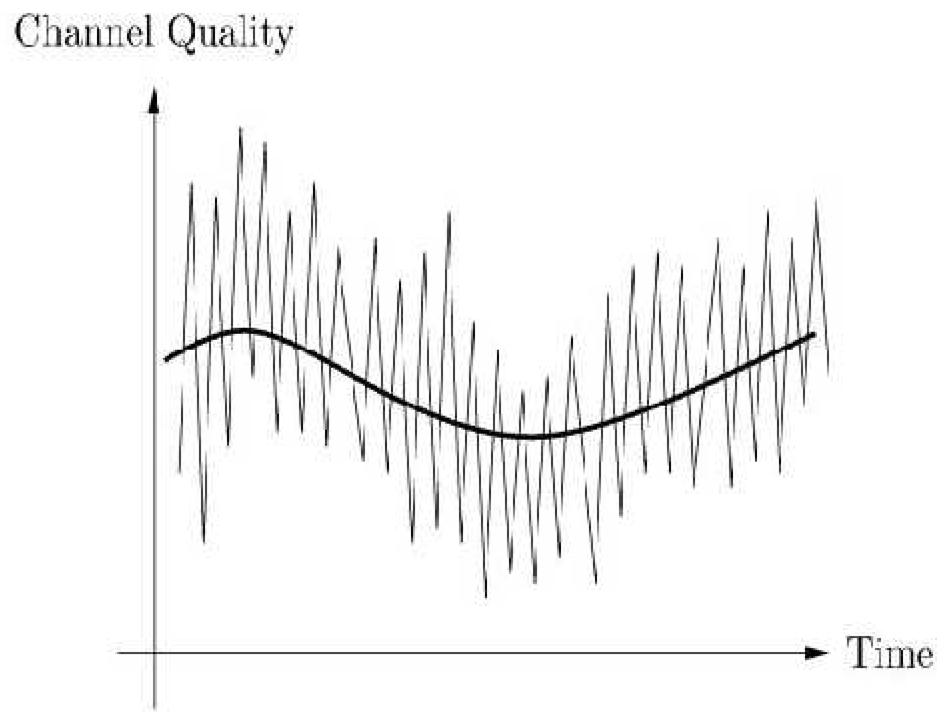
Figure 2.10: Contours of Constant Received Power.

Attenuation, Dispersion Effects: ISI!



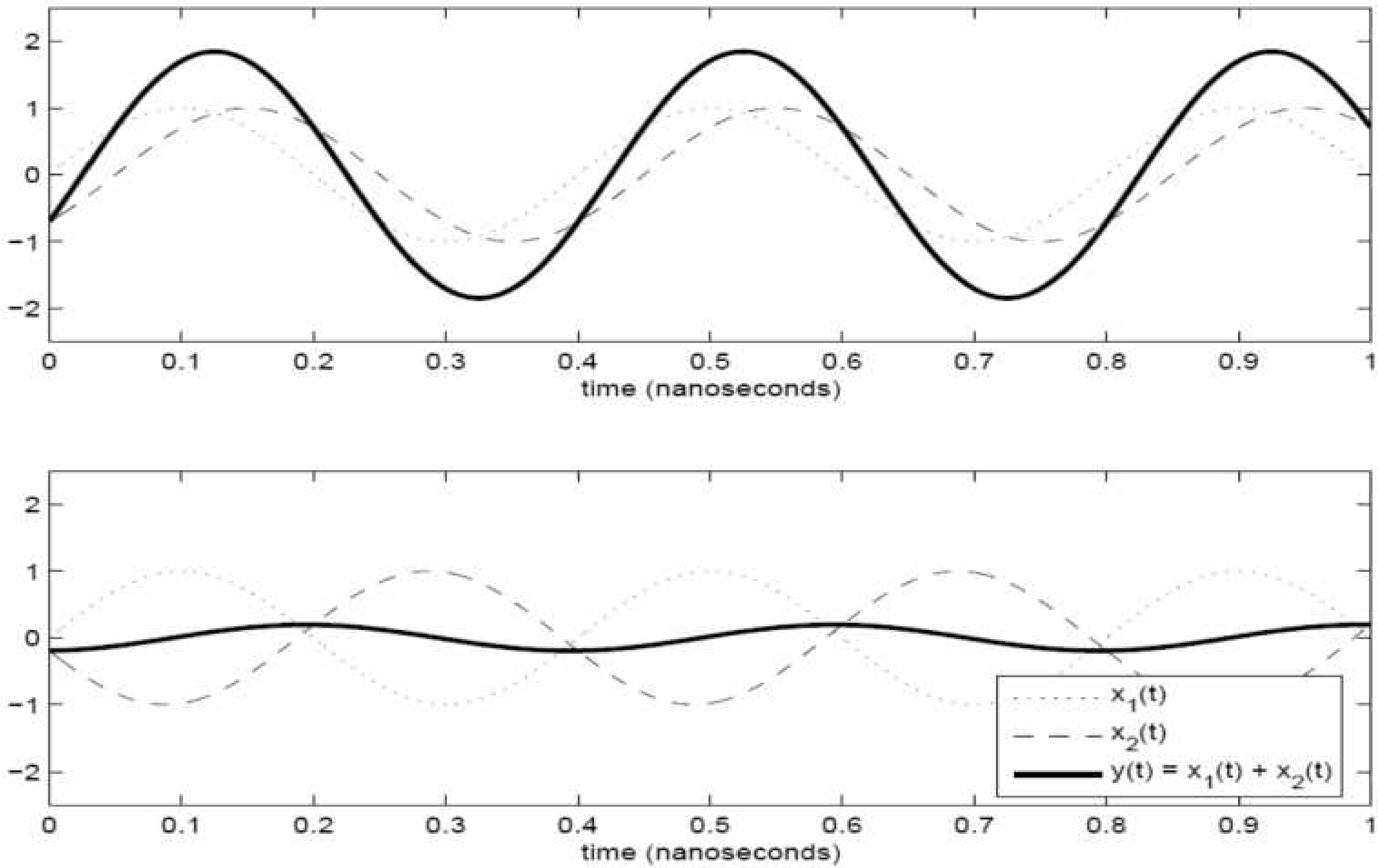
Wireless Multipath Channel





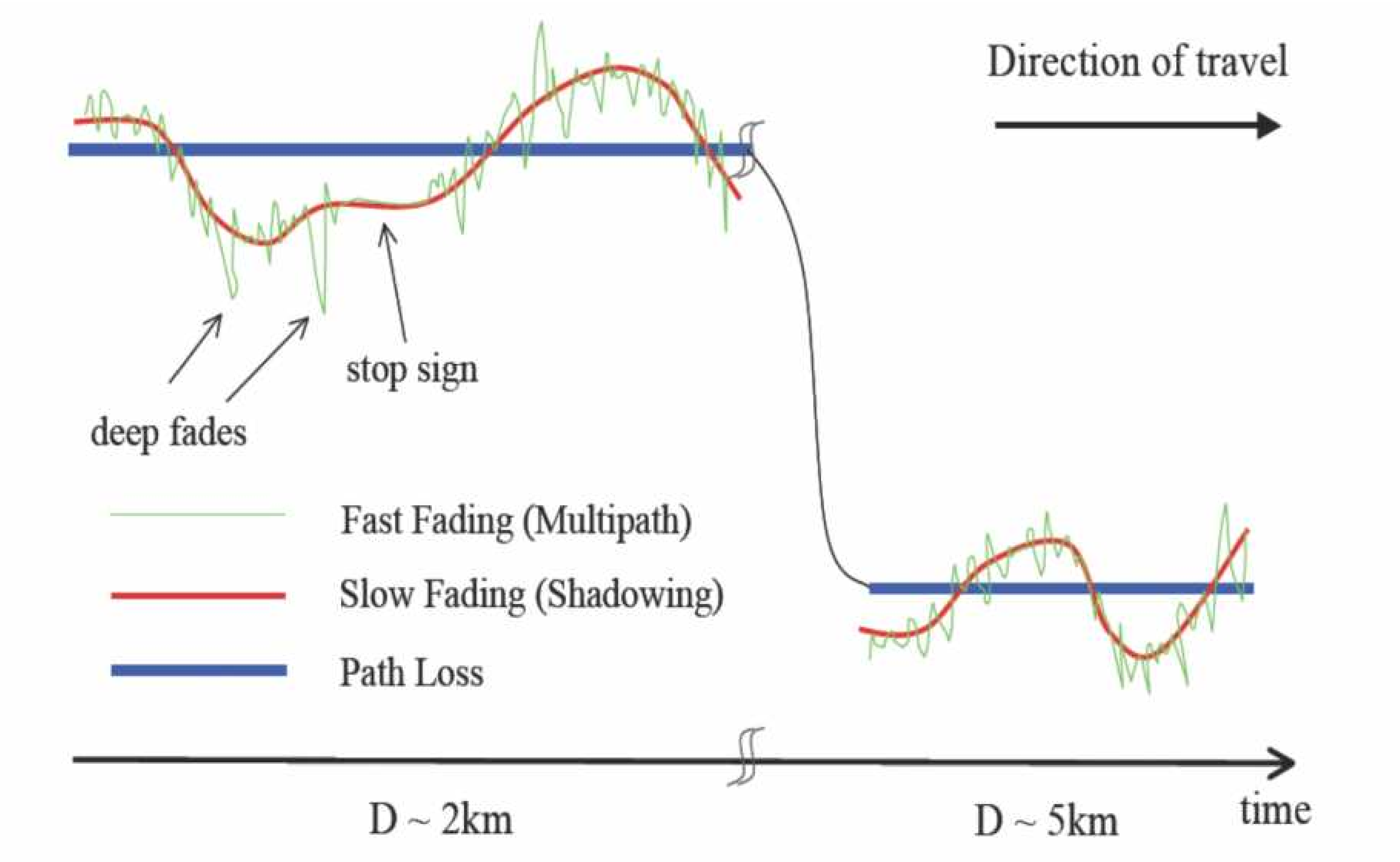
Channel varies at two spatial scales:
* Large scale fading: path loss, shadowing
* Small scale fading:
  Multi-path fading (frequency selectivity, coherence b/w, ~500kHz),
  Doppler (time-selectivity, coherence time, ~2.5ms)

Multi-Path Interference: Constructive & Destructive



The difference between constructive interference (top) and destructive interference (bottom) at $f_c = 2.5$ GHz is less than 0.1 nanoseconds in phase, which corresponds to about 3 cm.

Mobile Wireless Channel w/ Multipath



Overview

- To understand how the physical parameters such as
  - carrier frequency
  - mobile speed
  - bandwidth
  - delay spread
  - angular spread

  impact on the behavior of a wireless channel from the cell planning and communication system point of view.

Topic 1

Overview of Wireless Systems

Cellular Telephone Systems

Cordless Telephone Systems

Wireless LAN

Wide Area Wireless Data Services

Fixed Wireless Access

Paging Systems

Satellite Networks

Bluetooth

Home RF

Other Wireless Systems

Cellular Telephone Systems

History

- In 1895, the telephone was invented by **MARCONI** who demonstrated the first radio transmission from the Isle of Wight to a tugboat 18 miles away.
- Today most radio systems transmit digital signals composed of binary bits, obtained directly from a data signal or by digitizing an analog voice signal.
- Cellular telephone systems are designed to provide two-way voice.
- Cellular systems were initially designed for mobile terminals inside vehicles with antennas mounted on the vehicle roof.
- The basic feature of the cellular system is frequency reuse.

Cellular Telephone Systems

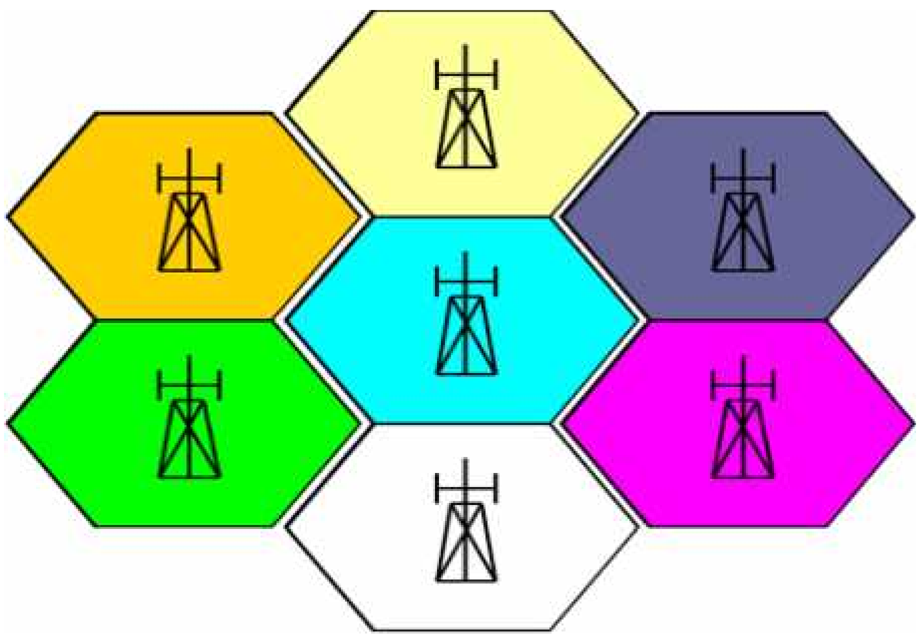
- In a cellular system, the signal from a mobile unit (cell phone) to a base station is transmitted by radio waves through the air, instead of through metallic wires.
- However, the signal from the base station is sent to a mobile switching center & to a telephone central office through electrical wires.
- The antenna at the base station converts the radio waves to electrical signals and circuits in the base station send the signal to the appropriate mobile switching center.

Cell concept

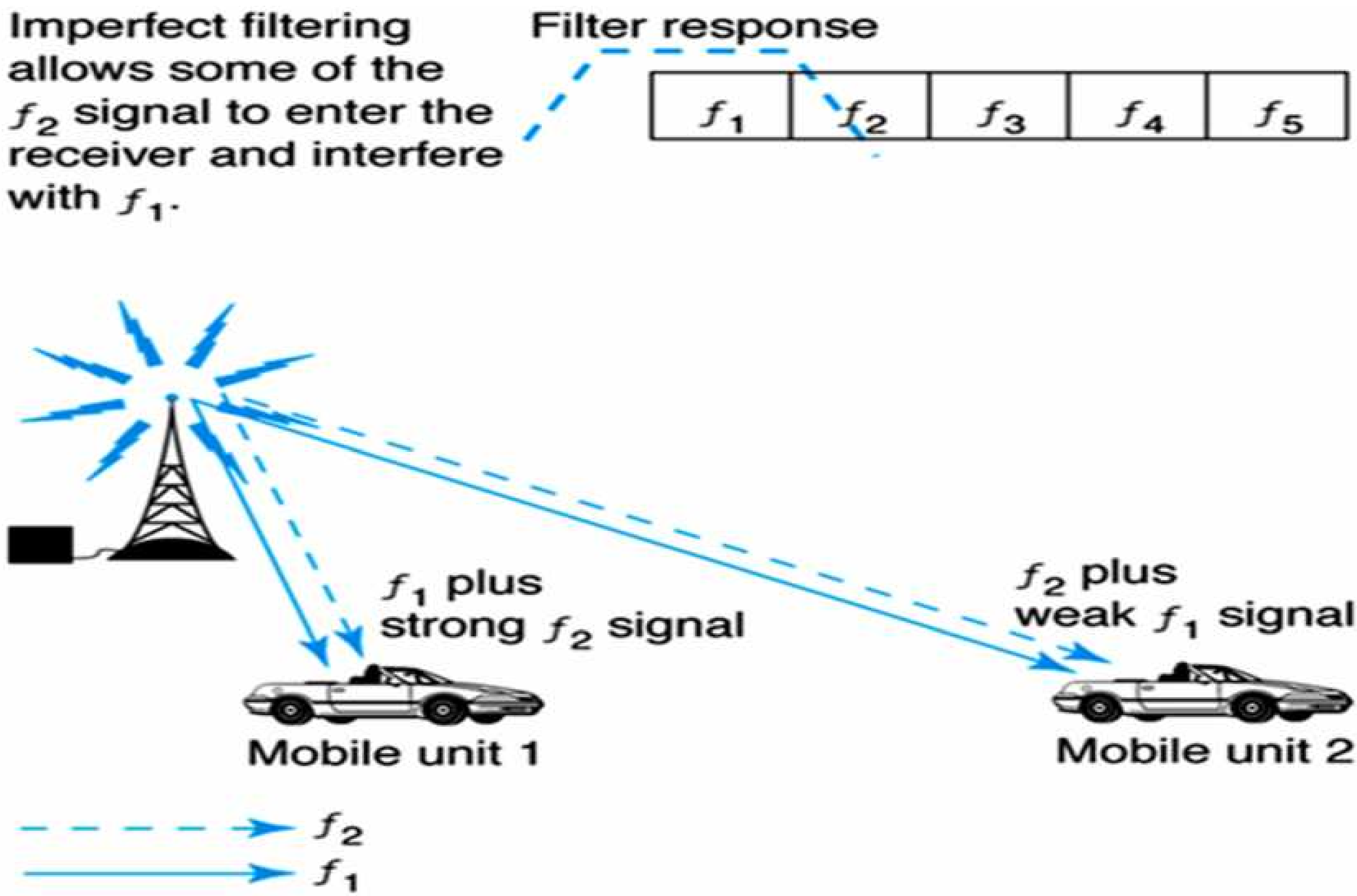
- Initial cellular system were mainly driven by high cost of base stations, about one million dollars each.
- For this reason early cellular systems used a small number of cells to cover an entire city or region.
- The cell base stations were placed on tall buildings or mountains & transmitted at very high power with cell coverage areas of several square miles.
- These large cells are called macro-cells.
- Signals propagated out from base stations uniformly in all directions, so a mobile moving in a circle around the base station would have approximately constant received power.
- Cellular telephone systems are evolving to smaller cells with base stations close to street level or inside buildings transmitting at much lower power.
- These smaller cells are called microcells or picocells, depending on their size.

Cell Concept (contd)

- In a cellular radio system, a land area with radio service is divided into regular shaped cells, which can be hexagonal, square, circular or some other regular shapes.
- Each of these cells is assigned multiple frequencies (f_1 - f_6) which have corresponding radio base stations.
- The group of frequencies can be reused in other cells.
- Cellular Concept is to increase both coverage and capacity.



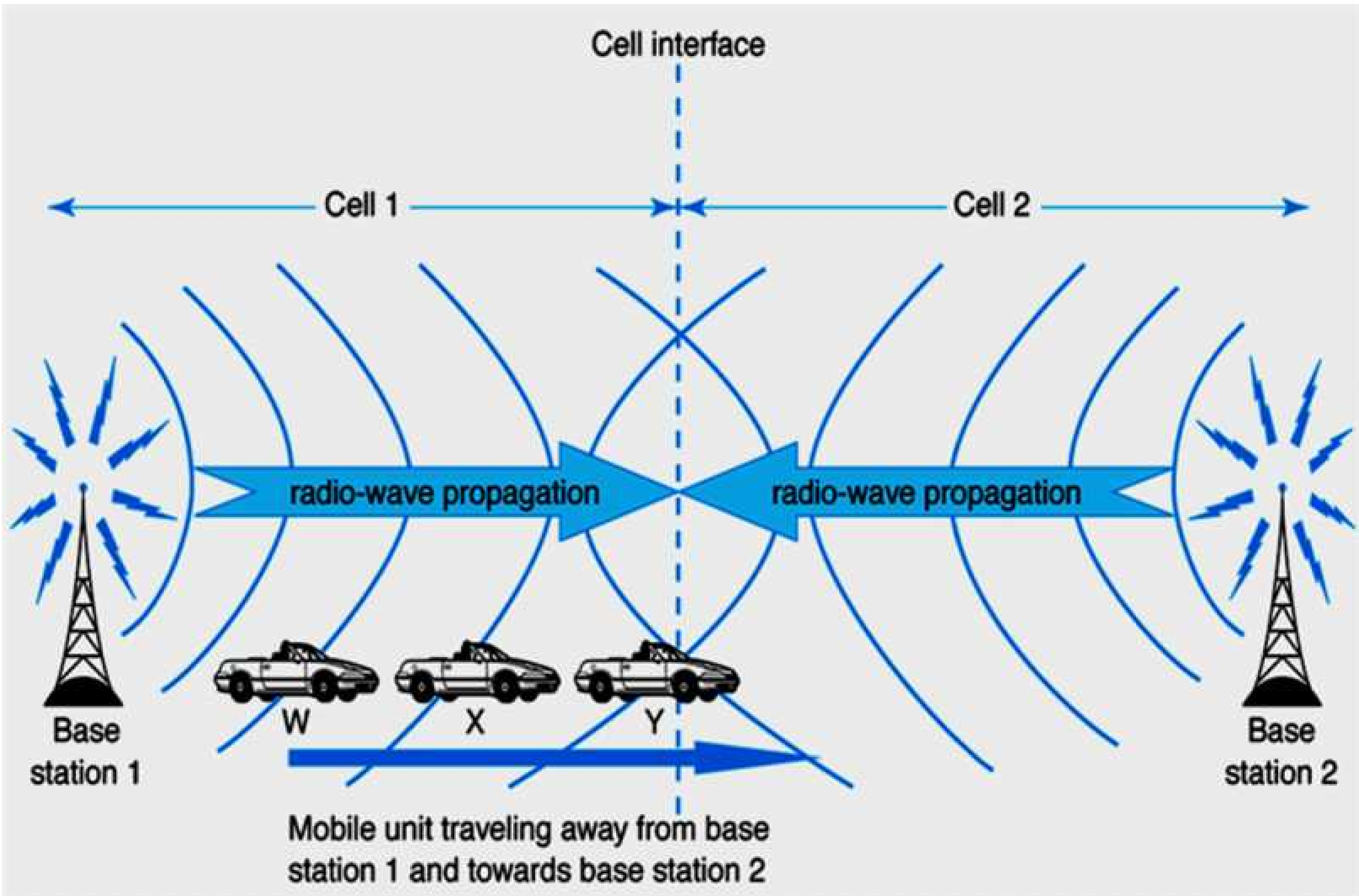
Frequencies Reused



Handoff

- The term **handover** or **handoff** refers to the process of transferring an ongoing call or data session from one channel connected to the core network to another.
- When the phone is moving away from the area covered by one cell and entering the area covered by another cell the call is transferred to the second cell in order to avoid call termination when the phone gets outside the range of the first cell.
- **Hard handoff** is one in which channel in the source cell is released and only then the channel in the target cell is engaged. Thus connection to the source is broken before the connection to the target is made.
- **Soft handoff** is one in which the channel in the source cell is retained and used for a while in parallel with the channel in the target cell. In this case the connection to the target is established before the connection to the source is broken.

Handoff Process

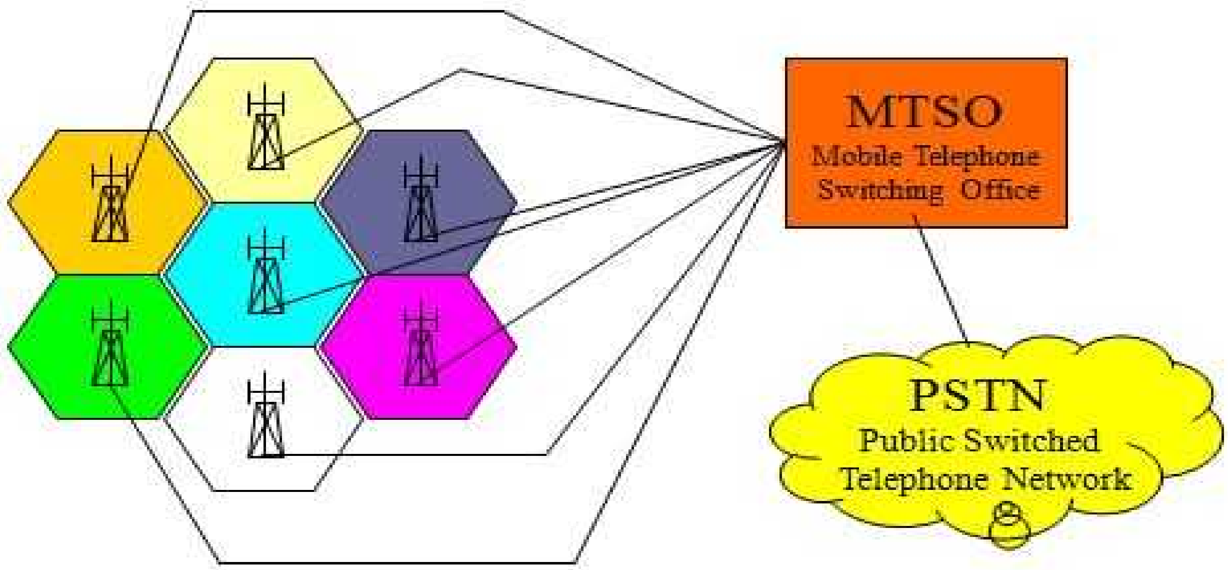


Operation

- The area is divided into a number of cells and a base station within each cell.
- If a user (mobile phone) is within a particular cell, the call is handled by the corresponding base station within that cell.
- The base station transmits the signal to mobile switching center (MTSO) which switches the signal to another base station, or to Public Switched Telephone Network (PSTN) depending on the destination of the call.
- As a user moves from one cell to another, the call is "handed over" to the base station of the other cell.
- All base stations in a city are connected via a high-speed link to a mobile telephone switching office (MTSO).
- The MTSO acts as a central controller for the network, allocating channels within each cell, coordinating handoffs between cells and routing calls to & from mobile users in conjunction with PSTN.

Operation (contd)

- A new user located in a given cell requests a channel by sending a call request to the cell's base station over a separate control channel.
- The request is relayed to MTSO, which accepts the call request if a channel is available in that cell.
- If no channel is available, the call request is rejected.



Operation (cond)

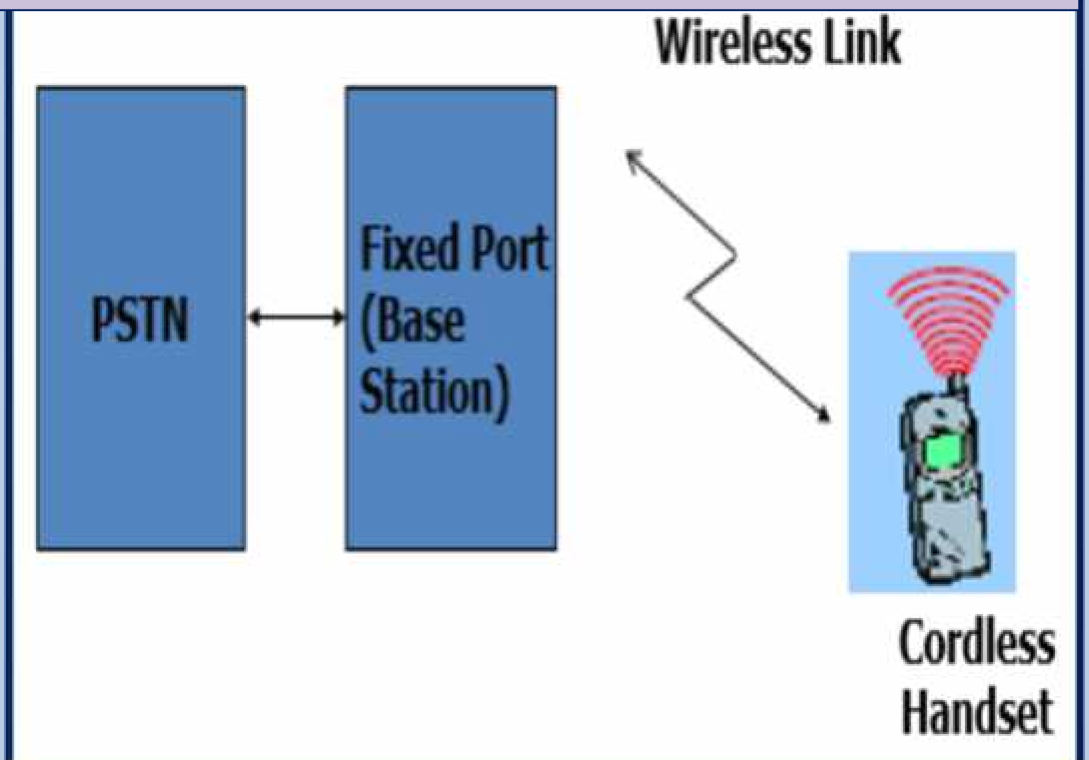
- All cellular systems being deployed today are digital & they provide voice mail, paging, and email services in addition to voice.
- Digital cellular systems can use any of the multiple access techniques - TDMA ,FDMA or CDMA.
- There are two standards in the 900 MHz (cellular) frequency band:
- IS-54 (Interim Standard), which uses a combination of TDMA & FDMA, and IS-95, which uses semi-orthogonal CDMA.
- IS-95 is a digital cellular phone system using CDMA and FDMA.
- GSM is a digital cellular phone system using TDMA and FDMA.

CORDLESS TELEPHONE SYSTEMS

CORDLESS TECHNOLOGY

Cordless" originates from the technique that made it possible for subscribers to connect a small base station to their telephones, thereby attaining a limited degree of mobility

It is full duplex communication systems that use radio to connect a portable handset and a dedicated Base Station, which is then connected to a dedicated telephone line with a specific telephone number on a Public Switched Telephone Network (PSTN).



CORDLESS TELEPHONE

- Cordless telephone is a telephone with a wireless handset that communicates via radio waves with a base station connected to a fixed telephone line, usually within a limited range of its base station (which has the handset cradle).

- There are various generations of cordless system CT0,CT1,CT2,DECT and PHP.

FREQUENCIES

1.7 MHz

- Used by Earliest analog models
- 5 channels
- No longer in production
- Very susceptible to interference from fluorescent lights & nearby automobile ignition systems
- quite crowded, depending on the density of users in a given area

43 MHz–50 MHz

- Allocated on 1984
- Enjoys 80 channels
- newer models
- readily identified by their shorter non-telescoping antennas
- much less crowded than the 46-MHz to 47-MHz band
- FM System

900 MHz (902 MHz - 928 MHz)

- have a huge installed base
- shorter antennas
- up to 30 channels
- higher resistance to interference
- analog, analog spread spectrum digital, and digital spread spectrum

1.9 GHz

- used by the popular DECT phone standard
- more secure than the other shared frequencies.

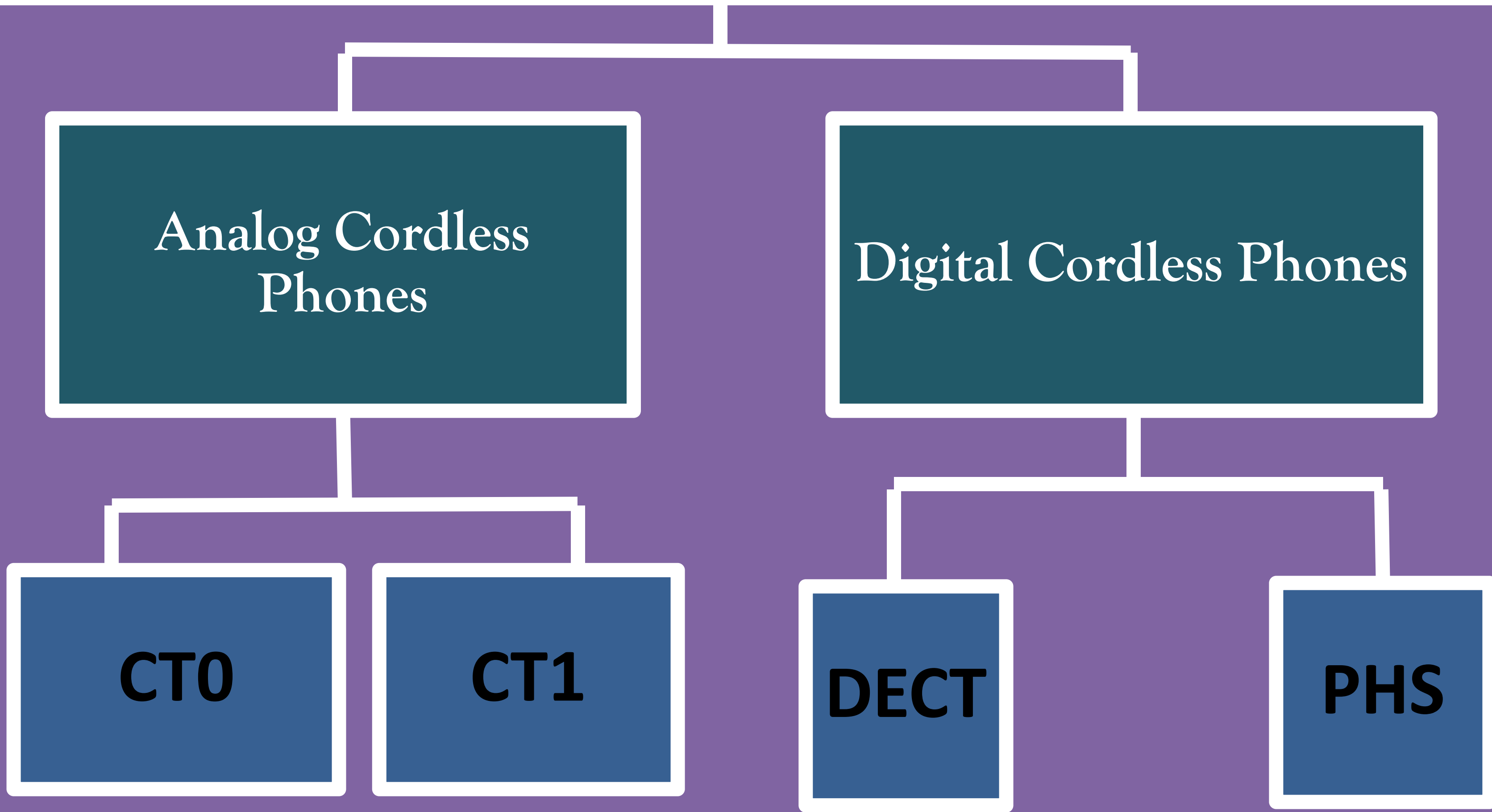
2.4 GHz

- Allocated on 1993
- Few radio scanners cover
- Analog and digital spread spectrum models are available to ensure privacy

5.8 GHz

- Contains a huge installed base of analog models
- Low-power walk-talkies and baby monitors share this same frequency band of 25 channels
- Some models use audio inversion for scrambling

TYPES OF CORDLESS TELEPHONE



The main distinction among types of cordless phones is the way to transmit their signals.

ANALOG PHONES

- These are least expensive
- Better voice quality than digital Phones
- Use 5.8 GHz frequency band

Drawbacks of Analog Phones

- Are of shorter rang than digital phones
- This is not a secure transmission
- We can listen voices by using RF scanner (Radio Frequency) or any comparable device
- Conference calls are not allowed

Analog Phones vs. Digital Phones

Analog phones are more open to outside interference & their sound quality is not as good as that of digital cordless models. Analog cordless signals are easily intercepted by many radio scanners.

Digital cordless phones have a much better sound quality than analog phones & their signals are much more secure.
Many digital phones after 1995 included digital spread spectrum (DSS) technology, which spreads a phone's signal out over several frequencies in pieces.
This feature made it impossible to intercept a cordless phone's signal.

ANALOG PHONES

CT1 - Cordless telephone generation 1

CT1 uses two radio frequencies and analogue technology to provide a full duplex speech path between the handset and the base station. The two frequencies are spaced well apart; in the direction base to handset the frequency is 1.7 MHz, and in the direction handset to base the frequency is 47 MHz

The CT1 system has a number of disadvantages:

- The quality of the received speech is not very good.
- Transmissions can be received by a sound broadcast radio receiver.
- Only eight R. F. channels are allocated.
- A telephone has no ability to search for a free channel & it can easily be blocked off by another cordless telephone set to use the same channel.
- The range is limited to about 50 m.

Digital Enhanced Cordless Telecommunications (DECT)

Beyond Europe, it has been adopted by Australia, and most countries in Asia and South America.

DECT is used primarily in home and small office systems, but is also available in many PBX systems for medium and large businesses.

Application of DECT

- Domestic cordless telephony, using a single base station to connect one or more handsets to the public telecoms network.
- Enterprise premises cordless PABXs and wireless LANs, using many base stations for coverage. Calls continue as users move between different coverage cells, through a mechanism called handover.
- Public access, using large numbers of base stations to provide high capacity building as part of a public telecoms network.

Application of DECT

- DECT has also been used for Fixed Wireless Access as a substitute for copper pairs in countries such as India and South Africa. By using directional antennas and sacrificing some traffic capacity, coverage could extend to over 10 km.
- The standard is also used in electronic cash terminals, traffic lights, and remote door openers

Features of DECT

- Multiple handsets to one base station and one phone line socket. This allows several cordless telephones to be placed around the house, all operating from the same telephone jack.
  Interference-free wireless operation to around 100 meters (109 yards) outdoors, much less indoors when separated by walls .
- For instance, generally immune to interference from other DECT systems, Wi-Fi networks, video senders, Bluetooth technology, baby monitors and other wireless devices.

Features of DECT

- Talk time several hours and standby time of several days on one battery charge.

  Some systems offer:

  A longer range between the telephone and base station (usable further from the base).

  Extended battery talk-time, sometimes up to 24 hours.

PHS (Personal Handy-Phone System)

- Developed in Japan as a cordless telecommunication system
- Operates on 1895 MHz-1918MHz
- In mid 1990s, UTStarcom introduce IP-based personal access system(iPAS)
- iPAS network is
  - Low-cost
  - Easy to deploy
  - Wireless alternative of copper wire
  - Portable
  - Support 55 million subscribers globally

PHS (Personal Handy-Phone System)

FEATURES	SERVICES POVIDED
PHS is Light weight PHS is Portable Handle voice, fax, and video signals	City wide mobility Email Mobile internet access (MIA) Short messaging Location based services

Wireless Local Area Network

Introduction

- WLAN stands for Wireless Local Area Network.
- Sometimes it is also called Local Area Wireless Network (LAWN).
- **Norman Abramson**, a professor at the University of Hawaii, developed the world’s first wireless computer communication network, ALOHA net (operational in 1971).
- WLAN is a wireless computer network that links two or more devices (using-spectrum or OFDM radio) within a limited area such as a home, school, computer laboratory, or office building.
- WLAN is a marketed under the Wi-Fi brand name.
- Wireless LANs have become popular in the home due to ease of installation and use.

Advantages of WLAN

- Installation speed and simplicity
  - No cable to pull.
  - Few transmitters/receivers for multiple for users.
- Reduced cost-of-ownership
  - Mobile devices are less expensive than computer workstations.
  - No need to build wiring closets.
- Mobility
  - Access to real-time information.
  - Provides service opportunities.
  - Promotes flexibility.
  - Supports productivity.

Disadvantages of WLAN

- Cost
  - Wireless network cards cost 4 times more than wired network cards.
  - The access points are more expensive than hubs and wires.
- Environmental Conditions
  - Susceptible to weather and solar activity.
  - Constrained by buildings, trees, terrain.
- Less Capacity
  - Slower bandwidth.

Types of WLAN

- 1. Infrastructure
  - – Most Wi-Fi networks are deployed in infrastructure mode.
  - – In infrastructure mode, a base station acts as a wireless access point hub & nodes communicate through the hub.
  - – The hub usually has a wired or fiber network connection, and may have permanent wireless connections to other nodes.
  - – Wireless access points are usually fixed & provide service to their client nodes within range.
  - – Wireless clients, such as laptops, smart phones etc. connect to the access point to join the network.

Types of WLAN (contd)

➢ 2. Peer To Peer

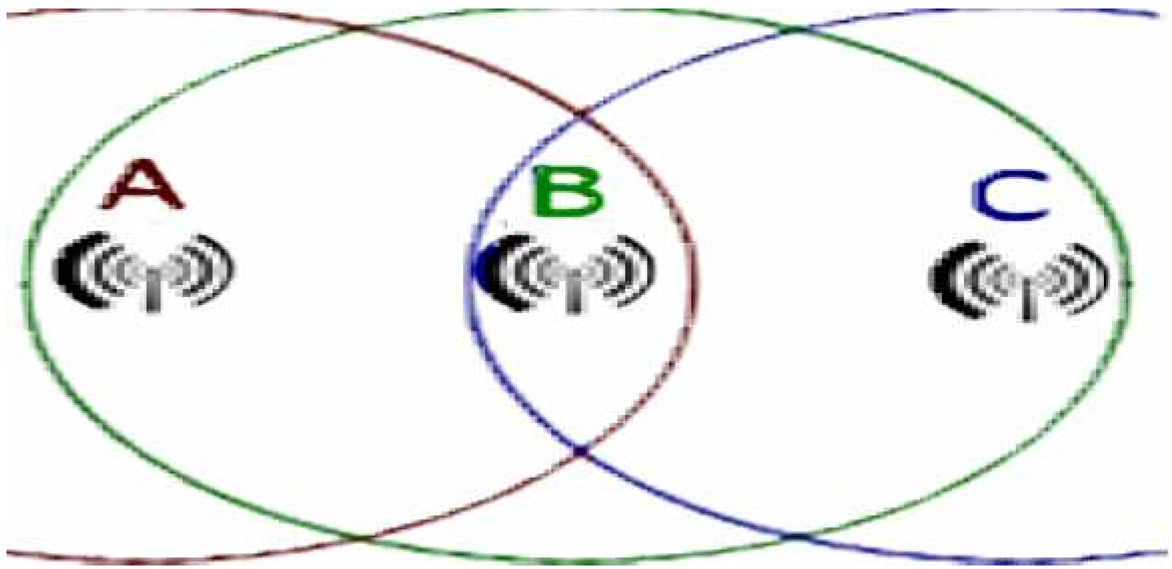
- Two PCs equipped with wireless adapter cards can be set up as an independent network whenever they are within range of one another.
- A peer-to-peer network allows wireless devices to directly communicate with each other.

Types of WLAN (contd)

- 3. Bridge
  - A bridge can be used to connect networks, typically of different types.
  - A wireless Ethernet bridge allows the connection of devices on a wired Ethernet network to a wireless network.
  - The bridge acts as the connection point to the Wireless LAN.

Types of WLAN (contd)

➢ 4. Wireless distribution system



- A Wireless Distribution System enables the wireless interconnection of access points in an IEEE 802.11 network.

Applications of WLAN

- Corporate
  - Mobile networking for e-mail, file sharing, and web browsing.
- Education
  - Connectivity to the University Network for collaborative class activities.
  - Ability to access research sources without requiring a hard point.
- Finance
  - Traders can receive up-to-the-second pricing information.
  - Facilitates electronic payments for goods and services.
  - Improve the speed and quality of trades.
- Healthcare
  - Emergency medical information readily available.
  - Access to schedule information.

Wide Area Wireless Data Services

Wide Area Wireless Data Services

- Wide area wireless data services provide low rate wireless data to high-mobility users over a large coverage area.
- In these systems a geographical region is serviced by base stations mounted on towers or mountains.
- The base stations can be connected to a backbone wired network or form a multi-hop adhoc network.
- Initial data rates for these systems were below 10 Kbps but gradually increased to 20 Kbps.
- Cellular digital packet data (CDPD) system is a wide area wireless data service overlaid on the analog cellular telephone network.
- CDPD shares the FDMA voice channels of the analog systems.
- The CDPD service provides packet data transmission at rates of 19.2 Kbps. & available throughout the U.S.

Wide Area Wireless Data Services

- All of these wireless data services have failed to to attract as many subscribers, especially in comparison with the rousing success of wireless voice systems.
- There is disagreement on why these systems have experienced such anemic growth.
- Data rates for these systems are clearly low, especially in comparison with their wire-line counterparts.
- Pricing for these services also remains high.

Fixed Wireless Access

Fixed Wireless Access

- Fixed wireless access provides wireless communications between a fixed access point & multiple terminals.
- These systems were initially proposed to support interactive video service to home, but application emphasis has now shifted to providing high speed data access to the Internet and to high speed data networks for both homes and businesses.
- In U.S. two frequency bands have been set aside for these systems:
- A part of the 28 GHz spectrum is allocated for local distribution systems (local multipoint distribution systems or LMDS).
- A band in the 2 GHz spectrum is allocated for metropolitan distribution systems (multichannel multipoint distribution services or MMDS).

Paging Systems

Paging Systems

- Paging systems provide very low rate one-way data services to highly mobile users over a very wide coverage area.
- Paging systems have experienced steady growth for many years & currently serve about 56 million customers in United States.
- However, the popularity of paging systems is declining as cellular systems have become cheaper.
- In order to remain competitive paging companies have slashed prices & few of these companies are currently profitable.
- To reverse their declining fortunes, a group of paging service providers have recently teamed up with Microsoft and Compaq to incorporate paging functionality & Internet access into palmtop computers.

Paging Systems (contd)

- Paging systems broadcast a short paging message simultaneously from many tall base stations or satellites transmitting at very high power.
- Systems with terrestrial transmitters are localized to a particular geographic area, such as a city or metropolitan region, while geosynchronous satellite transmitters provide national or international coverage.
- In both types of systems no location management or routing functions are needed, since the paging message is broad-cast over the entire coverage area.
- The high complexity and power of paging transmitters allows low-complexity, low-power, pocket paging receivers with a long usage time from small and lightweight batteries.

Satellite Networks

Satellite Networks

- Satellite systems provide voice, data & broadcast services with global coverage to high-mobility users as well as to fixed sites.
- Satellite systems have the same basic architecture as cellular systems, except that the cell base-stations are satellites orbiting the earth.
- There are three main types of satellite orbits: low-earth orbit (LEOs) at 500-2000 Kms, medium-earth orbit (MEO) at 10,000 Kms, and geosynchronous orbit (GEO) at 35,800 Kms.
- A geosynchronous satellite has a large coverage area since the earth and satellite orbits are synchronous.
- Satellites with lower orbits have smaller coverage areas, & these coverage areas change over time so that satellite hand-off is needed for stationary users.

Satellite Networks (contd)

- However, geosynchronous systems have several disadvantages for two-way communication.
- It takes a great deal of power for these satellites - so handsets are typically large & bulky.
- There is a large round-trip propagation delay in two-way voice communication.
- The current satellite systems is to use lower LEO orbits so that handheld devices can communicate with satellites & propagation delay does not degrade voice quality.
- The best known of LEO systems are Globalstar & Teledesic.
- Globalstar provides voice & data services to globally-roaming mobile users under 10 Kbps. This system requires roughly 50 satellites to maintain global coverage.
- Teledesic uses 288 satellites to provide global coverage to fixed-point users at data rates up to 2 Mbps.

Bluetooth

Bluetooth

- Bluetooth is a RF technology for short range connections between wireless devices.
- The Bluetooth standard is based on a microchip incorporating a radio transceiver built into digital devices.
- The transceiver takes the place of a connecting cable for devices such as cell phones, laptop & palmtop computers, portable printers & projectors etc.
- Bluetooth is mainly for short range communications, e.g. from a laptop to a nearby printer or from a cell phone to a wireless headset.
- Its normal range of operation is 10 m and this range can be increased to 100 m by increasing the transmit power from 1 mW to 100 mW.

Bluetooth

- The system operates in the unregulated 2.4 GHz frequency band, hence it can be used worldwide.
- The Bluetooth standard provides 1 data channel at 721 Kbps and up to three voice channels at 56 Kbps for an aggregate bit rate of 1 Mbps.
- Networking is done via a packet switching protocol based on frequency hopping at 1600 hops per second.
- Specifically, the following products all use Bluetooth technology: a wireless headset for cell phones (Ericsson), a wireless USB or RS232 connector (RTX Telecom, Adayma) etc.
- More details on Bluetooth, including Bluetooth products available or under development can be found at website http://www.bluetooth.com.

HomeRF

HomeRF

- HomeRF is a working group developing an open industry standard for wireless digital communication between PCs, intelligent home appliances & consumer electronic devices in and around the home.
- The working group was initiated by Intel, HP, Microsoft, Compaq, and IBM.
- The HomeRF protocol is Shared Wireless Access Protocol (SWAP), which operates in unregulated 2.4 GHz frequency band (same band as Bluetooth).
- The SWAP protocol is designed to carry both voice and data traffic and to interoperate with PSTN & Internet.
- The bandwidth sharing is enabled by frequency hopped spread spectrum at 50 hops/sec, but also supports a TDMA service for delivery of interactive voice services & CSMA/CA for high speed packet data.
- The transmit power for HomeRF is specified at 100 mW which provides a data rate of 1-2 Mbps.
- The range of HomeRF covers a typical home and backyard.

Other Wireless Systems

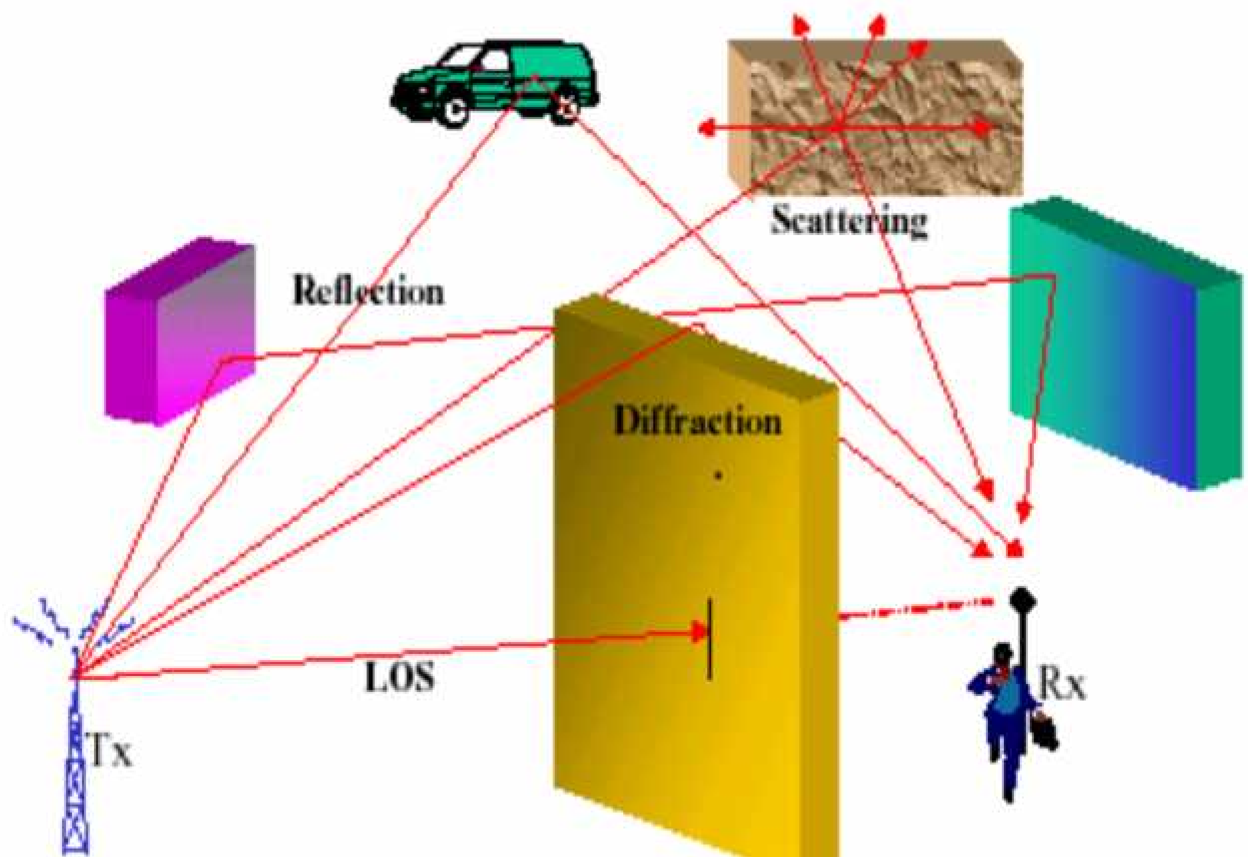
Other Wireless Systems

- Many other commercial systems using wireless technology are on the market today.
- Remote sensor net-works collect data from sensors & transmit this data back to a central processing location being used for both indoor (equipment monitoring, climate control) and outdoor (earth-quake sensing, remote data collection) applications.
- Satellite systems that provide vehicle tracking and dispatching (OMNITRACs) are very successful.
- Satellite navigation systems (the Global Positioning System or GPS) are also widely used for both military and commercial purposes.
- A wireless system for Digital Audio Broadcasting (DAB) has been available in Europe for quite some time & recently been introduced in the U.S. as satellite radio.
- New systems and standards are constantly being developed and this trend seems to be accelerating.
-

Topic 2

Physical Modeling for Wireless Channels

Physical Phenomena



Physical Phenomena

- Reflection - caused by smooth surface with very large dimensions

- Diffraction- Obstruction caused by a dense body with large dimensions
  - EM waves get bend around objects.
  - Reason for shadowing and RF energy being present without LOS.

- Scattering- Large rough surface with different directions.ie more than one direction.

Wireless Propagation

- Path loss inversely proportional to $1/d^n$, $n = 2$ to 4 for mobile channels: Large scale attenuation in signal strength

- Shadowing - Terrain dependent, medium scale variation in signal strength, comes because of big obstacles like buildings, hills.

- Multipath Fading - Small scale or short term variation on the order of $\lambda/2$

Path Loss Model

- If there are no objects which are between transmitter and receiver so that no reflection, refraction or absorption/diffraction happens.
  - Atmosphere is a uniform and non absorbing medium.

- Earth is treated as being infinitely far away from the propagating signal (having a negligible reflection coefficient).

- Under these conditions, RF power attenuates a s per inverse square law. For an isotropic antenna, this attenuation of Tx power is:

$$\left(\frac{4\pi d}{\lambda}\right)^2$$

Where λ is RF carrier the wavelength

& d is the distance between Tx and Rx

Path Loss Model

- Different, often complicated, models are used for different environments.
- A simple model for path loss, L, is

$$L = \frac{P_r}{P_t} = K.\frac{1}{d^\alpha}$$

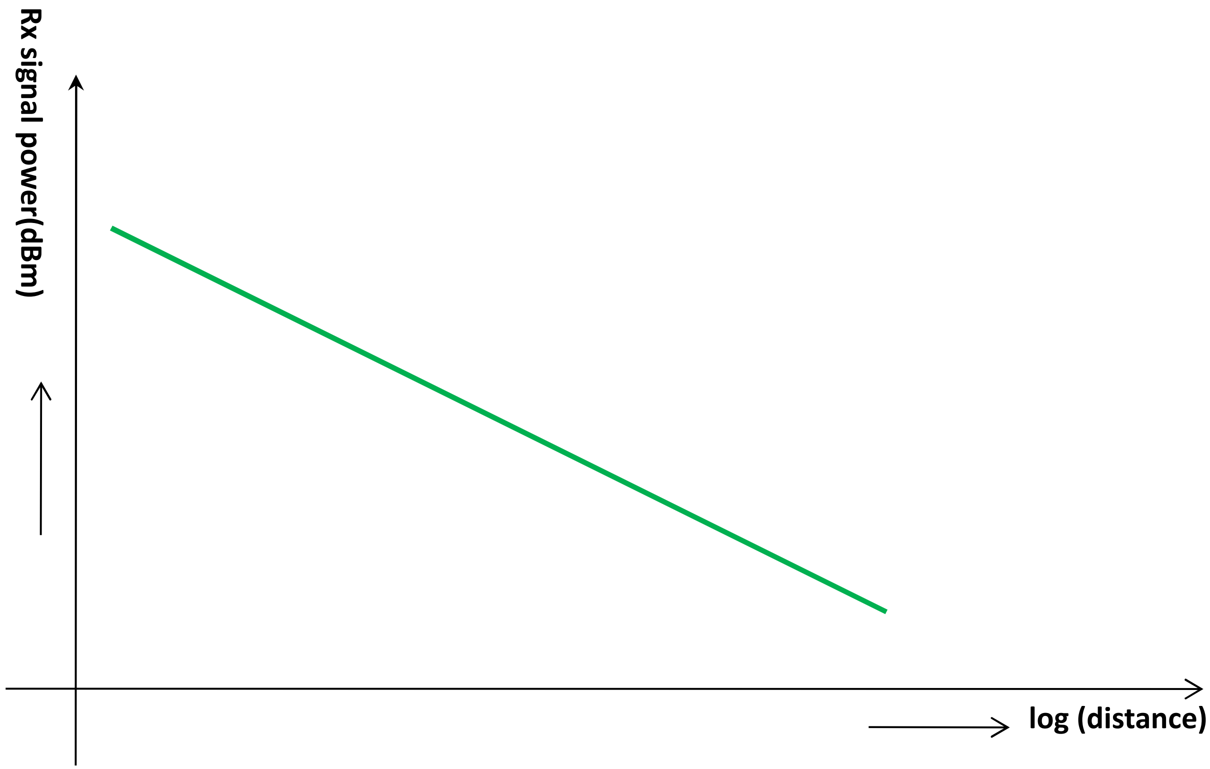
- Path loss exponent
- in free space and

$$\alpha = 2$$

- in typical environments

$$2 \leq \alpha \leq 4$$

Free Space Path Loss



Shadow Fading

- when the received signal is shadowed by observations such as hills and buildings, it results in variation of local mean received power,

$$P_r(dB) = \overline{P}_r(dB) + G_s$$

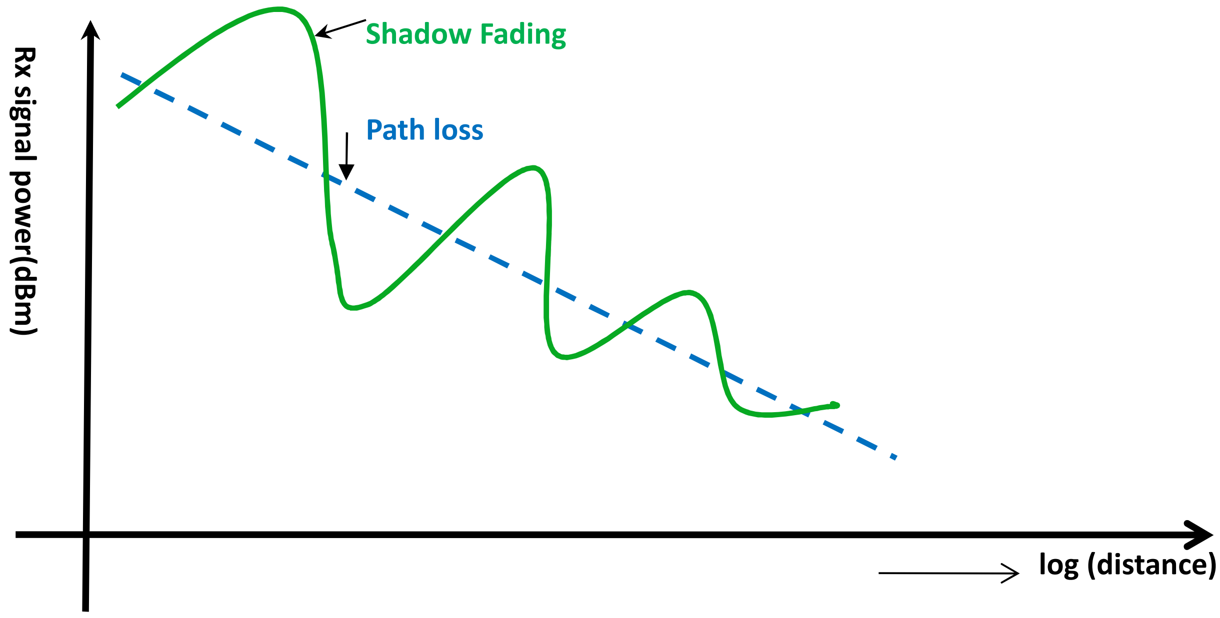
Where $\overline{P}_r(dB)$ is received signal power due to path loss & G_s – Gain.

- Implications:
  - Non-uniform coverage
  - Increases the required transmit power

$$G_s \sim N(0, \sigma_s^2), 4 \leq \sigma_s \leq 10\ dB$$

  - Gaussian distribution σ , with standard deviation in dB

With Shadow Fading



Large, Medium & Small scale fading

- Large Scale Fading: Average signal power attenuation or path loss due to motion over large areas.

- Medium scale fading: Local variation in the average signal power around mean average power due to shadowing by local obstructions

- Small scale fading: large variation in the signal power due to small changes in the distance between transmitter and receiver.
  - It is also called Rayleigh fading due to various multi-paths at the receiver with random amplitude & added delay.

Topic 3

Time & Frequency Coherence

Delay Spread Vs Coherence BW

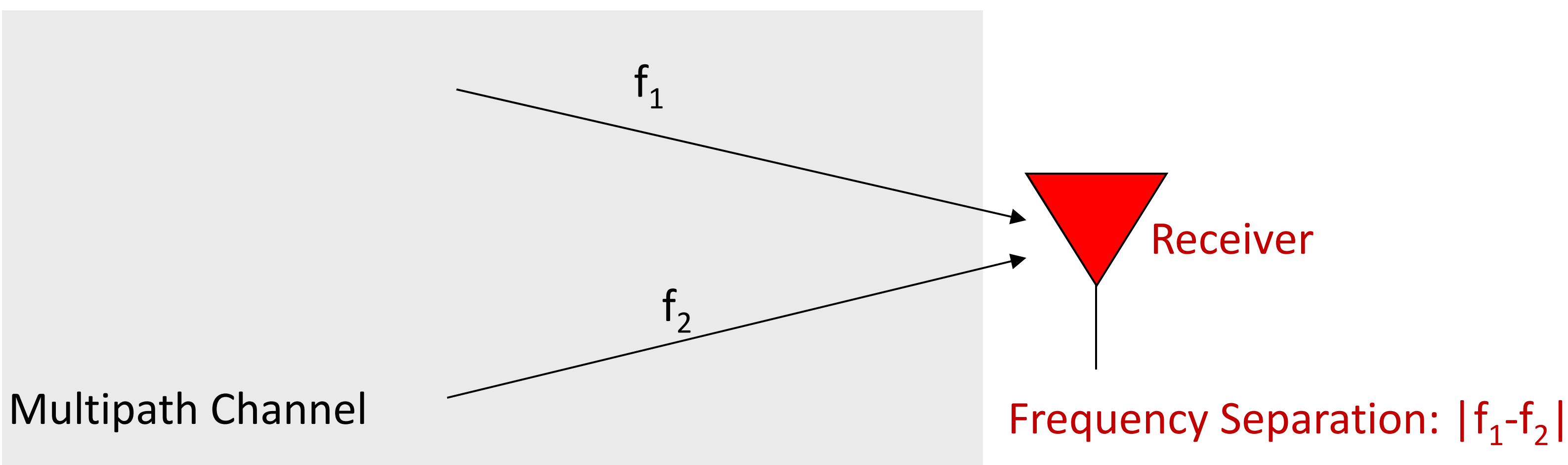
- Delay spread - Describes the time dispersive nature of a channel in a local area
- A received signal suffers spreading in time compared to the transmitted signal
- Delay spread can range from a few hundred nanoseconds for indoor scenario up to some microseconds in urban areas
- The coherence bandwidth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

Coherence Bandwidth (B_C)

– Range of frequencies over which the channel can be considered flat (i.e. channel passes all spectral components with equal gain and linear phase).

  – It is a definition that depends on RMS Delay Spread.

– Two sinusoids with frequency separation greater than B_c are affected quite differently by the channel.



Coherence Bandwidth (contd)

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

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

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

σ is rms delay spread

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

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

This is called 50% coherence bandwidth.

Doppler Spread B_D Vs Coherence Time T_c

- Doppler Spread and Coherence time are parameters which describe the time varying nature of the channel in a small-scale region.

- They don't offer information about the time varying nature of the channel caused by relative motion of transmitter and receiver.

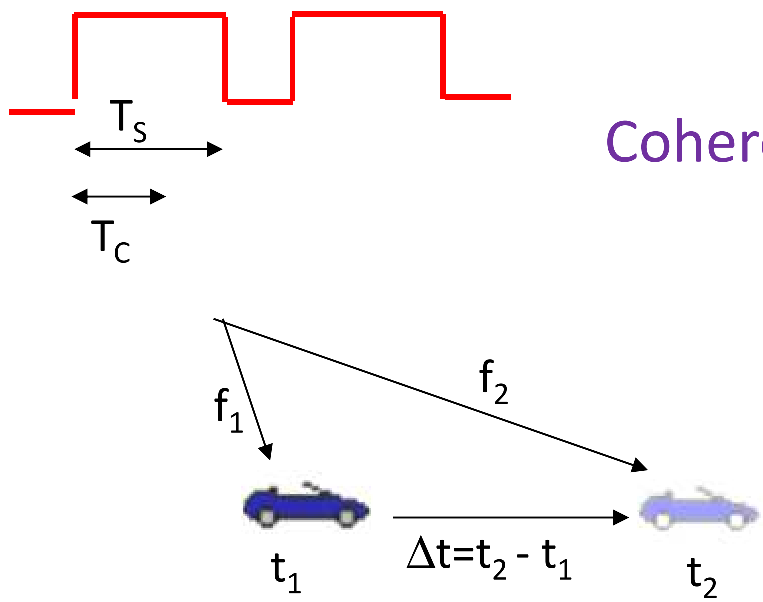
- Time varying nature of channel caused either by relative motion between Tx signal bandwidth B_S and mobile or by motions of objects in channel are categorized by Doppler spread B_D and Coherence time T_c

Doppler Spread

- Measure of spectral broadening caused by motion
- Doppler shift: f_{dv} *has to be computed*
- Doppler spread, B_D, is defined as the maximum Doppler shift: $f_m = v/\lambda$
- If Tx signal bandwidth (B_s) is large such that $B_s >> B_D$ then effects of Doppler spread are not important.
- Hence Doppler spread is only important for low bps (data rate) applications (e.g. paging), slow fading channel.

Coherence Time

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



Coherence time (T_C) is defined as:

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

Coherence Time (contd)

- Coherence time is also defined as:

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

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

Topic 4

Statistical Channel Models

Fading Distributions

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

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

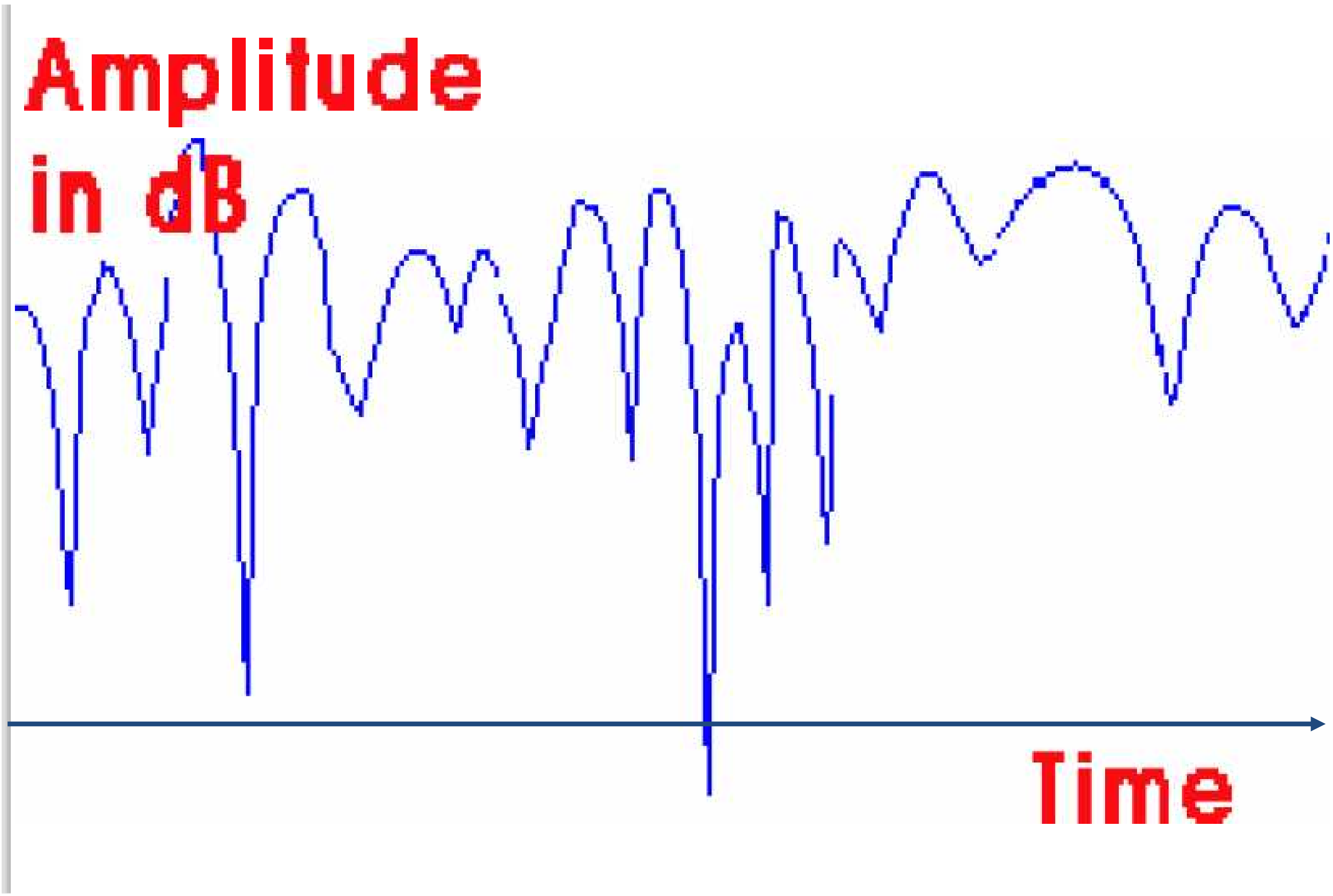
- Its is a statistical characterization of the multipath fading.
- Two distributions
  - – Rayleigh Fading
  - – Rician Fading

Rayleigh & Rician Distributions

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

- Describes the received signal envelope distribution for channels where one of the multipath components is LOS component.
  - i.e. there is one LOS component.

Rayleigh Fading



Rayleigh

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

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

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

Rayleigh (contd)

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

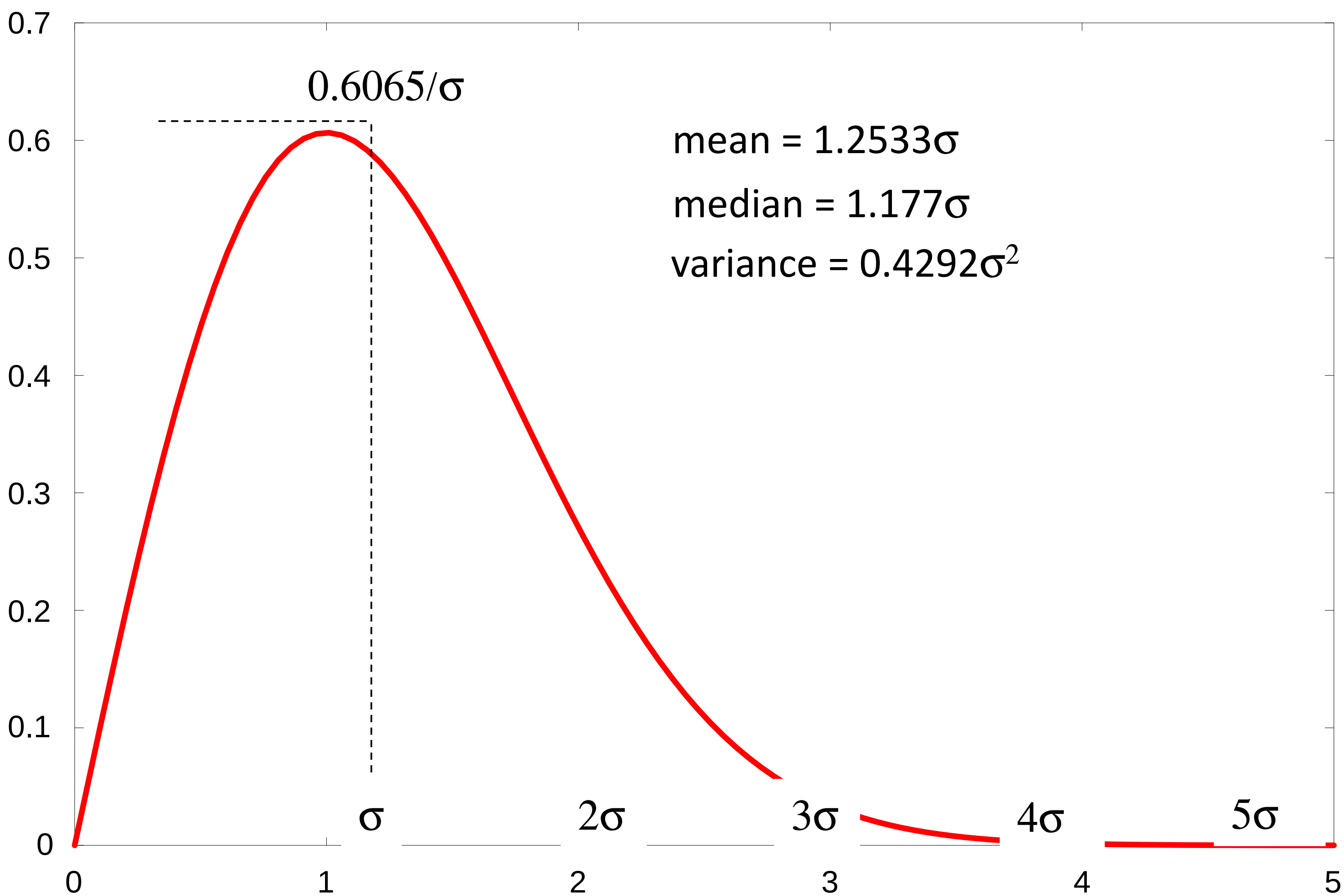
$$P(R) = P_r(r \le R) = \int_0^R p(r)dr = 1 - e^{-\frac{R^2}{2\pm^2}}$$

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

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

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

Rayleigh PDF

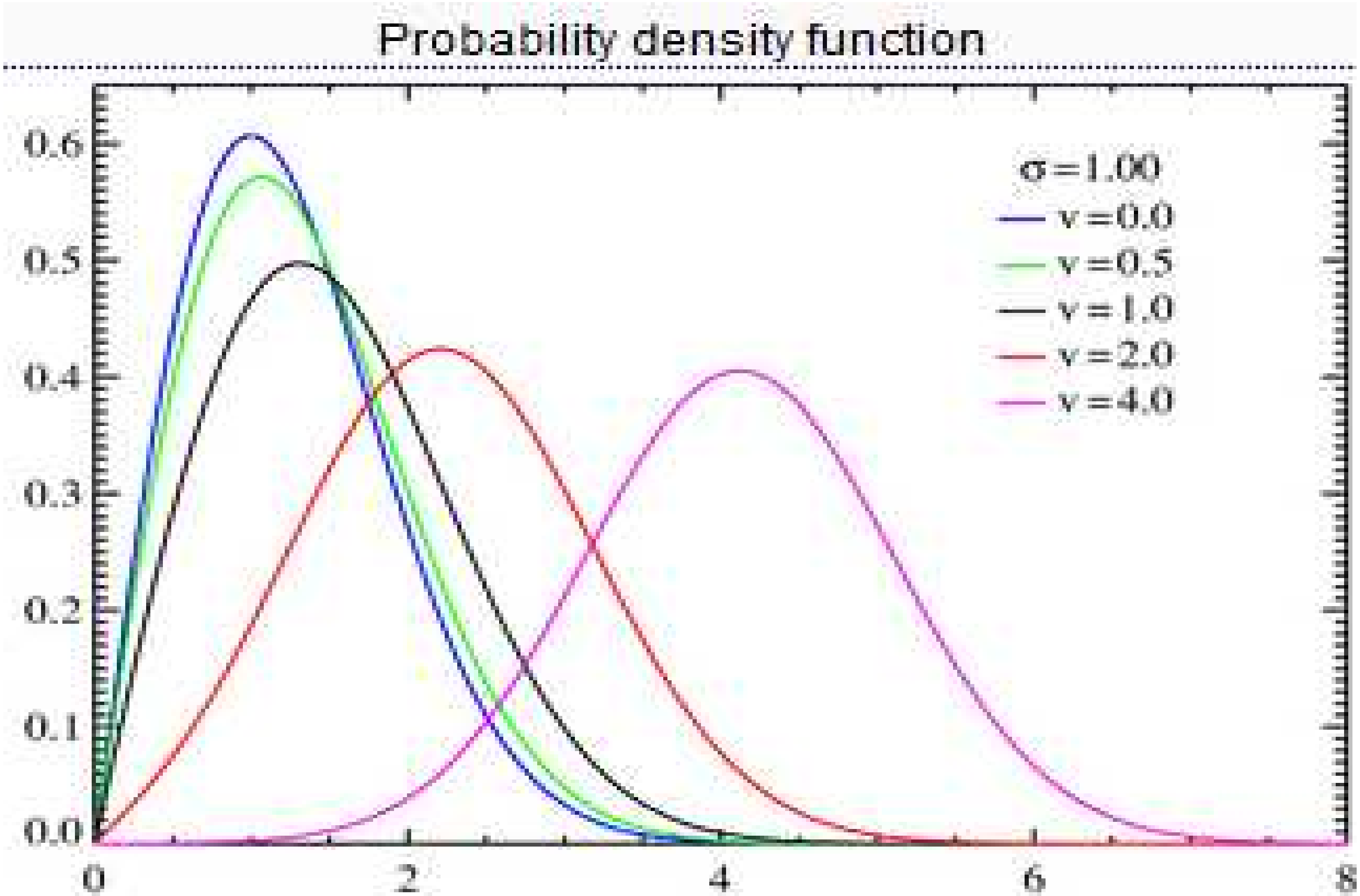


Rician Distribution

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

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

Rician Distribution



Capacity of Wireless Channels

Topic 5

Capacity in AWGN

Introduction

- The growing demand for wireless communication makes it important to determine the capacity limits of these channels.
- These capacity limits indicate the maximum data rates that can be achieved without any constraints on delay or complexity of the encoder & decoder.
- Shannon developed a mathematical theory of communication based on the concept of mutual information between the input & output of a channel.
- Shannon defined capacity as the mutual information maximized over all possible input distributions.
- The significance of this mathematical construct was Shannon's coding theorem.
- The theorem proved that data rate close to capacity can be achieved with negligible probability of error.

Capacity in AWGN

- Consider a discrete-time additive white Gaussian noise (AWGN) channel with channel input / output relationship $y[i] = x[i] + n[i]$, where $x[i]$ is the channel input at time i, $y[i]$ is the corresponding channel output, and $n[i]$ is a white Gaussian noise random process.
- Assume a channel bandwidth B and transmit power S. The channel SNR (the power in $x[i]$ divided by the power in $n[i]$), is constant and given by $\gamma = S / (N_0 B)$, where N_0 is the power spectral density of the noise.
- The capacity of this channel is given by Shannon's well-known formula -

$$C = B \log_2 (1 + \gamma),$$

- where the capacity units are bits/second (bps).

Capacity in AWGN (contd)

- Shannon's coding theorem proves that data rates close to capacity can be achieved with arbitrarily small probability of bit error.
- The theorem shows that any code with rate $R > C$ has a probability of error bounded away from zero.
- The theorems are proved using the concept of mutual information between the input and output of a channel.
- For a memory less time-invariant channel with random input X and random output Y , the channel's mutual information is defined as-

$$I(X;Y) = \sum_{x,y} p(x,y) \log \left(\frac{p(x,y)}{p(x)p(y)} \right)$$

- where the sum is taken over all possible input and output pairs (x, y).

Capacity in AWGN (contd)

- Shannon proved that channel capacity equals the mutual information of the channel maximized over all possible input as-

$$C = \max_{p(x)} I(X;Y) = \max_{p(x)} \sum_{x,y} p(x,y) \log\left(\frac{p(x,y)}{p(x)p(y)}\right)$$

- For AWGN channel, the maximizing input distribution is Gaussian, which results in the channel capacity. For channels with memory, mutual information & channel capacity are defined relative to input and output sequences X^n and Y^n
- Hence Shannon capacity is used as an upper bound on the data rates that can be achieved under real system constraints.

Capacity of Flat Fading Channels

Topic 6

Channel & System Model

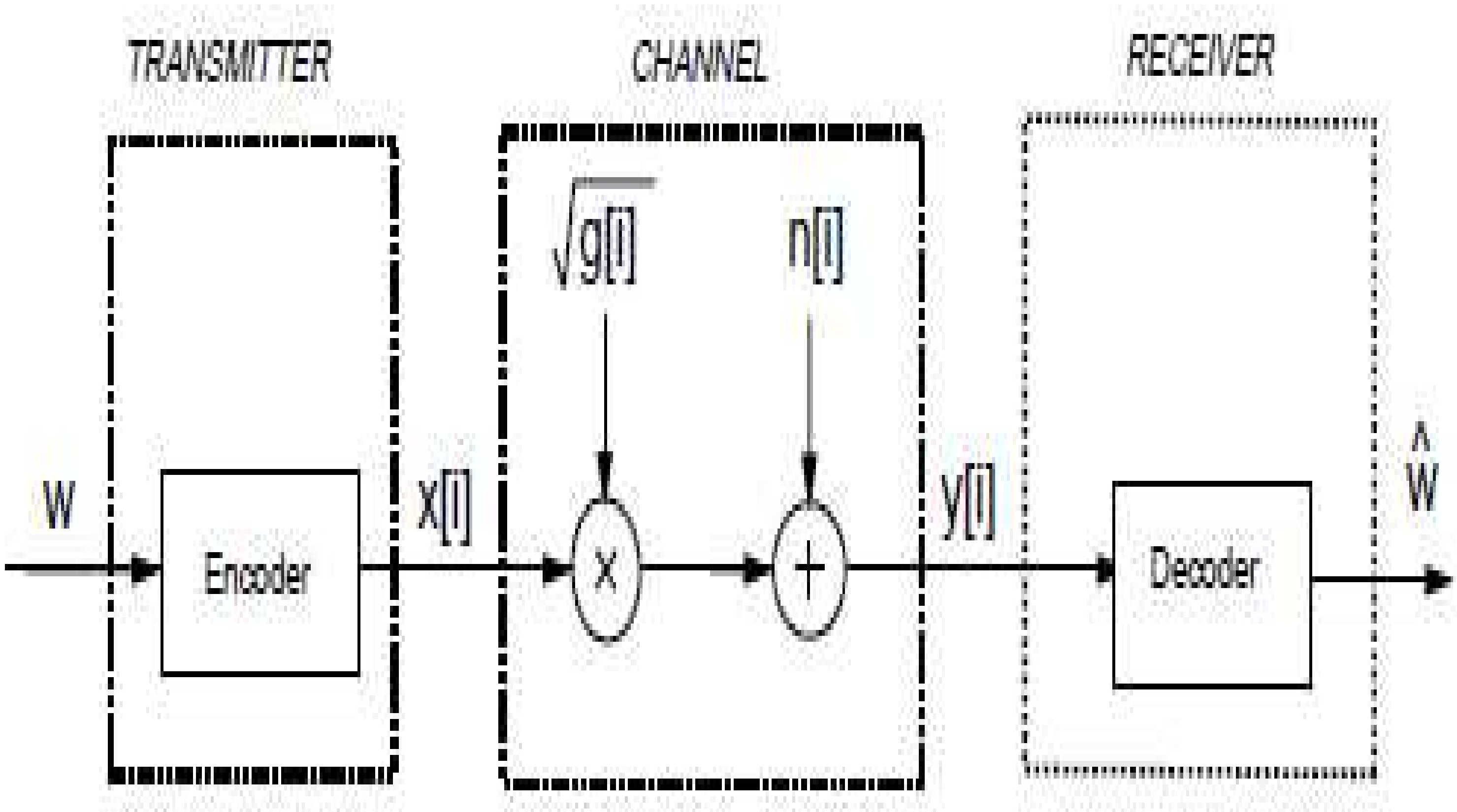
Channel & System Model

- Assume a discrete-time channel with stationary and ergodic time-varying gain $g[i]$ and AWGN $n[i]$, as shown in Figure 1.
- The channel power gain $g[i]$ follows a given distribution $p(g)$.
- Assume that $g[i]$ is independent of the channel input. The channel gain $g[i]$ can change at each time i, with some correlation over time.
- In a block fading channel $g[i]$ is constant over some block length T after which time $g[i]$ changes to a new independent value based on the distribution $p(g)$.
- Let S denote the average transmit signal power, N_0 denote the noise spectral density of $n[i]$, and B denote the received signal bandwidth.

Channel & System Model (contd)

- The instantaneous received signal-to noise ratio (SNR) is then $\gamma[i] = Sg[i] / (N_0B)$. Since $S / (N_0B)$ is a constant, the distribution of $g[i]$ determines the distribution of $\gamma[i]$ and vice versa.
- The system model is also shown in Figure 1, where an input message w is sent from the transmitter to the receiver.
- The message is encoded into the codeword x, which is transmitted over the time-varying channel as $x[i]$ at time i.
- The channel gain $g[i]$, also called the channel side information (CSI), changes during the transmission of code word.

Channel & System Model (contd)



Channel & System Model (contd)

- The capacity of this channel depends on the knowledge of $g[i]$ at the transmitter & receiver.
- Consider three different scenarios regarding this knowledge-
- 1. Channel Distribution Information (CDI): The distribution of $g[i]$ is known to the transmitter and receiver.
- 2. Receiver CSI: The value of $g[i]$ is known at the receiver at time i, and both the transmitter & receiver know the distribution of $g[i]$.
- 3. Transmitter and Receiver CSI: The value of $g[i]$ is known at the transmitter & receiver at time i, and both the transmitter & receiver know the distribution of $g[i]$.
- Transmitter and receiver CSI allows the transmitter to adapt both its power & rate to the channel gain at time i, thus leading to the highest capacity of the three scenarios.

Topic 7

Channel Distribution Information (CDI) Known

Channel Distribution Information Known

- Channel Distribution Information（CDI）provides only the distribution knowledge to the TX and Rx (e.,g Gaussian). The implication of that is related to the capacity achieving strategy.

Channel Distribution Information Known

- Consider the case where channel gain distribution $p(g)$ or the distribution of SNR $p(\gamma)$ is known to the transmitter & receiver.
- For Rayleigh fading the capacity of the channel can be solved by using capacity-achieving input distribution, i.e. the distribution achieving maximum with respect to fading.
- Moreover, fading correlation introduces channel memory, in which capacity-achieving input distribution is found by optimized over input blocks, which makes finding the solution even more difficult.
- For these reasons, finding capacity-achieving input distribution & corresponding capacity of fading channels under CDI remains an open problem for almost all channel distributions.

Channel Distribution Information Known (contd)

- The capacity-achieving input distribution & corresponding fading channel capacity under CDI is known for two specific models of interest:
- Rayleigh fading channels and finite state Markov channels.
- In Rayleigh fading the channel power gain is exponential & changes independently with each channel use.
- The optimal input distribution for this channel was found to be discrete with a finite number of mass points.
- This optimal distribution & its corresponding capacity must be found numerically.
- For flat-fading channels that are not necessarily Rayleigh , upper & lower bounds on capacity have been determined and these bounds are tight at high SNR's.

Channel Distribution Information Known (contd)

- Finite State Markov Channels approximates the fading correlation as a Markov process.
- The Markov nature of fading indicates that fading at a given time depends only on fading at the previous time sample.
- Hence the receiver must decode all past channel outputs jointly with the current output for optimal decoding.
- This complicates capacity analysis in a significant manner.
- The capacity of Finite State Markov channels can be computed for Rayleigh inputs and for general inputs separately.

Channel Distribution Information Known (contd)

- Channel capacity in both cases depends on the limiting distribution of the channel on all past inputs and outputs, which can be computed recursively.

- As with Rayleigh fading channel, the complexity of the capacity analysis along with the final result is very high.

- It indicates the difficulty of obtaining the capacity of channels when only CDI is available.

Thank You

Topic 8

Channel Side Information at the Receiver (CSI)

In wireless communications, **CSI** refers to known **channel** properties of a communication link. This **information** describes how a signal propagates from the transmitter to the **receiver** and represents the combined effect of, for example, scattering, fading, and power decay with distance.

Channel Side Information at the Receiver (CSI)

- Consider the case where $g[i]$ & $\gamma[i]$ is known at the receiver at time i.
- Assume that both the transmitter & receiver know the distribution of $g[i]$.
- In this case there are two definitions for channel capacity relevant to system design - Shannon capacity (ergodic capacity) & capacity with outage.
- Shannon capacity defines the maximum data rate that can be sent over the channel with small error probability for a AWGN channel.

Channel Side Information at the Receiver (CSI)

- For Shannon capacity the rate transmitted over the channel is constant - the transmitter cannot adapt its transmission strategy relative to CSI.

- Thus, poor channel states reduce Shannon capacity since the transmission strategy must incorporate the effect of these poor states.

Channel Side Information at the Receiver (contd)

- Capacity with outage is the maximum rate that can transmitted over a channel with some outage probability corresponding to the probability that the transmission cannot be decoded with negligible error probability.

- The basic concept of capacity with outage is - a high data rate can be sent over the channel & decoded correctly except when the channel is in deep fading.

- By allowing the system to lose some data due to deep fading, a higher data rate can be maintained than receiving all data correctly regardless of the fading state.

- The probability of outage represents the probability of data loss or equivalently of deep fading.

Shannon (Ergodic Capacity)

- Shannon capacity of a fading channel with receiver CSI can be obtained as –

$$C = \int_0^\infty B \log_2(1+\gamma) p(\gamma) d\gamma.$$

- The above formula is a probabilistic average - Shannon capacity is equal to Shannon capacity for an AWGN channel with SNR γ, given by $B \log_2(1 + \gamma)$, averaged over the distribution of γ.

- Hence Shannon capacity is also called Ergodic capacity.

- This average capacity is achieved by maintaining a capacity $B \log_2(1 + \gamma)$ when the instantaneous SNR is γ, since only the receiver knows the instantaneous SNR $\gamma[i]$, and a constant data rate transmitted over the channel.

Shannon (Ergodic Capacity)

- By Jensen's inequality,

$$E[B\log_2(1+\gamma)] = \int B\log_2(1+\gamma)p(\gamma)d\gamma \le B\log_2(1+E[\gamma]) = B\log_2[1+\bar{\gamma}],$$

where $\bar{\gamma}$ is the average SNR on the channel.

- Thus Shannon capacity of a fading channel with receiver CSI is less than the Shannon capacity of an AWGN channel with same average SNR.

- In other words, fading reduces Shannon capacity when only the receiver has CSI.

Capacity with Outage

- Capacity with outage applies to slowly-varying channels, where instantaneous SNR is constant over a transmission burst & then changes to a new value based on fading distribution.

- If the channel has received SNR γ during a burst, then data can be sent over the channel at rate $B \log_2 (1 + \gamma)$ with negligible probability of error.

- Since the transmitter does not know the SNR value γ, it must fix a transmission rate independent of the instantaneous received SNR.

- Specifically, the transmitter fixes a minimum received SNR γ_{min} & encodes for a data rate $C = B \log_2 (1 + \gamma_{min})$.

- The data is correctly received if the instantaneous received SNR is greater than or equal to γ_{min}.

Capacity with Outage (contd)

- If the received SNR is below γ_{min} then bits received over the transmission burst cannot be decoded correctly & the receiver declares an outage.

- The probability of outage is thus $p_{out} = p\ (\gamma < \gamma_{min})$.

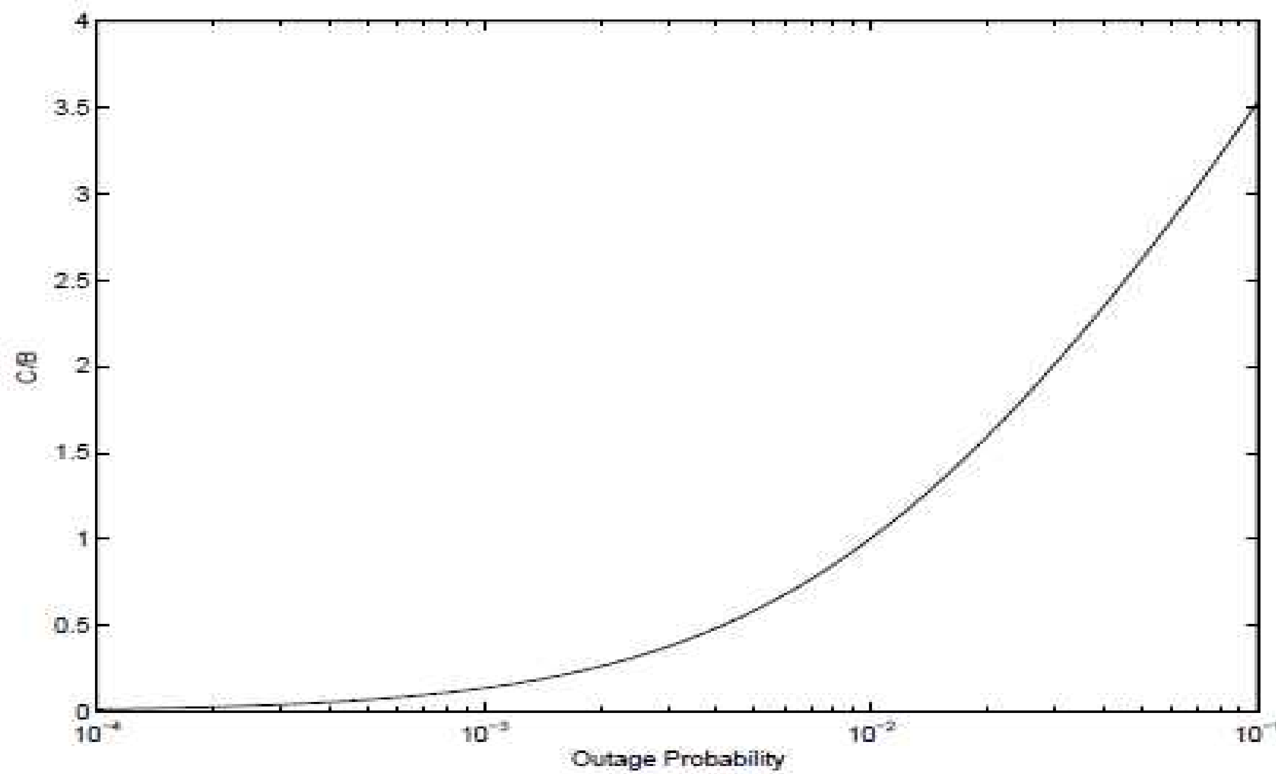
- The average rate received over many transmission bursts is $C_o = (1 - p_{out})\ B \log_2 (1 + \gamma_{min})$ since data is only correctly received on $1 - p_{out}$ transmissions.

- The value of γ_{min} is typically a design parameter based on the acceptable outage probability.

- In this plot the normalized capacity $C/B = \log_2 (1+\gamma_{min})$ as a function of outage probability $p_{out} = p\ (\gamma < \gamma_{min})$ for a Rayleigh fading channel with $\bar{\gamma}$ = 20 dB.

Capacity with Outage (contd)

- Here capacity approaches zero for small outage probability to correctly decode bits transmitted under severe fading & increases dramatically as outage probability increases.
- However these high capacity values for large outage probabilities have higher probability of incorrect data reception.



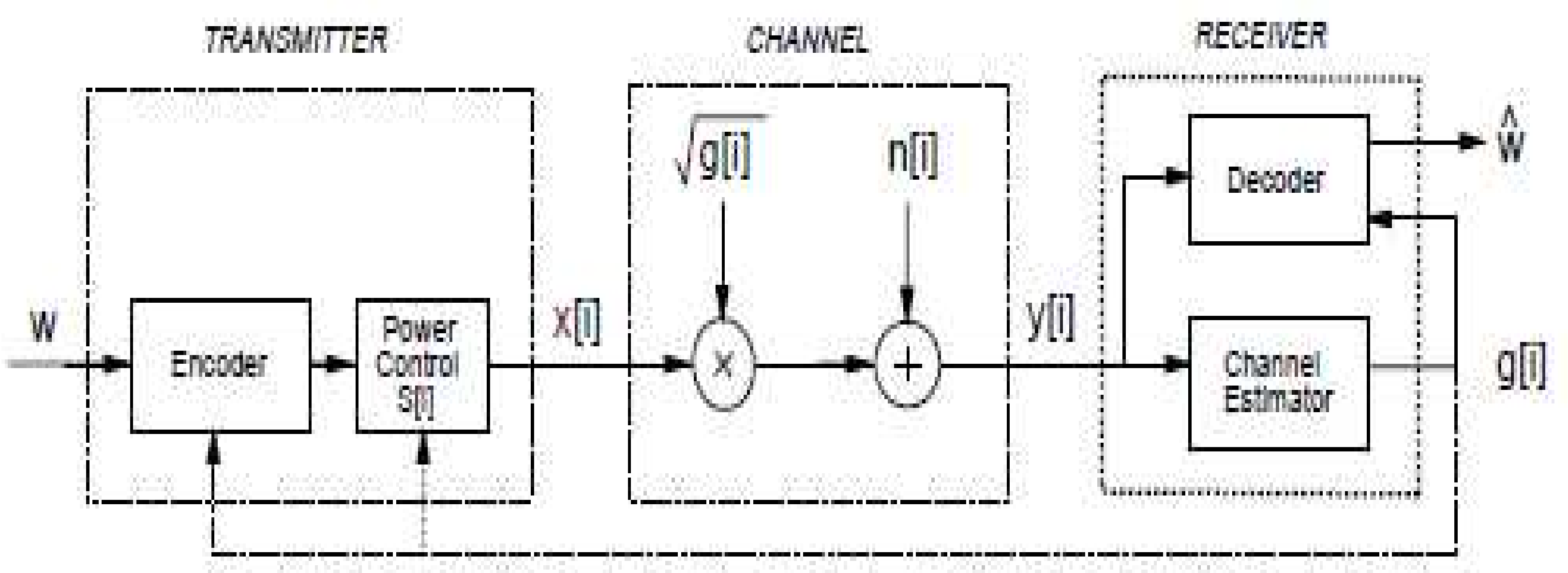
Thank You

Topic 9

Channel Side Information at Transmitter & Receiver

Introduction

- When both the transmitter & receiver have CSI, the transmitter can adapt its transmission strategy as shown in Figure.
- There is no concept of capacity with outage where the transmitter sends bits that cannot be decoded.
- Since transmitter knows the channel, it will not send bits unless they can be decoded correctly.



Shannon Capacity

- Consider the Shannon capacity when the channel power gain $g[i]$ is known to both the transmitter & receiver at time i.

- Let $s[i]$ be a stationary & ergodic stochastic process representing the channel state which takes a finite set 'S' of discrete memory less channels.

- Let C_s denote the capacity of a particular channel & $p(s)$ denote the probability or fraction of time

.

- The capacity of this tim $C = \sum_{s \in S} C_s p(s).$ then given by –

- The capacity of an AWGN channel with average received SNR γ is $C_\gamma = B \log_2 (1 + \gamma)$.

- Let $p(\gamma) = p\ (\gamma[i] = \gamma)$ denote the probability distribution of the received SNR.

Shannon Capacity (contd)

- The capacity of the fading channel with transmitter and receiver side information is –

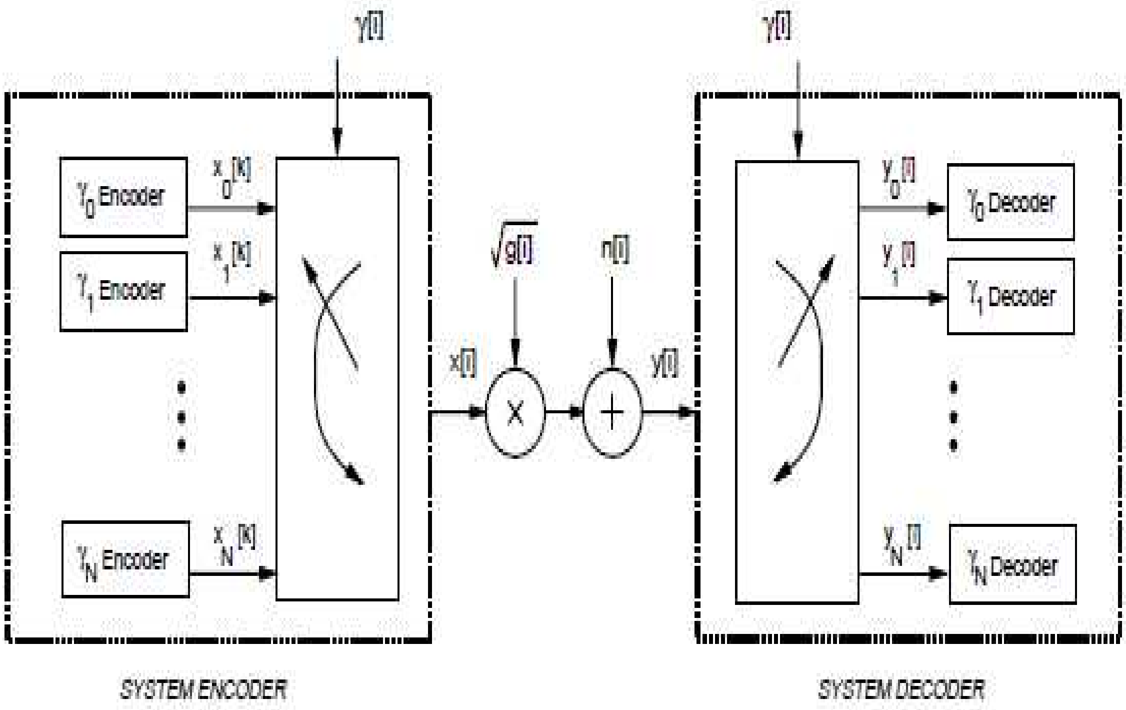
$$C = \int_0^\infty C_\gamma p(\gamma)d\gamma = \int_0^\infty B\log_2(1+\gamma)p(\gamma)d\gamma.$$

- Allowing the transmit power S(γ) to vary with γ, subject to an average power constraint $\overline{S}$: and defining the fading channel capacity as –

$$C = \max_{S(\gamma):\int S(\gamma)p(\gamma)d\gamma=\overline{S}} \int_0^\infty B\log_2\left(1+\frac{S(\gamma)\gamma}{\overline{S}}\right)p(\gamma)d\gamma.$$

- The capacity given above can be achieved & any rate larger than this capacity has probability of error bounded away from zero.
- The main idea is a "time diversity" system with multiplexed input & de-multiplexed output as shown in Figure .

Time Diversity System



- Time diversity implies that the same data is transmitted multiple times, or a redundant error correcting code is added. By means of bit-interleaving, the error bursts may be spread in time.

- **Time Diversity** is used in digital communication systems to combat that the transmissions channel may suffer from error bursts due to time-varying channel conditions.
- The error bursts may be caused by fading in combination with a moving receiver, transmitter or obstacle, or by irregular electromagnetic interference, for example from crosstalk in a cable, or co-channel interference from radio transmitters.

Time Diversity System

- The range of fading values are quantized to a finite set $\{\gamma_j : 1 \le j \le N\}$.
- For each γ_j , an encoder/decoder pair designed for an AWGN channel with SNR γ_j .
- The input x_j for encoder γ_j has average power $S(\gamma_j)$ and data rate $R_j \approx C_j$, where C_j is the capacity of a time-invariant AWGN channel with received SNR.
- These encoder/decoder pairs correspond to a set of input & output ports associated with each γ_j .
- The code words associated with each γ_j are multiplexed together for transmission & de-multiplexed at the channel output.
- This effectively reduces the time-varying channel to a set of time-invariant channels in parallel.

Zero Outage Capacity

- Consider a transmitter adaptation scheme where transmitter uses the CSI to maintain a constant received power, i.e., it inverts the channel fading.
- The channel then appears to the encoder & decoder as a time-invariant AWGN channel.
- This power adaptation called channel inversion, is given by $S(\gamma)/\overline{S} = \sigma/\gamma$, where σ equals the constant received SNR that can be maintained with the transmit power constraint.
- Channel capacity with inversion is just the capacity of an AWGN channel given by -

$$C = B\log_2[1+\sigma] = B\log_2\left[1+\frac{1}{\mathbf{E}[1/\gamma]}\right].$$

Zero Outage Capacity (contd)

- The transmission strategy for this capacity uses a fixed-rate encoder & decoder designed for an AWGN channel with SNR σ.
- This has advantage of maintaining a fixed data rate over the channel regardless of channel conditions.
- For this reason the channel capacity is called zero-outage capacity, since the data rate is fixed under all channel conditions & there is no channel outage.
- It is the simplest scheme to implement, since the encoder & decoder designed for an AWGN channel, independent of the fading statistics.

Outage Capacity & Truncated Channel Inversion

- The zero-outage capacity may be significantly smaller than Shannon capacity on a fading channel - the requirement to maintain a constant data rate in all fading states.
- By suspending transmission in bad fading states (outage channel states), a higher constant data rate can be maintained in the other states & thereby significantly increase capacity.
- Outage capacity is defined as the maximum data rate that can be maintained in all non-outage channel states times the probability of non-outage.
- Outage capacity is achieved with a truncated channel inversion policy for power adaptation that only compensates for fading above a certain cut-off fade depth γ_0.

$$\frac{S(\gamma)}{\overline{S}} = \begin{cases} \frac{\sigma}{\gamma} & \gamma \geq \gamma_0 \\ 0 & \gamma < \gamma_0 \end{cases}$$

Outage Capacity & Truncated Channel Inversion (contd)

- where γ_0 is based on the outage probability: $p_{out} = p\,(\gamma < \gamma_0)$.
- The outage capacity associated with a given outage probability p_{out} & corresponding cut-off γ_0 is given by -

$$C(p_{out}) = B \log_2 \left(1 + \frac{1}{\mathbf{E}_{\gamma_0}[1/\gamma]}\right) p(\gamma \geq \gamma_0).$$

- The maximum outage capacity can be obtained by maximizing outage capacity over all possible γ_0

$$C = \max_{\gamma_0} B \log_2 \left(1 + \frac{1}{\mathbf{E}_{\gamma_0}[1/\gamma]}\right) p(\gamma \geq \gamma_0).$$

- This maximum outage capacity will be less than Shannon capacity since truncated channel inversion is a sub-optimal transmission strategy.
- However, the transmit & receive strategies associated with truncated inversion may be easier to implement or have lower complexity compared to the water-filling schemes associated with Shannon capacity.

Thank You

Topic 10

Capacity with Receiver Diversity

Capacity with Receiver Diversity

- Receiver diversity is a well-known technique to improve the performance of wireless communications in fading channels.
- The main advantage of receiver diversity - it moderates the fluctuations due to fading so that the channel appears more like an AWGN channel.
- Since receiver diversity moderates the impact of fading, an interesting question is whether it will increase the capacity of a fading channel.
- The capacity calculation under diversity combining first requires that the distribution of the received SNR under the given diversity combining technique be obtained.
- Once this distribution is known it can be substituted into any of the capacity formulas to obtain the capacity under diversity combining.

Capacity with Receiver Diversity (contd)

- The specific capacity formula used depends on the assumptions about channel side information.
- For example, in case of perfect transmitter & receiver CSI the following formula can be used.

$$C = \int_{\gamma_0}^{\infty} B \log_2 \left(\frac{\gamma}{\gamma_0} \right) p(\gamma) d\gamma.$$

- The capacity with perfect transmitter & receiver CSI is bigger than with receiver CSI only, which in turn bigger than with channel inversion.
- The performance gap of these different formulas decreases as the number of antenna branches increases.
- Since a large number of antenna branches makes the channel look like AWGN, for which all different capacity formulas have roughly the same performance.

Capacity with Receiver Diversity (contd)

- Recently there has been much research activity on systems with multiple antennas at both the transmitter & the receiver.
- Indications show that the capacity of a fading channel with multiple inputs & outputs (a MIMO channel) is n times larger then the channel capacity without multiple antennas.
- Where $n = \min(n_t, n_r)$ for n_t the number of transmit antennas & n_r the number of receive antennas.

Thank You

Topic 11

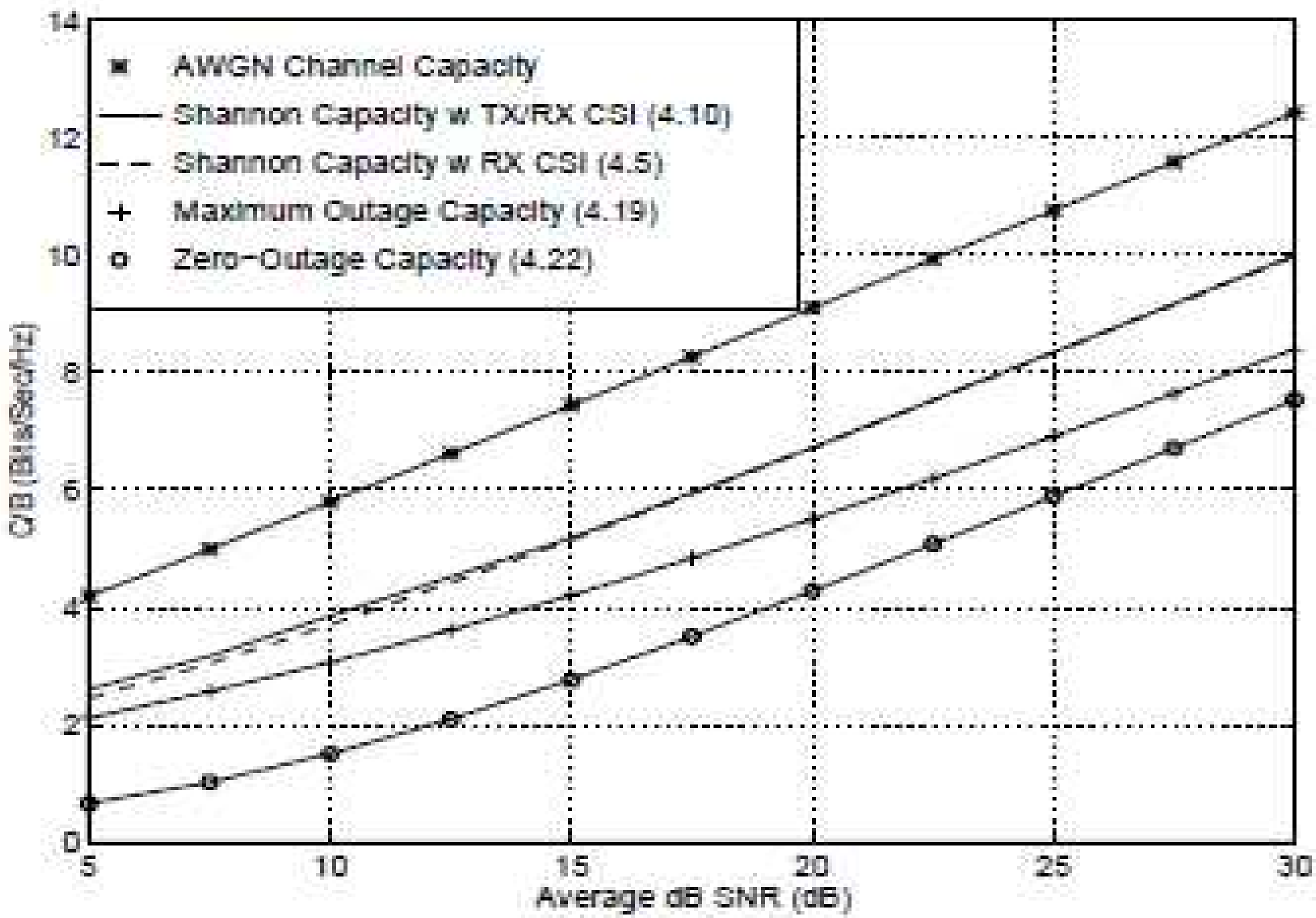
Capacity Comparisons

Capacity Comparisons

- The capacity with transmitter & receiver CSI for different power allocation policies is compared with the capacity under receiver CSI only.
- Figures 1, 2 & 3 show plots of different capacities as a function of average received SNR for log-normal fading ($\sigma = 8$ dB standard deviation), Rayleigh fading, & Nakagami fading (Nakagami parameter $m = 2$).
- The capacity in AWGN for the same average power is also shown for comparison.
- From the plots, the capacity of AWGN channel is larger than that of fading channel for all cases.
- However, at low SNRs the AWGN & fading channel with transmitter and receiver CSI have almost the same capacity.

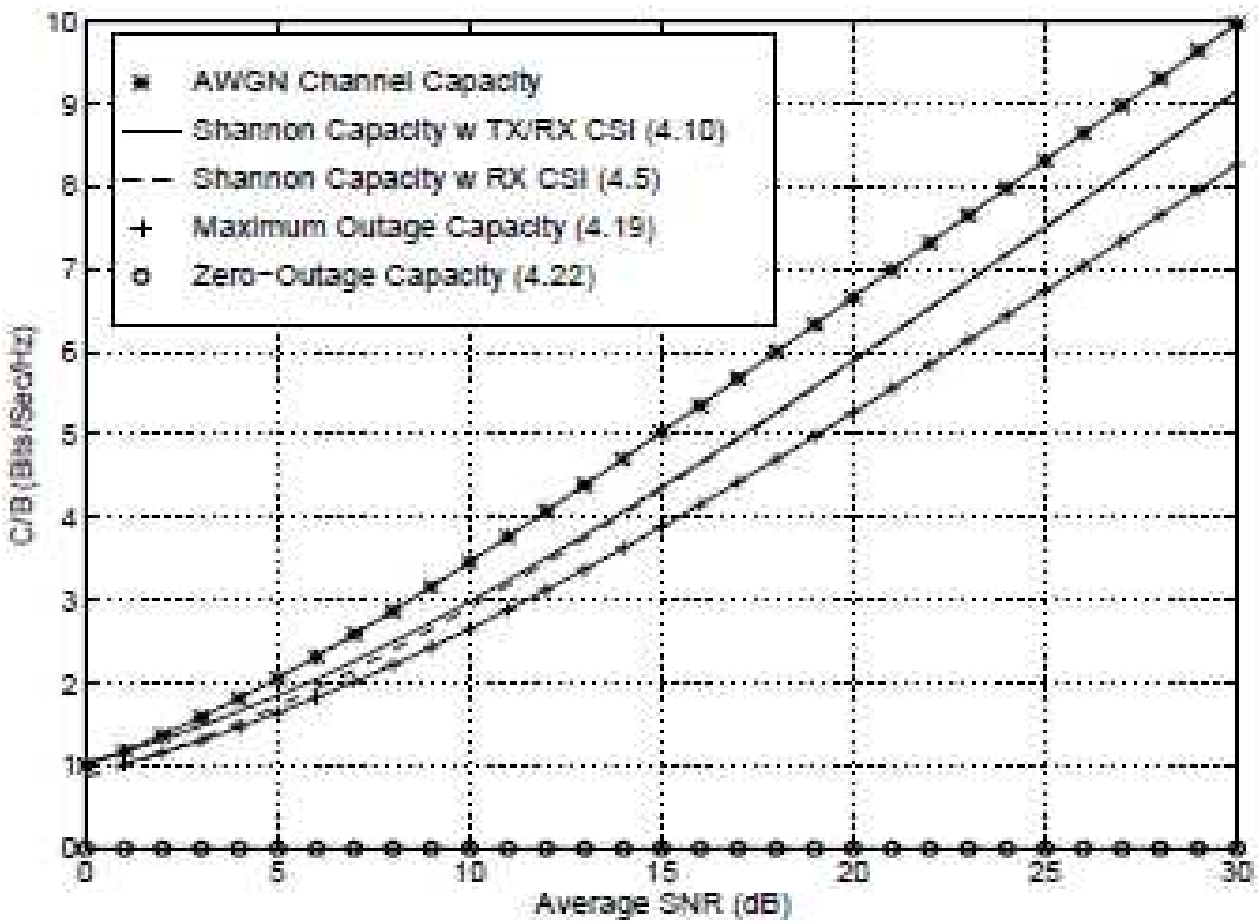
Capacity Comparisons

Figure 1. Capacity in Log Normal Shadowing



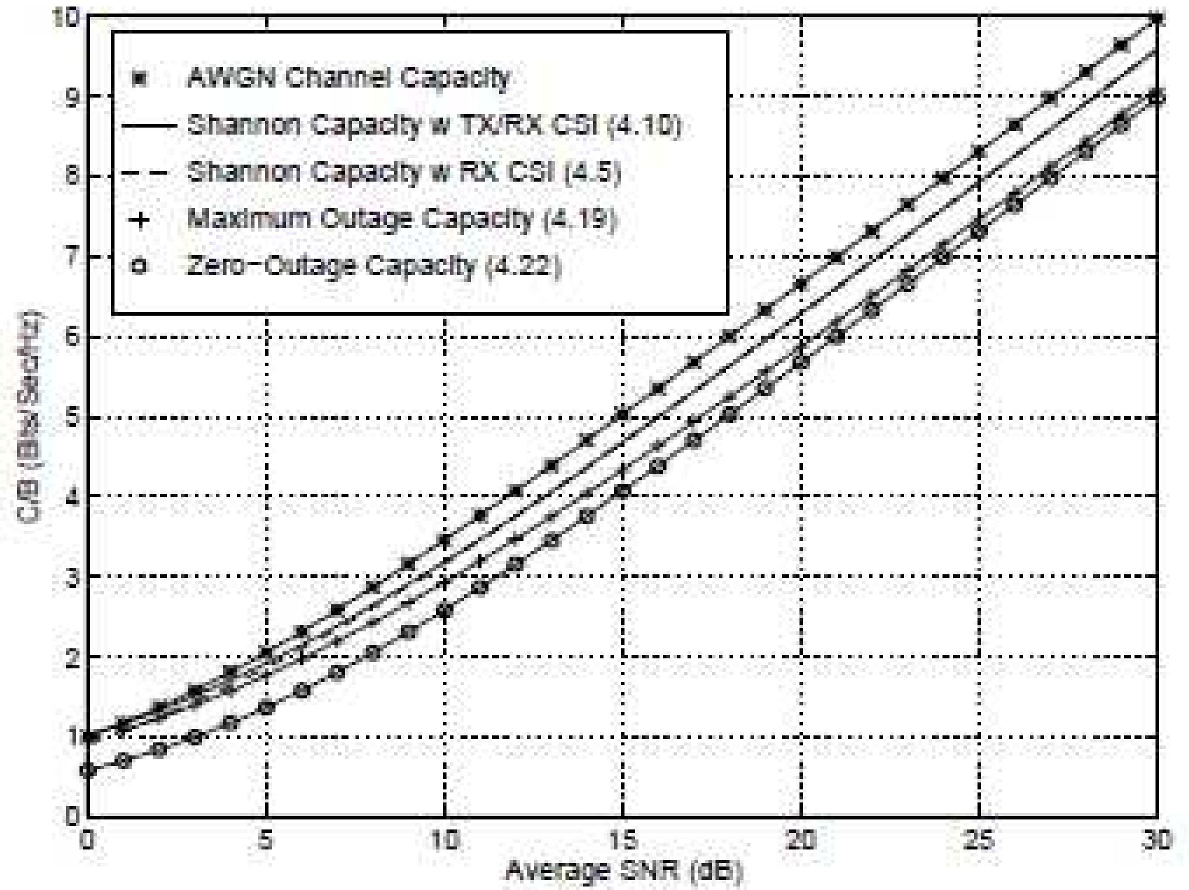
Capacity Comparisons

Figure 2. Capacity in Rayleigh Fading



Capacity Comparisons

Figure 3. Capacity in Nakagami Fading (m = 2)



AWGN channel capacity

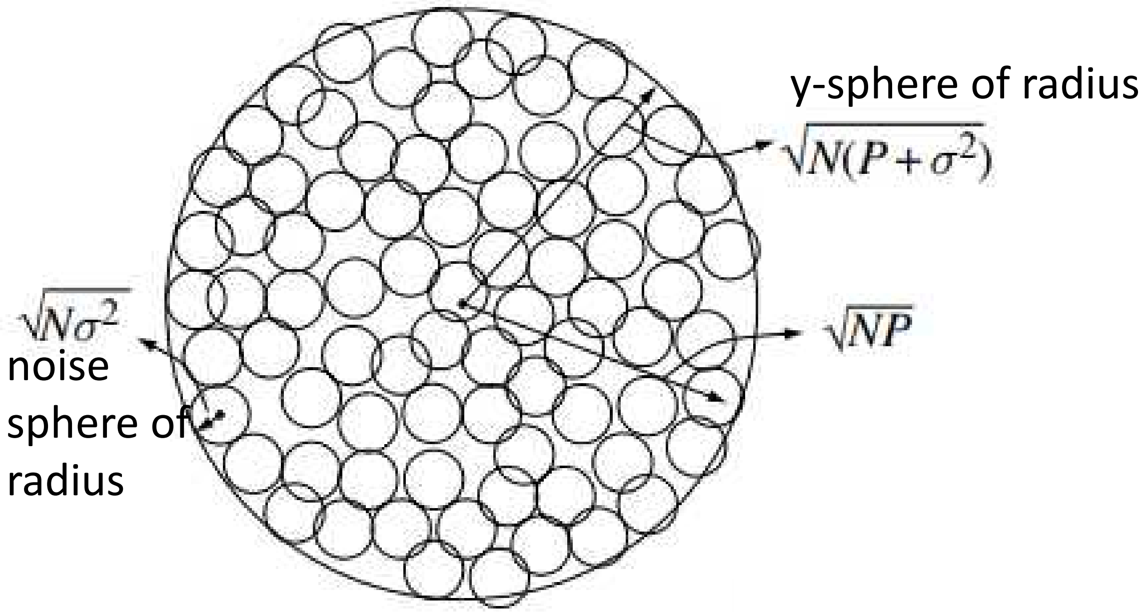


Figure . The number of noise spheres that can be packed into the *y*-sphere yields the maximum number of codewords that can be reliably distinguished.

- Power constraint of **P** joules/symbol
- Block length **N**
- Noise variance σ^2

- The capacity of the (real) AWGN channel with power constraint P and noise variance σ^2 is

$$C_{\text{awgn}} = \frac{1}{2}\log\left(1+\frac{P}{\sigma^2}\right),$$

Capacity Comparisons

- At low SNRs (below 0 dB), capacity of the fading channel with transmitter & receiver CSI is larger than corresponding AWGN channel capacity.
- Because the AWGN channel always has the same low SNR, thereby limiting it capacity.
- A fading channel with this same low average SNR will occasionally have a high SNR, since the distribution has infinite range.
- Hence if all power and rate is transmitted over the channel during these infrequent high SNR values, the capacity will be larger than that of AWGN channel with the same low average SNR.
- Comparing Figures 2 and 3 - as the severity of the fading decreases (Rayleigh to Nakagami with $m = 2$), the capacity difference between the various adaptive policies also decreases & their respective capacities approach that of AWGN channel.

Capacity Comparisons

- The difference between the capacity curves under transmitter and receiver CSI / receiver CSI only are negligible in all cases.
- When the transmission rate is adapted relative to the channel and adapting the power yields a negligible capacity gain.
- The transmitter adaptation yields a negligible capacity gain relative to using only receiver side information.
- In severe fading conditions (Rayleigh and log-normal fading), maximum outage capacity exhibits a 1-5 dB rate penalty and zero-outage capacity yields a large capacity loss relative to Shannon capacity.
- In mild fading conditions (Nakagami with m = 2) the maximum outage and zero-outage capacities are within 3 dB of each other and within 4 dB of the AWGN channel capacity.

Capacity Comparisons

- These differences will further decrease as the fading diminishes ($m \rightarrow \infty$ for Nakagami fading).
- The adaptive policy with transmitter & receiver side information requires more complexity in the transmitter.
- However, the decoder in the receiver is relatively simple.
- The non-adaptive policy has a simple transmission scheme, but its code design must use the channel correlation statistics & the decoder complexity is proportional to channel de-correlation time.
- The channel inversion & truncated inversion policies use codes designed for AWGN channels, and are least complex to implement, but in severe fading conditions they exhibit large capacity losses relative to the other techniques.

Thank You

Topic 12

Capacity of Frequency Selective Fading Channels

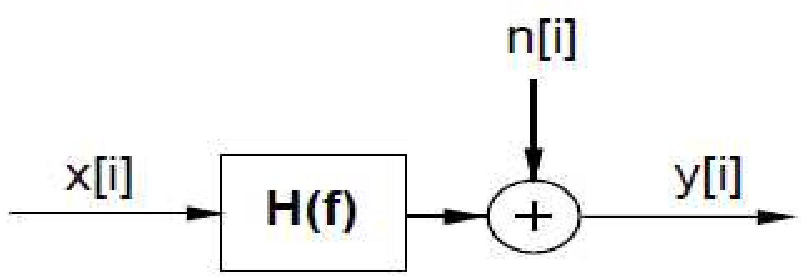
Time Invariant Channels

Time Invariant Channels

- Consider a time-invariant channel with frequency response H(f), with a transmit power constraint S, as shown in Figure 1.
- When the channel is time-invariant, then H(f) is known at both the transmitter and receiver.
- Assume that H(f) is block-fading, so that frequency is divided into sub-channels of bandwidth B, where H(f) = H_j is constant over each block as shown in Figure 2.
- Thus the frequency-selective fading channel consists of a set of AWGN channels in parallel with SNR $|H_j|^2 S_j / (N_0 B)$ on the j^{th} channel, where S_j is the power allocated to the j^{th} channel in this parallel set.
- Figure 1

  Time Invariant Frequency

  Selective Fading



Time Invariant Channels (contd)

- The capacity of this parallel set of channels is the sum of rates associated with each channel with power optimally allocated over all channels.

$$C = \sum_{\max S_j : \sum_j S_j \leq S} B \log_2 \left(1 + \frac{|H_j|^2 S_j}{N_0 B}\right).$$

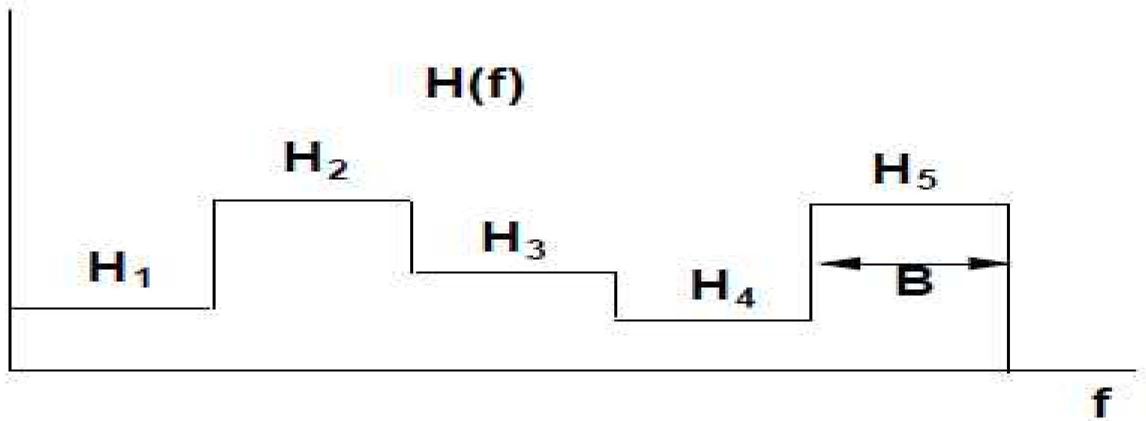


Figure 2. Block Frequency Selective Fading

- This is similar to the capacity & optimal power allocation for a flat-fading channel, with power & rate changing over frequency in a deterministic way.

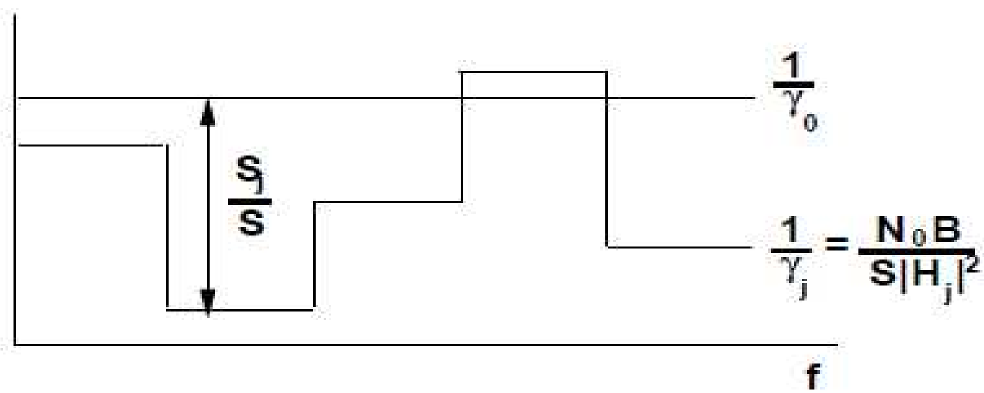
Time Invariant Channels (contd)

- The optimal power allocation is found via the same Lagrangian technique used in flat-fading which leads to the water-filling power allocation.

$$\frac{S_j}{S} = \begin{cases} \frac{1}{\gamma_0} - \frac{1}{\gamma_j} & \gamma_j \geq \gamma_0 \\ 0 & \gamma_j < \gamma_0 \end{cases}$$

- for some cutoff value γ_0, where $\gamma_j = |H_j|^2 S / (N_0 B)$ is the SNR associated with the j^{th} channel assuming the entire power budget allocated.
- This optimal power allocation is illustrated in

Figure 3 - Water-Filling in Block Frequency-Selective Fading



Time Invariant Channels (contd)

- The capacity of the channel becomes –

$$C = \sum_{j:\gamma_j \geq \gamma_0} B \log_2(\gamma_j/\gamma_0).$$

- This capacity is achieved by sending at different rates and powers over each sub-channel.

Capacity of Frequency Selective Fading Channels

Time Varying Channels

Time Varying Channels

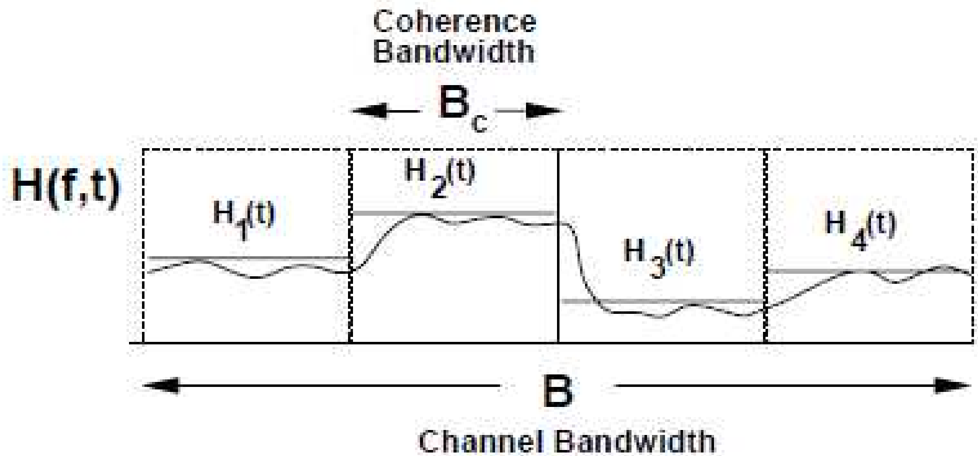
- The time-varying frequency-selective fading channel is similar to time invariant model except that H(f) = H(f, i), i.e. the channel varies over both frequency and time.
- It is difficult to determine the capacity of time-varying frequency-selective fading channels, even when the instantaneous channel H(f, i) is known perfectly at the transmitter & receiver, due to impact of ISI.
- In the case of transmitter & receiver side information, the optimal adaptation scheme must consider the effect of the channel on the past sequence of transmitted bits & the impact of ISI on future transmissions.
- The capacity of time-varying, frequency-selective fading channels is generally unknown, but upper and lower bounds & limiting formulas can be calculated.

Time Varying Channels (contd)

- Assume the channel bandwidth B of interest & divide into sub-channels the size of the channel coherence bandwidth B_c, as shown in Figure 1.
- Assume that each of the resulting sub-channels is independent, time-varying & flat-fading with $H(f, i) = H_j[i]$ on the j^{th} sub-channel.

Figure 1

Channel Division



- The total channel capacity is just equal to the sum of capacities on the individual narrowband flat-fading channels subject to the total average power constraint, averaged over both time and frequency.

$$C = \max_{\{\overline{S}_j\}: \sum_j \overline{S}_j \leq \overline{S}} \sum_j C_j(\overline{S}_j),$$

Time Varying Channels (contd)

- The optimal average power to be allocated to each sub-channel should follow a water-filling, where more average power is allocated to better sub-channels.
- Thus the optimal power allocation is a two-dimensional water-filling in both time & frequency.
- The Shannon capacity with perfect transmitter & receiver CSI is given by optimizing power adaptation relative to both time and frequency as -

$$C = \max_{S_j(\gamma_j):\sum_j \int_0^\infty S_j(\gamma_j)p(\gamma_j)d\gamma_j \le \overline{S}} \sum_j \int_0^\infty B_c \log_2\left(1 + \frac{S_j(\gamma_j)\gamma_j}{\overline{S}}\right) p(\gamma_j)d\gamma_j.$$

- The Lagrangian expressions are applied to find the optimal power allocation & the equation for capacity becomes –

$$C = \sum_j \int_{\gamma_0}^\infty B_c \log_2\left(\frac{\gamma_j}{\gamma_0}\right) p(\gamma_j)d\gamma_j.$$

Thank You

Model Question Bank

Unit - I

1. How does a wire channel differ from wireless channel?

Specifications	Wire Channel	Wireless Channel
Speed of Operation	High	Lower compare to wired networks.
System Bandwidth	High	Low as Frequency Spectrum is very scarce resource
Cost	Less as cables are not expensive	More as wireless subscriber stations, wireless routers, wireless access points etc
Installation	Wired network installation is cumbersome and it requires more time	Wireless network installation is easy and it requires less time
Mobility	Limited, as it operates in the area covered by connected systems with the wired network	Not limited, as it operates in the entire wireless network coverage
Transmission Medium	copper wires, optical fiber cables, Ethernet	EM waves or radio waves or infrared
Applications	requires hubs and switches for network coverage extension	More area covered by wireless base stations connected to one another.
Channel Interference	Interference is less as one wired network will not affect the other	Interference is higher due to obstacles between wireless transmitter and receiver
Quality of Service	Better	Poor due to high value of jitter and delay in connection setup
Reliability	High compare to wireless counterpart.	Reasonably high. This is due to failure of router will affect the entire network.

Part A

- 2. What is called Fading?

  In wireless communications, fading is variation of the attenuation of a signal with time, geographical position, and radio frequency. Fading is often modeled as a random process. A fading channel is a communication channel that experiences fading.

- 3. Mention the types of Fading.

  Large Scale Fading and Small Scale Fading – further divided into (i) Frequency selective fading and (ii) Flat Fading.

Part A

- 4. What is ISI?

  In telecommunication, I**nter symbol interference** (**ISI**) is a form of distortion of a signal in which one symbol interferes with subsequent symbols. This is an unwanted phenomenon, thus making the communication less reliable.

- 5. Define Doppler Shift.

  The **Doppler Effect** (or the **Doppler shift**) is the change in frequency or wavelength of a wave for an observer moving relative to its source.

Part A

- 6. Mention the physical parameters which affect the wireless channel.
  - carrier frequency
  - mobile speed
  - bandwidth
  - delay spread
  - angular spread

Part A

- 7. Differentiate between Large Scale Fading and Small Scale Fading

Large Scale Fading	Small Scale Fading
Long term variation in the mean signal level caused by the mobile unit moving into the shadow of surrounding objects	Short term fluctuation in the signal amplitude caused by the local multipath

Part A

- 8. Define Delay Spread.

  In telecommunications, the **delay spread** is a measure of the multipath richness of a communications channel. The delay spread is the variation in the propagation delays of multiple scattered rays.

Part A

- 9. Differentiate between Flat Fading and Frequency Selective Fading.

Flat Fading	Frequency Selective Fading
Being flat if the received multipath components of a symbol do not extend beyond the symbol's time duration	Being frequency selective if the received multipath components of a symbol extend beyond the symbol's time duration
Inter symbol Interference Absent	ISI present
Spectral Characteristics of transmitted signal preserved at the receiver	Spectral Characteristics of transmitted signal not preserved at the receiver
Symbol Bandwidth (Bs) less than the Coherence Bandwidth (Bc)	Symbol Bandwidth (Bs) greater than the Coherence Bandwidth (Bc)

Part A

- 10. Give the statement of Central Limit Theorem.

The **central limit theorem** (CLT) states that given a large sample size from a population with a finite level of variance, the mean of all samples from the same population will be approximately equal to the mean of the population.

11. Differentiate between Rayleigh Model and Rician Model for fading.

Rayliegh Model	Rician Model
Commonly used to describe the statistical time varying nature of the received envelope of a flat fading signal. The envelope of the sum of two quadrature Gaussian noise signals obeys a Rayleigh distribution	When there is a dominant stationary signal component present, such as a line-of sight Propagation path, the small-scale fading envelope distribution is Ricean.

Part A

- 12. Give the differences between Fast Fading and Slow Fading.

Fast Fading	Slow Fading
If the symbol duration (Ts) is greater than the coherence time (Tc).	If the symbol duration (Ts) is smaller than the coherence time (Tc)
Bandwidth of the signal lesser than the Doppler Spread.	Bandwidth of the signal greater than the Doppler Spread.
Varies quickly with frequency	Not Varies quickly with frequency
Fast fading originates due to effects of constructive and destructive interference patterns caused due to multipath.	It is result of signal path change due to shadowing and obstructions such as tree or buildings etc.

Part A

- 13. What are LTI Systems?

  Linear systems are systems whose outputs for a linear combination of inputs will be a linear combination. Time invariant systems are systems where the output does not depend on when an input was applied.

- 14. Define Coherence Time.

  Coherence time is the measure of period over which the fading process is correlated. It depends on carrier frequency and vehicular speed in the order of milliseconds or more.

Part A

- 15. Differentiate between Pass band and Baseband.

Pass band	Baseband
Shifts the signal to be transmitted in frequency to a higher frequency and then transmits it, where at the receiver the signal is shifted back to its original frequency.	Sends the information signal as it is without modulation (without frequency shifting)

Part A

- 16. What is sampling?

  In signal processing, **sampling** is the reduction of a continuous-time signal to a discrete-time signal. A common example is the conversion of a sound wave to a sequence of samples. A **sample** is a value or set of values at a point in time.

- 17. Define Shannon Capacity.

  In communication channels, S**hannon capacity** is the maximum amount of information that can pass through a channel without error, i.e., it is a measure of its "goodness." The actual amount of information depends on the code.

Part A

- 18. Define Mutual Information.

  Mutual information is a parameter to measure how much one random variable tells us about another. It is a dimensionless quantity which can be thought of as the reduction in uncertainty about one random variable given knowledge of another.

- 19. What is Block fading channel?

  It is a channel in which the gain g [i] is constant over some block length 'T' after which the gain changes to a new independent value based on the distribution.

- 20. What is CDI?

  If the distribution of gain over the channel is known to both transmitter and the receiver, then it is called Channel Distribution information (CDI).

Part A

- 21. What is CSI at the Receiver?

  If the distribution of gain over the channel is known to both transmitter and the receiver and if the value of gain is known to the receiver at a particular instant of time, then it is called Channel Side Information (CSI) at the receiver.

- 22. Define Capacity with Outage.

  Capacity with outage is defined as the maximum rate that can be transmitted over a channel with some outage probability that the transmission cannot be decoded with negligible error.

- 23. What is Outage Probability?

  The probability in which the transmission of received data cannot be decoded with negligible error in a wireless channel is called Outage Probability.

Part A

- 24. What is Time Diversity Systems?

  Time Diversity is a technique to combat the transmissions channel which may suffer from error bursts due to time-varying channel conditions. The error bursts may be caused by fading in combination with a moving receiver, transmitter or obstacle etc.

- 25. Give the expression for Capacity with Outage.

  The Capacity with Outage is given by –

$$C_o = (1 - p_{out}) B \log_2(1 + \gamma_{min})$$

Where

(1- pout)	-	Outage probability
B	–	Channel bandwidth
γmin	–	Minimum SNR for Correct decoding

Part B

- 1. Give an overview of Wireless Systems in detail.
- 2. Explain the Physical modeling for wireless channels.
- 3. Explain the Statistical modeling for wireless channels.
- 4. Write short notes on – (i) Coherence Time (ii) Coherence Frequency.
- 5. Explain the capacity of a Flat fading channel with neat diagrams.
- 6. Explain the capacity of a Frequency Selective fading channel with neat diagrams
- 7. Write short notes on (i) CSD at Receiver (ii) CSI at Transmitter & Receiver.
- 8. Explain Capacity of a channel with receiver diversity.

Mobile Communication

Unit – II / Performance of Digital Modulation Over Wireless Channels

Syllabus

- Fading – Outage Probability – Average Probability of Error –– Combined Outage and Average Error Probability – Doppler Spread – Inter symbol Interference.

Introduction

- Performance of the digital modulation techniques when used over AWGN channels and channels with flat-fading.

- There are two performance criteria:

1. **The Probability Of Error** defined relative to either symbol or bit errors.

2. **The Outage Probability** defined as the probability that the instantaneous signal-to-noise ratio falls below a given threshold.

Introduction

- Flat-fading can cause a dramatic increase in either the average bit-error-rate or the signal outage probability.

- Wireless channels may also exhibit frequency selective fading and Doppler shift.

- Frequency-selective fading gives rise to inter-symbol interference (ISI), which causes an irreducible error floor in the received signal.

Introduction

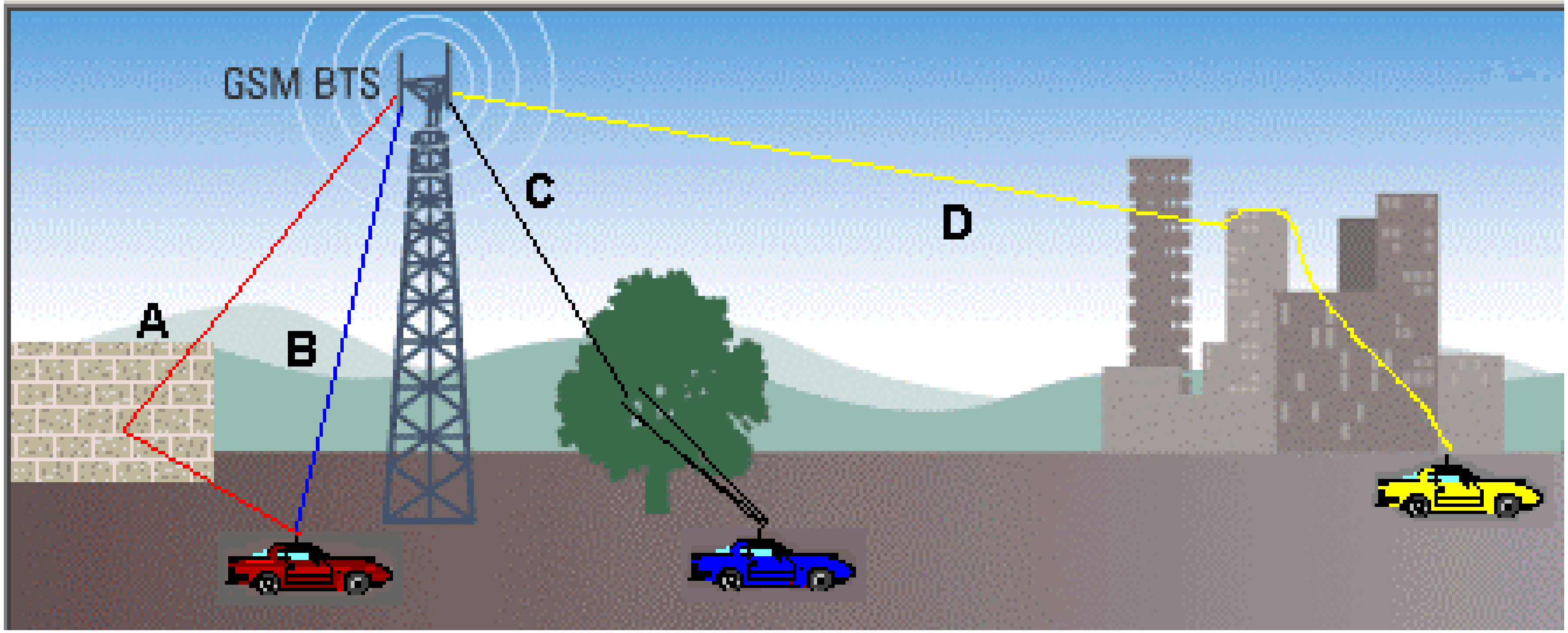
- Doppler causes spectral broadening, which leads to adjacent channel interference (typically small at reasonable user velocities), and also to an irreducible error floor in signals with differential phase encoding (e.g. DPSK), since the phase reference of the previous symbol partially de-correlates over a symbol time.

- This chapter describes the impact on digital modulation performance of noise, flat-fading, frequency-selective fading, and Doppler.

Topic 1

Fading

Fading



- A transmitted signal undergoes changes while traveling through the propagation path to the receiver. The effect of these changes is commonly called fading.

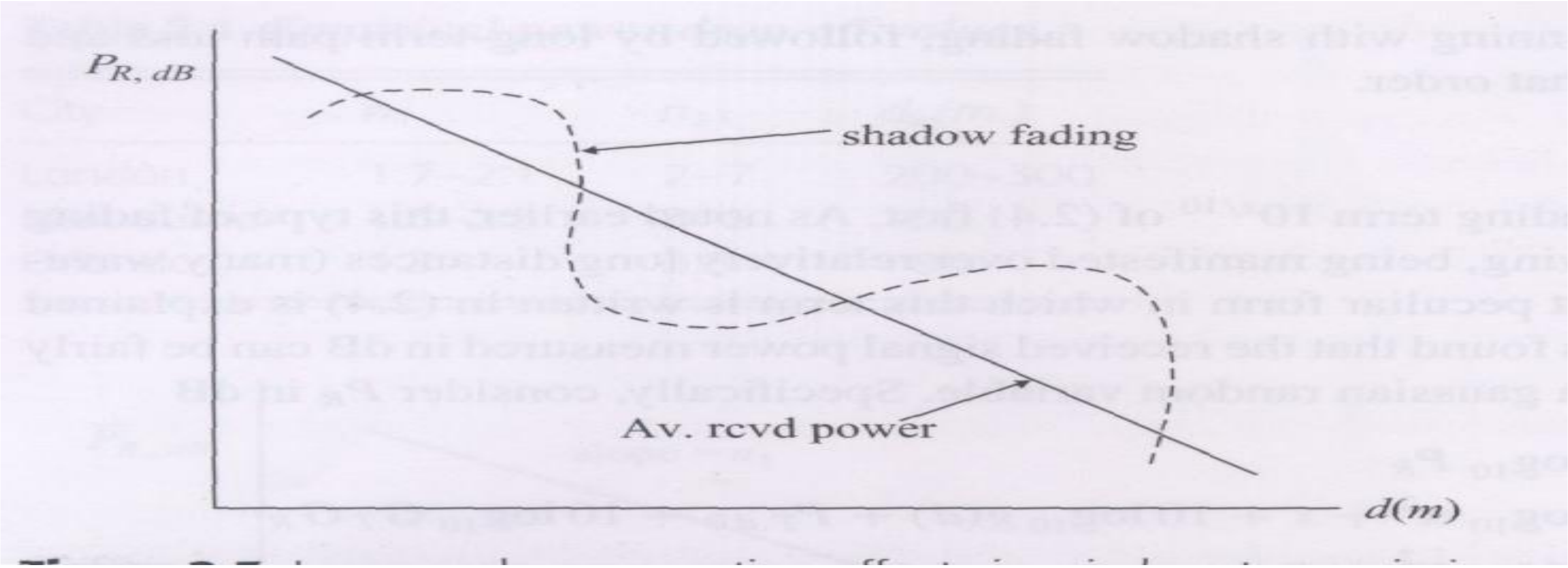
Introduction to Fading

- In wireless communications, fading is variation of the attenuation of a signal with time, geographical position & radio frequency.
- Fading is often modeled as a random process.
- Large-scale fading (shadowing)
  - Long term variations in the mean signal level caused by the mobile unit moving into the shadow of surrounding objects
- Small-scale fading (multipath)
  - Short term fluctuations in the signal amplitude caused by the local multipath

Large Scale Fading (Shadow Fading)

- Long term shadow fading due to variations in radio signal power due to encounters with terrain obstructions such as hills or manmade structures such as buildings
- The measured signal power differ at different locations even though at the same radial distance from a transmitter.
- Represents the medium scale fluctuations of the radio signal strength over distances from tens to hundreds of meters.
- Many empirical studies demonstrate that the received mean power fluctuates about the average power with a log-normal distribution.
- Can be modeled by a Gaussian random variable with standard deviation, delta (δ).

Large Scale Fading (Shadow Fading)

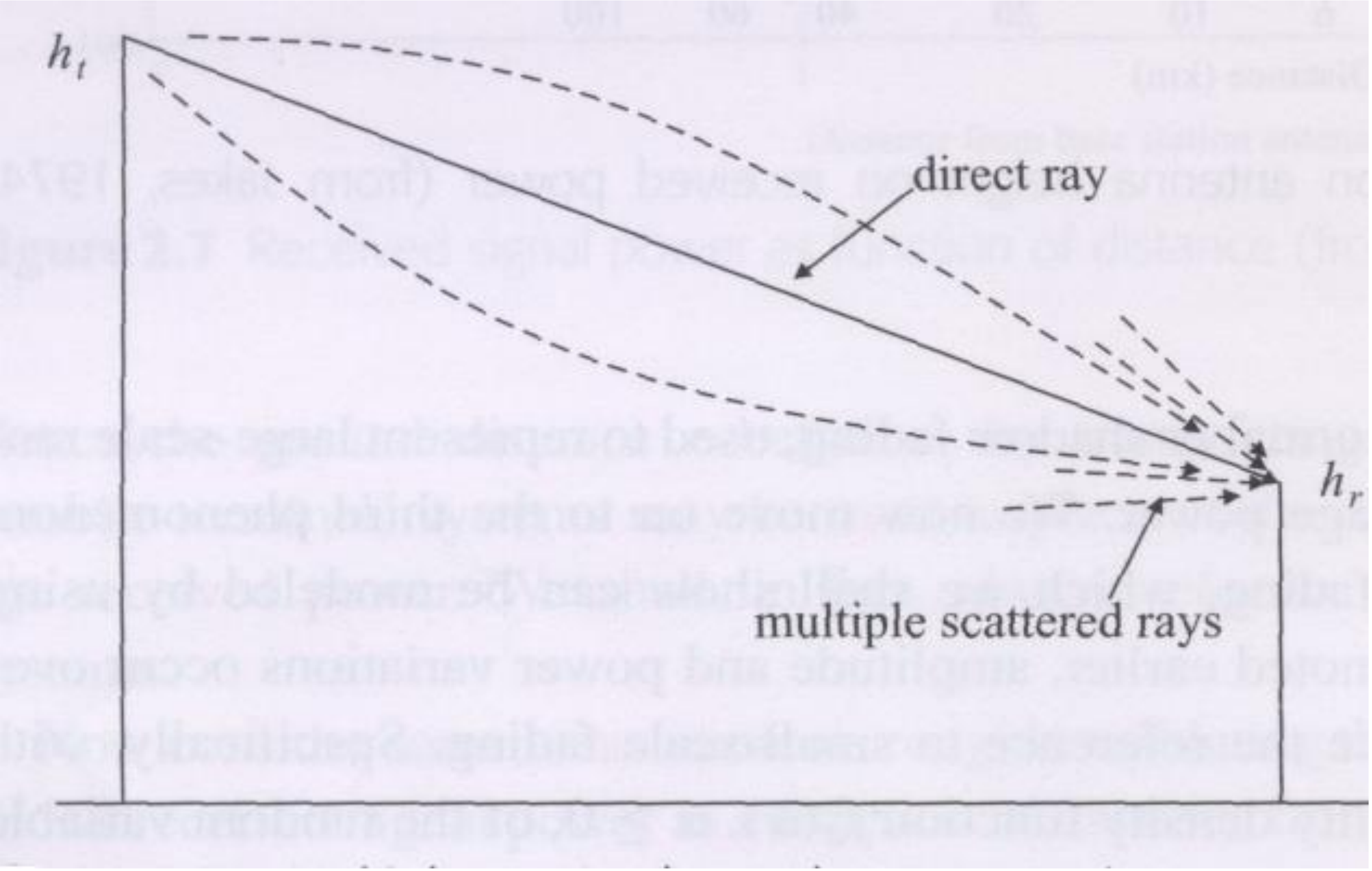


- Typical value of δ range **changing** from 6 to 10dB
- Shadowing complicates cellular planning
- To fully predict shadowing effect, up-to-date & highly detailed terrain data bases are needed

Small Scale Fading (Multipath Fading)

- A small scale fading that describes short-term, rapid amplitude fluctuations of the received signal during a short period of time
- The actual power received over a much smaller distance vary due to destructive/constructive interference of multiple signals that follow multiple paths to the receiver
- The direct ray made up of many rays due to scattering multiple times by obstructions along its path, all travelling about the same distance
- Each of these rays appearing at the receiver will differ randomly in amplitude & phase due to scattering.

Small Scale Fading (Multipath Fading)



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

Flat Fading

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

Frequency Selective Fading

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

Small-Scale Fading
(Based on Doppler spread)

Fast Fading

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

Slow Fading

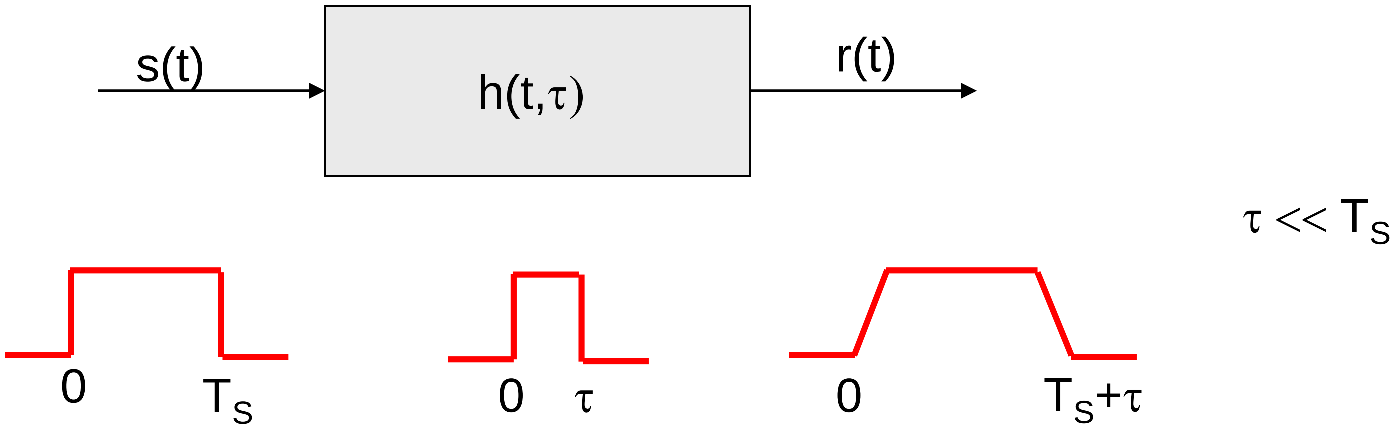
1. Low Doppler spread
2. Coherence time > Symbol period
3. Channel variations slower than baseband signal variations

Figure 5.11 Types of small-scale fading.

Flat Fading

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

Flat Fading



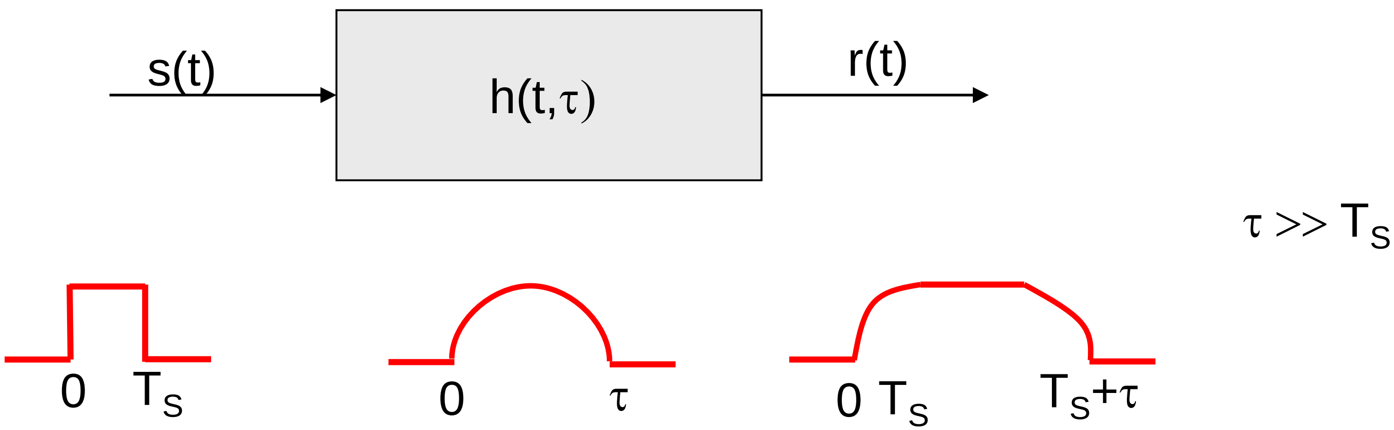
Occurs when:
$B_S << B_C$
and
$T_S >> \sigma_\tau$

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

Frequency Selective Fading

- A channel that is not a flat fading channel is called frequency selective fading because different frequencies within a signal are attenuated differently by the MRC.
- Occurs when channel multipath delay spread is greater than the symbol period.
  - Symbols face time dispersion
  - Channel induces Intersymbol Interference (ISI)
- Bandwidth of the signal s(t) is wider than the channel impulse response.

Frequency Selective Fading



Causes distortion of the received baseband signal

Causes Inter-Symbol Interference (ISI)

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

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

Fast Fading

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

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

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

Slow Fading

- Rate of change of the channel characteristics is **much smaller** than the Rate of change of the transmitted signal

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

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

Analysis of Fading

- In AWGN the probability of symbol error depends on the received SNR.
- In a fading environment the received signal power varies randomly over distance or time due to shadowing or multipath fading.
- Thus, in fading ‘γs’ is a random variable with distribution ‘Ps’ random.
- The performance metric for ‘γs’ random depends on the rate of change of fading.
- Three different performance criteria can be used to characterize the random variable ‘Ps’ -

Analysis of Fading (contd)

- The outage probability (P_{out}) - probability that 'γ_s' falls below a given value corresponding to the maximum allowable 'P_s'.
- The average error probability (P_s) averaged over the distribution of 'γ_s'.
- Combined average error probability and outage, defined as the average error probability that can be achieved some percentage of time or some percentage of spatial locations.

Analysis of Fading (contd)

- The average probability of symbol error applies when the signal fading is in the order of a symbol time (Ts = Tc), so that fading level is constant over one symbol time.
- The average error probability is a good figure of merit for the channel quality under these conditions.
- If the signal power is changing slowly (Ts << Tc), then a deep fade will affect many simultaneous symbols which may lead to large error bursts.
- In this case acceptable performance cannot be guaranteed without drastically increasing transmit power.

Analysis of Fading (contd)

- Under these circumstances, an outage probability is specified so that the channel is deemed unusable for some fraction of time or space.
- Outage and average error probability are often combined when the channel is modeled as a combination of fast and slow fading.
- E.g. log-normal shadowing with fast Rayleigh fading.
- When ($T_c << T_s$), the fading will be averaged out by the matched filter in the demodulator.
- Thus, for very fast fading, performance is the same as in AWGN.

Thank You

Topic 2

Outage Probability

Outage Probability

- In Information Theory, outage probability of a communication channel is the probability that a given information rate is not supported due to variable channel capacity.
- Outage probability is defined as the probability that information rate is less than the required threshold information rate.
- It is the probability that an outage will occur within a specified time period.
- **Outage probability** is a crude measure of performance.
- The importance of **outage probability** is that when **outage** occurs, there is more likely to have decoding failure.

Outage Probability (contd)

- For example, the channel capacity for slow-fading channel is $C = \log_2 (1 + h^2 \text{ SNR})$, where '$h$' is the fading coefficient & SNR is signal to noise ratio without fading.
- As 'C' is random, no constant rate is available.
- There may be a chance that information rate may go below to required threshold level.
- For slow fading channel, outage probability = $P(C < r) = P(\log_2 (1 + h^2 \text{ SNR}) < r)$, where '$r$' is the required threshold information rate.

Outage Probability (contd)

The outage probability relative to γ_0 is defined as

$$P_{out} = p(\gamma_s < \gamma_0) = \int_0^{\gamma_0} p_{\gamma_s}(\gamma) d\gamma,$$

where γ_0 typically specifies the minimum SNR required for acceptable performance.

For example, for digitized voice, $P_b = 10^{-3}$ is an acceptable error rate since it can't be detected by the human ear.

Thus, for a BPSK signal in Rayleigh fading, $\gamma_b < 7$ dB would be declared an outage, to set $\gamma_0 = 7$ dB.

Outage Probability (contd)

- In Rayleigh fading the outage probability becomes

$$P_{out} = \int_0^{\gamma_0} \frac{1}{\overline{\gamma}_s} e^{-\gamma_s/\overline{\gamma}_s} d\gamma_s = 1 - e^{-\gamma_0/\overline{\gamma}_s}.$$

- Inverting this formula shows that for a given outage probability, the required average SNR γ_s is

$$\overline{\gamma}_s = \frac{\gamma_0}{-\ln(1 - P_{out})}.$$

- 10 log γ_s must exceed the target 10 log γ_0 by F_d = −10 log[− ln(1 − P_{out})] to maintain acceptable performance more than 100 ∗ (1 − P_{out}) percent of the time.
- The quantity F_d is called the dB fade margin.

Thank You

Topic 3

Average Probability of Error

Average Probability of Error

- The average probability of error is used as a performance metric when $T_s \approx T_c$.
- The averaged probability of error is computed by integrating the error probability in AWGN over the fading distribution.

$$\overline{P}_s = \int_0^\infty P_s(\gamma) p_{\gamma_s}(\gamma) d\gamma,$$

- where $P_s(\gamma)$ is the probability of symbol error in AWGN with SNR γ.
- *F*or a given distribution of the fading amplitude *r* (i.e. Rayleigh, Rician, etc.), $p_{\gamma s}$ (γ) can be computed by making the change of variable.

$$p_{\gamma_s}(\gamma) d\gamma = p(r) dr.$$

Average Probability of Error (contd)

- For example, in Rayleigh fading the received signal amplitude '*r*' has the Rayleigh distribution given by-

$$p(r) = \frac{r}{\sigma^2} e^{-r^2/2\sigma^2}, \quad r \geq 0,$$

- The SNR per symbol for a given amplitude *r* is

$$\gamma = \frac{r^2 T_s}{2\sigma_n^2},$$

- where $\sigma_n^2 = N_0/2$ is the PSD of the noise in the in-phase and quadrature branches.
- Differentiating both sides of this expression yields-

$$d\gamma = \frac{r T_s}{\sigma_n^2} dr.$$

Average Probability of Error (contd)

- Substituiting the values of γ, dγ and p (r) into -

$$p_{\gamma_s}(\gamma) = \frac{T_s\sigma_n^2}{\sigma^2} e^{-\gamma T_s \sigma_n^2/\sigma^2}.$$

- Since the average SNR per symbol γ_s is just $\sigma^2/(T_s\sigma_n{}^2)$, it can be rewritten as –

$$p_{\gamma_s}(\gamma) = \frac{1}{\overline{\gamma}_s} e^{-\gamma/\overline{\gamma}_s},$$

- which is exponential. For binary signaling this reduces to –

$$p_{\gamma_b}(\gamma) = \frac{1}{\overline{\gamma}_b} e^{-\gamma/\overline{\gamma}_b},$$

- Integrating over the distribution yields the following average probability of error for both BPSK & Binary FSK in Rayleigh fading as-

Average Probability of Error (contd)

$$\overline{P}_b = \frac{1}{2}\left[1 - \sqrt{\frac{\overline{\gamma}_b}{1+\overline{\gamma}_b}}\right] \approx \frac{1}{4\overline{\gamma}_b},$$

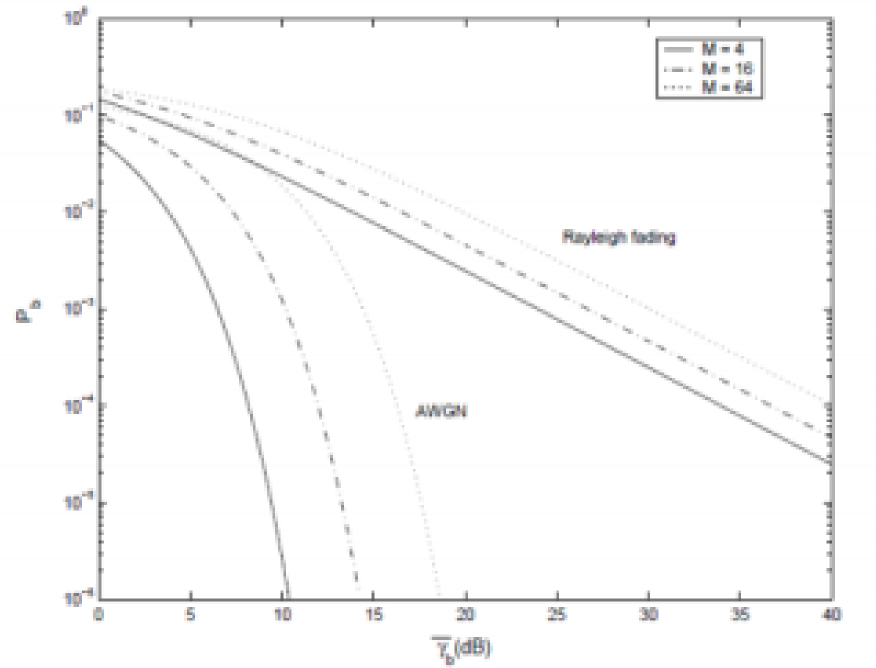
- For DPSK, this yields to-

$$\overline{P}_b = \frac{1}{2(1+\overline{\gamma}_b)} \approx \frac{1}{2\overline{\gamma}_b},$$

Average Probability of Error (contd)

- For binary PSK, FSK, and DPSK, the bit error probability in AWGN decreases exponentially with increasing γ_b.
- However, in fading the bit error probability for all the modulation types decreases just linearly with increasing γ_b.
- Similar behavior occurs for non-binary modulation.
- Thus, the power required to maintain a given P_b, for small values, is much higher in fading channels than in AWGN channels.

Average Probability of Error



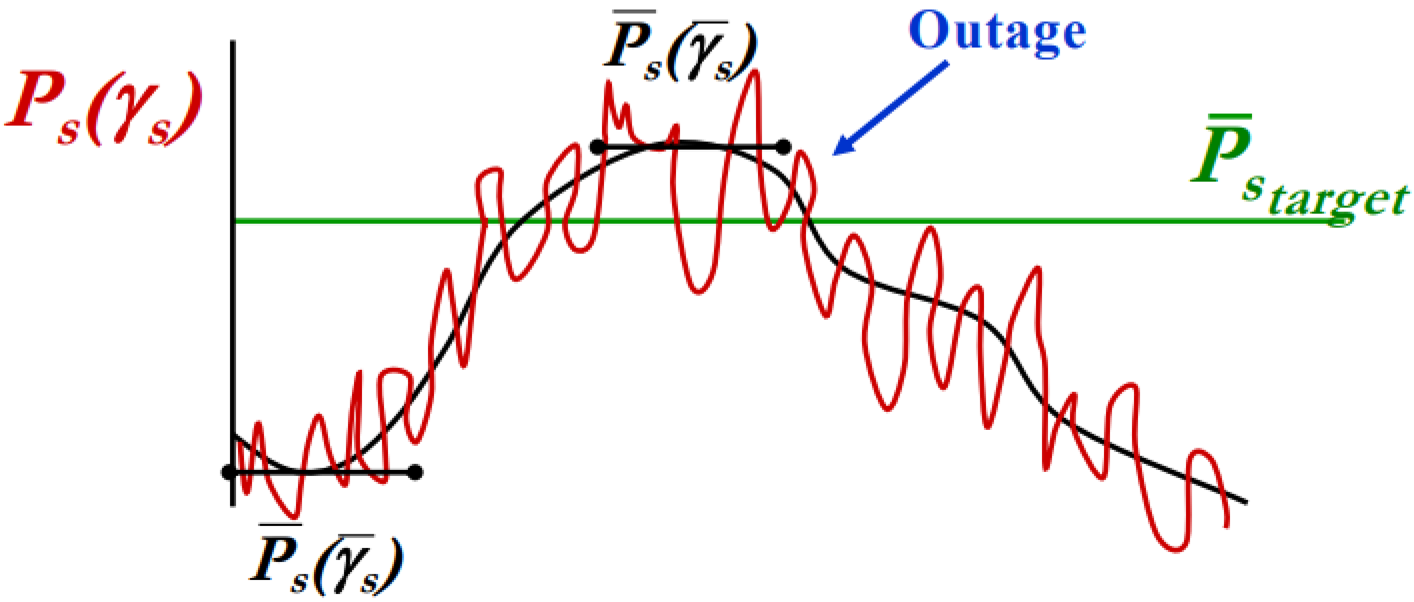
Fading severely degrades performance

Thank You

Topic 4

Combined - Outage & Average Error Probability

Combined outage and average P_s



- Used in combined shadowing and flat-fading
- $\overline{P}_s$ varies slowly, locally determined by flat fading
- Declare outage when $\overline{P}_s$ above target value

Combined Outage & Average Error Probability (contd)

- When the fading environment is a superposition of both fast and slow fading, a common performance metric - combined outage and average error probability,
- Where outage occurs when the slow fading falls below some target value & the average performance in non-outage is obtained by averaging over the fast fading.
- Let $\bar{\bar{\gamma}}_s$ denote the average SNR per symbol due to shadowing and path loss.
- Let $\bar{\gamma}_s$ denote the (random) SNR per symbol due to shadowing and path loss with average value $\bar{\bar{\gamma}}_s$

Combined Outage & Average Error Probability (contd)

- Let 'γ_s' denote the random SNR due to path loss, shadowing & multipath.
- With this notation we can specify an average error probability 'P_s' with some probability $(1 - P_{out})$.
- An outage is declared when the received SNR per symbol due to shadowing and path loss, $\overline{\gamma}_s$ falls below a given target value $\overline{\gamma}_{s0}$.
- When not in outage $(\overline{\gamma}_s \geq \overline{\gamma}_{s0})$, average probability of error is obtained by averaging over the distribution of the fast fading conditioned on the mean SNR.

$$\overline{P}_s = \int_0^\infty P_s(\gamma_s) p(\gamma_s | \overline{\gamma}_s) d\gamma_s.$$

Combined Outage & Average Error Probability (contd)

- Condition to determine the outage target, $\bar{\gamma}_{s0}$, is based on a given maximum average probability of error $\bar{P}_s \leq \bar{P}_{s0}$, where the target must then satisfy -
- $$\bar{P}_{s0} = \int_0^{\infty} P_s(\gamma_s) p(\gamma_s | \bar{\gamma}_{s0}) d\gamma_s.$$
- Clearly whenever $\bar{\gamma}_s > \bar{\gamma}_{s0}$, , the average error probability will be below the target value.

Example :

Consider BPSK modulation in a channel with both log-normal shadowing ($\sigma = 8$ dB) and Rayleigh fading.

The desired maximum average error probability is $P_{b0} = 10^{-4}$, which requires $\gamma_{b0} = 34$ dB. Determine the value

of γ_b that will insure $P_b \leq 10^{-4}$ with probability $1 - P_{out} = -1.6$

Solution: We must find γ_b, the average of γ_b in both the fast and slow fading, such that $p(\gamma_b > \gamma_{b0}) = 1 - P_{out}$.

For log-normal shadowing we compute this as:

$$p(\overline{\gamma_b} > 34) = p\left(\frac{\overline{\gamma_b} - \overline{\overline{\gamma_b}}}{\sigma} \geq \frac{34 - \overline{\overline{\gamma_b}}}{\sigma}\right) = Q\left(\frac{34 - \overline{\overline{\gamma_b}}}{\sigma}\right) = 1 - P_{out},$$

since $(\gamma_b - \gamma_b)/\sigma$ is a Gauss-distributed random variable with mean zero and standard deviation one. Thus, the

value of γ_b is obtained by substituting the values of P_{out} and σ in and using a table of Q functions or an

inversion program, which yields $(34 - \gamma_b)/8 = -1.6$ or $\gamma_b = 46.8$ dB.

Thank You

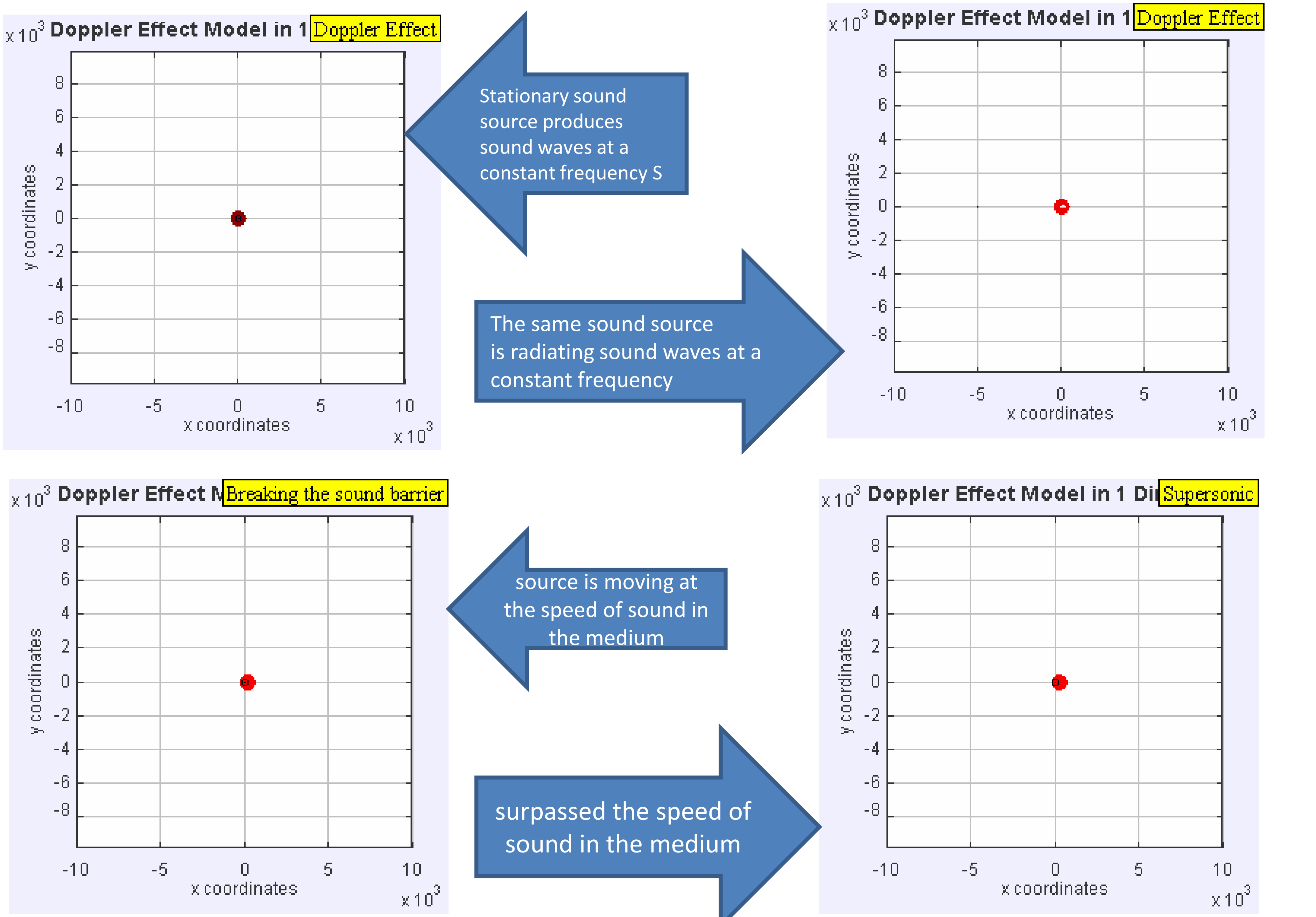
Topic 5

Doppler Spread

Doppler effect

An animation illustrating how the Doppler effect causes a car engine or siren to sound higher in pitch when it is approaching than when it is receding. The red circles represent sound waves.

Doppler effect



Doppler Effects

- High doppler causes channel phase to decorrelate between symbols
- Leads to an irreducible error floor for differential modulation
  - Increasing power does not reduce error
- Error floor depends on $f_D T_b$ as

$$P_{floor} = \frac{1 - J_0(2\pi f_D T_b)}{2} \approx .5(\pi f_D T_b)^2$$

Doppler Spread

- Doppler frequency shift is different from path to path when signal arrives at the wireless receiver.
- Hence transmitted signal frequency will experience Doppler spreading & seen as spectral widening in received signal power spectrum.
- This width of the spectrum is known as Doppler Spread or fading bandwidth.
- **Doppler spread** is a measure of the spectral broadening caused by the time rate of change of the mobile radio channel.

Doppler Spread (contd)

- Doppler spread results in an irreducible error floor for modulation techniques using differential detection.
- In differential modulation the signal phase associated with one symbol is used as a phase reference for the next symbol.
- If the channel phase de-correlates over a symbol, then the phase reference becomes extremely noisy, leading to a high symbol error rate independent of received signal power.
- The phase correlation between symbols & therefore the degradation in performance are functions of the Doppler frequency $f_D = v/\lambda$ and the symbol time T_s.

Doppler Spread (contd)

- The first analysis of irreducible error floor due to Doppler was done by Bello and Nelin.
- In that work analytical expressions for irreducible error floor of non-coherent FSK and DPSK due to Doppler are determined for a Gaussian Doppler power spectrum.
- But these expressions are not in closed-form, so must be evaluated numerically.
- Closed-form expressions for the bit error probability of DPSK in Rician fading, where the channel de-correlates over a bit time, can be obtained using the (moment-generating function) MGF technique.
- MGF obtained based on general quadratic form of complex Gaussian random variables.

Doppler Spread (contd)

- The resulting average bit error probability for DPSK is –

$$\overline{P}_b = \frac{1}{2}\left[\frac{1+K+\overline{\gamma}_b(1-\rho_C)}{1+K+\overline{\gamma}_b}\right]\exp\left(-\frac{K\overline{\gamma}_b}{1+K+\overline{\gamma}_b}\right),$$

where ρ_C is the channel correlation co-efficient after a bit time T_b, K is the fading parameter of the Rician distribution, and $\overline{\gamma}_b$ *is* the average SNR per bit.

For Rayleigh fading ($K = 0$) this simplifies to

$$\overline{P}_b = \frac{1}{2}\left[\frac{1+\overline{\gamma}_b(1-\rho_C)}{1+\overline{\gamma}_b}\right].$$

Doppler Spread (contd)

- Letting $\overline{\gamma}_b \rightarrow \infty$ in the above equation yields the irreducible error floor as –

$$\text{DPSK:} \quad \overline{P}_{floor} = \frac{(1-\rho_C)e^{-K}}{2}.$$

- Using a similar approach to bound the bit error probability of DQPSK in fast Rician fading as –

$$\text{DQPSK:} \quad \overline{P}_{floor} = \frac{1}{2}\left[1-\sqrt{\frac{(\rho_C/\sqrt{2})^2}{1-(\rho_C/\sqrt{2})^2}}\right]\exp\left[-\frac{(2-\sqrt{2})(K/2)}{1-\rho_C/\sqrt{2}}\right].$$

- The channel correlation $A_C\,(t)$ over time 't' equals the inverse Fourier transform of the Doppler power spectrum $S_C\,(f\,)$ as a function of Doppler frequency 'f' .

- The correlation co-efficient is thus $\rho_C = A_C\,(T\,)\,/\,A_C\,(0)$ evaluated at $T = T_s$ for DQPSK or $T = T_b$ for DPSK.

Correlation Coefficients for Different Doppler Power Spectra Models

Type	Doppler Power Spectrum $S_C(f)$	$\rho_C = A_C(T)/A_C(0)$
Rectangular	$\frac{S_0}{2B_D}, \lvert f \rvert < B_D$	$\text{sinc}(2B_D T)$
Gaussian	$\frac{S_0}{\sqrt{\pi} B_D} e^{-f^2/B_D^2}$	$e^{-(\pi B_D T)^2}$
Uniform Scattering	$\frac{S_0}{\pi\sqrt{B_D^2 - f^2}}, \lvert f \rvert < B_D$	$J_0(2\pi B_D T)$
1st Order Butterworth	$\frac{S_0 B_D}{\pi(f^2 + B_D^2)})$	$e^{-2\pi B_D T}$

Example

Assume a Rayleigh fading channel with uniform scattering and a maximum Doppler of $f_D = 80$ Hertz. For what approximate range of data rates will the irreducible error floor of DPSK be below 10^{-4}.

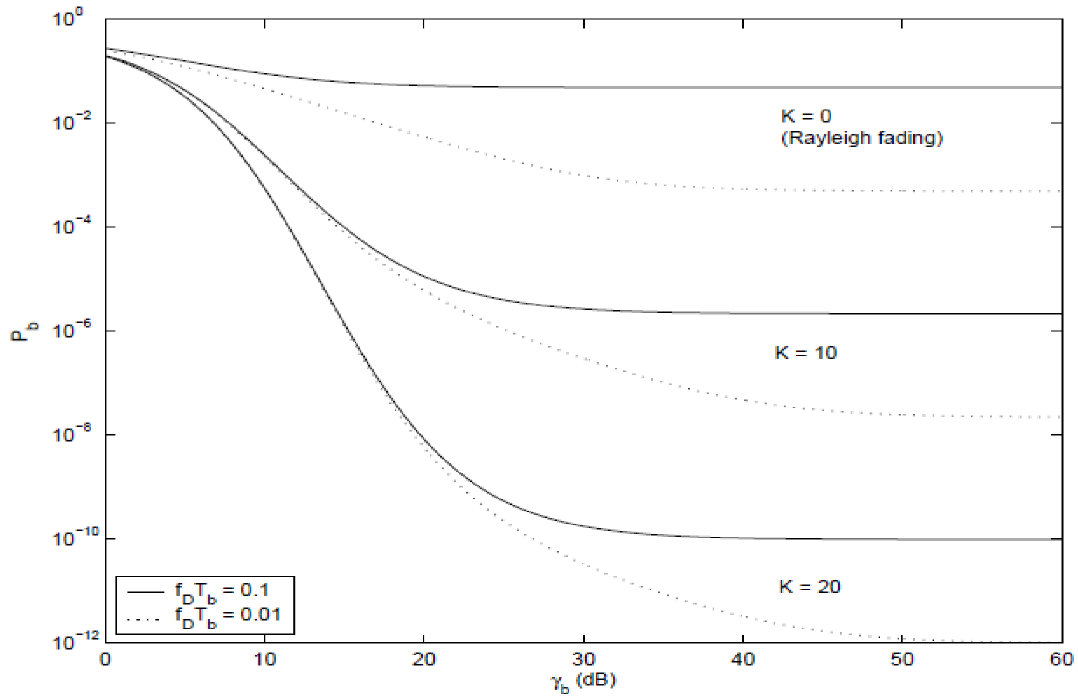


Figure: Average P_b for DPSK in Fast Rician Fading with Uniform Scattering

Solution: We have $P_{floor} \approx .5(\pi f_D T_b)^2 < 10^{-4}$. Solving for T_b with $f_D = 80$ Hz, we get

$$T_b < \frac{\sqrt{2 \cdot 10^{-4}}}{\pi \cdot 80} = 5.63 \cdot 10^{-5},$$

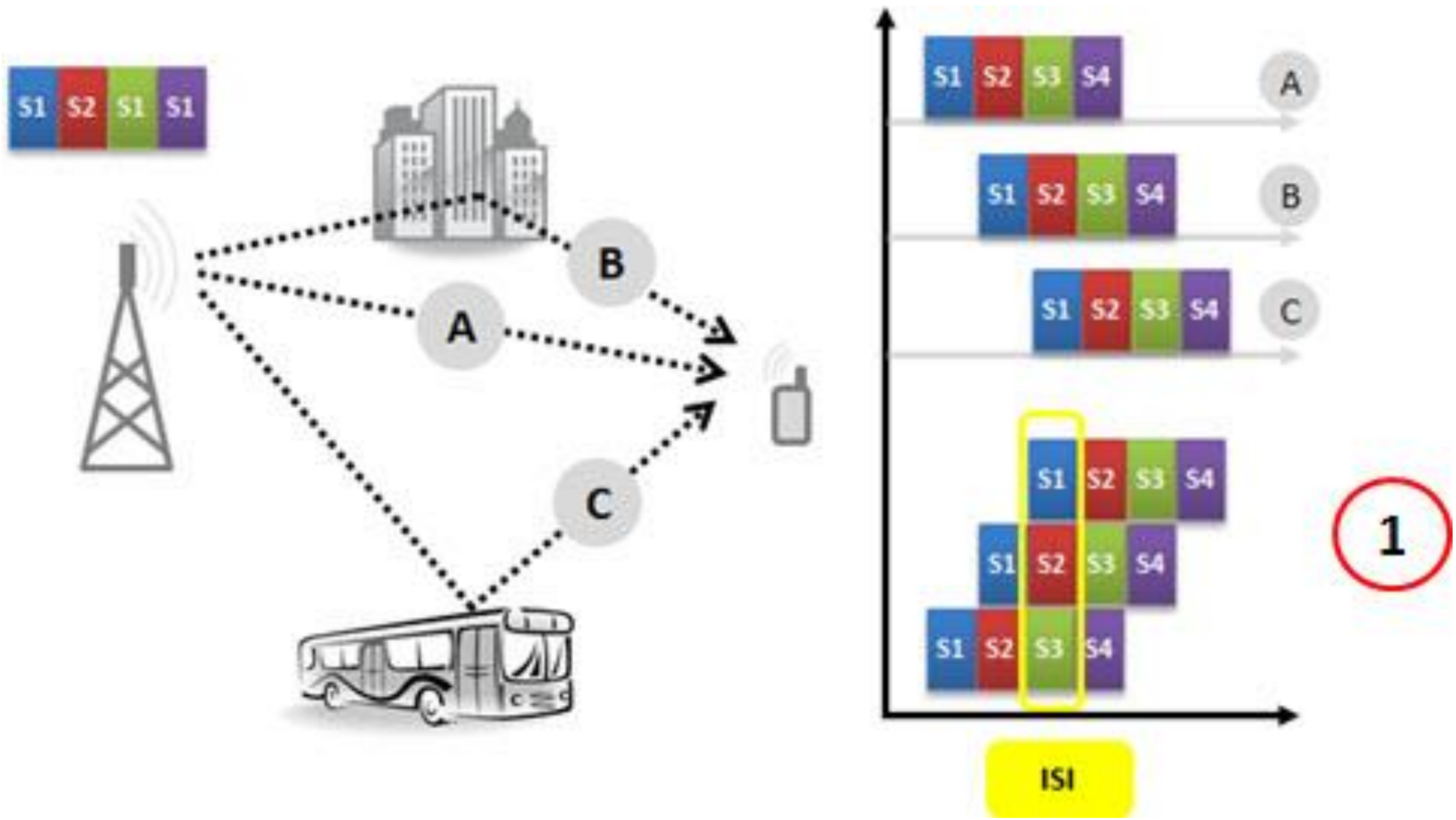
which yields $R > 17.77$ Kbps.

Thank You

Topic 6

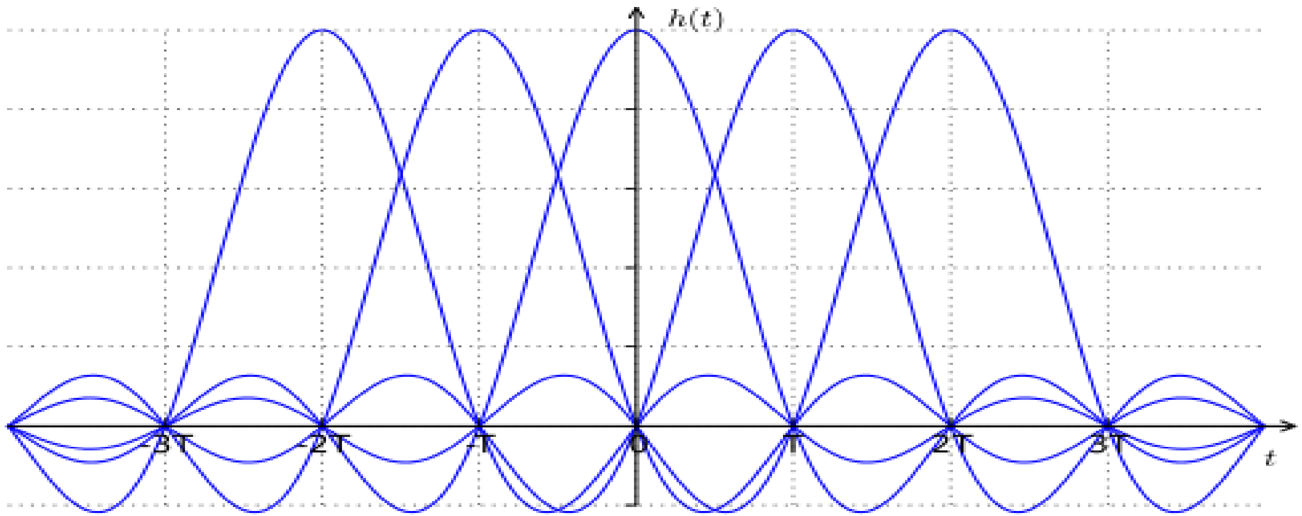
Inter symbol Interference (ISI)

Inter symbol Interference (ISI)



ISI

- In telecommunication, **inter symbol interference** (**ISI**) is a form of distortion of a signal in which one symbol interferes with subsequent symbols.
- This is an unwanted phenomenon as the previous symbols have similar effect as noise, thus making the communication less reliable.



ISI (contd)

- One of the causes for Intersymbol interference is multipath propagation in which a wireless signal from a transmitter reaches the receiver via multiple paths.
- The causes include reflection, refraction and atmospheric effects such as atmospheric ducting and ionosphere reflection.
- Since various paths can be of different lengths, this results in the different versions of the signal arriving at the receiver at different times.
- A part or all of a given symbol will be spread into the subsequent symbols, thereby interfering with the correct detection of those symbols.

ISI (contd)

- Another cause for intersymbol interference is the transmission of a signal through a band-limited channel.
- Passing a signal through such a channel results in the removal of frequency components above the cutoff frequency.
- In addition, components of the frequency below the cutoff frequency may also be attenuated by the channel.
- This filtering of the transmitted signal affects the shape of the pulse that arrives at the receiver.
- The effects of filtering a rectangular pulse not only change the shape of the pulse within the first symbol period, but also spread out over the subsequent symbol periods.

ISI (contd)

- Frequency-selective fading give rise to ISI, where the received symbol over a given symbol period experiences interference from other symbols delayed by multipath.
- Since increasing signal power also increases the power of the ISI, this interference gives rise to an irreducible error floor independent of signal power.
- The irreducible error floor is difficult to analyze, since it depends on ISI characteristics & modulation format, and ISI characteristics depend on the characteristics of the channel & sequence of transmitted symbols.

ISI (contd)

- The first extensive analysis of ISI degradation to symbol error probability was done by Bello and Nelin.
- In that work, analytical expressions for the irreducible error floor of coherent FSK and non-coherent DPSK are determined assuming a Gaussian delay profile for the channel.
- To simplify the analysis, only ISI associated with adjacent symbols was taken into account.
- Even with this simplification, the expressions are very complex and must be approximated for evaluation.

ISI (contd)

- An approximation to symbol error probability with ISI can be obtained by treating the ISI as uncorrelated white Gaussian noise.
- Then the SNR becomes –

$$\hat{\gamma}_s = \frac{P_r}{N_0 B + I},$$

- where "*I*" is the power associated with the ISI.
- In a static channel the resulting probability of symbol error will be $P_s(\hat{\gamma}_s)$ where P_s is the probability of symbol error in AWGN.
- If both transmitted signal & ISI experience flat-fading, then $\hat{\gamma}_s$ will be a random variable with a distribution $p(\hat{\gamma}_s)$, and the average symbol error probability is then-

$$\overline{P}_s = \int P_s(\hat{\gamma}_s) p(\hat{\gamma}_s)$$

Example:

Using the approximation $P_{floor} \leq (\sigma_{T_m}/T_s)^2$,find the maximum data rate that can be transmitted through a channel with delay spread $\sigma_{T_m} = 3\mu$ sec using either BPSK or QPSK modulation such that the probability of bit error P_b is less than 10^{-3}

Solution: For BPSK, we set $P_{floor} = (\sigma_{T_m}/T_b)^2$, so we require $T_b \geq \sigma_{T_m}/\sqrt{P_{floor}} = 94.87\mu$secs, which leads to a data rate of $R = 1/T_b = 10.54$ Kbps. For QPSK, the same calculation yields $T_s \geq \sigma_{T_m}/\sqrt{P_{floor}} = 94.87\mu$secs. Since there are 2 bits per symbol, this leads to a data rate of $R = 2/T_s = 21.01$ Kbps. This indicates that for a given data rate, QPSK is more robust to ISI than BPSK, due to that fact that its symbol time is slower. This result is also true using the more accurate error floors associated with Figure 6.5 rather than the bound in this example.

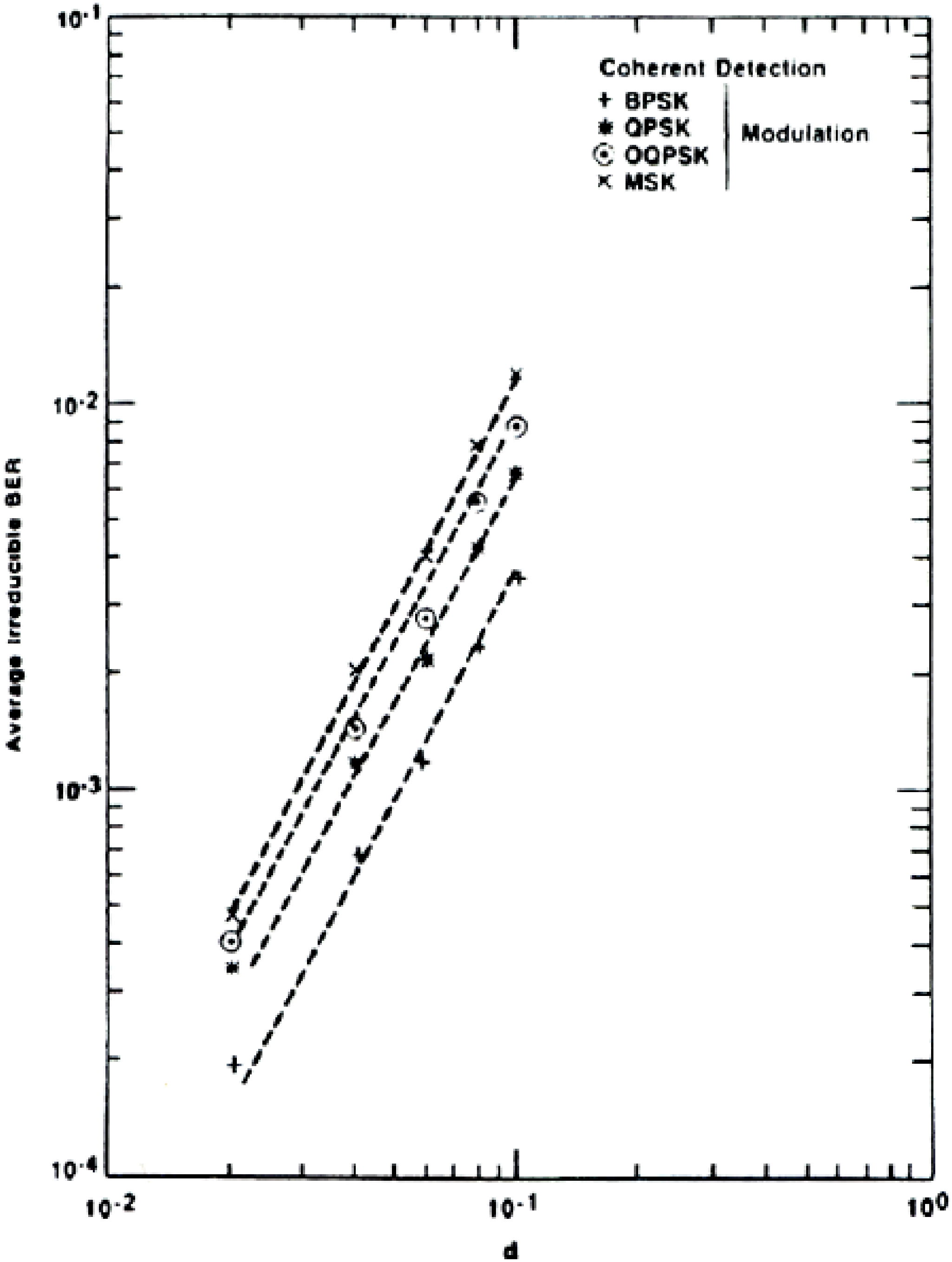


Figure :

Irreducible error versus normalized rms delay spread $d = \sigma_{Tm}/T_s$ for Gaussian power delay profile
(from [26] c IEEE).

Thank You

Model Question Bank

Unit - II

Part A

- 1. Define Capacity with Outage.

  Capacity with outage is defined as the maximum rate that can be transmitted over a channel with some outage probability that the transmission cannot be decoded with negligible error.

- 2. What is Outage Probability?

  The probability in which the transmission of received data cannot be decoded with negligible error in a wireless channel is called Outage Probability.

Part A

- 3. What is called Fading?

  In wireless communications, fading is variation of the attenuation of a signal with time, geographical position, and radio frequency. Fading is often modeled as a random process. A fading channel is a communication channel that experiences fading.

- 4. Mention the types of Fading.

  Large Scale Fading and Small Scale Fading – further divided into (i) Frequency selective fading and (ii) Flat Fading.

Part A

- 5. What is ISI?

  In telecommunication, I**nter symbol interference** (**ISI**) is a form of distortion of a signal in which one symbol interferes with subsequent symbols. This is an unwanted phenomenon, thus making the communication less reliable.

- 6. Define Doppler Spread.

  It is a measure of the spectral broadening caused by the time rate of change of the mobile radio channel, & defined as the range of frequencies over which the received **Doppler** spectrum is essentially non-zero.

Part A

- 7. Differentiate between Large Scale Fading and Small Scale Fading

Large Scale Fading	Small Scale Fading
Long term variation in the mean signal level caused by the mobile unit moving into the shadow of surrounding objects	Short term fluctuation in the signal amplitude caused by the local multipath

Part A

- 8. Differentiate between Flat Fading and Frequency Selective Fading.

Flat Fading	Frequency Selective Fading
Being flat if the received multipath components of a symbol do not extend beyond the symbol's time duration	Being frequency selective if the received multipath components of a symbol extend beyond the symbol's time duration
Inter symbol Interference Absent	ISI present
Spectral Characteristics of transmitted signal preserved at the receiver	Spectral Characteristics of transmitted signal not preserved at the receiver
Symbol Bandwidth (Bs) less than the Coherence Bandwidth (Bc)	Symbol Bandwidth (Bs) greater than the Coherence Bandwidth (Bc)

Part A

- 9. Give the differences between Fast Fading and Slow Fading.

Fast Fading	Slow Fading
If the symbol duration (Ts) is greater than the coherence time (Tc).	If the symbol duration (Ts) is smaller than the coherence time (Tc)
Bandwidth of the signal lesser than the Doppler Spread.	Bandwidth of the signal greater than the Doppler Spread.
Varies quickly with frequency	Not Varies quickly with frequency
Fast fading originates due to effects of constructive and destructive interference patterns caused due to multipath.	It is result of signal path change due to shadowing and obstructions such as tree or buildings etc.

Part A

- 10. What is average probability of error?

  The probability of error is considered as the probability of making a wrong decision and would have a different value for each type of error. The averaged probability of error is computed by integrating the error probability in AWGN over the fading distribution.

$$\overline{P}_s = \int_0^\infty P_s(\gamma) p_{\gamma_s}(\gamma) d\gamma,$$

  where $P_s(\gamma)$ is the probability of symbol error in AWGN with SNR γ.

  11. What is MGF Technique?

  In probability theory, the moment-generating function of a random variable is an alternative specification of its probability distribution. It provides an alternative route to analytical results compared with working directly with probability functions or cumulative distribution functions.

Part A

- 12. Mention the various reasons for ISI.

  1) The causes include reflection, refraction & atmospheric effects such as atmospheric ducting and ionosphere reflection.

  2) Transmission of a signal through a band-limited channel.

Part B

- 1. What is fading? Explain the types of fading in detail.
- 2. What is outage probability? Derive an expression for outage probability for acceptable performance.
- 3. What is average probability of error? Derive an expression for maximum average probability of error suitable for all types of modulations.
- 4. Derive an expression for combined outage and average probability of error of a fading environment in a wireless channel.
- 5. Write a short note on Doppler Spread.
- 6. Explain Inter symbol Inference with neat diagram.

Mobile Communication

Unit – III / Multi-antenna Communication

Syllabus

- Realization of Independent Fading Paths – Receiver Diversity – Selection Combining – Threshold Combining – Maximal-Ratio Combining – Equal-Gain Combining – Transmitter Diversity – Channel known at Transmitter – Channel unknown at Transmitter (The Alamouti Scheme) – Transmit & Receive Diversity (MIMO Systems).

DIVERSITY TECHNIQUES

Diversity-scheme

- Superposition of multiple signal at the receiver cause random amplitude variation which is known as Fading.

- A Diversity mechanism is used to decrease the effect of fading is called Diversity.

- In Diversity mechanism, multiple copies of the same data is transmitted to the receiver through multiple paths or channels and the decision is made by the receiver without knowing to the transmitter.

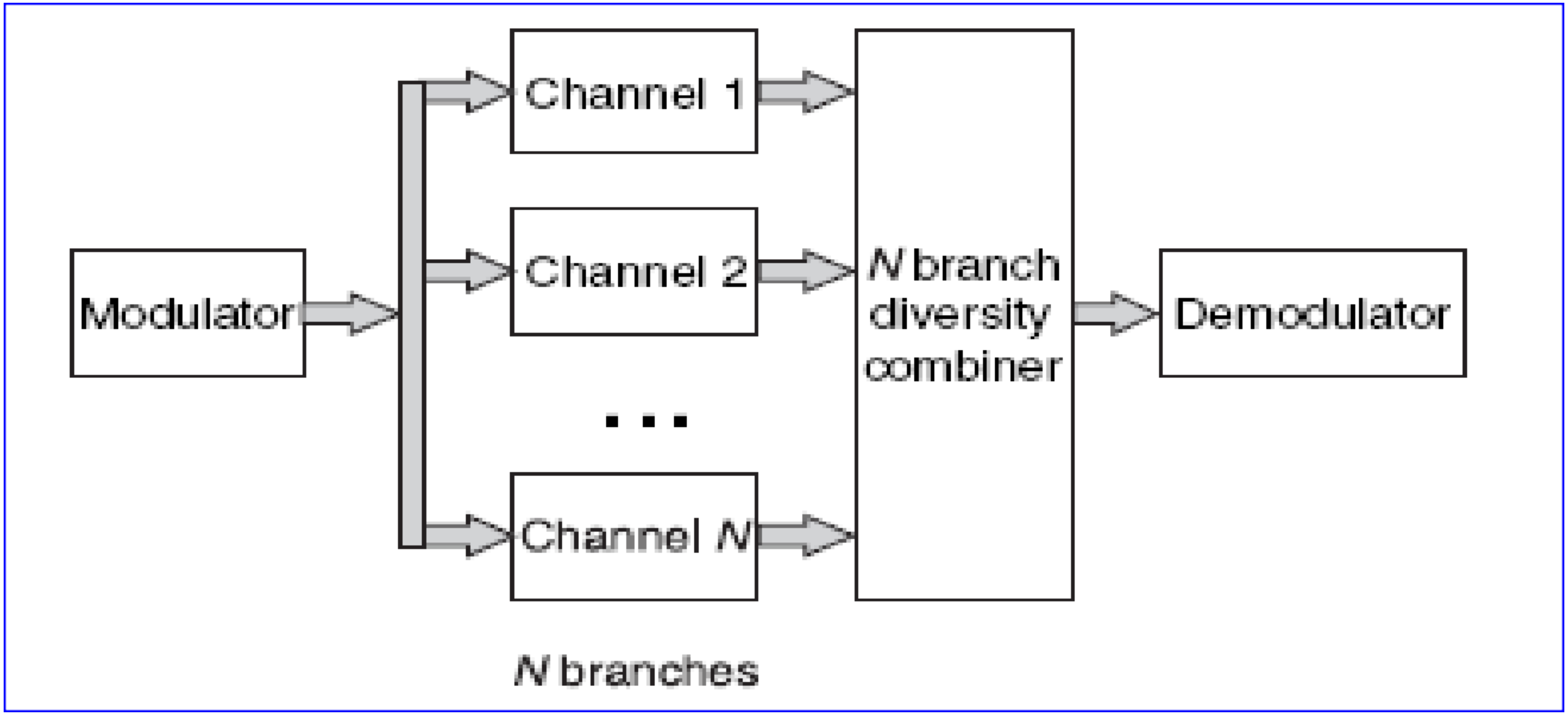
- Introduction.
- Need of Diversity.
- Classification of Diversity.
- Diversity Techniques.
- Frequency diversity.
- Time Diversity.

INTRODUCTION

- Diversity- is a powerful communication technique that provides wireless link improvements at relatively low cost.
- Diversity exploits the random nature of radio propagation by finding independent signal path for communication.
- These independent paths are highly uncorrelated.

NEED OF DIVERSITY

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



DIVERSITY- IMPORTANT CRITERIA

Two criteria are necessary to obtain a high degree of improvement from a diversity system are:

- First, the fading in individual branches should have low cross-correlation or highly uncorrelated.
- Second, the mean power available from each branch should be almost equal.

CLASSIFICATION OF DIVERSITY

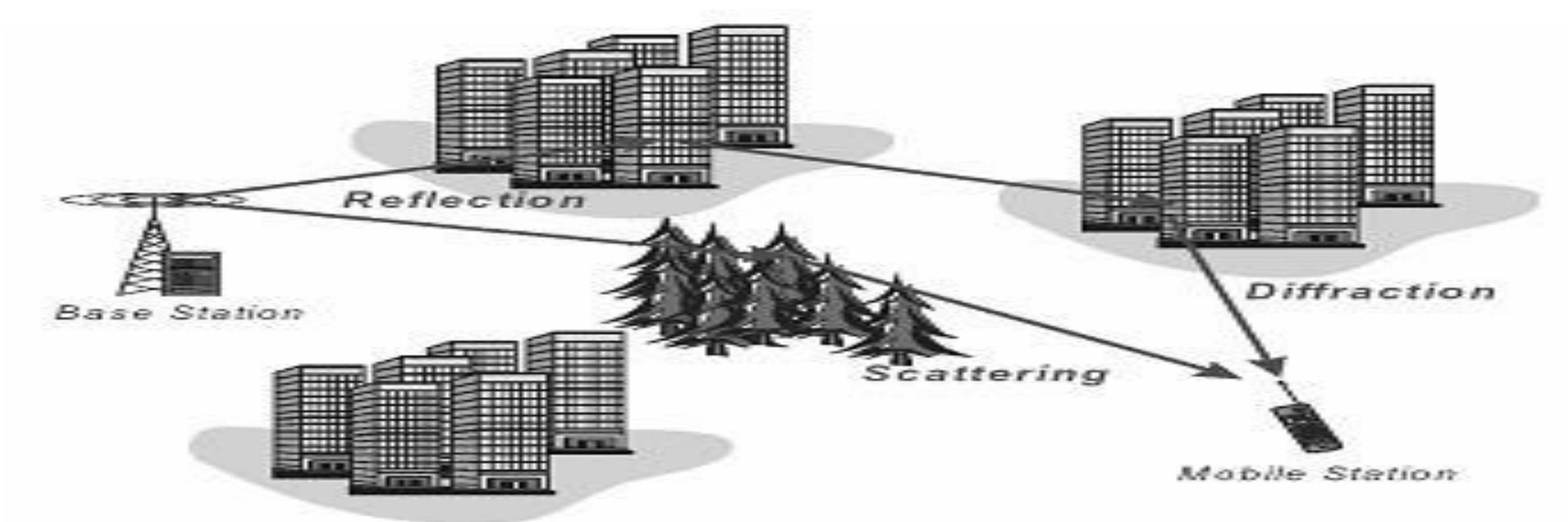
- Macro diversity: provides a method to mitigate the effects of shadowing , as in case of Large scale fading.

- Micro diversity: provides a method to mitigate the effects of multi-path fading as in case of small scale fading.

MACRO DIVERSITY

- Large scale fading is caused by shadowing due to the presence of fixed obstacles in the radio path.

- Long term fading can be mitigated by macroscopic diversity (apply on separated antenna sites) like the diversity using two base stations

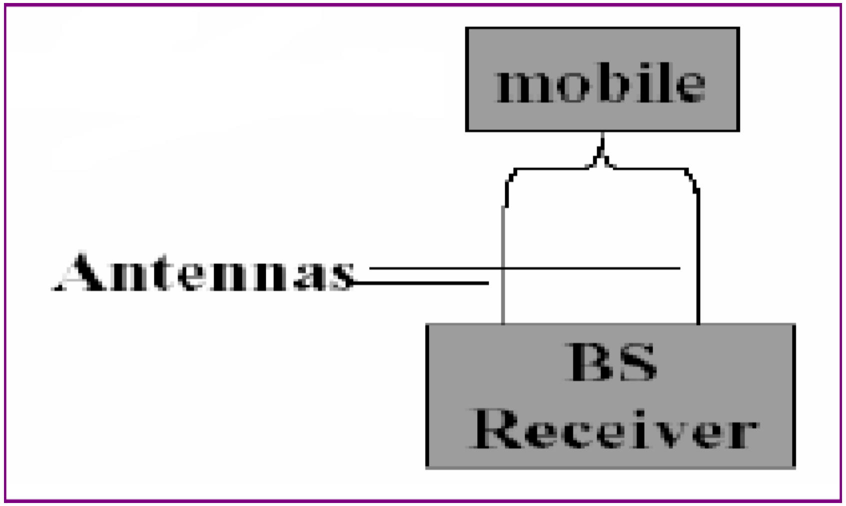


MICRO DIVERSITY

Small scale fades are characterized by deep and rapid amplitude fluctuations which occur as the mobiles moves over distances of just a few wavelengths

These fades are caused by multiple reflections from surroundings in the vicinity of the mobile.

Short term fading can be mitigated by the diversity using multiple antennas on the base station or mobile unit.



DIVERSITY TECHNIQUES

♣Space Diversity:

- Using antennas spaced enough (at Tx or Rx).

- ♣Polarization Diversity:

- Using antennas with different polarizations.

- ♣Frequency Diversity:

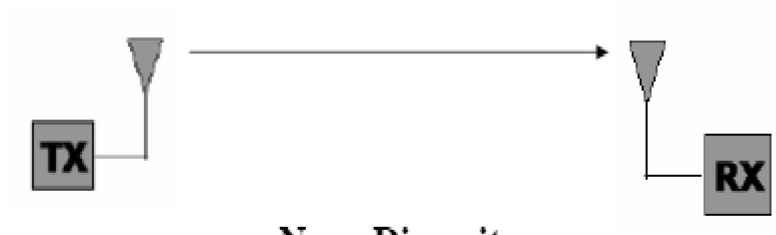
- Using frequency channels separated in frequency more than the channel coherence bandwidth.

- ♣Time Diversity:

- Using time slots separated in time more than the channel coherence time.

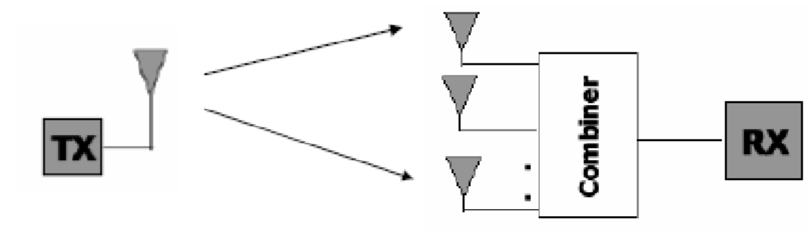
SPACE DIVERSITY

- Use more than one antenna to receive the signal.



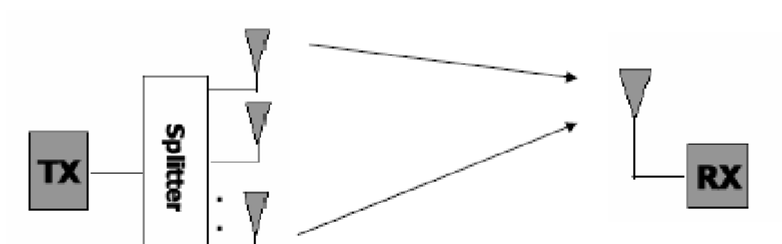
None Diversity

Single Input Single Output (SISO)



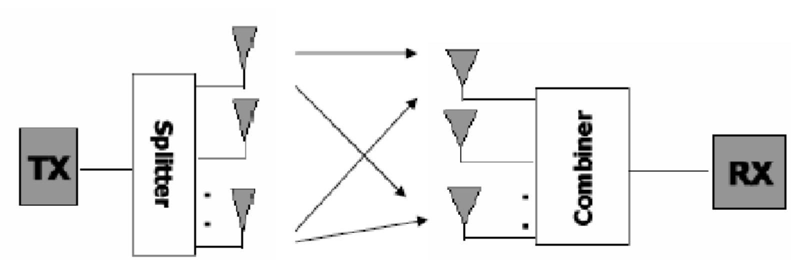
Receiving Diversity

Single Input Multi Output (SIMO)



Transmit Diversity

Multi Input Single Output (MISO)



Transmit/Receiving Diversity

Multi Input Multi Output (MIMO)

POLARIZATION DIVERSITY

- Polarization diversity uses antennas of different polarizations i.e. horizontal and vertical.

- The antennas take advantage of the multipath propagation characteristics to receive separate uncorrelated signals

- SNR is improved by up to 12 dB even in line-of-sight channels.

FREQUENCY DIVERSITY (1)

- Frequency diversity is implemented by transmitting same information on more than one carrier frequency.

- Our aim is to make these carrier frequency uncorrelated to each other, so that they will not experience the same fades.

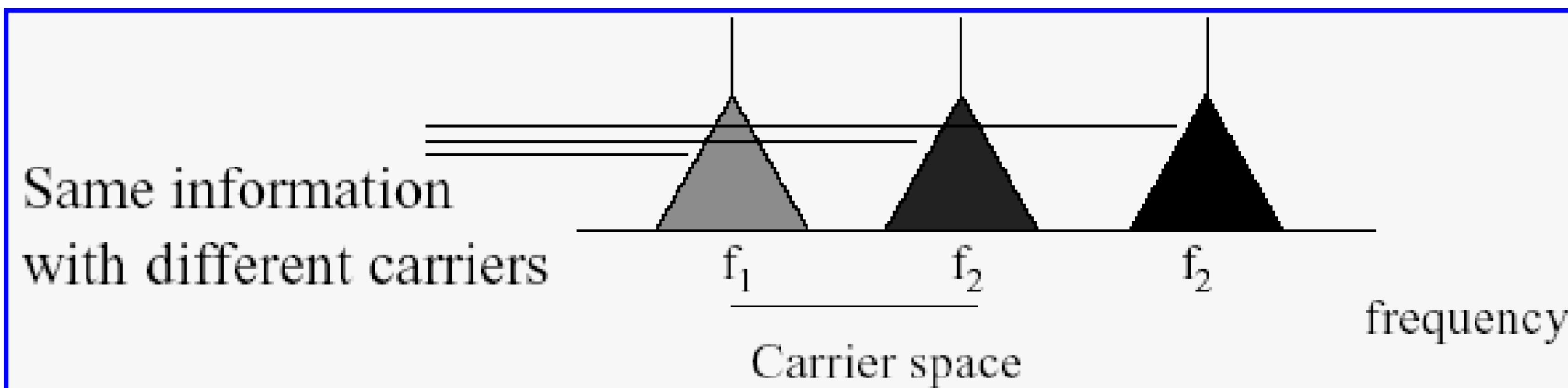
- To make them least correlated, these carrier frequencies are separated by more than the coherence bandwidth of the channel.

FREQUENCY DIVERSITY (2)

- Theoretically if the channels are uncorrelated , then the probability of simultaneous fading will be the product of the individual fading probabilities.

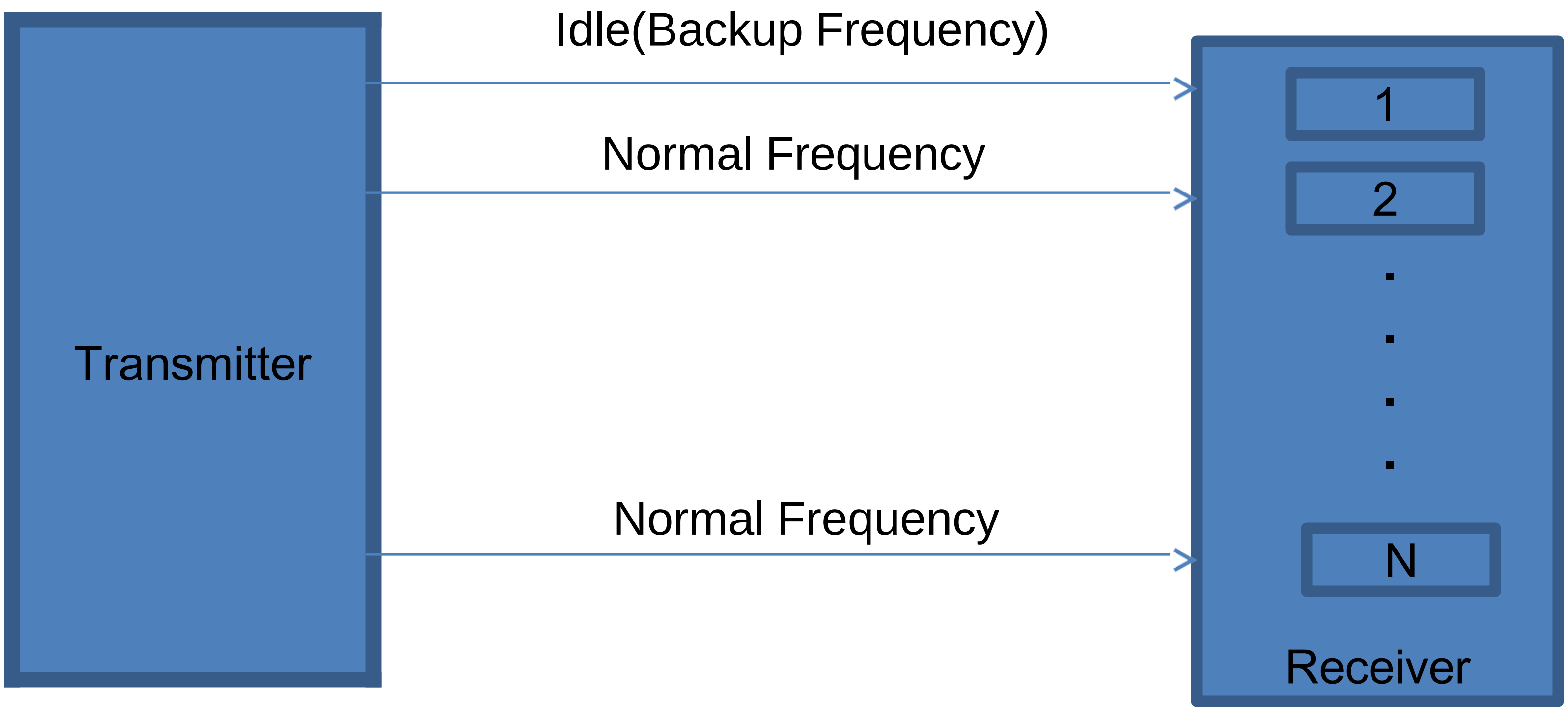
- Frequency diversity is often employed in microwave line –of-sight links.

- These links uses Frequency division multiplexing mode(FDM).



FREQUENCY DIVERSITY (3)

- In Practice 1:N protection switching is used as shown below.



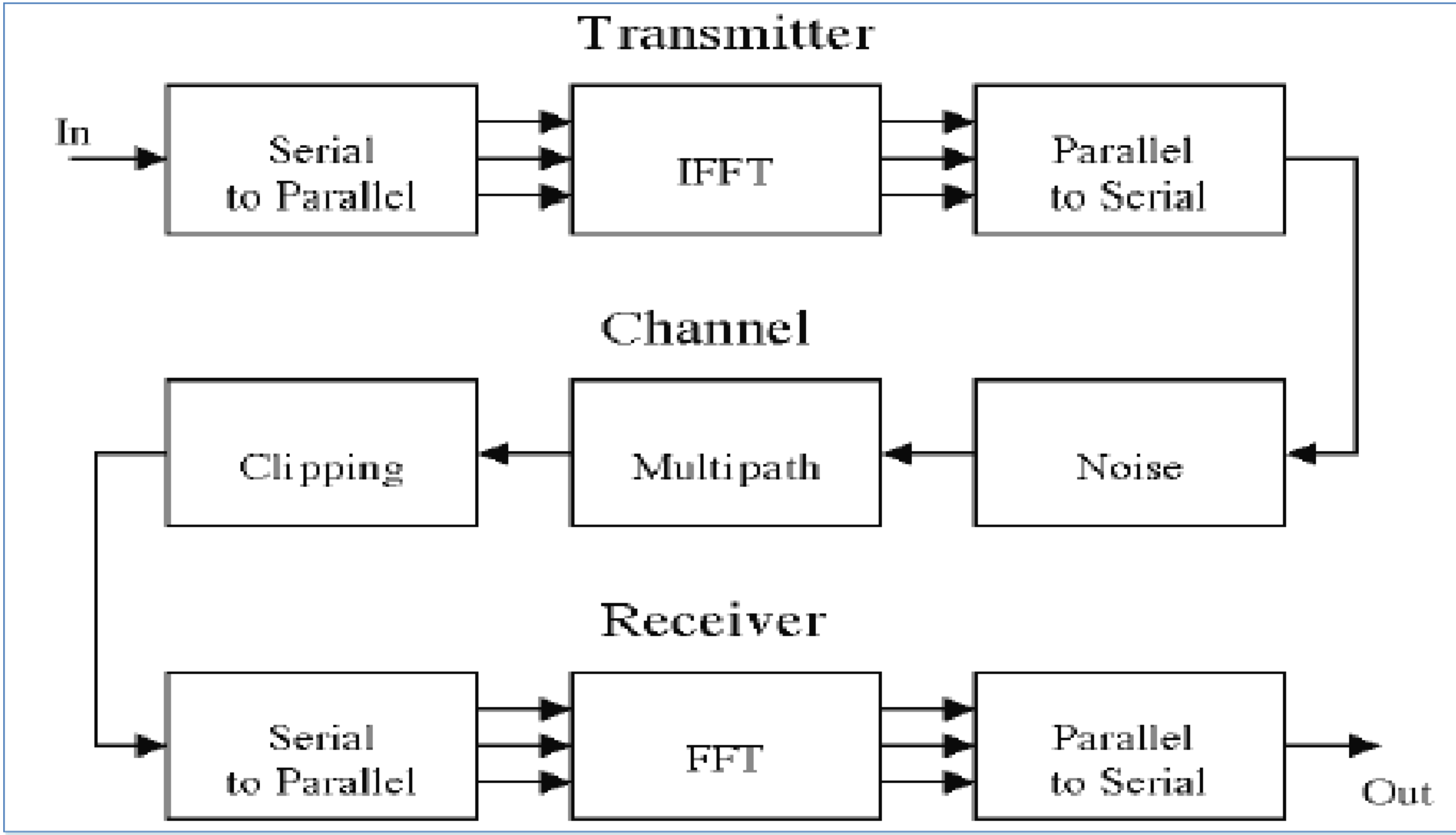
FREQUENCY DIVERSITY (4)

- Protection switching is provided by a radio licensee.
- In this case one frequency is nominally idle but is available on a stand by basis to provide frequency diversity switching for any one of the other N carrier.
- When diversity is needed , the appropriate traffic is simply switched to backup frequency.

FREQUENCY DIVERSITY (5)

- FH-SS is a special case of frequency diversity.
- New OFDM modulation and access techniques exploit frequency diversity.
- This can be achieved by providing simultaneous modulation signals with error control coding across a large bandwidth.
- If a particular frequency undergoes a fade , the composite signal will still be demodulated.

FREQUENCY DIVERSITY (6)

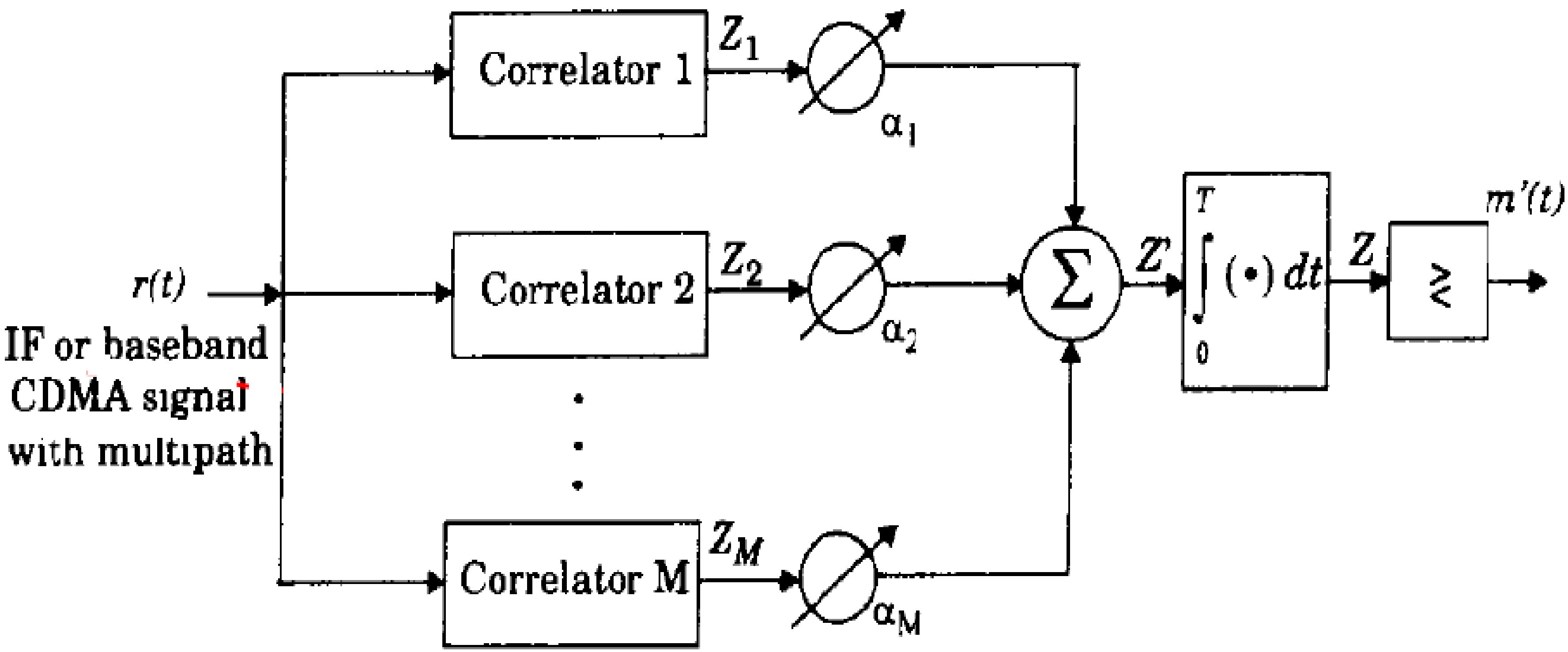


TIME DIVERSITY (1)

- Time diversity repeatedly transmits information at the time spacing that exceeds the coherence time of the channel.
- Multiple repetitions of the signals will be received with independent fading conditions, thereby providing diversity.
- Our modern implementation of time diversity involves the use of RAKE receiver for spread spectrum CDMA.

TIME DIVERSITY (2)

♠The rake receiver is so named because it reminds the function of a garden rake, each finger collecting symbol energy similarly to how tines on a rake collect leaves.



RAKEReceiver

TIME DIVERSITY (3)

- A rake receiver is a radio receiver designed to counter the effects of multipath fading, It does this by using several "sub-receivers" called *fingers*.
- The rake receiver was patented in the US in 1956 by " Price and Green".
- Each correlator detects a time-shifted version of the original transmission, and each finger correlates to a portion of the signal, which is delayed by at least one chip in time(1/Rc) from the other fingers.
- This will result in higher SNR (E_b/N_0) in a multipath environment than in a "clean" environment.

TIME DIVERSITY (4)

- Multipath component appears like uncorrelated noise at a CDMA receiver and equalization is not required.

- The outputs of each correlator are weighted to provide better estimate of the transmitted signal than is provided by a single component.

- The weighting coefficients are based on the power or the SNR from each correlator output.

  - If the power or SNR is small out of a particular correlator, it will be assigned a small weighting factor or vice versa.

INTERLEAVING AS TIME DIVERSITY (5)

♣Interleaving is used to obtain time diversity in the digital communication system.

♣Interleaving is a way to arrange data in a non-contiguous way to increase performance.

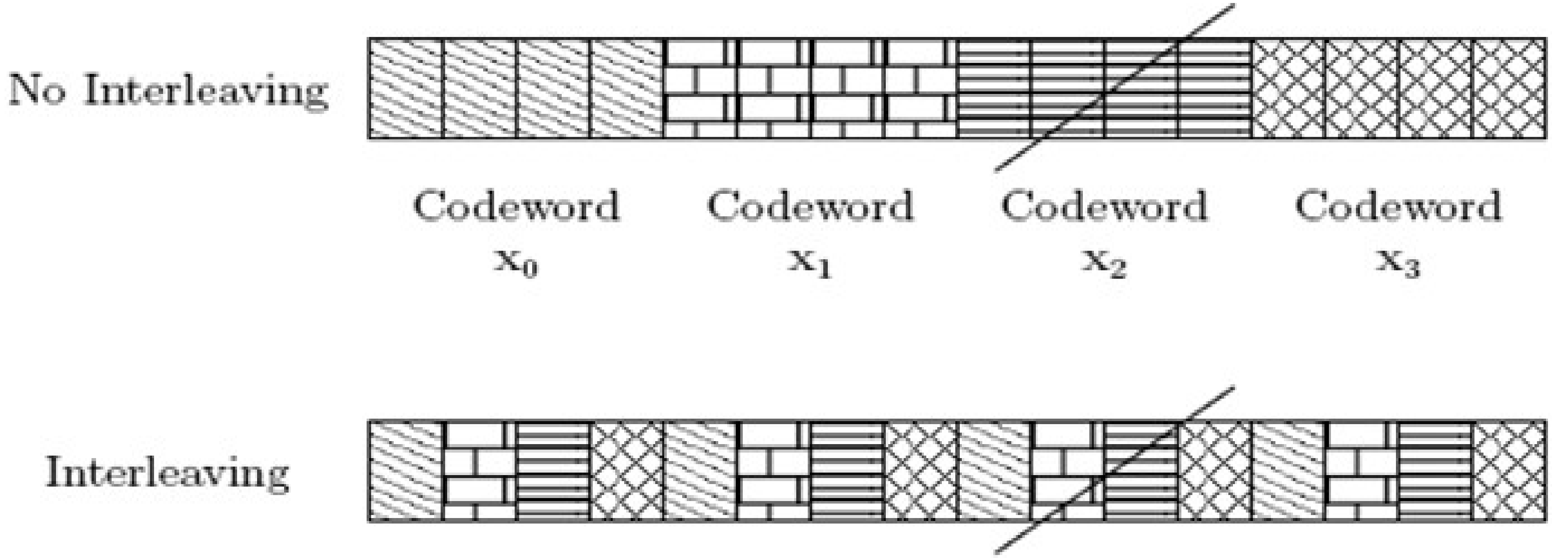
♣It is typical for many speech coders to produce several important bits in succession.

♣The function of interleaver is to spread these bits out in time so that if there is a deep fade or error burst, the important bits from a block of source data are not corrupted at the same time.

INTERLEAVING AS TIME DIVERSITY (6)

♣At the receiver , de-interleaver is used.

♣Convolutional interleaver can be used in place of block interleaver and ideally suited for use with convolutional codes.




Thank you

Topic 1

Realization of Independent Fading Paths

First Method of Realization

- There are many ways of achieving independent fading paths in a wireless system.
- One method is to use multiple receive antennas, also called an antenna array, where the elements of the array are separated in distance.
- This type of diversity is called as space diversity.
- In space diversity, independent fading paths are realized without an increase in transmit signal power or bandwidth.
- The separation between antennas must be that the fading amplitudes corresponding to each antenna are approximately independent.
- For example, in a uniform scattering environment with isotropic transmit & receive antennas the minimum antenna separation required for independent fading on each antenna is approximately one half wavelength.

Second Method of Realization

- If the transmit or receive antennas are directional, then the multipath is confined to a small angle relative to the LOS ray, which means a larger antenna separation required to get independent fading samples.
- A second method of achieving diversity is by using either two transmit antennas or two receive antennas with different polarization (e.g. vertically and horizontally polarized waves).
- The two transmitted waves follow the same path however, since the multiple random reflections distribute the power equally relative to both polarizations.
- Since scattering angle relative to each polarization is random, it is highly improbable that signals received on two different polarized antennas would be simultaneously in deep fades.
- There are two disadvantages of polarization diversity .

Angle or Directional Diversity

- First disadvantage is - two diversity branches, corresponding to the two types of polarization.
- The second disadvantage is - polarization diversity loses effectively half of the 3 dB power.
- Directional antennas provide angle or directional diversity by restricting the receive antenna beam-width to a given angle.
- If the angle is very small then one of the multipath rays will fall within the receive beam-width, so there is no multipath fading from multiple rays.
- However, this diversity technique requires sufficient number of directional antennas to span all possible directions of arrival or a single antenna whose directivity to be steered

Frequency & Time Diversity

- Frequency diversity is achieved by transmitting the same narrowband signal at different carrier frequencies separated by the coherence bandwidth of the channel.
- Spread spectrum techniques are described as providing frequency diversity since the channel gain varies across the bandwidth of the transmitted signal.
- However, this is not equivalent to sending the same information signal over independently fading paths.
- Time diversity is achieved by transmitting the same signal at different times, where the time difference is greater than the channel coherence time.
- Time diversity can also be achieved through coding and interleaving.


Thank you

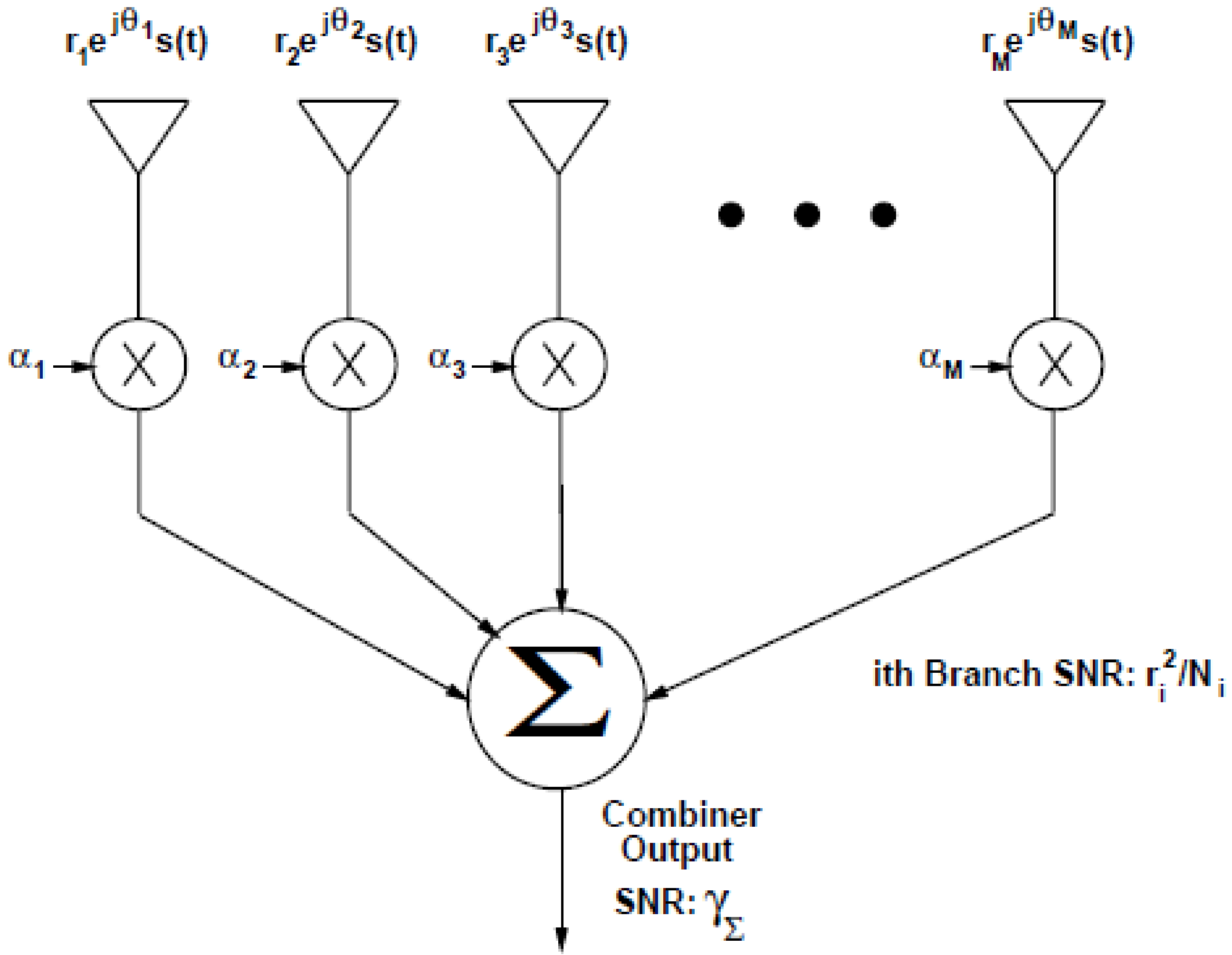
Topic 2

Receiver Diversity

Receiver Diversity

- A diversity system combines the independent fading paths to obtain a resultant signal, then passed through a standard demodulator.
- The combining can be done in several ways which vary in complexity & overall performance.
- Space diversity used as a reference to describe the diversity systems & different combining techniques.
- Thus, the combining techniques will be defined as operations on an antenna array.
- Most combining techniques are linear - the output of the combiner is a weighted sum of different fading paths as shown in Figure 1 for M -branch diversity.
- When all but one of the complex α_is are zero, only one path is passed to the combiner output.

Figure 1 – Linear Combiner



Receiver Diversity (contd)

- When more than one of the α_is is nonzero, the combiner adds together multiple paths, where each path may be weighted by different value.
- Combining more than one branch signal requires co-phasing, where the phase θ_i of the ith branch is removed through the multiplication by $\alpha_i = a_i e^{-j\theta_i}$ for some real-valued a_i.
- This phase removal requires coherent detection of each branch to determine its phase θ_i.
- The multiplication by α_i can be performed either before detection or after detection with no difference in performance.
- Combining is typically performed post-detection, since the branch signal power is required to determine the appropriate α_i value.
- Post-detection requires a dedicated receiver for each branch to determine the branch phase, which increases hardware complexity & power consumption for a large number of branches.

Receiver Diversity (contd)

- The signal output from the combiner equals the original transmitted signal s(t) multiplied by a random complex amplitude term $\alpha_\Sigma = \sum_i \alpha_i r_i e^{j\theta_i}$ that results from the path combining.
- This complex amplitude term results in a random SNR γ_Σ at the combiner output, where the distribution of γ_Σ is a function of the number of diversity paths, the fading distribution on each path, & combining technique.
- Since the combiner output is fed into a standard demodulator for the transmitted signal s(t), the performance of the diversity system in terms of Ps and P_{out} defined as -

$$\overline{P}_s = \int_0^\infty P_s(\gamma) p_{\gamma_\Sigma}(\gamma) d\gamma, \quad P_{out} = p(\gamma_\Sigma \le \gamma_0) = \int_0^{\gamma_0} p_{\gamma_\Sigma}(\gamma) d\gamma,$$

- for some target SNR value γ_0.


Thank you

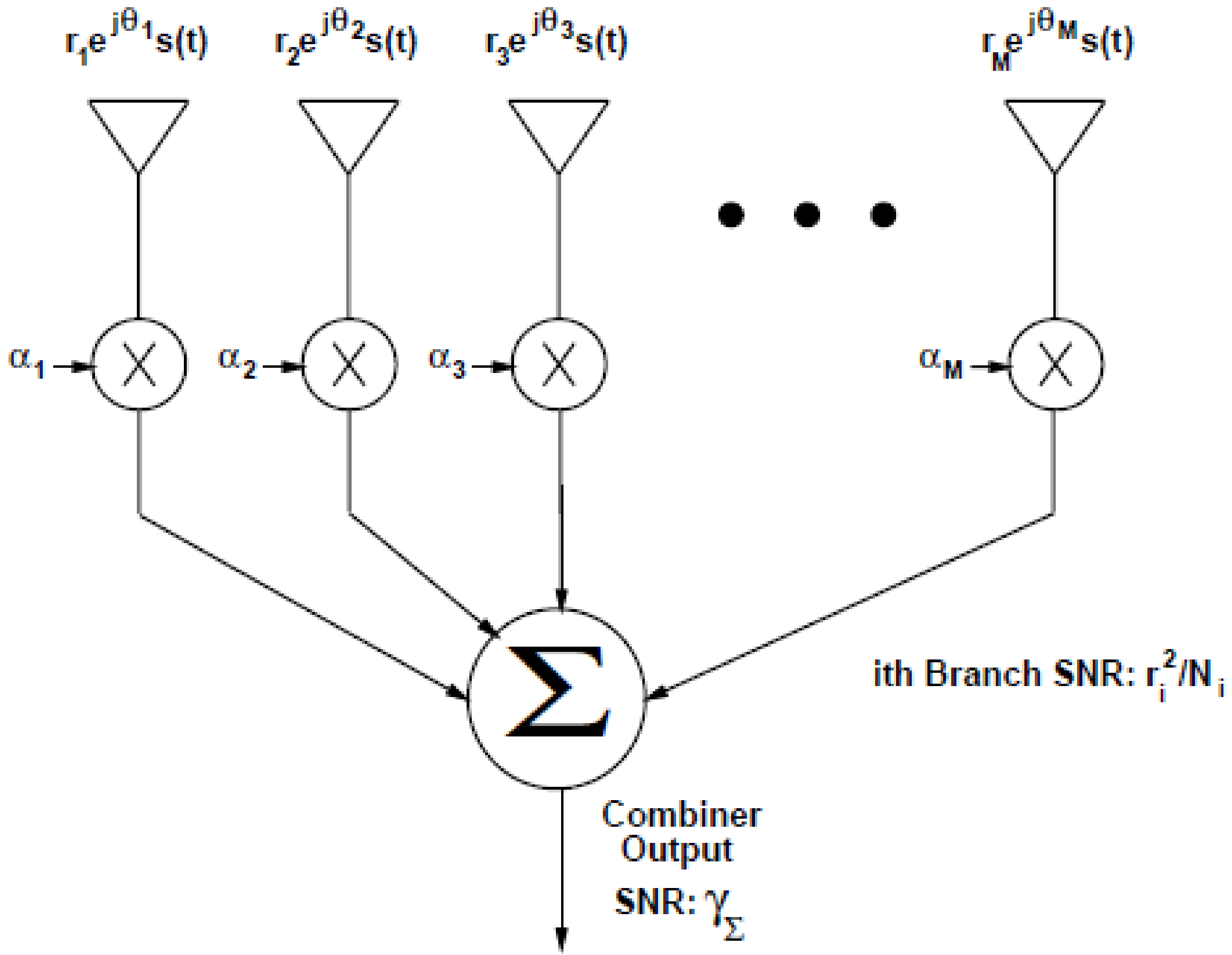
Topic 3

Selection Combining

Selection Combining

- In selection combining (SC), the combiner outputs the signal on the branch with the highest SNR r_i^2/N_i.
- This is equivalent to choosing the branch with the highest $r_i^2 + N_i$ if the noise $N_i = N$ is the same on all branches.
- Since only one branch is used at a time, SC requires just one receiver switched into the active antenna branch.
- However, a dedicated receiver on each antenna branch needed for systems that transmit continuously in order to monitor SNR on each branch.
- With SC the path output from the combiner has an SNR equal to the maximum SNR of all the branches.
- Moreover, since only one branch output is used, co-phasing of multiple branches not required & this technique can be used with either coherent or differential modulation.

Figure 1 – Linear Combiner



Selection Combining (contd)

- For M branch diversity, the CDF of γ_Σ is given by

$$P_{\gamma_\Sigma}(\gamma) = p(\gamma_\Sigma < \gamma) = p(\max[\gamma_1, \gamma_2, \ldots, \gamma_M] < \gamma) = \prod_{i=1}^{M} p(\gamma_i < \gamma).$$

- The pdf of γ_Σ obtained by differentiating $P_{\gamma\Sigma}(\gamma)$ relative to γ & the outage probability by evaluating $P_{\gamma\Sigma}(\gamma)$ at $\gamma = \gamma_0$.
- The instantaneous SNR on the ith branch is therefore given by $\gamma_i = r_i^2/N$.
- Defining the average SNR on the ith branch as $\gamma_i = E[\gamma_i]$, the SNR distribution will be exponential-

$$p(\gamma_i) = \frac{1}{\overline{\gamma}_i} e^{-\gamma_i/\overline{\gamma}_i}.$$

- The outage probability of the selection-combiner for the target γ_0 is then

$$P_{out}(\gamma_0) == \prod_{i=1}^{M} p(\gamma_i < \gamma_0) = \prod_{i=1}^{M} \left[1 - e^{-\gamma_0/\overline{\gamma}_i}\right].$$

Selection Combining (contd)

- If the average SNR for all of the branches are the same for all *i*, then this reduces to-

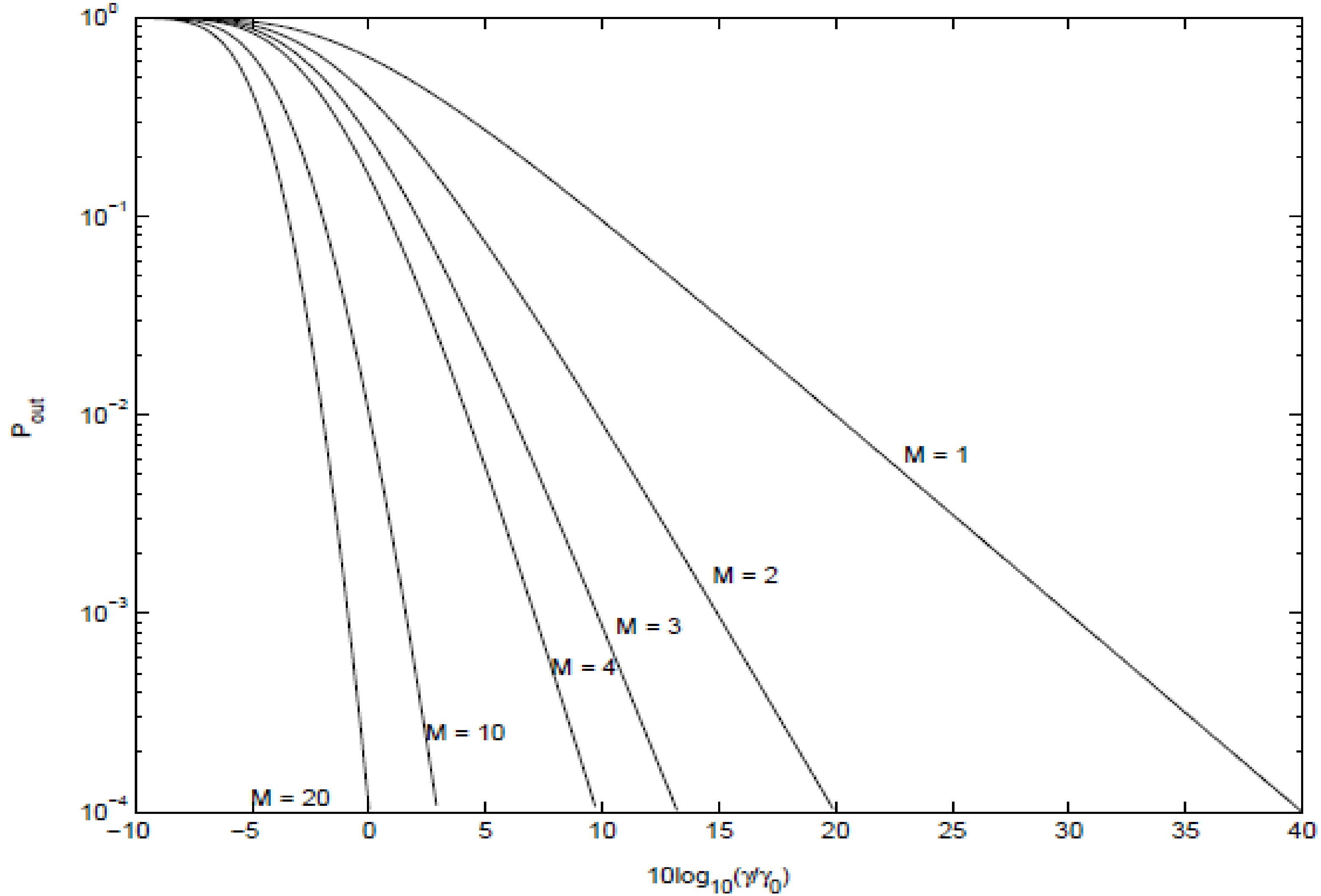
$$P_{out}(\gamma_0) = p(\gamma_\Sigma < \gamma_0) = \left[1 - e^{-\gamma_0/\bar{\gamma}}\right]^M .$$

- Differentiating the above expression relative to γ_0 yields the pdf for γ_Σ

$$p_{\gamma_\Sigma}(\gamma) = p(\gamma_\Sigma = \gamma) = \frac{M}{\bar{\gamma}}\left[1 - e^{-\gamma/\bar{\gamma}}\right]^{M-1} e^{-\gamma/\bar{\gamma}}.$$

- Thus, the average SNR gain increases with *M* , but not linearly.
- The biggest gain is obtained by going from no diversity to two-branch diversity.
- Increasing the number of diversity branches from two to three will give much less gain than going from one to two & increasing *M* yields diminishing returns in terms of SNR gain.
- This trend is also illustrated in the Figure 2, which shows P_{out} versus γ/γ_0 for different *M* in Rayleigh fading.

Figure 2 - Outage Probability of Selection Combining in Rayleigh Fading



Selection Combining (contd)

- In figure 2, there is dramatic improvement even with just two-branch selection combining -
- Going from M = 1 to M = 2 at 1% outage probability there is an approximate 12 dB reduction in required SNR.
- At 0.01% outage probability there is an approximate 20 dB reduction in required SNR.
- However, at 0.01% outage, going from two-branch to three-branch diversity results in additional reduction of approximately 7 dB.
- From three-branch to four-branch results in additional reduction of approximately 4 dB.
- Clearly the power savings is going from no diversity to two-branch diversity, with diminishing returns as the number of branches increased.

Example : Find the outage probability of BPSK modulation at $P_b = 10^{-3}$ for a Rayleigh fading channel with SC diversity for $M = 1$ (no diversity), $M = 2$, and $M = 3$. Assume equal branch SNRs of $\gamma = 15$ dB.

Solution:

A BPSK modulated signal with $\gamma_b = 7$ dB has $P_b = 10^{-3}$. Thus, we have $\gamma_0 = 7$ dB. Substituting

$\gamma_0 = 10^{0.7}$ and $\gamma = 10^{1.5}$into yields $P_{out} = .1466$ for $M = 1$, $P_{out} = .0215$ for $M = 2$, and $P_{out} = 0.0031$ For $M = 2$.

$$P_{out}(\gamma_0) = p(\gamma_\Sigma < \gamma_0) = \left[1 - e^{-\gamma_0/\overline{\gamma}}\right]^M .$$

We see that each additional branch reduces outage probability by almost an order of magnitude.


Thank you

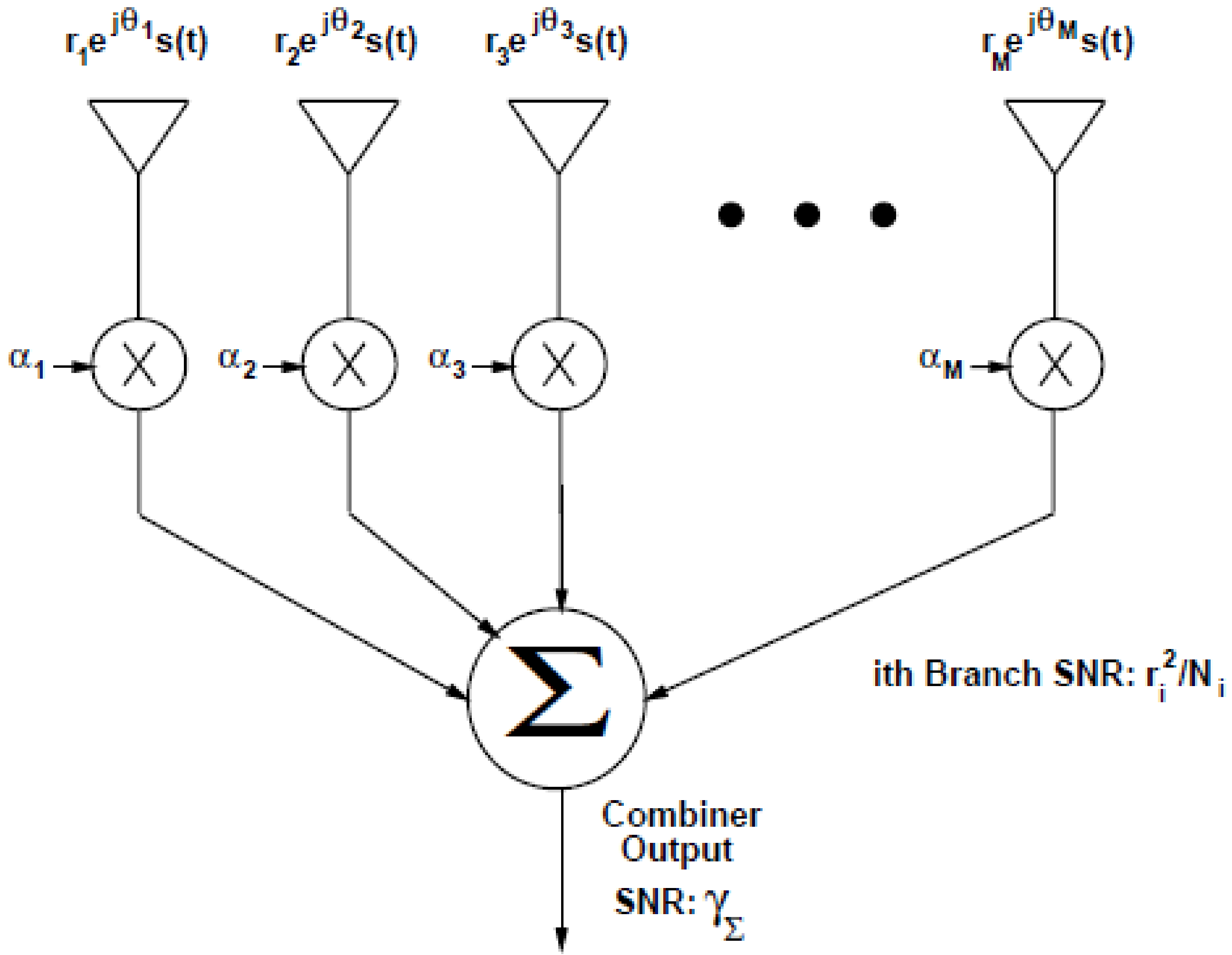
Topic 4

Threshold Combining

Threshold Combining

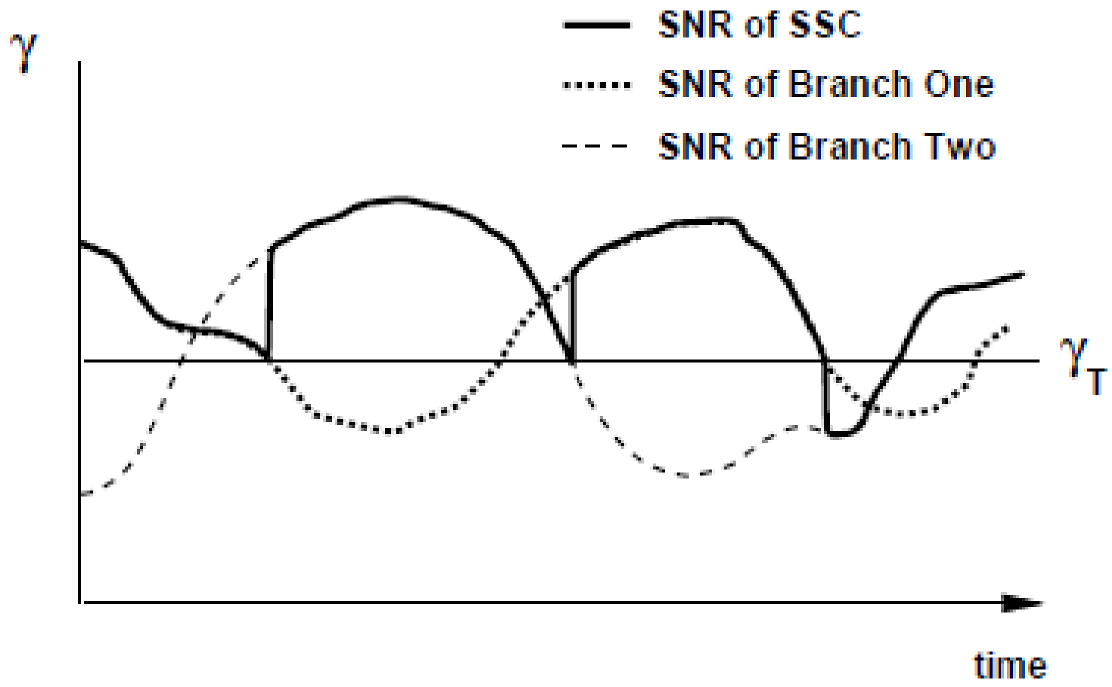
- SC for systems that transmit continuously may require a dedicated receiver on each branch to monitor branch SNR.
- A simpler type of combining - threshold combining - avoids the need for a dedicated receiver on each branch by scanning each of the branches in sequential order & outputting the first signal with SNR above a given threshold γ_T .
- As in SC, since only one branch output is used at a time, co-phasing is not required.
- This technique can be used with either coherent or differential modulation.
- Once a branch is chosen, as long as the SNR remains above the desired threshold, the combiner outputs that signal.
- If the SNR on selected branch falls below the threshold, the combiner switches to another branch.
- There are several criteria the combiner can use to decide which branch to switch to.
- The simplest criterion is to switch randomly to another branch.

Figure 1 – Linear Combiner



Threshold Combining (contd)

- With only two-branch diversity - equivalent to switching to the other branch when the SNR on the active branch falls below γ_T .
- This method is called switch and stay combining (SSC).
- The switching process & SNR associated with SSC is illustrated in Figure 3.



Threshold Combining (contd)

- Let us denote the SNR on the i^{th} branch by γ_i & SNR of the combiner output by γ_Σ.
- The CDF of γ_Σ will depend on the threshold level γ_T & CDF of γ_i.
- For two-branch diversity, the CDF of the combiner output $P_{\gamma\Sigma}(\gamma) = p(\gamma_\Sigma \leq \gamma)$ can be expressed in terms of the CDF $P_{\gamma i}(\gamma) = p(\gamma_i \leq \gamma)$ & pdf $p_{\gamma i}(\gamma)$ of the individual branch SNRs as –

$$P_{\gamma_\Sigma}(\gamma) = \begin{cases} P_{\gamma_1}(\gamma_T)P_{\gamma_2}(\gamma) & \gamma < \gamma_T \\ p(\gamma_T \leq \gamma_1 \leq \gamma) + P_{\gamma_1}(\gamma_T)P_{\gamma_2}(\gamma) & \gamma \geq \gamma_T. \end{cases}$$

- For Rayleigh fading in each branch with $\overline{\gamma}_i = \overline{\gamma}, i = 1,2$ this yields -

$$P_{\gamma_\Sigma}(\gamma) = \begin{cases} 1 - e^{-\gamma_T/\overline{\gamma}} - e^{-\gamma/\overline{\gamma}} + e^{-(\gamma_T+\gamma)/\overline{\gamma}} & \gamma < \gamma_T \\ 1 - 2e^{-\gamma/\overline{\gamma}} + e^{-(\gamma_T+\gamma)/\overline{\gamma}} & \gamma \geq \gamma_T. \end{cases}$$

Threshold Combining (contd)

- The outage probability P_{out} associated with a given γ_0 is obtained by evaluating $P_{\gamma\Sigma}(\gamma)$ at $\gamma = \gamma_0$ –

$$P_{out}(\gamma_0) = P_{\gamma_\Sigma}(\gamma_0) = \begin{cases} 1 - e^{-\gamma_T/\overline{\gamma}} - e^{-\gamma_0/\overline{\gamma}} + e^{-(\gamma_T+\gamma_0)/\overline{\gamma}} & \gamma < \gamma_T \\ 1 - 2e^{-\gamma_0/\overline{\gamma}} + e^{-(\gamma_T+\gamma_0)/\overline{\gamma}} & \gamma \geq \gamma_T. \end{cases}$$


Thank you

Topic 5

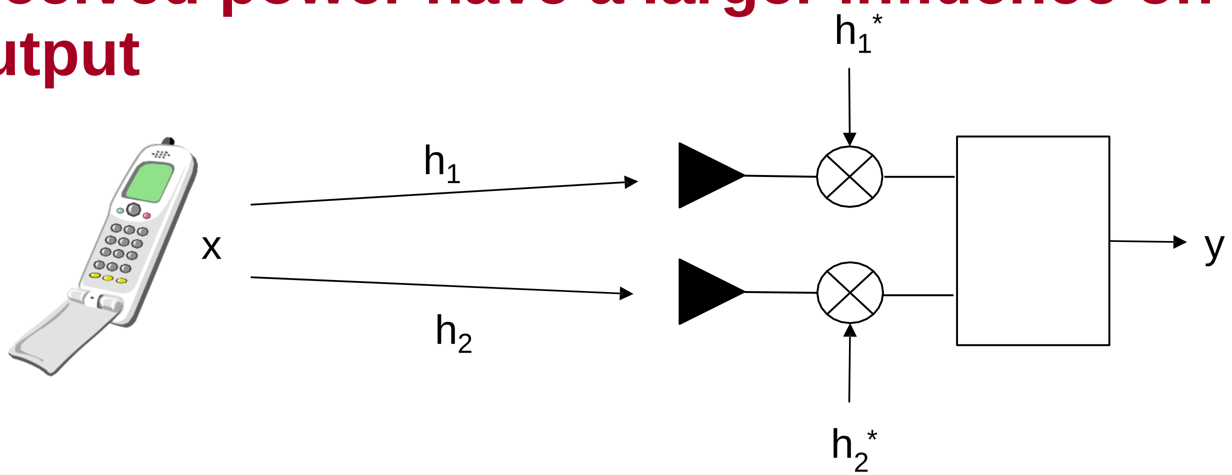
Maximal Ratio Combining

Maximal Ratio Combining

- **All paths cophased and summed with optimal weighting to maximize combiner output SNR**

- **Optimal technique to maximize output SNR**

- **A means of combining the signals from all receiver branches, so that signals with a higher received power have a larger influence on the final output**



Maximal Ratio Combining

- In Maximum Ratio combining each signal branch is multiplied by a weight factor that is proportional to the signal amplitude.
- That is, branches with strong signal are further amplified, while weak signals are attenuated.

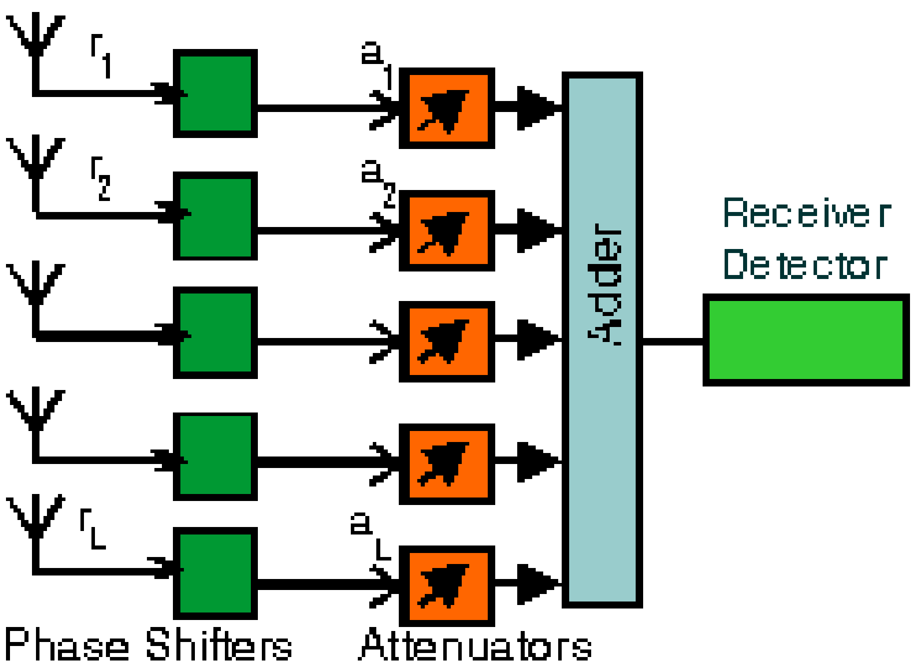


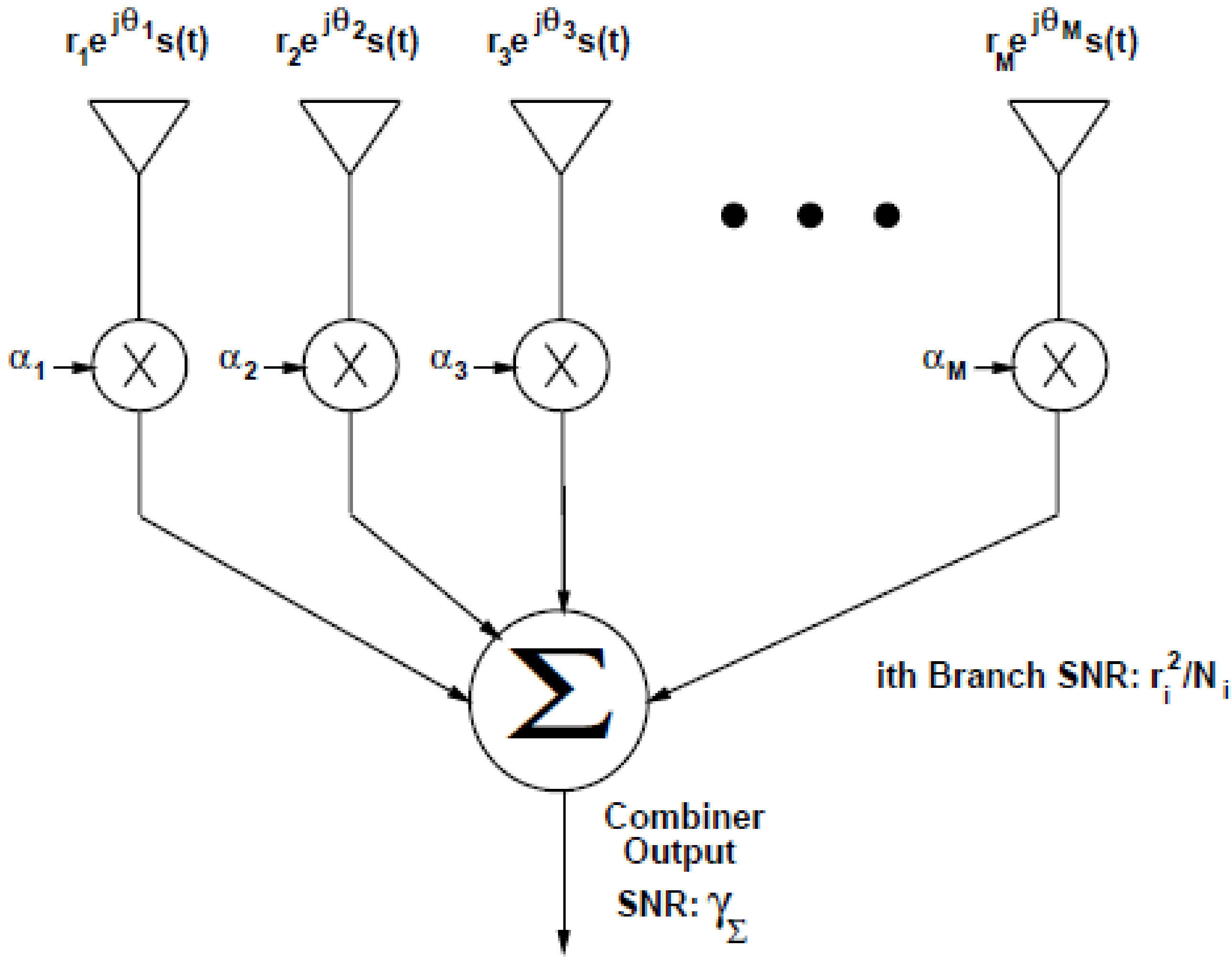
Figure: L-branch antenna diversity receiver (L = 5). With MRC, the attenuation/amplification factor is proportional to the signal amplitude $a_i = r_i$ for each channel i.

Maximal Ratio Combining

- In Selection Combining and Switch & Stay Combining (SSC), the output of the combiner equals the signal on one of the branches.
- In maximal ratio combining (MRC) the output is a weighted sum of all branches, so the α_is in Figure 1 are all nonzero. Since the signals are co-phased, $\alpha_i = a_i e^{-j\vartheta_i}$, where ϑ_i is the phase of the incoming signal on the i^{th} branch.
- Thus, the envelope of the combiner output will be $r = \sum_{i=1}^{M} a_i r_i$.
- Assuming same noise power N in each branch yields a total noise power *Ntot* at the combiner output of $N_{tot} = \bar{N}_{tot} = \sum_{i=1}^{M} a_i^2 N$.
- Thus, the output SNR of the combiner is –

$$\gamma_\Sigma = \frac{r^2}{N_{tot}} = \frac{1}{N} \frac{\left(\sum_{i=1}^{M} a_i r_i\right)^2}{\sum_{i=1}^{M} a_i^2}.$$

Figure 1 – Linear Combiner



Maximal Ratio Combining (contd)

- The goal is to chose α_is to maximize γ_Σ.
- Generally branches with a high SNR should be weighted more than branches with a low SNR, so the weights a^2_i should be proportional to the branch SNRs r_i^2/N .
- The a_is that maximize γ_Σ can be computed by taking partial derivatives of above equation.
- The average combiner SNR increases linearly with the number of diversity branches *M*, in contrast to diminishing returns associated with average combiner SNR in SC.
- To obtain the distribution of γ_Σ the product of the exponential moment generating function can be taken -

$$p_{\gamma_\Sigma}(\gamma) = \frac{\gamma^{M-1} e^{-\gamma/\bar{\gamma}}}{\bar{\gamma}^M (M-1)!}, \quad \gamma \geq 0.$$

Maximal Ratio Combining (contd)

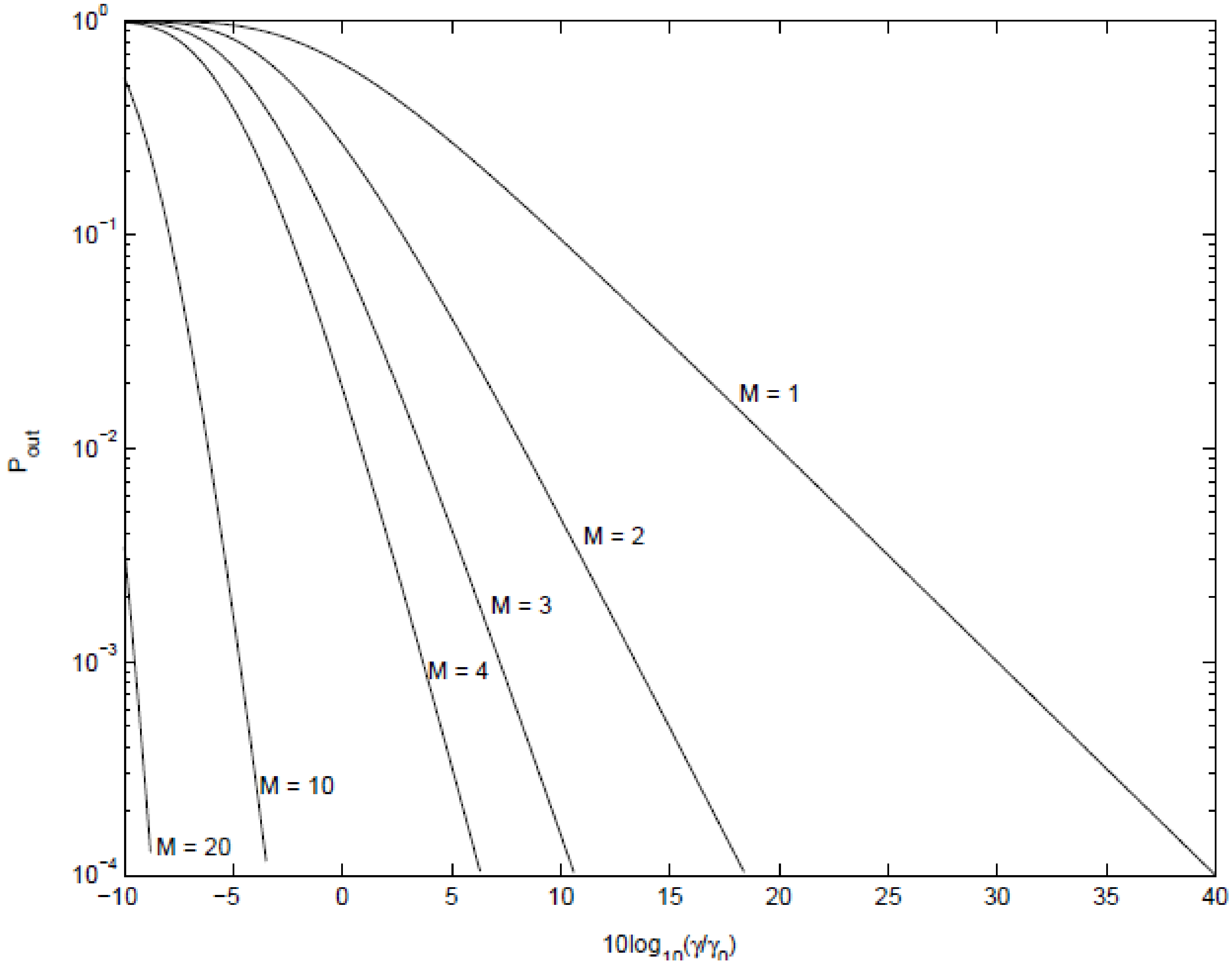
- The corresponding outage probability for a given threshold γ_0 is given by –

$$P_{out} = p(\gamma_\Sigma < \gamma_0) = \int_0^{\gamma_0} p_{\gamma_\Sigma}(\gamma)d\gamma = 1 - e^{-\gamma_0/\bar{\gamma}} \sum_{k=1}^{M} \frac{(\gamma_0/\bar{\gamma})^{k-1}}{(k-1)!}.$$

- Figure 2 - plots P_{out} for maximal ratio combining indexed by the number of diversity branches.
- The average probability of bit error for BPSK modulation with Rayleigh fading given by-

$$\overline{P}_b = \int_0^{\infty} Q(\sqrt{2\gamma})p_{\gamma_\Sigma}(\gamma)d\gamma = \left(\frac{1-\Gamma}{2}\right)^M \sum_{m=0}^{M-1} \binom{M-1+m}{m} \left(\frac{1+\Gamma}{2}\right)^m$$

Figure 2 - P_{out} for MRC with Rayleigh fading



Maximal Ratio Combining

- The idea to boost the strong signal components and attenuate the weak (relatively noisy) components, as performed in MRC diversity, is exactly the same as the type of filtering and signal weighting used in the matched filter receiver.

- A particularly interesting application of this concept is the Rake receiver for detecting direct-sequence CDMA signals over a dispersive channel.

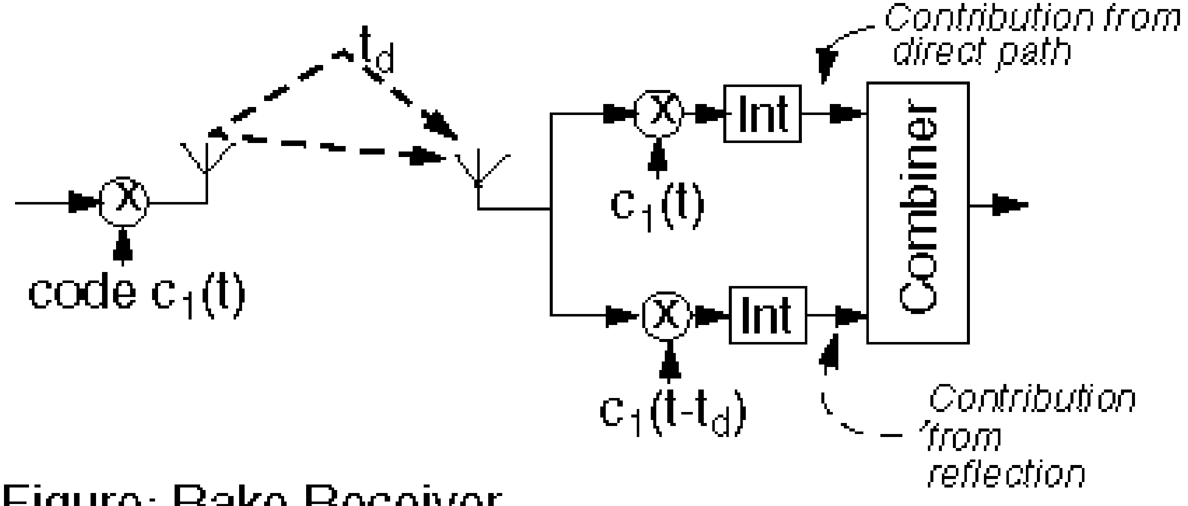


Figure: Rake Receiver

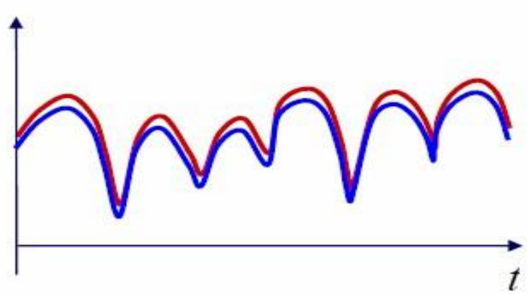

Thank you

Topic 6

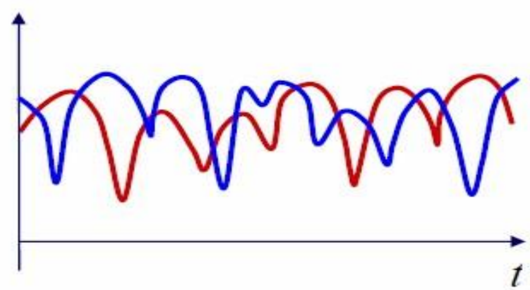
Equal Gain Combining

Motivation of Diversity Techniques

- **If a fading radio signal is received through only one channel, then in a deep fade, the signal could be lost, and there is nothing that can be done**
- **Diversity is a way to protect against deep fades, a choice to combat fading**
- **<u>The key</u>: create multiple channels or branches that have uncorrelated fading**



The fading of two highly correlated channels



Two channels with uncorrelated fading

Basic Diversity Techniques

- **Diversity combats fading by providing the receiver with multiple uncorrelated replicas of the same information bearing signal**

- **There are several types of receiver diversity methods**

  - **Time Diversity**
  - **Frequency Diversity**
  - **Multiuser Diversity**
  - **Space Diversity**

Basic Diversity Combining Techniques

- **Once you have created two or more channels or branches that have uncorrelated fading, what do you do with them?**
- **Techniques applied to combine the multiple received signals of a diversity reception device into a single improved signal**
  - **Selection Combining (SC)**
  - **Feedback or Scanning Combining (FC or SC)**
  - **Maximal Ratio Combining (MRC)**
  - **Equal Gain Combining (EGC)**
  - **Zero Forcing (ZF)**
  - **Minimum Mean Square Error (MMSE)**

Equal Gain Combining

- **Simplified method of Maximal Ratio Combining**
- **Combine multiple signals into one**
- **The phase is adjusted for each receive signal so that**
    - **The signal from each branch are co-phased**
    - **Vectors add in-phase**
- **Better performance than selection diversity**

Equal Gain Combining

- The adaptively controller amplifiers / attenuators are not needed.
- Moreover, no channel amplitude estimation is needed.

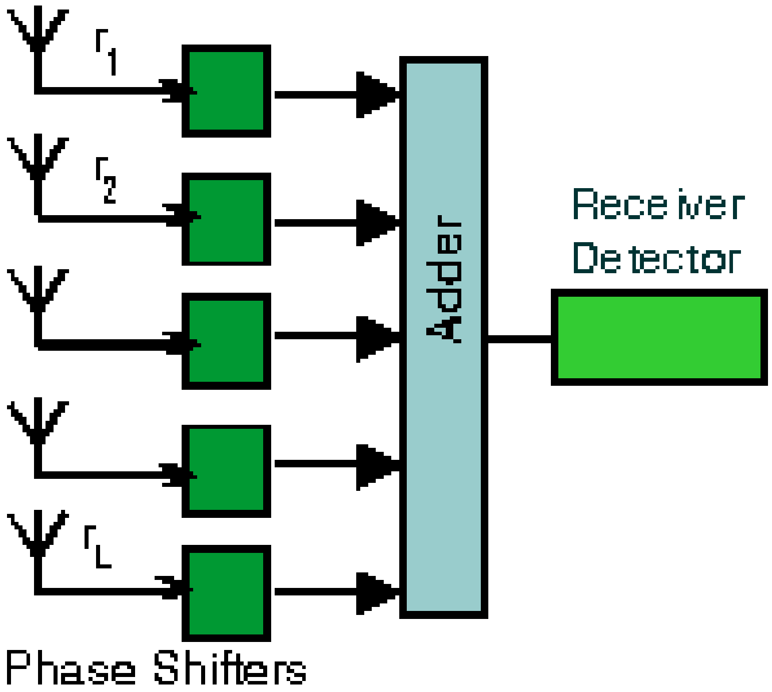


Figure: *L*-branch Equal Gain Combining antenna diversity receiver (*L* = 5).

Equal Gain Combining

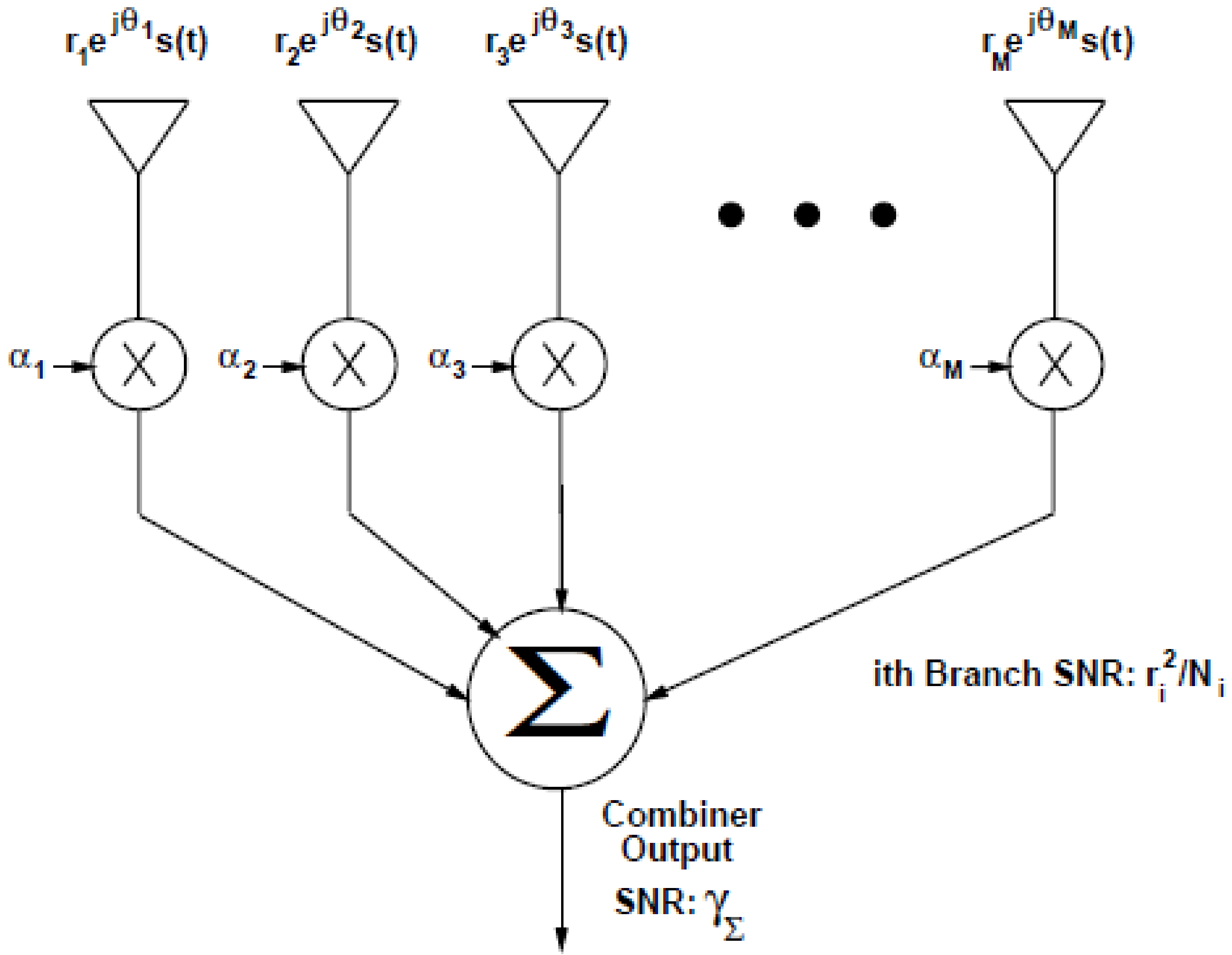
- MRC requires knowledge of the time-varying SNR on each branch & can be very difficult to measure.
- A simpler technique - equal-gain combining, which co-phases the signals on each branch & then combines them with equal weighting, $\alpha_i = e^{-\vartheta_i}$.
- The SNR of combiner output, assuming equal noise power N in each branch given by

$$\gamma_\Sigma = \frac{1}{NM}\left(\sum_{i=1}^{M} r_i\right)^2 .$$

- The pdf and CDF of γ_Σ do not exist in closed-form.
- For Rayleigh fading and two-branch diversity and average branch SNR γ, an expression for the CDF in terms of the Q function can be derived as –

$$P_{\gamma_\Sigma}(\gamma) = 1 - e^{-2\gamma/\bar{\gamma}}\sqrt{\frac{\pi\gamma}{\bar{\gamma}}}e^{-\gamma/\bar{\gamma}}\left(1 - 2Q\left(\sqrt{2\gamma/\bar{\gamma}}\right)\right).$$

Figure 1 – Linear Combiner



Equal Gain Combining (contd)

- The resulting outage probability is given by-

$$P_{out}(\gamma_0) = 1 - e^{-2\gamma_R} - \sqrt{\pi\gamma_R}e^{-\gamma_R}\left(1 - 2Q\left(\sqrt{2\gamma_R}\right)\right),$$

- Where $\gamma_R = \gamma_0/\overline{\gamma}$. Differentiating the second equation relative to γ yields

$$p_{\gamma_\Sigma}(\gamma) = \frac{1}{\overline{\gamma}}e^{-2\gamma/\overline{\gamma}} + \sqrt{\pi}e^{-\gamma/\overline{\gamma}}\left(\frac{1}{\sqrt{4\gamma\overline{\gamma}}} - \frac{1}{\overline{\gamma}}\sqrt{\frac{\gamma}{\overline{\gamma}}}\right)\left(1 + 2Q(\sqrt{2\gamma/\overline{\gamma}})\right)$$

- For BPSK, the average probability of bit error given by-

$$\overline{P}_b = \int_0^\infty Q(\sqrt{2\gamma})p_{\gamma_\Sigma}(\gamma)d\gamma = .5\left(1 - \sqrt{1 - \left(\frac{1}{1+\overline{\gamma}}\right)^2}\right).$$

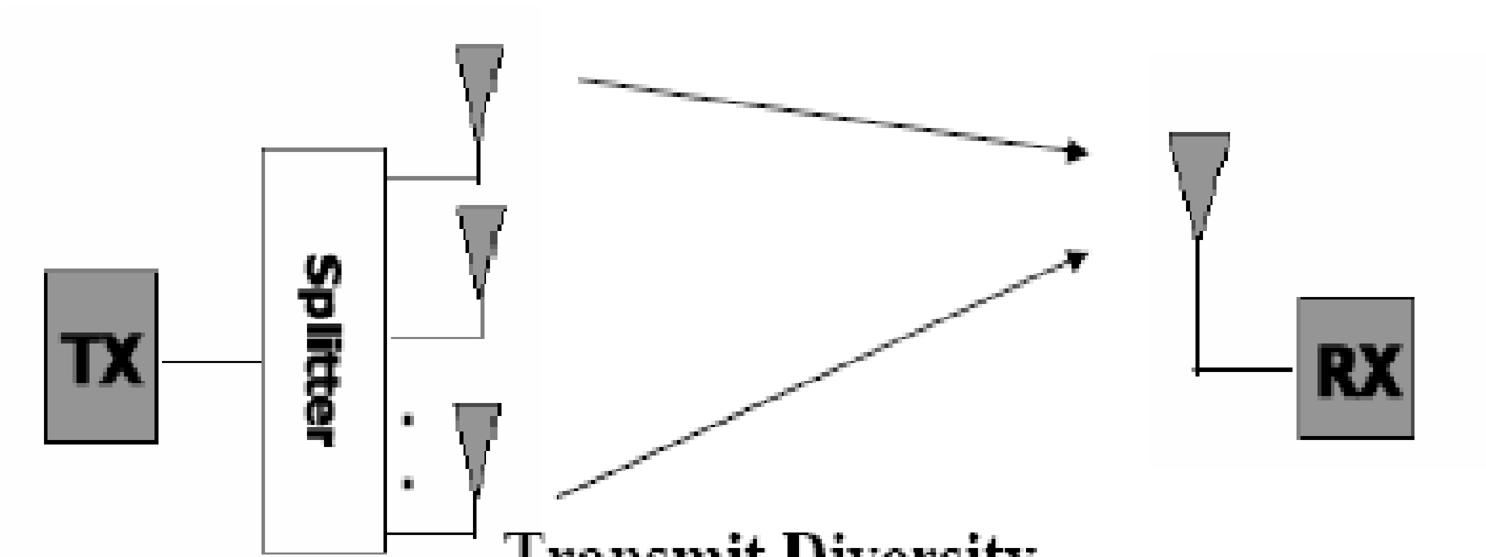
- The performance of EGC is quite close to that of MRC, exhibiting less than 1 dB of power penalty. This is the price paid for the reduced complexity of using equal gains.


Thank you

Topic 7

Transmitter Diversity

Transmitter Diversity



Transmit Diversity

Multi Input Single Output (MISO)

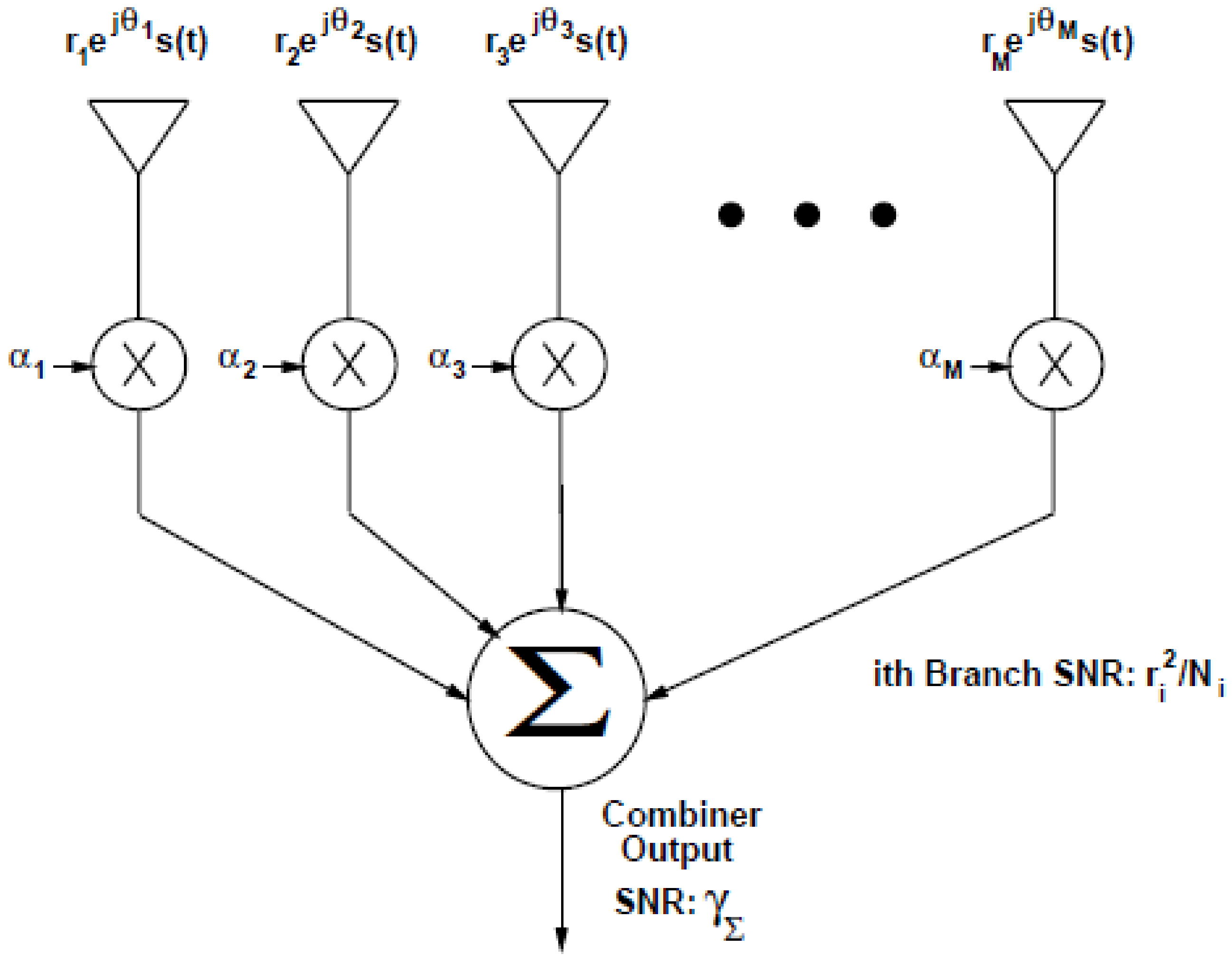
Transmitter Diversity

- In transmit diversity - multiple antennas available at the transmitter & transmitted signal s(t) is sent over the i^{th} antenna with a branch weight α_i.
- Transmit diversity is desirable in systems such as cellular systems where more space, power, processing capability is available on the transmit side versus the receive side.
- The path gain associated with the i^{th} antenna is $r_i e^{j\theta_i}$ & signals transmitted over all antennas are added "in the air", which leads to a received signal given by –

$$r(t) = \sum_{i=1}^{M} \alpha_i r_i e^{j\theta_i} s(t).$$

- This system works the same as with receiver diversity so that the transmit weights α_i are same as if the diversity was implemented at the receiver & analysis is then also identical.

Figure 1 – Linear Combiner



Transmitter Diversity (contd)

- Thus, transmitter diversity provides the same diversity gains as receiver diversity.
- The complication of transmit diversity is to obtain the channel phase & for SC and MRC, the channel gain, at the transmitter.
- These channel values can be measured at the receiver using a pilot technique & fed back to the transmitter.
- In cellular systems with time-division, the base station can measure the channel gain & phase on transmissions from the mobile to the base & then use these measurements in transmitting back to the mobile.
- Other forms of transmit diversity use space-time coding.
- A particularly simple and prevalent scheme for this was developed by Alamouti.

Space Time Coding

- Space–time coding is a technique used in wireless communications to transmit multiple copies of a data stream across a number of antennas & to exploit the various received versions of the data to improve the reliability of data transfer.
- In Alamouti’s space-time code, two transmit antennas use a simple repetition code decoded in the receiver using maximum-likelihood decoding.
- This scheme provides the same diversity gain as two-branch MRC in the receiver.
- It also requires knowledge of the channel gain & phase associated with each of the transmit antennas.


Thank you

Topic 8

Channel Known at Transmitter

Channel Known at Transmitter

What is the “channel known at transmitter”?

- Usually obtained via feedback (frequency division duplex - FDD) or Time division duplex -(TDD)
- The transmitter can tune the covariance matrix S_x to match the transmitter
- This may be via power allocation

$$\mathbf{S}_x^{\text{opt}} = \max_{\mathbf{S}_x} C$$

$$= \max_{\mathbf{S}_x} \log_2 \det \left[\mathbf{I} + \frac{1}{\sigma^2} \mathbf{H} \mathbf{S}_x \mathbf{H}^H \right]$$

Constraints: $\mathbf{S}_x$ must be positive-definite

$\mathbf{S}_x$ must satisfy a power constraint

Introduction

- Consider a transmit diversity system with M transmit antennas & one receive antenna.
- The path gain associated with the i^{th} antenna given by $r_i e^{j\theta_i}$ is known at the transmitter.
- This is called as having channel side information (CSI) at the transmitter (CSIT).
- Let $s(t)$ denote the transmitted signal with total energy per symbol E_s.
- This signal is multiplied by a complex gain $\alpha_i = a_i e^{-j\theta_i}$, $0 \le a_i \le 1$ & sent through the i^{th} antenna.
- This multiplication performs both co-phasing & weighting relative to the channel gains.
- The weighted signals transmitted over all antennas are added in the air leading to -

$$r(t) = \sum_{i=1}^{M} a_i r_i s(t).$$

Maximum SNR

- Let N_0 denote the noise Power spectral density (PSD) in the receiver.
- Setting the branch weights to maximize received SNR using a similar analysis as in receiver given by -

$$a_i = \frac{r_i}{\sqrt{\sum_{i=1}^{M} r_i^2}},$$

- And the resulting SNR given by –

$$\gamma_\Sigma = \frac{E_s}{N_0} \sum_{i=1}^{M} r_i^2 = \sum_{i=1}^{M} \gamma_i,$$

- for $\gamma_i = r_i^2 E_s / N_0$ equal to branch SNR between the i^{th} transmit antenna & the receive antenna.
- Thus transmit diversity is very similar to receiver diversity with MRC.
- The received SNR is the sum of SNRs on each of the individual branches.

Factor of M

- Integrating over the chi-squared distribution for γ_Σ yields –

$$\overline{P}_s \leq \alpha_M \prod_{i=1}^{M} \frac{1}{1+\beta_M \overline{\gamma}_i/2}.$$

- In limit of high SNR & assuming that γ_i are identically distributed with $\gamma_i = \gamma$, this yields

$$\overline{P}_s \approx \alpha_M \left(\frac{\beta_M \overline{\gamma}}{2} \right)^{-M}$$

- At high SNR, the diversity order of transmit diversity with MRC is *M* - MRC achieves full diversity order.
- However, the performance of transmit diversity is worse than receive diversity due to extra factor of *M* in the denominator to divide the transmit power among all transmit antennas.
- Receiver diversity collects energy from all receive antennas, so it does not have this penalty.

Complication of Transmit Diversity

- The complication of transmit diversity is to obtain the channel phase and for SC & MRC, the channel gain, at the transmitter.

- These channel values can be measured at the receiver using a pilot technique & fed back to the transmitter.

- In cellular systems with time-division, the base station can measure the channel gain & phase on transmissions from the mobile to the base & then use these measurements in transmitting back to the mobile.


Thank you

Topic 9

Channel Unknown at Transmitter (The Alamouti Scheme)

Introduction

- Compared to a single antenna system, the channel capacity of a multiple antenna system with N_T transmitters & N_R receiver antennas can be increased by a factor of min (N_T, N_R).
- Without using additional transmission power or spectral bandwidth.
- Due to increasing demand for faster data transmission speeds in telecommunication systems, multiple antenna systems have been deployed in broadband wireless access networks .
- MIMO technologies can be divided into two main categories: Diversity & Spatial-multiplexing.

Introduction

- Diversity techniques intend to receive the same signals in multiple antennas, thereby improving the transmission reliability.

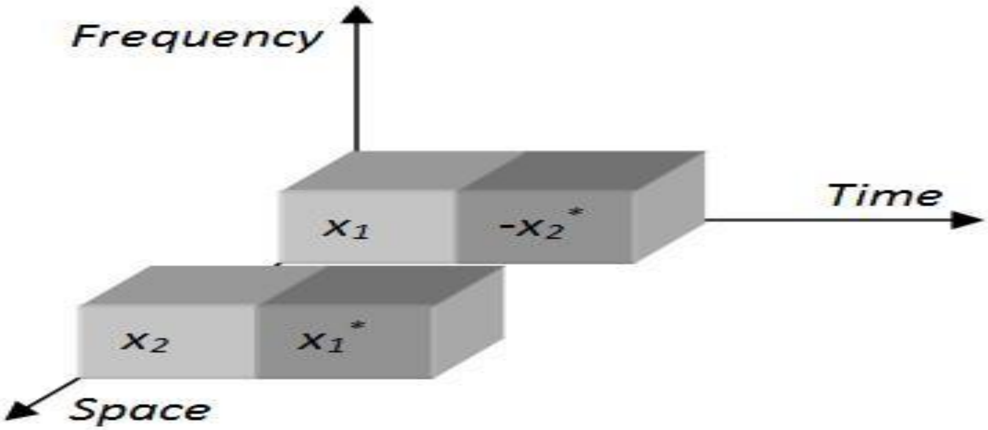
- In spatial-multiplexing techniques, the multiple independent data streams are simultaneously transmitted by multiple transmission antennas, thereby achieving a higher transmission speed.

Space Time Coding

- Space–time coding is a technique used in wireless communications to transmit multiple copies of a data stream across a number of antennas.
- To exploit the various received versions of the data to improve the reliability of data transfer.
- In Alamouti’s space-time code, two transmit antennas use a simple repetition code decoded in the receiver using maximum-likelihood decoding.
- This scheme provides the same diversity gain as two-branch MRC in the receiver.
- It also requires knowledge of the channel gain & phase associated with each of the transmit antennas.

Alamouti Block Code

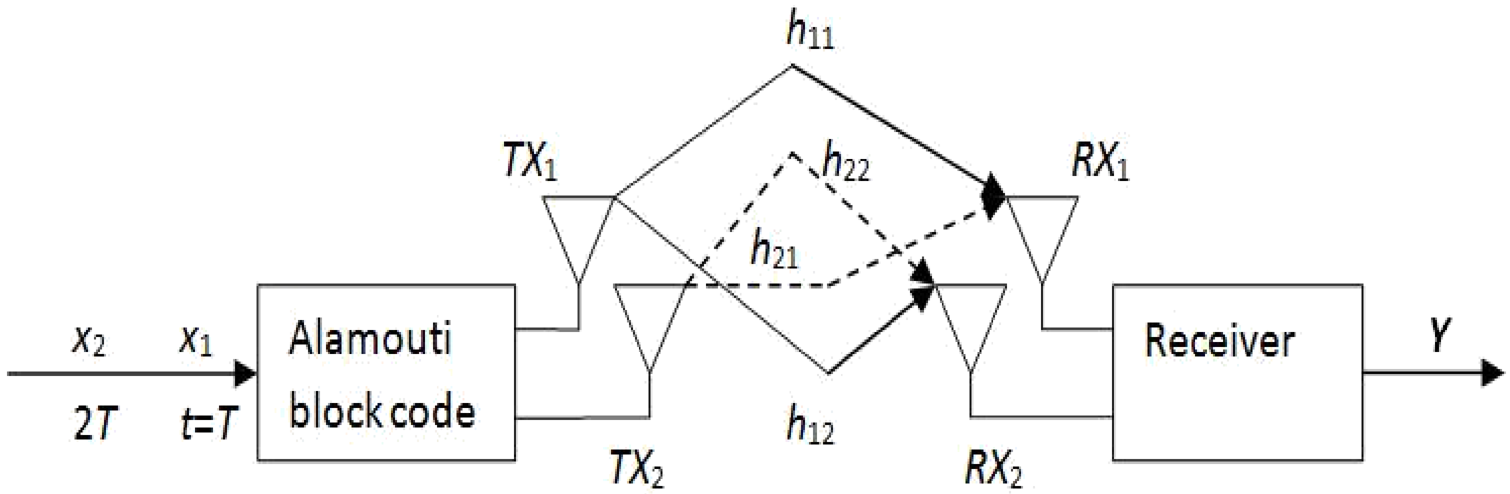
- In OFDM design, the diversity technique used is called Alamouti block code.
- It is a complex space- time diversity technique used in 2×1 MISO mode or in a 2×2 MIMO mode.
- The Alamouti block code is the only complex block code that has a data rate of *1* while achieving maximum diversity gain.
- Such performance is achieved using the following space-time block code:



Alamouti Space-time diversity

Alamouti Block Code (contd)

- Two antennas are used, to send two OFDM symbols & their conjugate, in two time slots, which brings a diversity gain without compromise on the data rate.
- Over the air, the transmitted symbols will suffer from channel fading and at the receiver, their sum will be received.
- Here is the schematic diagram of an Alamouti wireless system in 2×2 MIMO mode-



Alamouti Block Code (contd)

- Since the transmission is done over two periods of time, the decoding will also be done over two periods of time.
- At the receiver, the received vector ***Y*** can be represented by the following equation in the first & second time periods for antennas 1 & 2 respectively.

$$\boldsymbol{Y} = \begin{bmatrix} y_1^1 \\ y_2^1 \end{bmatrix} = \begin{bmatrix} h_{11} & h_{12} \\ h_{21} & h_{22} \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} + \begin{bmatrix} n_1^1 \\ n_2^1 \end{bmatrix}$$

$$\boldsymbol{Y} = \begin{bmatrix} y_1^2 \\ y_2^2 \end{bmatrix} = \begin{bmatrix} h_{11} & h_{12} \\ h_{21} & h_{22} \end{bmatrix} \begin{bmatrix} -x_2^* \\ x_1^* \end{bmatrix} + \begin{bmatrix} n_1^2 \\ n_2^2 \end{bmatrix}$$

- Both the above equations combined to produce the result.

$$\boldsymbol{Y} = \begin{bmatrix} y_1^1 \\ y_2^1 \\ y_1^{2*} \\ y_2^{2*} \end{bmatrix} = \begin{bmatrix} h_{11} & h_{12} \\ h_{21} & h_{22} \\ h_{12}^* & -h_{11}^* \\ h_{22}^* & -h_{21}^* \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} + \begin{bmatrix} n_1^1 \\ n_2^1 \\ n_1^{2*} \\ n_2^{2*} \end{bmatrix}$$

Isolation of Unknowns

- The next step is to find a way to isolate the transmitted symbols, x_1 and x_2.
- One way to reduce the number of unknowns is by using a channel estimator to estimate the channel coefficients.
- In OFDM reference design, OFDM symbols are sent with each transmitted packet to enable estimating those channel coefficients at the receiver.
- Given the following matrix:

$$\boldsymbol{H} = \begin{bmatrix} h_{11} & h_{12} \\ h_{21} & h_{22} \\ h_{12}^* & -h_{11}^* \\ h_{22}^* & -h_{21}^* \end{bmatrix}$$

- Isolate x_1 & x_2 by simply multiplying the matrix $\boldsymbol{Y}$ by the inverse of $\boldsymbol{H}$.
- However, this matrix is not square, hence need to use the Moore-Penrose pseudo-inverse $\boldsymbol{H}^+$ to solve our equations-

Isolation of Unknowns (contd)

$$H^{+} = \left(H^{H}H\right)^{-1}H^{H}$$

- Using this inverse matrix expression, the noisy estimated transmitted symbols can be found using following expression:

$$\begin{bmatrix} \widetilde{x_1} \\ x_2 \end{bmatrix} = \left(H^{H}H\right)^{-1}H^{H}\begin{bmatrix} y_1^1 \\ y_2^1 \\ y_1^{2*} \\ y_2^{2*} \end{bmatrix}$$

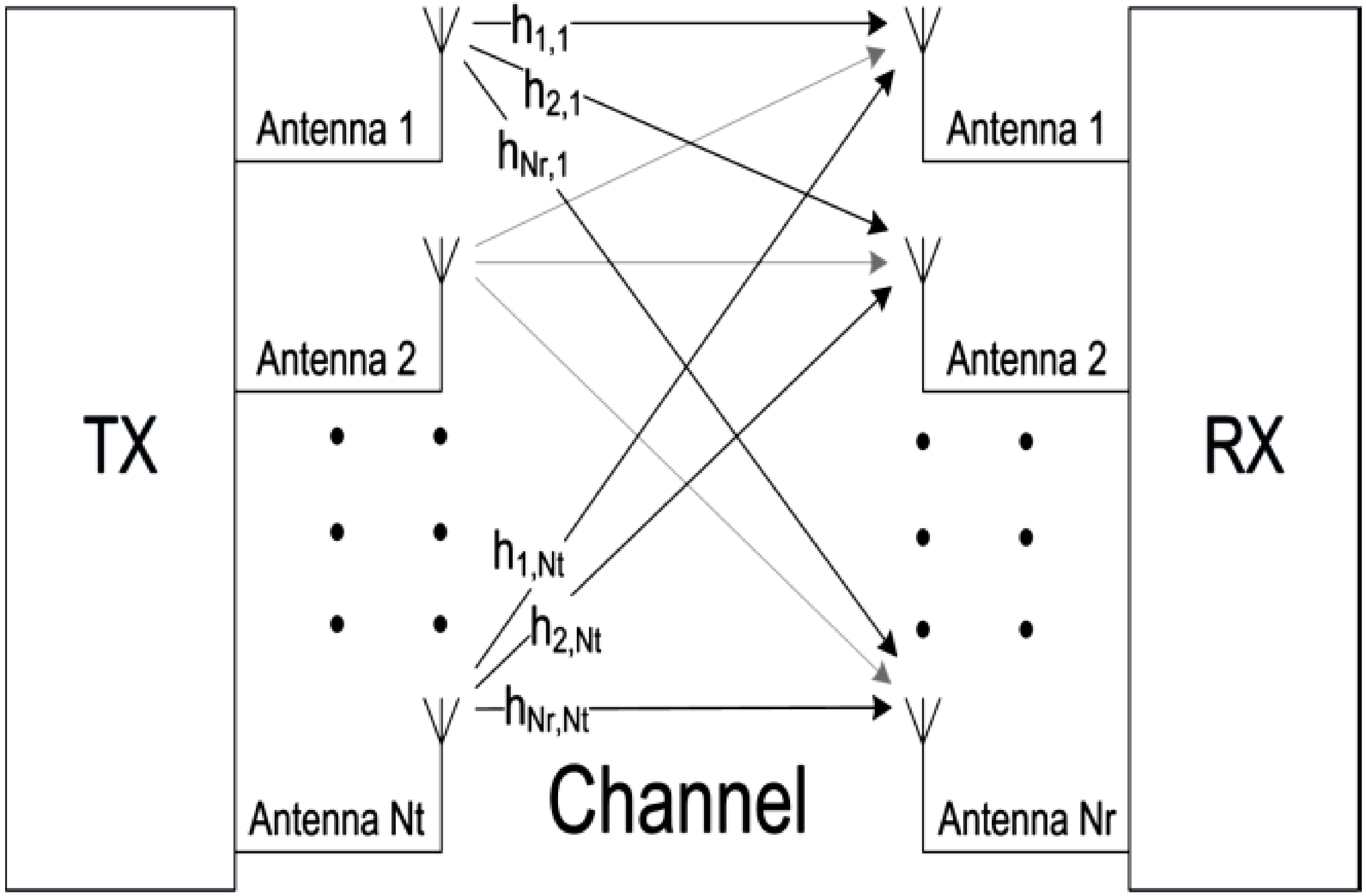
- The last step would be to make a final decision on the transmitted symbols.
- In OFDM reference design, the decision is made based on the minimum squared Euclidian distance criterion.
- It is concluded that the addition of diversity to the system brings a significant performance gain in terms of BER.


Thank you

Topic 10

Transmit & Receive Diversity (MIMO Systems)

MIMO Systems



Introduction

- MIMO systems are defined as point-to-point communication links with multiple antennas at both the transmitter and receiver
- The use of multiple antennas at both transmitter and receiver provide enhanced performance over diversity systems.
- In particular, MIMO systems can significantly increase the data rates of wireless systems without increasing transmit power or bandwidth.
- The cost of this increased rate is the added cost of deploying multiple antennas, the space requirements of extra antennas & the added complexity required for multi-dimensional signal processing.

Narrowband Multiple Antenna System Model

- A narrowband point to point communication system employing *n* transmit and *m* receive antennas is shown in Figure 1.

- This system can be represented by the following discrete time model.

$$\begin{bmatrix} y_1 \\ \vdots \\ y_m \end{bmatrix} = \begin{bmatrix} h_{11} & \cdots & h_{1n} \\ \vdots & \ddots & \vdots \\ h_{m1} & \cdots & h_{mn} \end{bmatrix} \begin{bmatrix} x_1 \\ \vdots \\ x_n \end{bmatrix} + \begin{bmatrix} N_1 \\ \vdots \\ N_m \end{bmatrix}$$

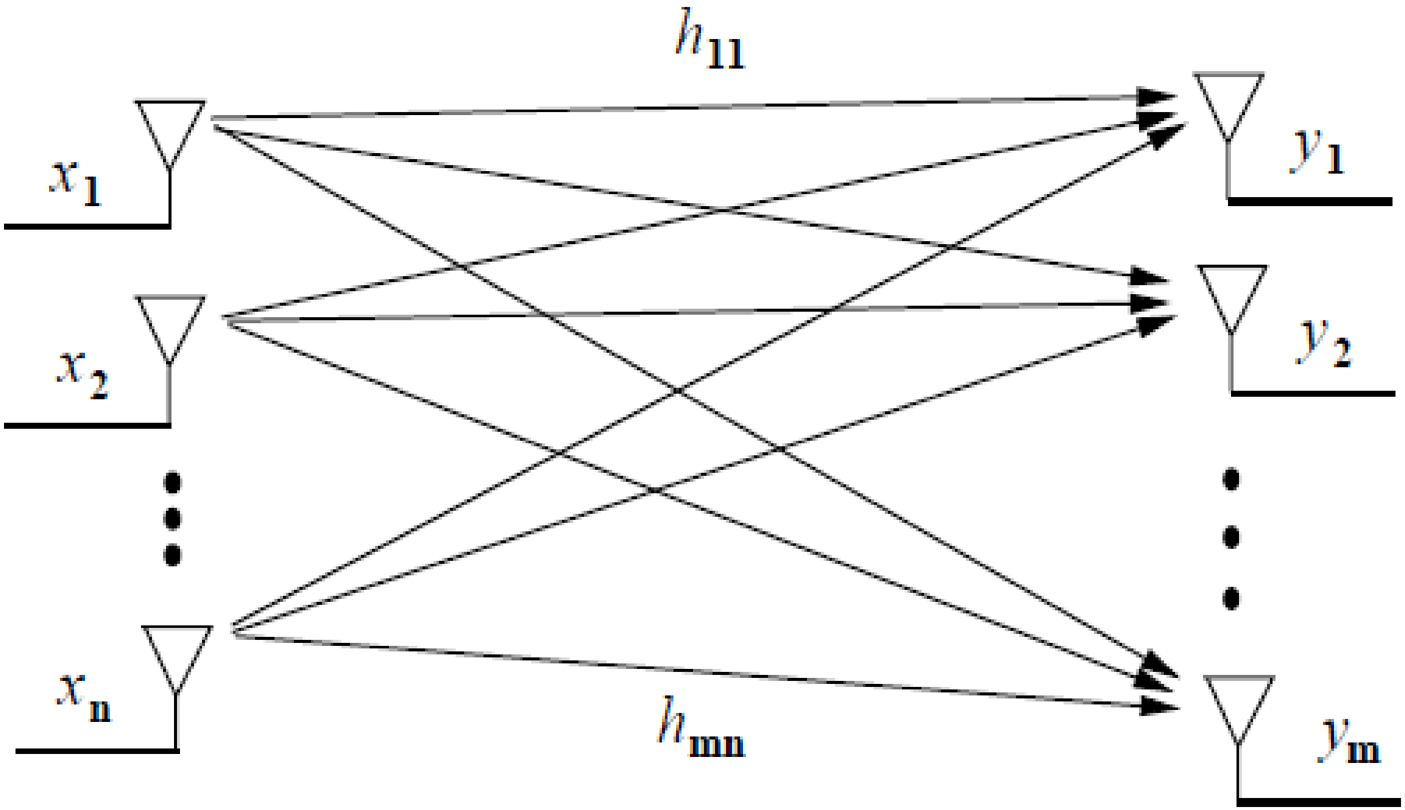
$$\overline{y} = H\overline{x} + \overline{N}.$$

- or simply as Here *x* represents the *n*-dimensional transmitted symbol, *N* is the *m*-dimensional AWGN vector, and the channel matrix *H* consists of zero mean Gaussian random variables h_{ij} representing the channel gain from transmit antenna *j* to receive antenna *i*.

- Without loss of generality, the noise is normalized so that noise covariance matrix is an identity matrix.

Narrowband Multiple Antenna System Model (contd)

- Assume that the receiver is able to estimate the channel state *H* perfectly.
- The transmit power constraint is given as $\sum_{i=1}^{n} \mathrm{E}[x_i x_i^*] = P,$

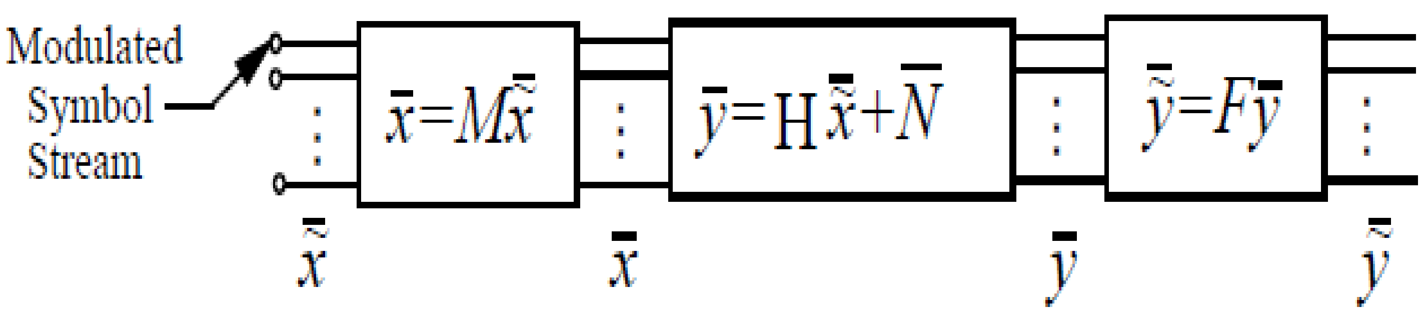


Transmit Precoding & Receiver Shaping

- In general an R symbols/s - input data stream can be split into r parallel, independent data streams, producing r-tuples $\tilde{x}$ at a rate R/r symbols/s.
- The actual input to the antennas is generated through a linear transformation as –

$$\bar{x} = M\bar{\tilde{x}},$$

  where M is an $n \times r$ fixed matrix.
- This operation is called transmit precoding.
- A similar operation, called receiver shaping, can be performed at the receiver by multiplying the channel output with a $r \times n$ matrix F , as shown in Figure 2.



Transmit Precoding & Receiver Shaping

- The overall system can be described as –

$$\begin{aligned}\tilde{\bar{y}} &= F\bar{y} \\ &= FH\bar{x} + F\bar{N} \\ &= FHM\tilde{\bar{x}} + F\bar{N}\end{aligned}$$

- The rank of the input covariance matrix $Q = E[xx^{\dagger}]$ is equal to r, the number of independent streams being simultaneously transmitted.
- Optimal decoding of the received signal requires maximum likelihood demodulation.
- If the modulated symbols are selected from an alphabet of size $|X|$, then ML demodulation requires a search over $|X|^r$ possibilities for the input r-tuple.
- In general, when the transmitter does not know H this complexity cannot be reduced further. So optimal decoding complexity without the channel state information at the transmitter (CSIT) is exponential in the rank of the input covariance matrix.

MIMO Channel Capacity

- The MIMO decomposition allows a simple characterization of the MIMO channel capacity when both transmitter and receiver have perfect knowledge of the channel matrix H.
- The capacity formula can be written as –

$$C = \max_{\{P_i\}:\sum_i P_i \le P} \sum_i B \log\left(1 + \frac{\lambda_i^2 P_i}{N_0 B}\right),$$

- which is similar to the capacity formula in flat fading or in frequency-selective fading with constant channel gains.
- To get a water-filling power allocation for the MIMO channel with the channel gain given by

$$\frac{P_i}{P} = \begin{cases} \frac{1}{\gamma_0} - \frac{1}{\gamma_i} & \gamma_i \ge \gamma_0 \\ 0 & \gamma_i < \gamma_0 \end{cases}$$

- for some cutoff value γ_0, where $\gamma_i = \lambda^2_i P /(N_0 B)$. The resulting capacity is -

$$C = \sum_{i=1(\gamma_i \ge \gamma_0)} B \log(\gamma_i/\gamma_0).$$


Thank you

Model Question Bank

Unit - III

Part - A

- 1) What is Space diversity?

  It is a method to use multiple receive antennas, also called an antenna array, where the elements of the array are separated in distance. This type of diversity is called space diversity.

- 2) Mention the ways of realizing independent fading paths in a wireless channel.

  One method is to use multiple receive antennas, where the elements of the antenna array are separated in distance.

  Second method is to use two transmit or two receive antennas with different polarization.

Part - A

- 3) What is polarization diversity?

  A method of achieving diversity is by using either two transmit antennas or two receive antennas with different polarization (e.g. vertically and horizontally polarized waves).

- 4) Mention the disadvantages of polarization diversity.

  1) Two diversity branches, corresponding to the two types of polarization.

  2) Polarization diversity loses effectively half of the 3 dB power.

Part - A

- 5) What is the advantage of using directional antennas?

  Directional antennas provide angle or directional diversity by restricting the receive antenna beam-width to a given angle so that no multi-path fading available.

- 6) What is Frequency diversity?

  Frequency diversity is achieved by transmitting the same narrowband signal at different carrier frequencies separated by the coherence bandwidth of the channel.

Part - A

- 7) What are spread spectrum techniques?

  Spread spectrum techniques are the means of providing frequency diversity since the channel gain varies across the bandwidth of the transmitted signal.

- 8) What is Time diversity?

  Time diversity is achieved by transmitting the same signal at different times, where the time difference is greater than the channel coherence time. It can also be achieved through coding and interleaving.

Part - A

- 9) What is Receiver diversity?

  A diversity system combines the independent fading paths to obtain a resultant signal & then passed through a standard demodulator.

- 10) What is called Selection Combining?

  In selection combining (SC), the combiner outputs the signal on the branch with the highest SNR r_i^2/N_i. However, a dedicated receiver on each antenna branch required in order to monitor SNR on that branch.

Part - A

- 11) Differentiate between Selection Combining & Threshold Combining.

  SC for systems that transmit continuously may require a dedicated receiver on each branch to monitor branch SNR.

  But threshold combining avoids the need for a dedicated receiver on each branch by scanning all the branches in sequential order & outputting first signal with SNR above a given threshold .

- 12) What is called Switch & Stay Combining (SSC) ?

  In Threshold Combining, with two-branch diversity - equivalent to switching to the other branch when the SNR on the active branch falls below threshold value. This method is called switch and stay combining (SSC).

Part - A

- 13) Differentiate between Selection Combining & Maximal Ratio Combining.

  In SC and SSC, the output of the combiner equals the signal on one of the branches. In maximal ratio combining (MRC) the output is a weighted sum of all branches.

- 14) What is Equal Gain Combining?

  A simpler technique - equal-gain combining, which co-phases the signals on each branch & then combines them with equal weighting, $\alpha_i = e^{-\vartheta}i$.

Part - A

- 15) What is Transmitter diversity?

  In transmit diversity - multiple antennas available at the transmitter & transmitted signal s(t) is sent over the ith antenna with a branch weight α_i.

- 16) Mention the disadvantages of Transmitter diversity.

  The complication of transmit diversity is to obtain the channel phase & for SC and MRC, the channel gain, at the transmitter. These channel values can be measured at the receiver using a pilot technique & fed back to the transmitter.

Part - A

- 17) What is Space Time Coding?

  Space–time coding is a technique used in wireless communications to transmit multiple copies of a data stream across a number of antennas for better reliability of data transfer.

- 18) What are MIMO Systems?

  MIMO systems are defined as point-to-point communication links with multiple antennas at both the transmitter and receiver for enhanced data rate and performance of the system.

Part - A

- 19) What is Transmit Pre-coding?

  The actual input to the antennas is generated through a linear transformation as –
  $$\overline{x} = M\overline{\tilde{x}},$$
  where *M* is an *n* × *r* fixed matrix. This operation is called transmit precoding.

- 20) What is Alamouti Block code?

  In Alamouti's space-time code, two transmit antennas use a simple repetition code decoded in the receiver using maximum-likelihood decoding. This scheme provides the same diversity gain as two-branch MRC in the receiver.

Part - B

- 1) Explain the various methods of realizing independent fading paths in a wireless channel.
- 2) Describe Transmitter & Receiver diversity in detail.
- 3) Write short notes on – (i) Selection Combining (ii) Threshold Combining.
- 4) Explain about – (i) Maximum Ratio Combining (ii) Equal Gain Combining.
- 5) Explain the Alamouti Scheme in detail.
- 6) Describe about MIMO Systems and how its channel capacity can be evaluated.

Mobile Communication

Unit -IV - MULTICARRIER MODULATION

UNIT IV - MULTICARRIER MODULATION

Data Transmission using Multiple Carriers – Multicarrier Modulation with Overlapping Sub channels – Mitigation of Subcarrier Fading – Discrete Implementation of Multicarrier Modulation – Peak to average Power Ratio- Frequency and Timing offset – Case study IEEE 802.11a

Introduction to Multi-carrier Modulation

- The basic idea of multicarrier modulation is to divide the transmitted bit stream into different sub streams and send them over different sub channels.
- The data rate on each of the sub channels is much less than the total data rate, and the corresponding sub channel bandwidth is much less than the total system bandwidth.
- The number of sub streams is chosen that each sub channel has a bandwidth less than the coherence bandwidth of the channel, so the sub channels experience relatively flat fading.
- Thus, the ISI on each sub channel is small. The subchannels in multicarrier modulation need not be adjoining, so a large continuous block of spectrum is not needed for high rate multicarrier communications.

Introduction to Multi-carrier Modulation

- In this discrete implementation, called orthogonal frequency division multiplexing (OFDM), the ISI can be completely eliminated through the use of a cyclic prefix.
- Multicarrier modulation is currently used in many wireless systems. There are also a number of newly emerging uses for multicarrier techniques, including fixed wireless broadband services, mobile wireless broadband known as FLASH-OFDM and for ultra wideband radios.
- Multicarrier modulation is also used for the air interface in next generation cellular systems.
- The multicarrier technique can be implemented in multiple ways, including vector coding and OFDM.

Introduction to Multi-carrier Modulation

- These techniques are based on the same premise of breaking a wideband channel into multiple parallel narrowband channels by means of an orthogonal channel partition.
- Multicarrier techniques are common in high data rate wireless systems with moderate to large delay spread, as they have significant advantages over time-domain equalization.
- In particular, the number of taps required for an equalizer with good performance in a high data rate system is typically large.
- Thus, these equalizers are highly complex.
- For these reasons, most emerging high rate wireless systems use either multicarrier modulation or spread spectrum instead of equalization to compensate for ISI.

Topic 1

Data Transmission using Multiple Carriers

Data Transmission using Multiple Carriers

- The multicarrier modulation divides the data stream into multiple sub streams to be transmitted over different orthogonal sub channels centered at different subcarrier frequencies.
- The number of sub streams is chosen to make the symbol time on each sub stream much greater than the delay spread of the channel or to make the sub stream bandwidth less than the channel coherence bandwidth.
- Consider a linearly-modulated system with data rate R and pass band bandwidth B.
- The coherence bandwidth for the channel is assumed to be $B_c < B$, so the signal experiences frequency-selective fading.

Data Transmission using Multiple Carriers

- The basic objective of multicarrier modulation is to break this wideband system into N linearly-modulated subsystems in parallel, each with sub-channel bandwidth $B_N = B/N$ and data rate $R_N \approx R/N$.
- For N sufficiently large, the sub channel bandwidth $B_N = B/N << Bc$, which insures flat fading on each sub channel.
- $B_N << Bc$ implies that $T_N \approx 1/B_N >> 1/Bc \approx Tm$, where Tm denotes the delay spread of the channel.
- Thus, if N is sufficiently large, the symbol time is much bigger than the delay spread, so each sub channel experiences little ISI degradation.
- Figure 4.1 shows a multicarrier transmitter. The bit stream is divided into N sub streams via a serial-to-parallel converter.

Data Transmission using Multiple Carriers

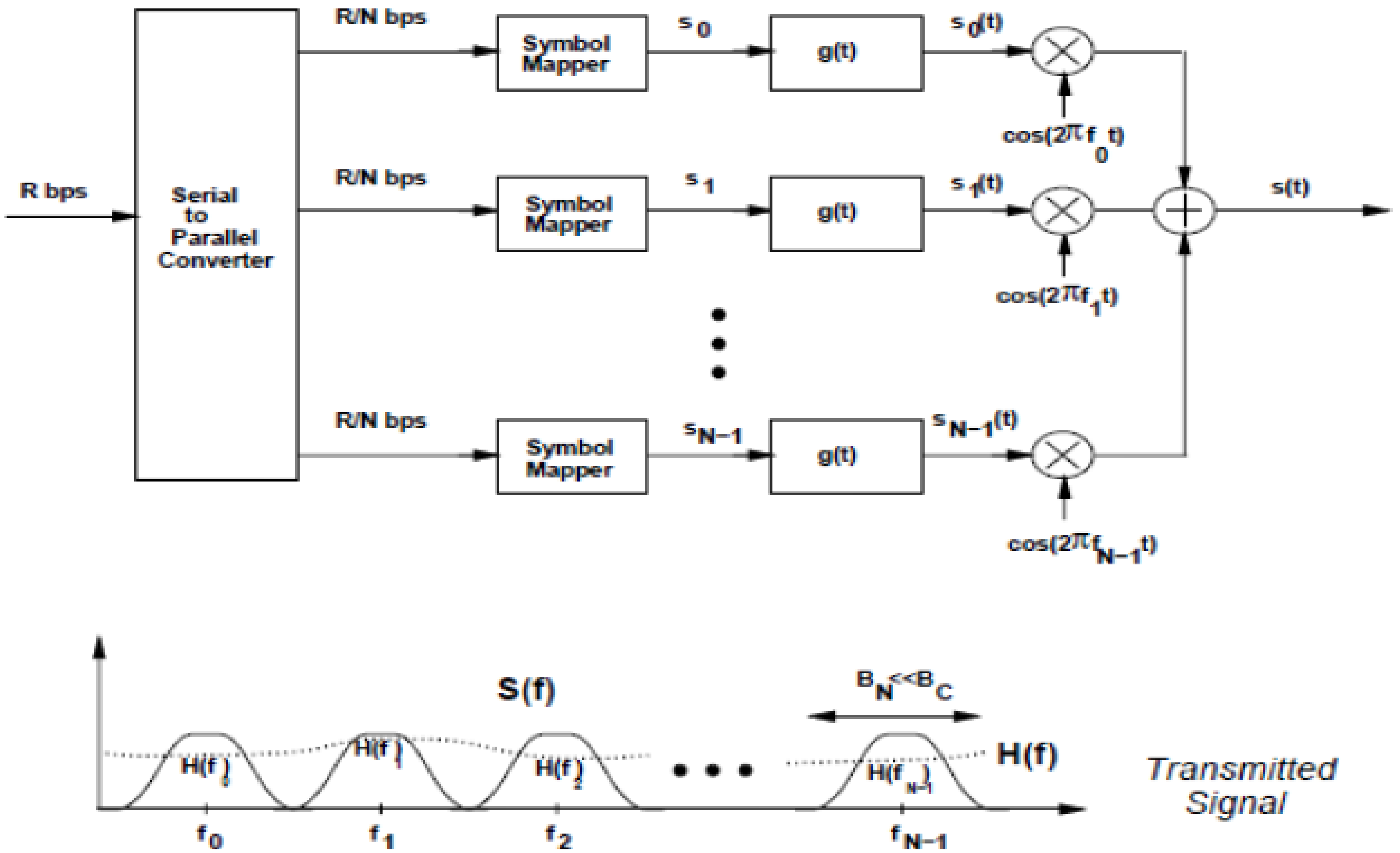


Figure 4.1 Multicarrier Transmitter

Data Transmission using Multiple Carriers

- The n^{th} sub stream is linearly-modulated relative to the subcarrier frequency f_n and occupies pass band bandwidth B_N.
- If assumed cosine pulses for g(t) we get a symbol time $T_N = (1 + \beta)/B_N$ for each sub stream, where β is the roll off factor of the pulse shape.
- The modulated signals associated with all the sub channels are summed together to form the transmitted signal, given as ,

$$s(t) = \sum_{i=0}^{N-1} s_i g(t) \cos(2\pi f_i t + \phi_i),$$

- Where s_i is the complex symbol associated with the i^{th} subcarrier and φ_i is the phase offset of the i^{th} carrier.

Data Transmission using Multiple Carriers

- For non-overlapping sub channels we set $f_i = f_0 + i(B_N)$, $i = 0, \ldots, N - 1$.
- The sub streams then occupy orthogonal sub channels with pass band bandwidth B_N, obtaining a total pass band bandwidth $N B_N = B$ and data rate $N R_N \approx R$.
- Thus, this form of multicarrier modulation does not change the data rate or signal bandwidth relative to the original system, but it almost completely eliminates ISI for $B_N << B_c$.
- The receiver for this multicarrier modulation is shown in Figure 4.2. Each sub stream is passed through a narrowband filter to remove the other sub streams, demodulated, and combined via a parallel-to-serial converter to form the original data stream.

Data Transmission using Multiple Carriers

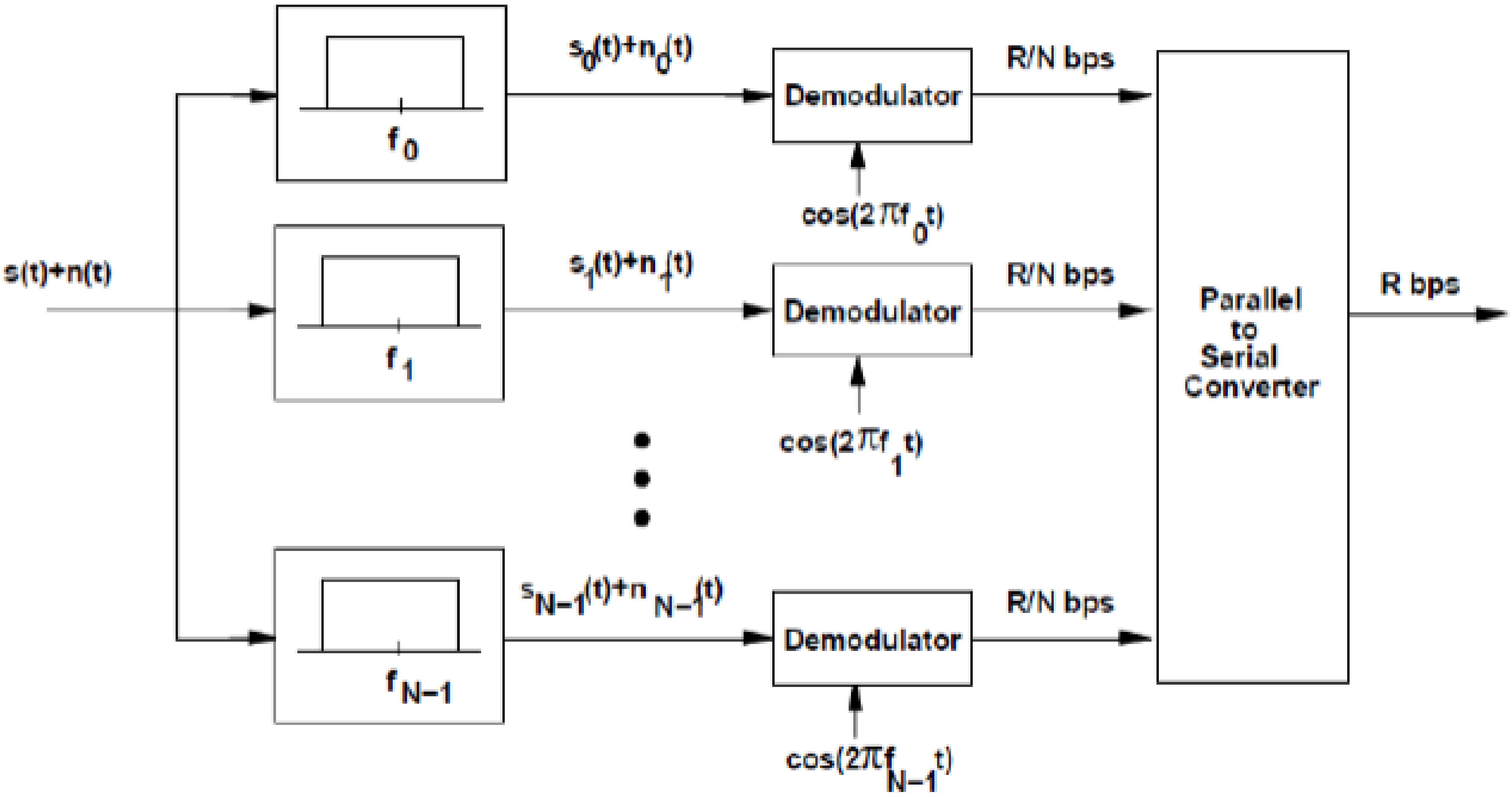


Figure 4.2 Multicarrier Receiver

Data Transmission using Multiple Carriers

- Although this simple type of multicarrier modulation is easy to understand, it has several demerits.
- First of all the sub channels will occupy a larger bandwidth than under ideal raised cosine pulse shaping since the pulse shape must be time-limited
- Let ε/T_N denote the additional bandwidth required due to time-limiting of these pulse shapes. The sub channels must be separated by $(1 + \beta + \varepsilon)/T_N$, and since the multicarrier system has N sub channels, the bandwidth penalty for time limiting is N/T_N .
- In particular, the total required bandwidth for non-overlapping sub channels is

$$B = \frac{N(1+\beta+\epsilon)}{T_N}.$$

Data Transmission using Multiple Carriers

- Thus, this form of multicarrier modulation can be spectrally inefficient.
- Hence near-ideal low pass filters will be required to maintain the orthogonally of the subcarriers at the receiver.
- This scheme requires N independent modulators and demodulators, which entails significant expense, size, and power consumption.

Thank You

Topic 2

Multicarrier Modulation with Overlapping Sub channels

Multicarrier Modulation with Overlapping Sub channels

- The spectral efficiency of multicarrier modulation can be improved by overlapping the sub channels.
- The subcarriers must be orthogonal so that they can be separated out by the demodulator in the receiver.
- The subcarriers $\{\cos(2\pi(f_0 + i/T_N) + \varphi_i), i = 0, 1, 2 \ldots\}$ form a set of orthogonal basis functions on the interval $[0, T_N]$ for any set of subcarrier phase offsets $\{\varphi i\}$ since –

$$\int_0^{T_N} \cos(2\pi(f_0 + i/T_N)t + \phi_i)\cos(2\pi(f_0 + j/T_N)t + \phi_j)dt$$

Multicarrier Modulation with Overlapping Sub channels

$$
\begin{aligned}
&= \int_0^{T_N} .5\cos(2\pi(i-j)t/T_N + \phi_i - \phi_j)dt + \int_0^{T_N} .5\cos(2\pi(2f_0+i+j)t/T_n + \phi_i + \phi_j)dt \\
&\approx \int_0^{T_N} .5\cos(2\pi(i-j)t/T_N + \phi_i - \phi_j)dt \\
&= .5T_N\delta(i-j),
\end{aligned}
$$

- Where the approximation follows that the second integral in above expression is approximately zero for f $0T_N$ >>1.
- Moreover, it is shown that no set of subcarriers with a smaller frequency separation forms an orthogonal set on $[0,T_N]$ for arbitrary subcarrier phase offsets.
- This implies that the minimum frequency separation required for subcarriers to remain orthogonal over the symbol interval $[0,T_N]$ is $1/T_N$.

Multicarrier Modulation with Overlapping Sub channels

- Since the carriers are orthogonal, the set of functions $\{g(t)\cos(2\pi(f_0 + i/T_N)t + \varphi_i), i = 0, 1, \ldots N - 1\}$ also form a set of functions for appropriately chosen baseband pulse shapes g(t): the family of raised cosine pulses are a common choice for this pulse shape.
- Consider a multicarrier system where each sub channel is modulated using raised cosine pulse shapes with roll off factor β.
- The pass band bandwidth of each sub channel is then $B_N = (1 + \beta)/T_N$.
- The i^{th} subcarrier frequency is set to $(f_0 + i/T_N)$, $i = 0, 1 \ldots N - 1$ for some f_0, so the subcarriers are separated by $1/T_N$.
- However, the pass band bandwidth of each sub channel is $B_N = (1 + \beta)/T_N > 1/T_N$ for $\beta > 0$, so the sub channels overlap.

Multicarrier Modulation with Overlapping Sub channels

- Excess bandwidth due to time windowing will increase the subcarrier bandwidth by an additional /T $_N$.
- However, β and do not affect the total system bandwidth due to the sub channel overlap except in the first and last sub channels, as illustrated in Figure 4.3. The total system bandwidth with overlapping sub channels is given by

$$B = \frac{N + \beta + \epsilon}{T_N} \approx \frac{N}{T_N},$$

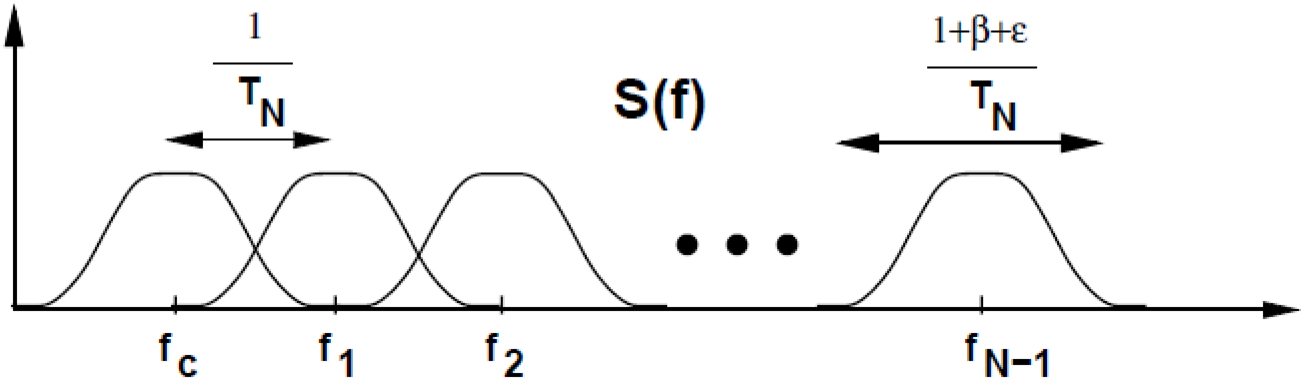


Figure 4.3 Multicarrier with Overlapping Subcarriers

Multicarrier Modulation with Overlapping Sub channels

- Where the approximation holds for N large.
- Thus, with N large, the impact of β and on the total system bandwidth is negligible, in contrast to the required bandwidth $B = N(1 + \beta +)/T_N$ when the sub channels do not overlap.
- In order to separate out overlapping subcarriers, a different receiver structure is needed than the one shown in Figure 4.2. In particular, overlapping sub channels are demodulated with the receiver structure shown in Figure 4.4, which demodulates the appropriate symbol without interference from overlapping sub channels.
- Specifically, if the effect of the channel h(t) and noise n(t) are neglected then for received signal s(t), the input to each symbol de-mapper in Figure 4.4 is

Multicarrier Modulation with Overlapping Sub channels

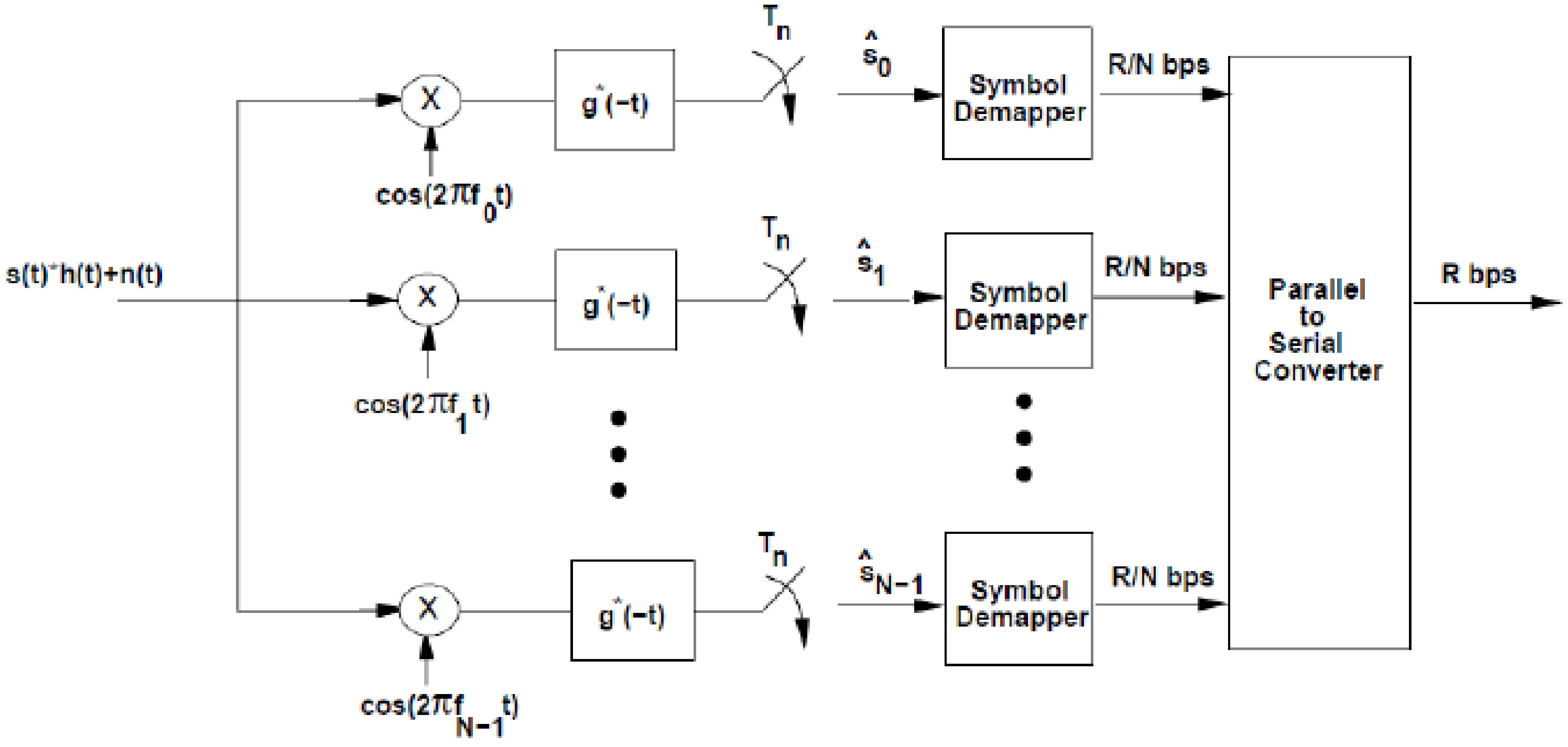


Figure 4.4 Multicarrier Receiver for Overlapping Subcarriers

Multicarrier Modulation with Overlapping Sub channels

$$\begin{aligned}
\hat{s}_i &= \int_0^{T_N} \left(\sum_{j=0}^{N-1} s_j g(t) \cos(2\pi f_j t + \phi_j) \right) g(t) \cos(2\pi f_i t + \phi_i) dt \\
&= \sum_{j=0}^{N-1} s_j \int_0^{T_N} g^2(t) \cos(2\pi(f_0 + j/T_N)t + \phi_j) \cos(2\pi(f_0 + i/T_N)t + \phi_i) dt \\
&= \sum_{j=0}^{N-1} s_j \delta(j - i) \\
&= s_i,
\end{aligned}$$

- Where the functions $\{g(t) \cos(2\pi f_j\ t + \varphi_j\ )\}$ form a set of orthonormal basis functions on $[0, T_N\ ]$.
- If the channel and noise effects are included, the symbol in the i^{th} sub channel is scaled by the channel gain $\alpha_i = H(f_i)$ and corrupted by the noise sample, so $s\hat{}_i = \alpha_i s_i + n_i$, where n_i is AWGN with power $N_0 B_N$ ..

Multicarrier Modulation with Overlapping Sub channels

- This multicarrier system makes much more efficient use of bandwidth than in systems with non-overlapping subcarriers. However, if the subcarriers overlap, their orthogonally is compromised by timing and frequency offset

Thank You

Topic 3

Mitigation of Subcarrier Fading

Mitigation of Subcarrier Fading

- In multicarrier modulation, each sub channel is relatively narrowband, which mitigates the effect of delay spread.
- However, each sub channel experiences flat-fading, which can cause large BERs on some of the sub channels.
- If the transmit power on subcarrier i is P_i, and the fading on that subcarrier α_i, then the received SNR is $\gamma_i = \alpha_i^2 P_i/(N_0 B_N)$, where B_N is the bandwidth of each sub channel. If α_i is small then the received SNR on the i^{th} sub channel is quite low, which can lead to a high BER on that sub channel.
- Moreover, in wireless channels the α_i's will vary over time resulting in the same performance degradation associated with flat fading for single carrier systems.

Mitigation of Subcarrier Fading

- Since flat fading can degrade performance in each sub channel, it is important to compensate for flat fading in the sub channels.
- There are several techniques for doing this, including coding with interleaving over time and frequency, frequency equalization, precoding, and adaptive loading.
- Coding with interleaving is the most commonly adopted as part of the European standards for digital audio and video broadcasting.
- Moreover, in rapidly changing channels it is difficult to estimate the channel at the receiver and feed this information back to the transmitter.
- Without channel information at the transmitter, preceding and adaptive loading cannot be done, so only coding with interleaving is effective at fading mitigation.

Coding with Interleaving over Time and Frequency

- The basic idea in coding with interleaving over time and frequency is to encode data bits into code words, interleave the resulting coded bits over both time and frequency, and then transmit the coded bits over different sub channels such that the coded bits within a given code word all experience independent fading.
- If most of the sub channels have a high SNR, the code word will have most coded bits received correctly, and the errors associated with the few bad sub channels can be corrected.

Coding with Interleaving over Time and Frequency

- Coding across sub channels exploits the frequency diversity inherent to a multicarrier system to correct for errors.
- This technique only works well if there is sufficient frequency diversity across the total system bandwidth.
- If the coherence bandwidth of the channel is large, then the fading across sub channels will be highly correlated, which will reduce the effect of coding.

Frequency Equalization

- In frequency equalization the flat fading α_i on the i^{th} sub channel is basically inverted in the receiver.
- Specifically, the received signal is multiplied by $1/\alpha_i$, which gives a resultant signal power $\alpha_i 2P_i/\alpha_i^2 = P_i$. While this removes the impact of flat fading on the signal, it enhances the noise.
- Specifically, the incoming noise signal is also multiplied by $1/\alpha_i$, so the noise power becomes $N_0 B_N / \alpha_i^2$ and the resultant SNR on the i^{th} sub channel after frequency equalization is the same as before equalization. Hence frequency equalization does not really change the performance degradation associated with subcarrier flat fading.

Precoding

- Precoding uses the same idea as frequency equalization, except that the fading is inverted at the transmitter instead of the receiver.
- This technique requires that the transmitter have knowledge of the sub channel flat fading gains α_i, $i = 0, \ldots, N - 1$, which must be obtained through estimation.
- If the desired received signal power in the i^{th} sub channel is P_i, and the channel introduces a flat-fading gain α_i in the i^{th} sub channel, then under precoding the power transmitted in the i^{th} sub channel is P_i/α_i^2.
- The sub channel signal is corrupted by flat-fading with gain α_i, so the received signal power is $P_i\alpha_i^2/\alpha_i^2 = P_i$ as desired. The channel inversion takes place at the transmitter instead of the receiver, so the noise power remains as N_0B_N .

Precoding

- Precoding is quite common on wire line multicarrier systems like HDSL.
- There are two main problems with precoding in a wireless setting. First, precoding is basically channel inversion, and inversion is not power-efficient in fading channels.
- The other problem with precoding is the need for accurate channel estimates at the transmitter, which are difficult to obtain in a rapidly fading channel.

Adaptive Loading

- Adaptive loading is based on the adaptive modulation techniques.
- It is commonly used on slowly changing channels like digital subscriber lines where channel estimates at the transmitter can be obtained easily.
- The basic idea is to vary the data rate and power assigned to each sub channel relative to that sub channel gain.
- In the case of precoding, this requires knowledge of the sub channel fading $\{\alpha_i, i = 0, \ldots, N - 1\}$ at the transmitter.
- In adaptive loading power and rate on each sub channel is adapted to maximize the total rate of the system using adaptive modulation such as variable-rate variable-power MQAM.

Adaptive Loading

- Consider the capacity of the multicarrier system with N independent sub channels of bandwidth B_N and sub channel gain $\{\alpha_i, i = 0, \ldots, N - 1\}$. Assuming a total power constraint P, this capacity is given by:

$$C = \max_{P_i : \sum P_i = P} \sum_{i=0}^{N-1} B_N \log\left(1 + \frac{\alpha_i^2 P_i}{N_0 B_N}\right).$$

- The power allocation Pi that maximizes this expression is given by –

$$\frac{P_i}{P} = \begin{cases} \frac{1}{\gamma_0} - \frac{1}{\gamma_i} & \gamma_i \geq \gamma_0 \\ 0 & \gamma_i < \gamma_0 \end{cases}$$

Adaptive Loading

- for some cutoff value γ_0, where $\gamma_i = \alpha_i 2P/(N_0 B_N)$. The cutoff value is obtained by substituting the power adaptation formula into the power constraint. The capacity then becomes

$$C = \sum_{i:\gamma_i \geq \gamma_0} B_N \log(\gamma_i/\gamma_0).$$

- Applying the variable-rate variable-power MQAM modulation scheme described in to the subchannels, the total data rate is given by

$$R = B_N \sum_{i=1}^{N} \log(1 + K\gamma_i P_i/P),$$

- where $K = -1.5/\ln(5P_b)$ for P_b is the desired target BER in each sub channel

Thank You

Topic 4

Discrete Implementation of Multi-carrier Modulation

Discrete Implementation of Multi-carrier Modulation

- The requirement of multicarrier modulation for separate modulators and de-modulators on each sub-channel was too complex for most system implementations at the time.
- However, the development of simple and cheap implementations of the discrete Fourier transform (DFT) and the inverse DFT (IDFT) combined with the realization that multicarrier modulation can be implemented with these algorithms, ignited its widespread use.

The DFT and its Properties

- Let x[n], $0 \le n \le N-1$, denote a discrete time sequence. The N -point DFT of x[n] is defined as –

$$\mathrm{DFT}\{x[n]\} = X[i] \triangleq \frac{1}{\sqrt{N}} \sum_{n=0}^{N-1} x[n] e^{-j\frac{2\pi n i}{N}}, \; 0 \le i \le N-1.$$

- The DFT is the discrete-time equivalent to the continuous-time Fourier transform, as X[i] characterizes the frequency content of the time samples x[n] associated with the original signal x(t).

- Both the continuous-time Fourier transform and the DFT are based on the fact that complex exponentials are eigen functions for any linear system. The sequence x[n] can be recovered from its DFT using the IDFT

$$\mathrm{IDFT}\{X[i]\} = x[n] \triangleq \frac{1}{\sqrt{N}} \sum_{i=0}^{N-1} X[i] e^{j\frac{2\pi n i}{N}}, 0 \le n \le N-1.$$

The DFT and its Properties

- The DFT and its inverse are typically performed in hardware using the fast Fourier transform (FFT) and inverse FFT (IFFT).

- When an input data stream x[n] is sent through a linear time-invariant discrete-time channel h[n], the output y[n] is the discrete-time convolution of the input and the channel impulse response:

$$y[n] = h[n] * x[n] = x[n] * h[n] = \sum_k h[k]x[n-k].$$

- The N-point circular convolution of x[n] and h[n] is defined as -

$$y[n] = x[n] \otimes h[n] = h[n] \otimes x[n] = \sum_k h[k]x[n-k]_N,$$

where $[n-k]_N$ denotes $[n-k]$ modulo N . In other words, $x[n-k]_N$ is a periodic version of $x[n-k]$ with period N

The DFT and its Properties

The circular convolution in time leads to multiplication in frequency:

$$\text{DFT}\{y[n] = x[n] \otimes h[n]\} = X[i]H[i],\ 0 \leq i \leq N-1.$$

- By the above equation, if the channel and input are circularly convoluted then if h[n] is known at the receiver, the original data sequence x[n] can be recovered by taking the IDFT of Y [i]/H[i], $0 \leq i \leq N - 1$.

- But the channel output is not a circular convolution but a linear convolution. However, the linear convolution between the channel input and impulse response can be turned into a circular convolution by adding a special prefix to the input called a cyclic prefix.

The Cyclic Prefix

- Consider a channel input sequence $x[n] = x[0], \ldots, x[N-1]$ of length N and a discrete-time channel with finite impulse response (FIR)

$$h[n] = h[0], \ldots, h[\mu] \text{ of length } \mu + 1 = Tm/Ts,$$

  -where Tm is the channel delay spread and Ts the sampling time associated with the discrete time sequence.
- The cyclic prefix for x[n] is defined as $\{x[N-\mu], \ldots, x[N-1]\}$: it consists of the last μ values of the x[n] sequence.
- For each input sequence of length N, these last μ samples are appended to the beginning of the sequence. This yields a new sequence

$$\tilde{x}[n], -\mu \leq n \leq N-1, \text{ of length } N+\mu,$$

-where $\tilde{x}[-\mu], \ldots, \tilde{x}[N-1] = x[N-\mu], \ldots, x[N-1], x[0], \ldots, x[N-1]$, as shown in Figure.

The Cyclic Prefix

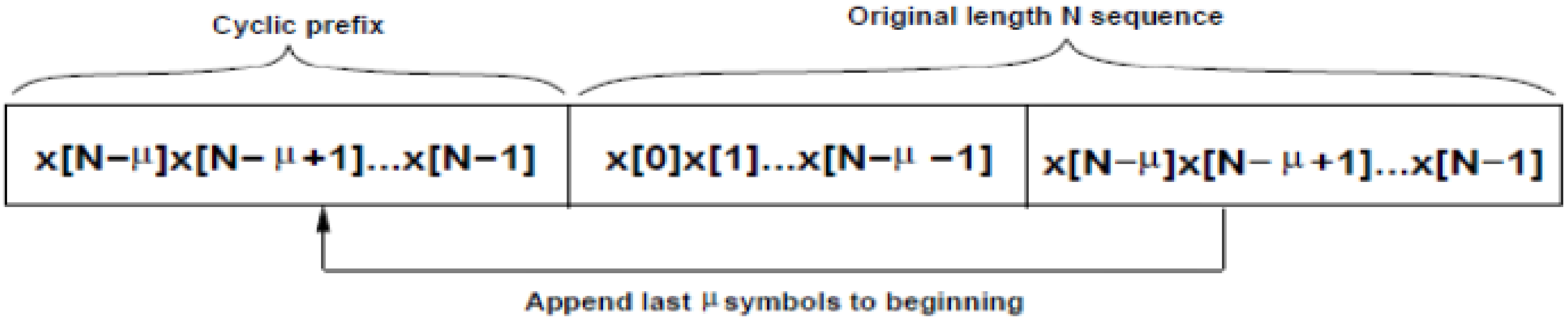


Figure : Cyclic Prefix of Length μ

- Suppose x˜[n] is input to a discrete-time channel with impulse response h[n]. The channel output y[n], $0 \le n \le N-1$ is then,

$$\begin{aligned} y[n] &= \tilde{x}[n] * h[n] \\ &= \sum_{k=0}^{\mu-1} h[k]\tilde{x}[n-k] \\ &= \sum_{k=0}^{\mu-1} h[k]x[n-k]_N \\ &= x[n] \otimes h[n], \end{aligned}$$

- Where the third equality follows from the fact that for $0 \le k \le \mu - 1$, $\tilde{x}[n-k] = x[n-k]_N$ for $0 \le n \le N-1$.
- Thus, by appending a cyclic prefix to the channel input, the linear convolution associated with the channel impulse response y[n] for $0 \le n \le N-1$ becomes a circular convolution.

The Cyclic Prefix

- Taking the DFT of the channel output in the absence of noise then obtains –

$$Y[i] = \mathrm{DFT}\{y[n] = x[n] \otimes h[n]\} = X[i]H[i], \;\; 0 \leq i \leq N-1,$$

and the input sequence x[n], $0 \leq n \leq N - 1$, can be recovered from the channel output y[n], $0 \leq n \leq N - 1$, for known h[n] by

$$x[n] = \mathrm{IDFT}\{Y[i]/H[i]\} = \mathrm{IDFT}\{\mathrm{DFT}\{y[n]\}/\mathrm{DFT}\{h[n]\}\}.$$

The Cyclic Prefix

- The cyclic prefix serves to eliminate ISI between the data blocks since the first μ samples of the channel output affected by this ISI can be discarded without any loss relative to the original information sequence.
- In continuous time this is equivalent to using a guard band of duration Tm after every block of N symbols of duration N Ts to eliminate the ISI between these data blocks.
- In OFDM the input data is divided into blocks of size N referred to as an OFDM symbol. A cyclic prefix is added to each OFDM symbol to induce circular convolution of the input and channel impulse response.
- At the receiver, the output samples affected by ISI between OFDM symbols are removed.
- The DFT of the remaining samples are used to recover the original input sequence

Orthogonal Frequency Division Multiplexing (OFDM)

- The OFDM implementation of multicarrier modulation is shown in Figure 4.6.
- The input data stream is modulated by a QAM modulator, resulting in a complex symbol stream X[0], X[1], . . . , X[N − 1].
- This symbol stream is passed through a serial-to-parallel converter, whose output is a set of N parallel QAM symbols X[0], . . . , X[N −1] corresponding to the symbols transmitted over each of the subcarriers.
- Thus, the N symbols output from the serial-to-parallel converter are the discrete frequency components of the OFDM modulator output s(t).
- In order to generate s(t), these frequency components are converted into time samples by performing an inverse DFT on these N symbols, which is efficiently implemented using the IFFT algorithm.

Orthogonal Frequency Division Multiplexing (OFDM)

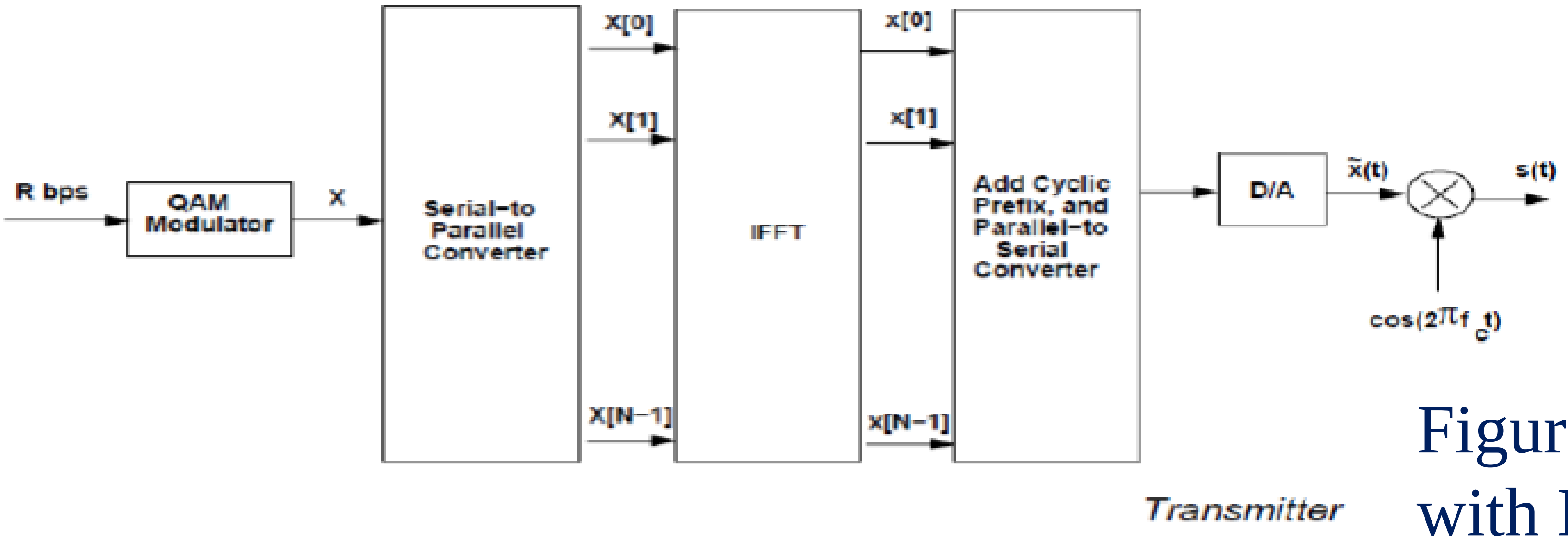
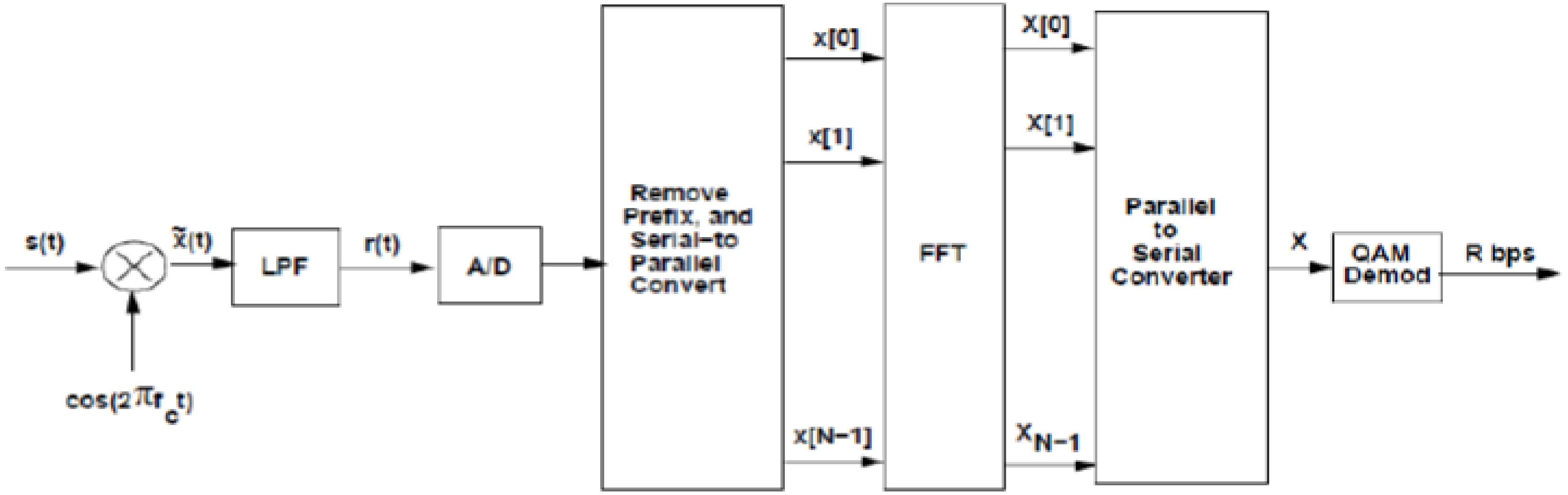


Figure 4.6 OFDM with IFFT/FFT Implementation



Orthogonal Frequency Division Multiplexing (OFDM)

- The IFFT yields the OFDM symbol consisting of the sequence $x[n] = x[0], \ldots, x[N-1]$ of length N , where

$$x[n] = \frac{1}{\sqrt{N}} \sum_{i=0}^{N-1} X[i] e^{j2\pi ni/N}, \quad 0 \leq n \leq N-1.$$

- This sequence corresponds to samples of the multicarrier signal and the right hand side of above expression corresponds to samples of a sum of QAM symbols X[i] each modulated by carrier frequency $e^{j2\pi it/T}N$,

$$i = 0, \ldots, N-1.$$

- The cyclic prefix is then added to the OFDM symbol, and the resulting time samples $\tilde{x}[n] = \tilde{x}[-\mu], \ldots, \tilde{x}[N-1] = x[N-\mu], \ldots, x[0], \ldots, x[N-1]$ are ordered by the parallel-to-serial converter and passed through a D/A converter, resulting in the baseband OFDM signal $\tilde{x}(t)$, which is then up converted to frequency f_0.

Orthogonal Frequency Division Multiplexing (OFDM)

- The transmitted signal is filtered by the channel impulse response h(t) and corrupted by additive noise, so that the received signal is $y(t) = \tilde{x}(t) * h(t) + n(t)$.
- This signal is down converted to baseband and filtered to remove the high frequency components.
- The A/D converter samples the resulting signal to obtain $y[n] = \tilde{x}[n] * h[n] + \nu[n], -\mu \leq n \leq N - 1$.
- The prefix of y[n] consisting of the first μ samples is then removed.
- This results in N time samples whose DFT in the absence of noise is $Y[i] = H[i]X[i]$.
- These time samples are serial-to-parallel converted and passed through an FFT. This results in scaled versions of the original symbols H[i]X[i], where $H[i] = H(f_i)$ is the flat-fading channel gain associated with the i^{th} subchannel.

Orthogonal Frequency Division Multiplexing (OFDM)

- The FFT output is parallel-to-serial converted and passed through a QAM demodulator to recover the original data.
- The OFDM system decomposes the wideband channel into a set of narrowband orthogonal sub-channels with a different QAM symbol sent over each subchannel.
- The demodulator can use the channel gains to recover the original QAM symbols by dividing out these gains: $X[i] = Y[i]/H[i]$. This process is called frequency equalization.
- However, or continuous-time OFDM, frequency equalization leads to noise enhancement, since the noise in the i^{th} subchannel is also scaled by $1/H[i]$.
- Precoding, adaptive loading, and coding across subchannels are better approaches to mitigate the effects of flat fading across subcarriers.

Orthogonal Frequency Division Multiplexing (OFDM)

- An alternative to using the cyclic prefix is to use a prefix consisting of all zero symbols. In this case the OFDM symbol consisting of $x[n]$, $0 \leq n \leq N - 1$ is preceded by μ null samples, as shown in Figure 4.7.

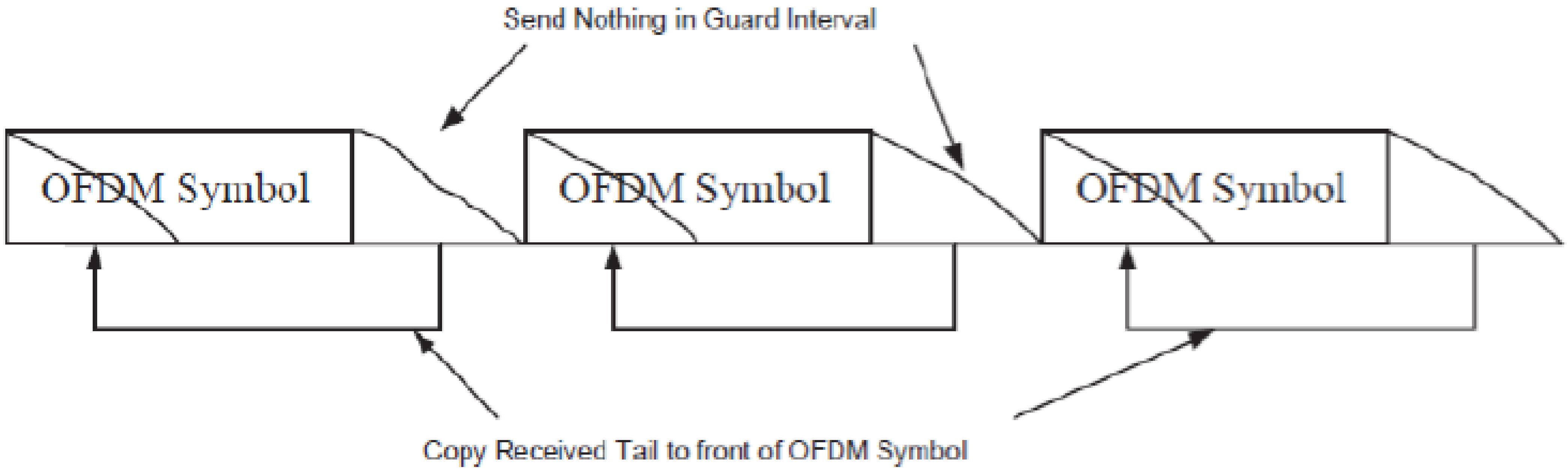


Figure 4.7 Creating a Circular Channel with an All-Zero Prefix

Thank You

Topic 5

Peak to Average Power Ratio

Peak to Average Power Ratio

- The peak to average power ratio (PAR) is a very important attribute of a communication system.
- A low PAR allows the transmit power amplifier to operate efficiently, whereas a high PAR forces the transmit power amplifier to have a large backoff in order to ensure linear amplification of the signal.
- This is shown in Figure 4.8 showing a typical power amplifier response.
- Operation in the linear region of this response is generally required to avoid signal distortion, so the peak value is constrained to be in this region.

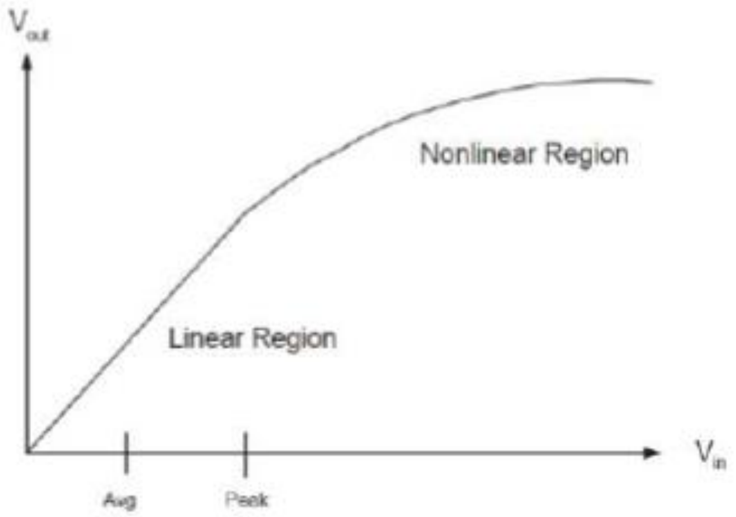


Figure 4.8 Typical Power Amplifier Response

Peak to Average Power Ratio

- It would be desirable to have the average and peak values close together as possible in order to have the power amplifier operate at the maximum efficiency.

- Additionally, a high PAR requires high resolution for the receiver A/D convertor, since the dynamic range of the signal is much larger for high PAR signals. High resolution A/D conversion places a complexity and power burden on the receiver front end.

- The PAR of a continuous-time signal is given by

$$\text{PAR} \triangleq \frac{\max_t |x(t)|^2}{E_t[|x(t)|^2]}.$$

Peak to Average Power Ratio

- And for a discrete time signal it is given by –

$$\text{PAR} \triangleq \frac{\max_n |x[n]|^2}{E_n[|x[n]|^2]}.$$

- Any constant amplitude signal has PAR = 0 dB. A sine wave has PAR = 3 dB since max [sin2(t/T)] = 1 and so PAR=1/.5=2.

- In general PAR should be measured with respect to the continuous time signal since the input to the amplifier is an analog signal

$$E[\sin^2(t/T)] = \int_0^T \sin^2(t/T)dt = .5,$$

Peak to Average Power Ratio

- The PAR given by above expression is sensitive to the pulse shape g(t) used in the modulation, and does not generally lead to simple analytical formulas. Let us focus on the PAR associated with the discrete-time signal, since it lends itself to a simple characterization. Consider the time domain samples output from the IFFT:

$$x[n] = \frac{1}{\sqrt{N}} \sum_{i=0}^{N-1} X[i] e^{j\frac{2\pi i n}{N}}, \ 0 \leq n \leq N-1.$$

- If N is large, the Central Limit Theorem is applicable and x[n] are zero-mean complex Gaussian random variables since the real and imaginary parts are summed.
- The Gaussian approximation for IFFT outputs is generally quite accurate for a reasonably large number of subcarriers ($N \geq 64$).

Peak to Average Power Ratio

- For x[n] complex Gaussian, the envelope of the OFDM signal is Rayleigh distributed with variance σn^2, and the phase of the signal is uniform.
- Since the Rayleigh distribution has infinite support, the peak value of the signal will exceed any given value with nonzero probability.
- The probability that the PAR given exceeds a threshold $P_0 = \sigma_0^2/\sigma_n^2$ is given by – $p(\mathrm{PAR} \geq P_0) = 1 - (1 - e^{-P_0})^N.$
- Hence the maximum PAR is N for N subcarriers.
- PAR increases approximately linearly with the number of subcarriers.
- So, in order to keep the overhead associated with the cyclic prefix down, a large PAR is an important penalty that must be paid for large N .
- There are a number of ways to reduce the PAR of OFDM signals, including clipping the OFDM signal above some threshold, peak cancellation with a complementary signal, allowing non-linear distortion from the power amplifier.

Thank You

Topic 6

Frequency and Timing Offset

Frequency and Timing Offset

- OFDM modulation encodes the data symbols X_i onto orthogonal sub channels, where orthogonality is assured by the subcarrier separation $\Delta_f = 1/T_N$.
- The sub channels may overlap in the frequency domain, as shown in Figure 4.9 for a rectangular pulse shape in time.
- In practice, the frequency separation of the subcarriers is imperfect: so Δ_f is not exactly equal to $1/T_N$.
- This is caused by mismatched oscillators, Doppler frequency shifts, or timing synchronization errors.
- For example, if the carrier frequency oscillator is accurate to 0.1 parts per million (ppm), the frequency offset $\Delta_f \approx (f0)(0.1 \times 10{-}6)$.

Frequency and Timing Offset

- If f_0 = 5 GHz, the carrier frequency for 802.11a WLANs, then Δ_f = 500 Hz, which will degrade the orthogonality of the subchannels, since now the received samples of the FFT will contain interference from adjacent subchannels.

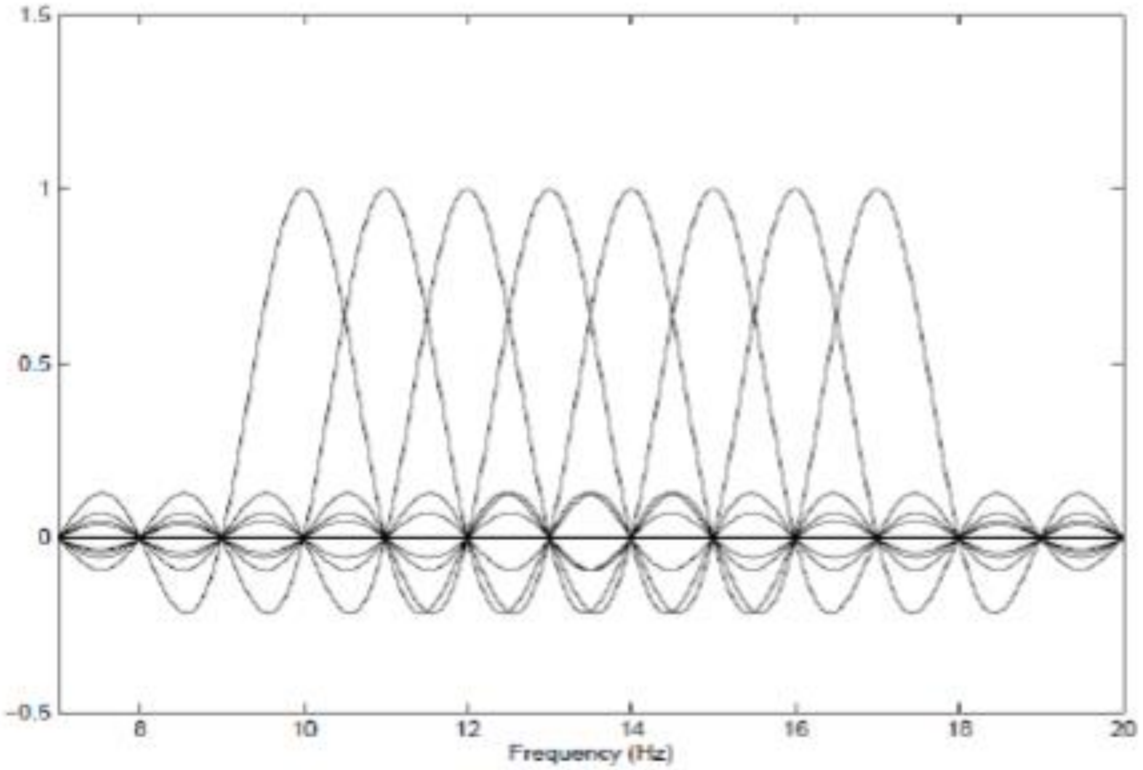


Figure 4.9 OFDM Overlapping Subcarriers

Frequency and Timing Offset

- The signal corresponding to subcarrier i can be simply expressed for the case of rectangular pulse shapes (suppressing the data symbol and the carrier frequency) as

$$x_i(t) = e^{j\frac{2\pi i t}{T_N}}.$$

- An interfering subchannel signal can be written as –

$$x_{i+m}(t) = e^{j\frac{2\pi (i+m) t}{T_N}}.$$

- If the signal is demodulated, then this interference becomes –

$$x_{i+m}(t) = e^{j\frac{2\pi (i+m+\delta) t}{T_N}}.$$

Frequency and Timing Offset

- The ICI between the subchannel signals is given by

$$I_m = \int_0^{T_N} x_i(t) x_{i+m}(t) dt = \frac{T_N \left(1 - e^{-j2\pi(\delta+m)}\right)}{j2\pi(m+\delta)}.$$

- If T_N increases, the subcarriers grow narrower and more closely spaced, which results in more ICI.
- Second, the ICI grows with the frequency offset δ, and the growth is about quadratic. But picking large value of N forces T_N to also be large, which causes the subcarriers to be closer.
- Along with the larger PAR that comes with large N , the increased ICI is another reason to pick N as low as possible. In order to further reduce the ICI for a given choice of N , non-rectangular windows can also be used.

Thank You

Topic 7

Case Study IEEE 802.11a

Case Study: The IEEE 802.11a Wireless LAN Standard

- The IEEE 802.11a Wireless LAN standard, which occupies 20 MHz of bandwidth in the 5 GHz unlicensed band, is based on OFDM.
- The IEEE 802.11g standard is virtually identical, but operates in the smaller and more crowded 2.4 GHz unlicensed ISM band.
- In this section, the properties of this OFDM design and some of the design choices are studied.
- In 802.11a, $N = 64$ subcarriers are generated, although only 48 are actually used for data transmission, with the outer 12 zeroed in order to reduce adjacent channel interference, and 4 used as pilot symbols for channel estimation.
- The cyclic prefix consists of $\mu = 16$ samples, so the total number of samples associated with each OFDM symbol, including both data samples and the cyclic prefix, is 80.

Case Study: The IEEE 802.11a Wireless LAN Standard

- The transmitter gets periodic feedback from the receiver about the packet error rate, which uses to pick an appropriate error correction code and modulation technique.
- The same code and modulation must be used for all the subcarriers at any given time.
- The error correction code is a convolutional code with one of three possible coding rates: r = ½, 2/3, or 3/4.
- The modulation types used on the subchannels are BPSK, QPSK, 16QAM, or 64QAM.
- Since the bandwidth B (and sampling rate $1/T_s$) is 20 MHz, and there are 64 subcarriers evenly spaced over that bandwidth, the subcarrier bandwidth is:

$$B_N = \frac{20 \text{ MHz}}{64} = 312.5 \text{ KHz}.$$

Case Study: The IEEE 802.11a Wireless LAN Standard

- Since μ = 16 and 1/Ts = 20MHz, the maximum delay spread for which ISI is removed is

$$T_m < \mu T_s = \frac{16}{20\text{MHz}} = 0.8\ \mu\text{sec},$$

- Which corresponds to delay spread in an indoor environment. Including both the OFDM symbol and cyclic prefix, there are 80=64+16 samples per OFDM symbol time, so the symbol time per subchannel is

$$T_N = 80T_s = \frac{80}{20 \times 10^6} = 4\ \mu s$$

Case Study: The IEEE 802.11a Wireless LAN Standard

- The data rate per subchannel is $\log_2 M/T_N$. Thus, the minimum data rate for this system, corresponding to BPSK (1 bit/symbol), an r = ½ code, and taking into account that only 48 subcarriers actually carry usable data, is given by

$$\begin{aligned} R_{min} &= 48 \text{ subcarriers} \times \frac{1/2 \text{ bit}}{\text{codedbit}} \times \frac{1 \text{ coded bit}}{\text{subcarrier symbol}} \times \frac{1 \text{ subcarrier symbol}}{4 \times 10^{-6} \text{ seconds}} \\ &= 6 \text{ Mbps} \end{aligned}$$

- The maximum data rate that can be transmitted is –

$$R_{max} = 48 \text{ subcarriers} \times \frac{3/4 \text{ bit}}{\text{coded bit}} \times \frac{6 \text{ coded bits}}{\text{subcarrier symbol}} \frac{1 \text{ subcarrier symbol}}{4 \times 10^{-6} \text{ seconds}} = 54 \text{ Mbps}.$$

Thank You

Model Questions

Part – A

1. What is multi-carrier modulation?

The basic idea of multicarrier modulation is to divide the transmitted bit stream into many different sub streams and send these over many different sub channels. Typically the sub channels are orthogonal under ideal propagation conditions

2. Give the advantages and disadvantages of Data transmission using multiple carriers.

Advantage: Since Symbol time duration on each subsystem greater than delay spread of the channel, Significant ISI will not there.

Disadvantage: Spectrally inefficient because non-ideal low pass filters will be required to maintain the orthogonally of the carriers at the receiver.

Part – A

3. What is the technique employed to improve the spectral efficiency in Multi-carrier modulation?

The spectral efficiency of multi-carrier modulation can be improved by overlapping the sub channels. The sub carriers must be orthogonal and can be separated out by a demodulator in the receiver.

4. What are the merits and demerits of overlapping sub channels in multi-carrier modulation?

Merits: Efficient use of Bandwidth

Demerits: Orthogonality is compromised by timing and frequency offset.

Part – A

5. What is coding with Interleaving over time and frequency?

The basic concept in coding with interleaving over time and frequency is to encode data bits into code words, interleave the resulting coded bits over both time and frequency, and then transmit the coded bits over different sub channels.

6. What is frequency equalization?

In frequency equalization the flat fading αi on the i^{th} sub-channel is basically inverted in the receiver. Specifically, the received signal is multiplied by $1/\alpha_i$, which gives a resultant signal power $\alpha_i^2 P_i/\alpha_i^2 = Pi$.

Part – A

7. What is called Pre-coding?

Pre-coding uses the same concept of frequency equalization, except that the fading is inverted at the transmitter instead of the receiver. This technique requires that the transmitter must have knowledge of the sub-channel flat fading gain.

8. What is Adaptive Loading?

It is a technique used to vary the data rate and power assigned to each sub channel relative to that sub channel gain. It is commonly used on slowly changing channels like digital subscriber lines where channel estimates at the transmitter can be obtained fairly easily.

Part – A

9. What is OFDM?

Orthogonal frequency division multiplexing (OFDM) is a technique for digital multi-carrier modulation using many closely spaced subcarriers - a previously modulated signal modulated into another signal of higher frequency and bandwidth.

10. What is meant by Vector Coding?

It is a method based on combining positional number codes of the projections of vectors. This method has been considered for binary number codes which can be easily generalized in order to utilize non-binary number codes.

Part – A

11. Mention the factors corresponding to challenges in Multi-carrier Systems?

Peak to Average Power Ratio, Frequency & Timing Offset are the factors corresponding to challenges in Multi-carrier Systems.

12. What is IEEE 802.11a Standard?

The IEEE 802.11a is a Wireless LAN standard, which occupies 20 MHz of bandwidth in the 5 GHz unlicensed band based on OFDM.

Part – B

1. Explain the Data transmission using multiple carriers with relevant diagrams.

2. Explain how Multicarrier modulation can be achieved with overlapping subcarriers.

3. Write a short note on Mitigation of Subcarrier fading.

4. Describe the Discrete implementation of Multicarrier modulation.

5. Explain the case study on IEEE 802.11a Standard.

6. Explain in detail, the challenges in Multicarrier modulation.

Mobile Communication

Unit – V / Cellular Concepts

Syllabus

- Frequency Reuse – Channel Assignment Strategies – Hand off Strategies – Interference & system capacity- Co-Channel Interference- Adjacent Channel Interference – Trunking and Grade of service – Improving coverage & capacity in cellular systems - Cell Splitting- Sectoring- Repeaters for Range Extension- Microcell Zone Concept.

Introduction to Cellular System

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 number of neighboring BS.
- Interference between neighboring BS's is minimized by allocating different channels.

Cellular Systems-Basic Concepts

- Same frequencies are reused by spatially separated BS's.
- Interference between co-channels stations is kept below acceptable level.
- Additional radio capacity is achieved.
- Frequency Reuse-Fix number of channels serve an arbitrarily large number of subscribers

Topic 1

Frequency Re-use

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 be no longer used.
- 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 cell = basic geographical unit of a cellular network & 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 cluster 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 & 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

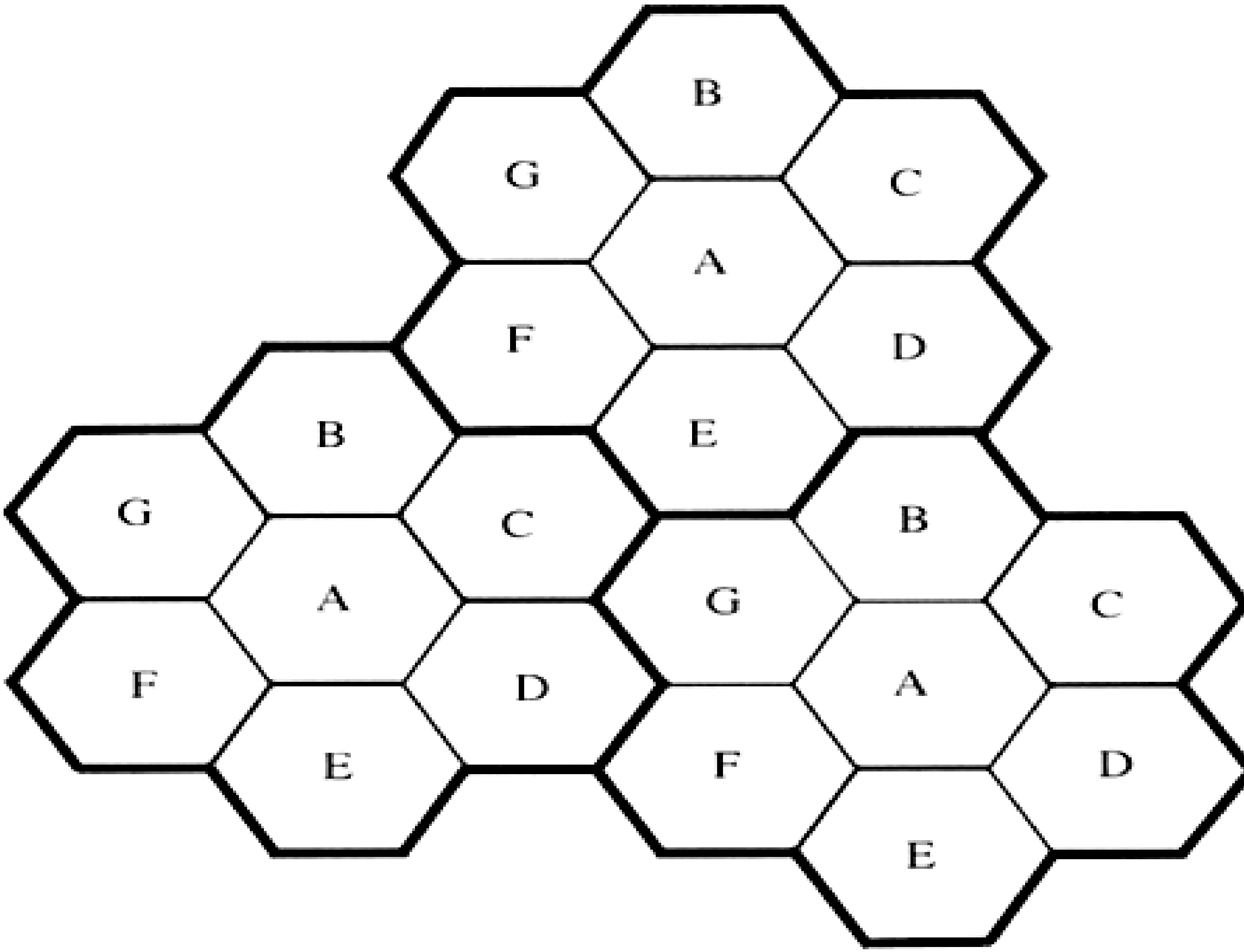


Illustration of the cellular frequency reuse concept.

Frequency Reuse

- In hexagonal cell model, BS transmitter can be in center 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, - a group of adjacent cells.
- If cluster repeated M times, the capacity C of system is given as

$$C = MkN = MS$$

- Capacity of system is directly proportional to the number of times the cluster 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.

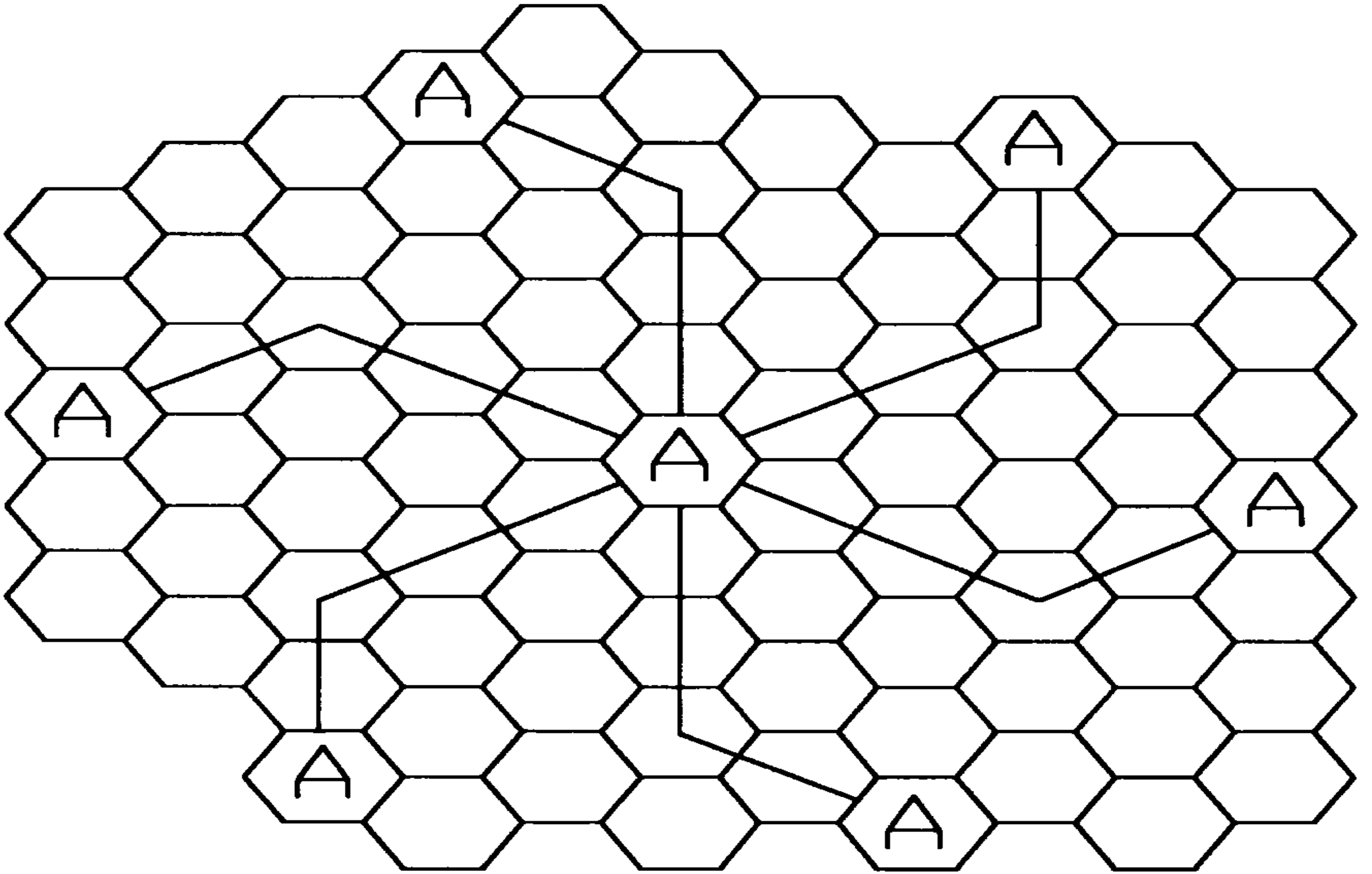
Frequency Reuse

- 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.

Locating co-channel Cell



Topic 2

Channel Assignment Strategies

Fixed Assignment Strategy

- A scheme for increasing capacity and minimizing interference is required for effective utilization of radio spectrum.
- CAS can be classified as either fixed or dynamic
- Choice of CAS impacts the performance of system for call management.
- 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 – called borrowing strategy, 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, 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.

Dynamic Channel Assignment (contd)

- This increases the storage and computational load on the system
- But provides the advantage of increased channel utilization and decreased probability of a blocked call.

Topic 3

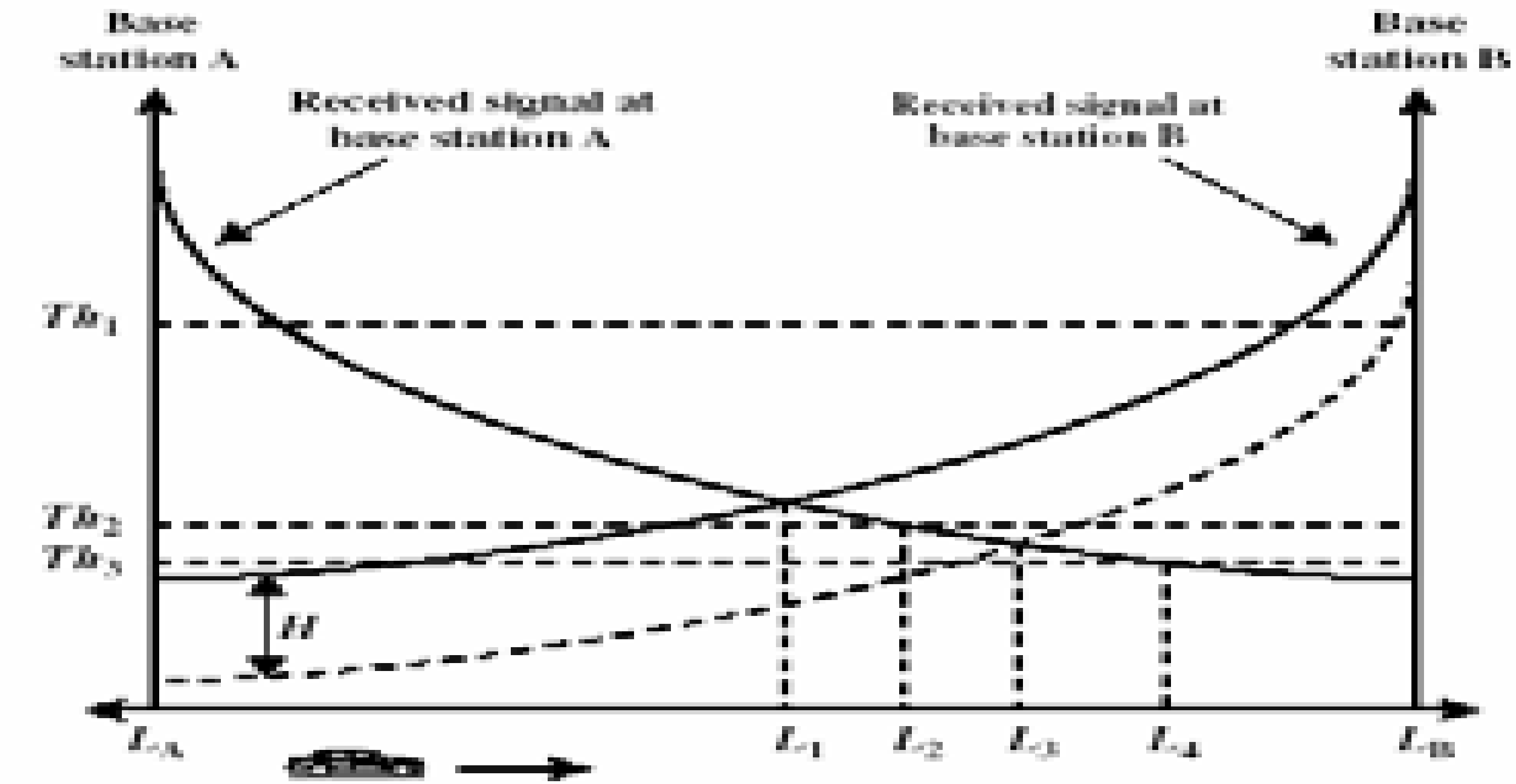
Hand off Strategies

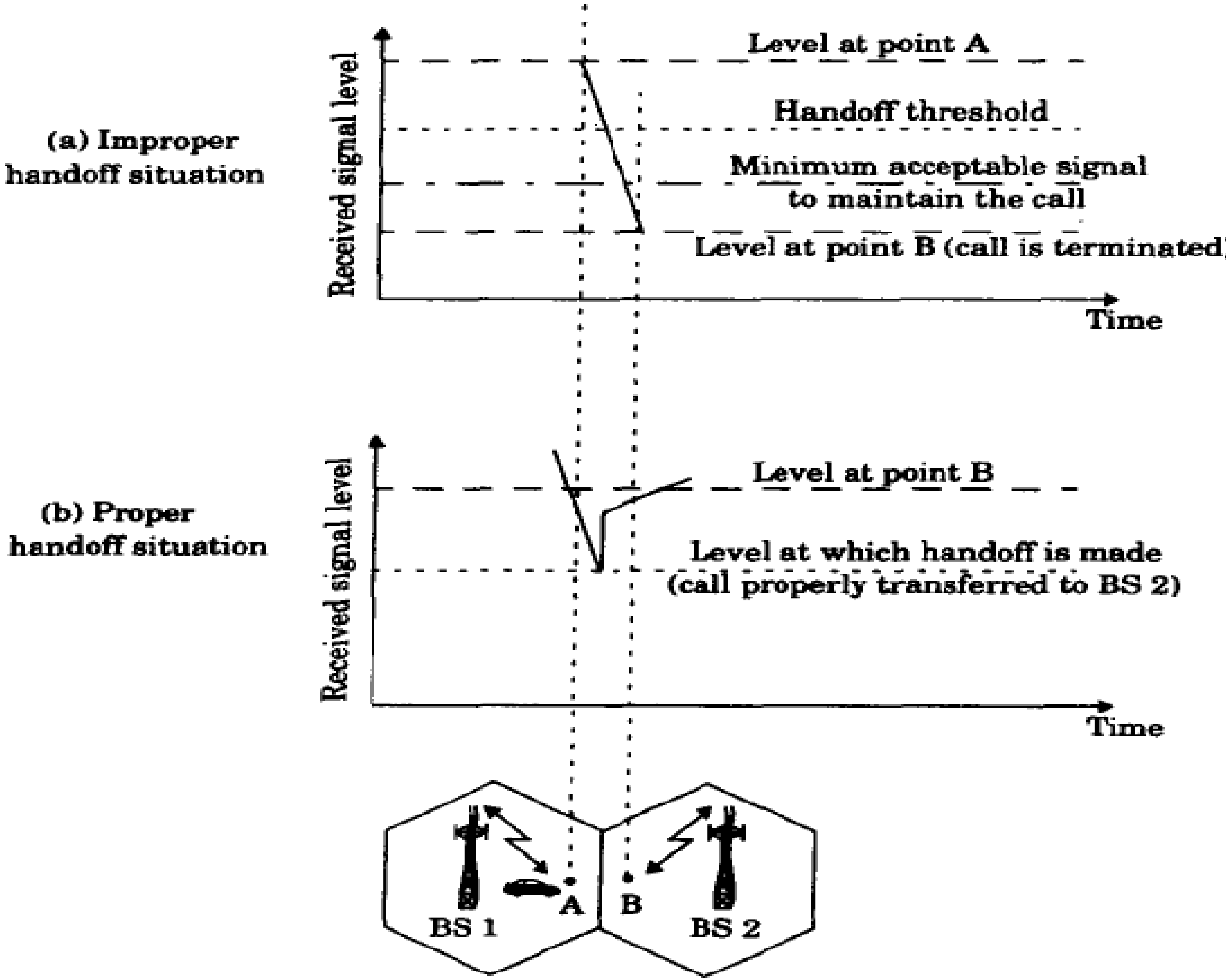
Introduction to Hand-off

- 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.
- Minimum usuable signal for acceptable voice qualtiy → 90 to -100 dBm
- A slight higher value is used as threshold

Introduction to Hand-off (contd)

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




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

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

$$\Delta = Power_{handoff} - Power_{min\ usable}$$

- Large Δ results in unecesarry handoff and for small Δ unsufficient time to complete handoff, so carefully chosen to meet the requirements.
- Figure 2a, 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.

Hand-off Strategies (contd)

- 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 , 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 – First Generation

- 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 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 host base station
  - MSC monitors RSS from all base stations & decides on handoff

Hand-off strategies – 2nd Generation

- In 2nd generation systems, Mobile Assisted Handoffs (MAHO) are used
- In MAHO, every MS measures the received power from the surrounding BS & 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 Vs Inter-system 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.
- If a mobile moves from one cellular system to another system controlled by a different MSC, an inter-system handoff is required.
- MSC engages in intersystem handoff when signal becomes weak in a given cell.

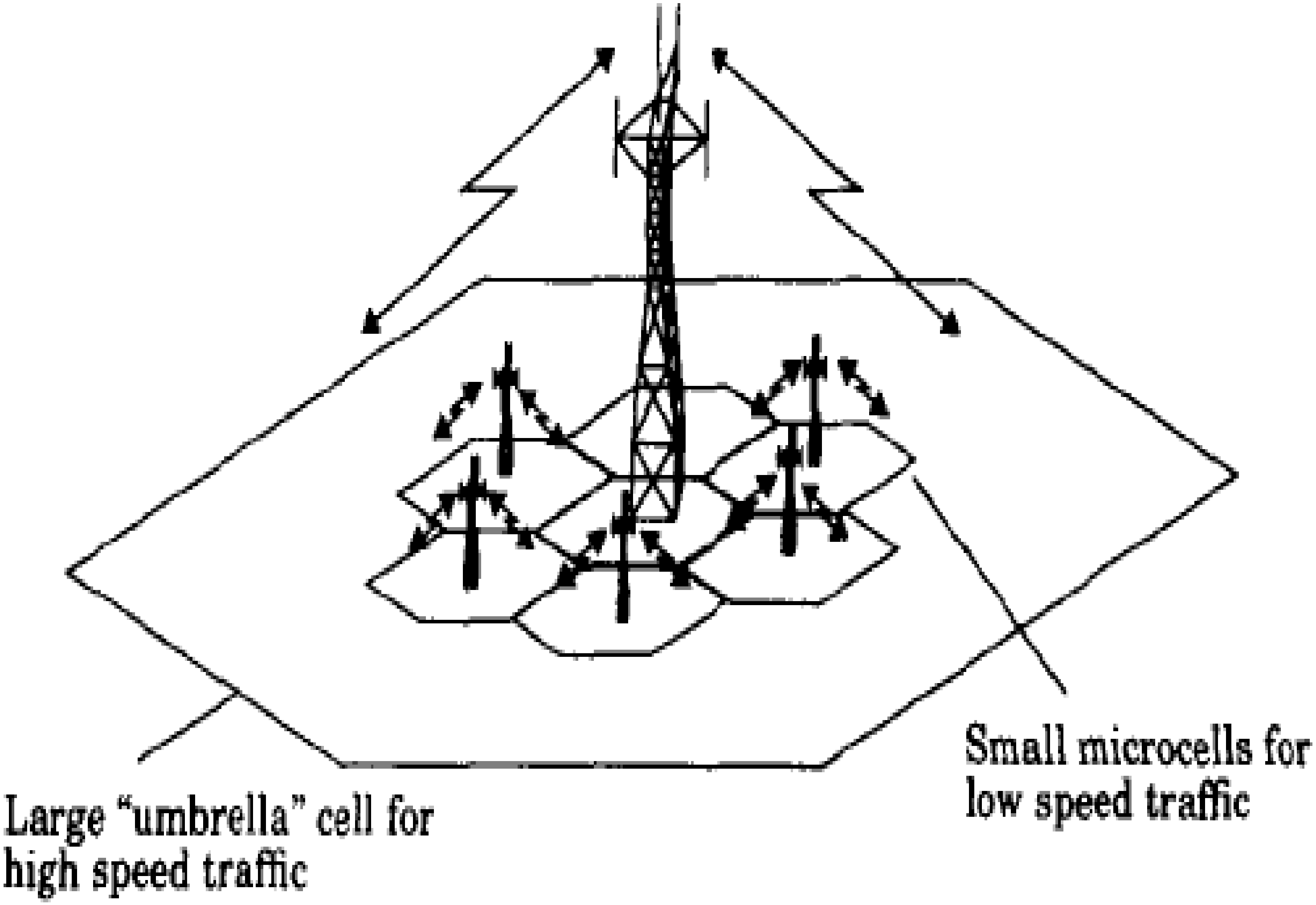
Prioritizing Handoffs

- Perceived Grade of Service (GOS) – service quality as viewed by users
  - **“quality” in terms of dropped or blocked calls**
  - **assign higher priority to handoff Vs new call request**
  - **a dropped call more aggravating than an occasional blocked call**
- Guard Channels
  - **% of total available cell channels set aside for handoff requests**
  - **makes fewer channels available for new call requests**
  - **a good strategy for dynamic channel allocation**
- Queuing of Handoff Requests
  - **use time delay between handoff threshold & minimum useable signal level**
  - **a handoff request during that time period, instead of having a single block/no block decision**
  - **prioritize requests & handoff as required**
  - **calls 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 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 & Tx power levels to provide large and small cell coverage**
  - **multiple antennas & Tx can be co-located at single location if required**
  - **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



Topic 4

Interference & System Capacity

Interference

- Interference is the major limiting factor in the performance of cellular radio systems.
- Sources of interference include -
  - **another mobile in the same cell**
  - **a call in progress in a neighboring cell**
  - **other base stations operating in same frequency band**
  - **any non-cellular system which leaks energy into band**
- Interference on voice channels causes cross talk due to an undesired transmission.
- Interference on control channels, leads to missed & blocked calls due to errors in digital signaling.
- Interference is more severe in urban areas, due to RF noise floor & large number of base stations / mobiles.
- Interference is a major bottleneck in increasing capacity & often responsible for dropped calls

Interference (contd)

- The two major types of cellular interference are Co-channel interference (CCI) & Adjacent channel interference (ACI).
- Even though interfering signals are often generated within the cellular system, they are difficult to control due to random propagation effects.
- More difficult to control is interference due to out-of-band users due to front end overload of subscriber equipments.
- 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.

Topic 5

Co-channel Interference

Co-channel Interference

- Frequency reuse indicates that in a given coverage area there are several cells using the same set of frequencies.
- These cells are called co-channel cells & interference between signals from these cells is called co-channel interference.
- Co-channel interference cannot be combated by simply increasing the carrier power of a transmitter.
- Because an increase in carrier transmit power increases the interference to neighboring co-channel cells.
- To reduce co-channel interference, co-channel cells must be separated by a minimum distance to provide sufficient isolation due to propagation.
- Co-channel interference is independent of the transmitted power & depends upon the radius of the cell (R) and the distance between centers of the nearest co-channel cells (D).

Co-channel Interference (contd)

- By increasing D/R ratio, the spatial separation between co-channel cells relative to the coverage distance of a cell is increased.
- Thus, interference is reduced from improved isolation of RF energy from the co-channel cell.
- The parameter Q - called the co-channel reuse ratio is related to the cluster size.

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

- A small value of Q provides larger capacity since the cluster size N is small, whereas a large value of Q improves the transmission quality, due to a smaller level of co-channel interference.

Signal to Interference Ratio (S/I)

- Let i_0 be the number of co-channel interfering cells.
- The signal-to-interference ratio (S/I) for a mobile receiver which monitors a forward channel given by -

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

- where S is desired signal power from the desired base station & I_i is the interference power caused by the i^{th} interfering co-channel cell base station.
- The average received power P_r at a distance d from the transmitting antenna is approximated by

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

- where P_0 is the power received in far field region of the antenna at a small distance d_0 from the transmitting antenna & n is the path loss exponent.

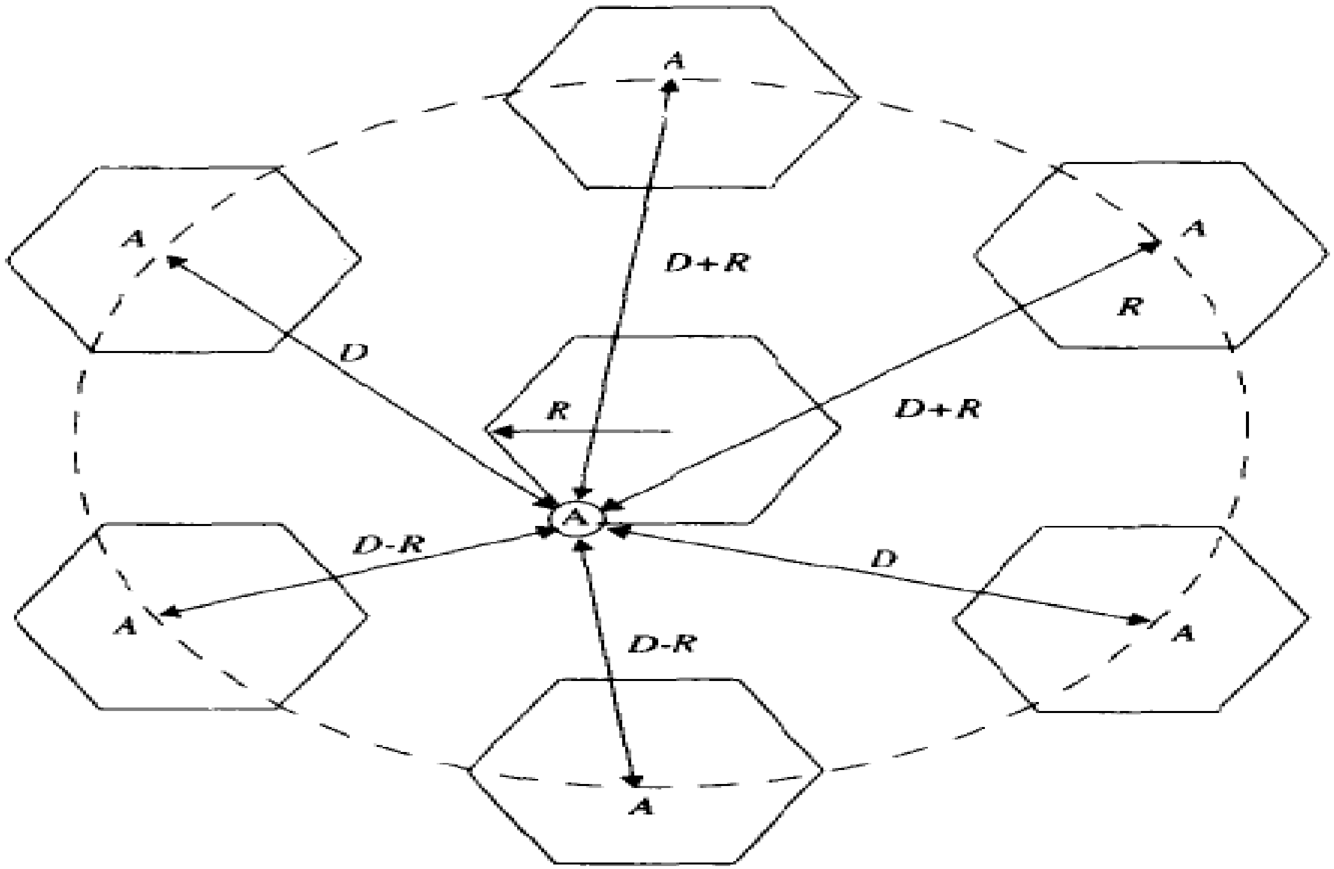
Signal to Interference Ratio (contd)

- When the transmit power of each base station is equal & path loss exponent is the same throughout, *S/I* for a mobile can be approximated as-
$$\frac{S}{I} = \frac{R^{-n}}{\sum_{i=1}^{i_0} (D_i)^{-n}}$$
- If all the interfering base stations are equidistant from the desired base station & equal to distance *D* between cell centers, then above simplifies to-
$$\frac{S}{I} = \frac{(D/R)^n}{i_0} = \frac{(\sqrt{3N})^n}{i_0}$$
- For a seven-cell cluster, with mobile unit at the cell boundary, the mobile is a distance *D* – *R* from the two nearest co-channel interfering cells & exactly *D* + *R*/2, *D*, *D* – *R*/2, and *D* + *R* from the other interfering cells in the first tier, as shown in figure 1.

Figure 1. First tier of co-channel cells for cluster size of *N* = 7

- Using the approximate geometry shown in Figure 1 & assuming *n* = 4, the signal-to-interference ratio for the worst case can be approximated as -

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



Topic 6

Adjacent Channel Interference

Near–Far Effect

- Interference resulting from signals adjacent in frequency to the desired signal is called adjacent channel interference.
- Adjacent channel interference results from imperfect receiver filters which allow nearby frequencies to leak into the pass-band.
- The problem can be serious if an adjacent channel user is transmitting in very close range to a subscriber's receiver, while the receiver attempts to receive a base station on the desired channel.
- This is called as the near–far effect, where a nearby transmitter captures the receiver of the subscriber.
- It also occurs when a mobile close to a base station transmits on a channel close to one being used by a weak mobile.

Minimizing Interference

- The base station may have difficulty in discriminating the desired mobile user from the "bleed-over" caused by the close adjacent channel mobile.
- Adjacent channel interference can be minimized through careful filtering & channel assignments.
- Since each cell is given only a fraction of the available channels, a cell need not be assigned channels adjacent in frequency.
- By keeping the frequency separation between each channel in a given cell larger, the adjacent channel interference may be reduced.
- If the frequency reuse factor is large, the separation between adjacent channels at the base station not sufficient to keep the adjacent channel interference level within tolerable limits.

Minimizing Interference (contd)

- For example, if a close-in mobile is 20 times as close to the base station as another mobile & has energy spill-out of its pass-band, the signal-to-interference ratio at the base station for the weak mobile is given by -

$$\frac{S}{I} = (20)^{-n}$$

- For a path loss exponent $n = 4$, this is equal to –52 dB.
- If the intermediate frequency (IF) filter of the base station receiver has a slope of 20 dB/octave, then an adjacent channel interferer must be displaced by at least six times the pass-band bandwidth to achieve -52 dB attenuation.
- This indicates more than six channel separations required to bring the adjacent channel interference to an acceptable level.
- In practice, base station receivers are preceded by a high Q cavity filter to reject adjacent channel interference.

Topic 7

Trunking & Grade of Service

Trunking

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

- Trunking allows a large number of users to share a 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
- Holding Time: Average duration of a typical call.
- Request Rate: The average number of calls requests per unit time (λ)
- Traffic Intensity: Measure of channel time utilization measured in Erlangs. Dimensionless quantity. Denoted by A
- Load: Traffic intensity across the entire TRS (Erlangs)

Erlang- 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.
- 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- Unit of Traffic (contd)

- 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**

Grade of Service

- In a TRS, when a particular user requests service & 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 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)’’.

Grade of Service (contd)

- Grade of Service (GOS): Measure of ability of a user to access a trunked system during the busiest hour.
- Also a Measure of the congestion which is specified as a probability.
- It is a benchmark to define the desire performance of a particular trunk system.
- The probability of a call being blocked -
- Blocked calls cleared (BCC) or Erlang B systems.
- The probability of a call being delayed beyond a certain amount of time before being granted access -
- Blocked call delayed (BCD) or Erlang C systems.

Blocked Call Cleared Systems (BCC)

- When a user requests service, there is a minimal call set-up time & 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
  - Nearly an infinite number of users
  - Call requests are memory less so 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 is exponentially distributed.
  - Longer calls less likely to happen
  - Finite number of channels available in the trunking pool.
  - Inter-arrival times of call requests are independent of each other

Modeling of BCC Systems (contd)

- 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.
- 'A' is the total offered traffic.

Traffic Intensity in Erlang B (BCC)

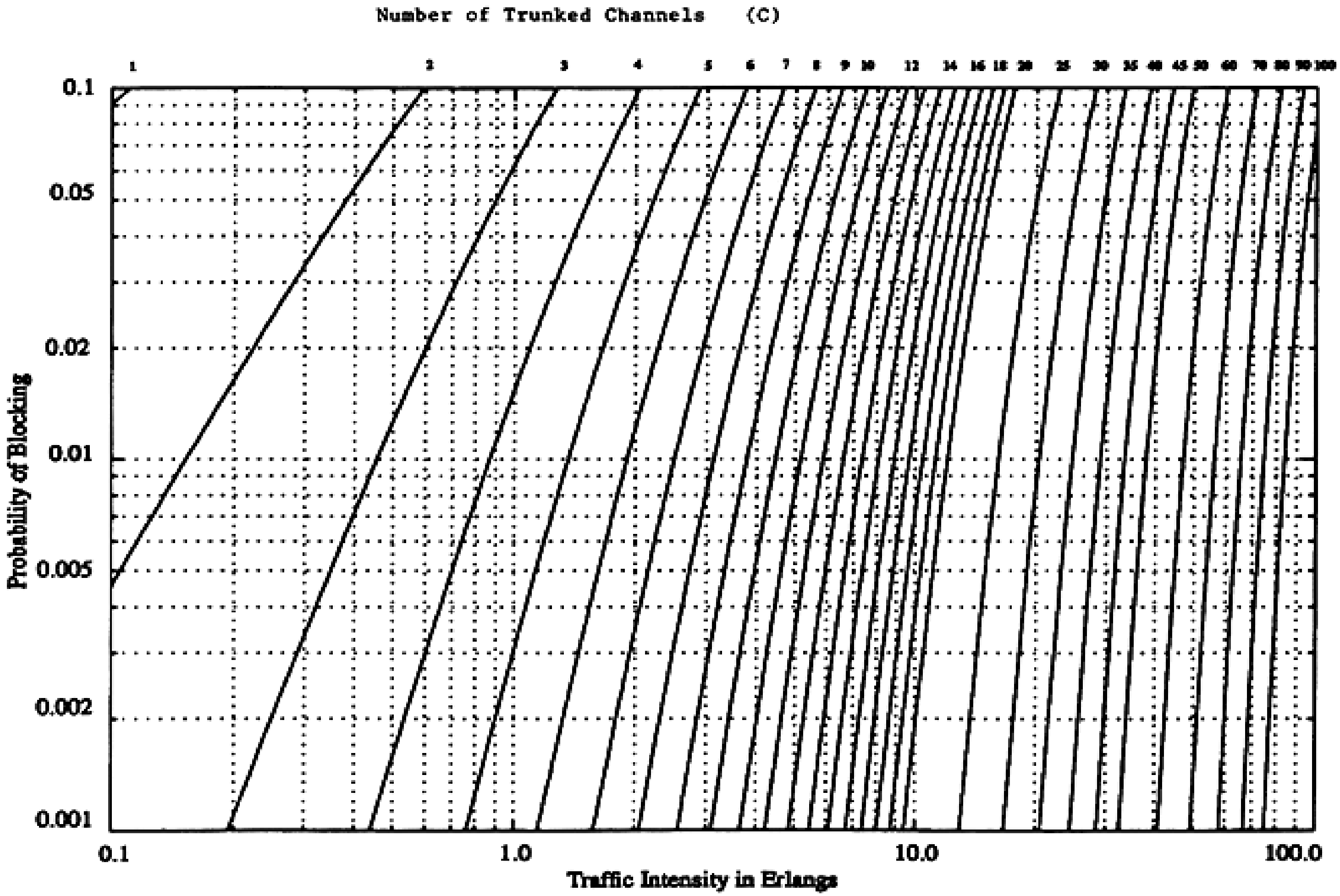


Figure 3.6 The Erlang B chart showing the probability of blocking as functions of the number of channels and traffic intensity in Erlangs.

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

Blocked Call Delayed Systems (BCD)

- Queues are used to hold call requests that are initially blocked.
- When a user attempts a call & 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
  - 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 (contd)

- Erlang C formula 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;

$$Pr\ [delay>t] = Pr\ [delay>0]\ Pr\ [delay>t \mid delay>0]$$

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

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

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

Traffic Intensity in Erlang C (BCD)

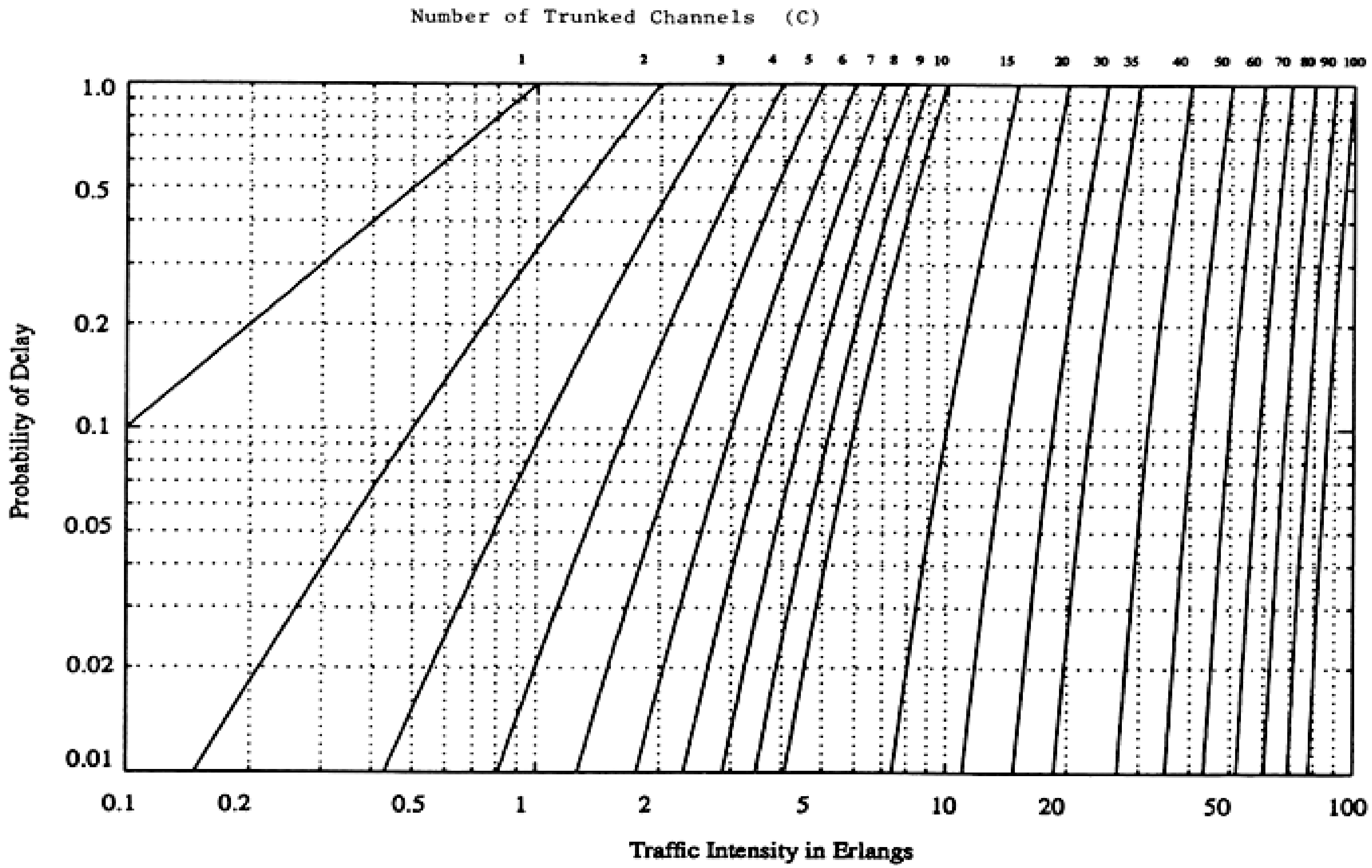


Figure 3.7 The Erlang C chart showing the probability of a call being delayed as a function of the number of channels and traffic intensity in Erlangs.

Topic 8

Improving Coverage & Capacity in Cellular Systems

Improving Coverage

- As the demand for wireless service increases, the number of channels assigned to a cell becomes insufficient to support the required number of users.
- Hence cellular design techniques are needed to provide more channels per unit coverage area.
- Techniques such as cell splitting, sectoring & coverage zone approaches are used to expand the capacity of cellular systems.
- Cell splitting allows an orderly growth of the cellular system.
- Sectoring uses directional antennas to control the interference and frequency reuse of channels.

Improving Capacity

- The zone microcell concept distributes the coverage of a cell & extends the cell boundary to hard-to-reach places.
- While cell splitting increases the number of base stations to increase capacity, sectoring & zone microcells depend on base station antenna placements to improve capacity by reducing co-channel interference.
- Cell splitting & zone microcell techniques do not suffer trunking inefficiencies experienced by sectored cells.
- They enable base station to oversee all handoff chores related to the microcells, thus reducing the computational load at the MSC.

Topic 9

Cell Splitting

Introduction to Cell Splitting

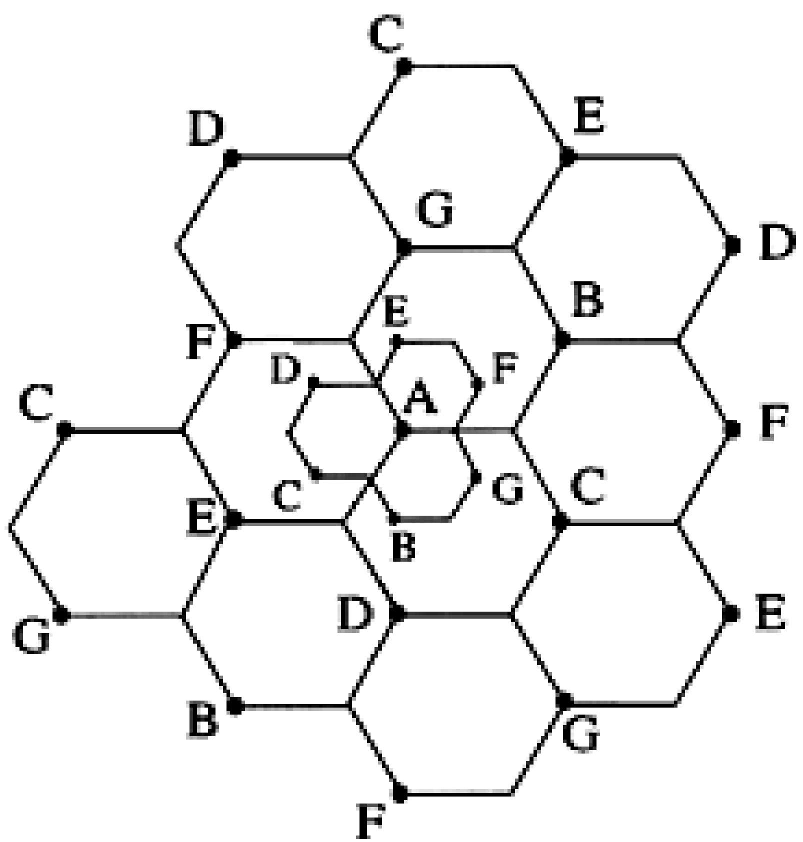
- Cell splitting is the process of subdividing a congested cell into smaller cells with
  - their own BS
  - a corresponding reduction in antenna height
  - a corresponding reduction in transmit power
- Splitting the cell reduces the cell size & thus more number of cells to be used
- For the new cells 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

Example for Cell Splitting

- An example of cell splitting is shown in Figure 1.
- The base stations are placed at corners of the cells & area served by base station *A* is assumed to be saturated with traffic.
- New base stations are needed in the region to increase the number of channels in the area & to reduce the area served by the single base station.
- In figure 1, the original base station *A* has been surrounded by six new microcells.
- The smaller cells were added in such a way to preserve the frequency reuse plan of the system.
- For example, the microcell base station labeled *G* was placed half way between two larger stations utilizing the same channel set *G*.

Figure 1 – Cell Splitting

- This is also the case for the other microcells in the figure.
- Hence cell splitting merely scales the geometry of the cluster.
- In this case, the radius of each new microcell is half that of the original cell.



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?

$$\text{Pr [at old cell boundary]} = \text{Pt1} (R)^{-n}$$

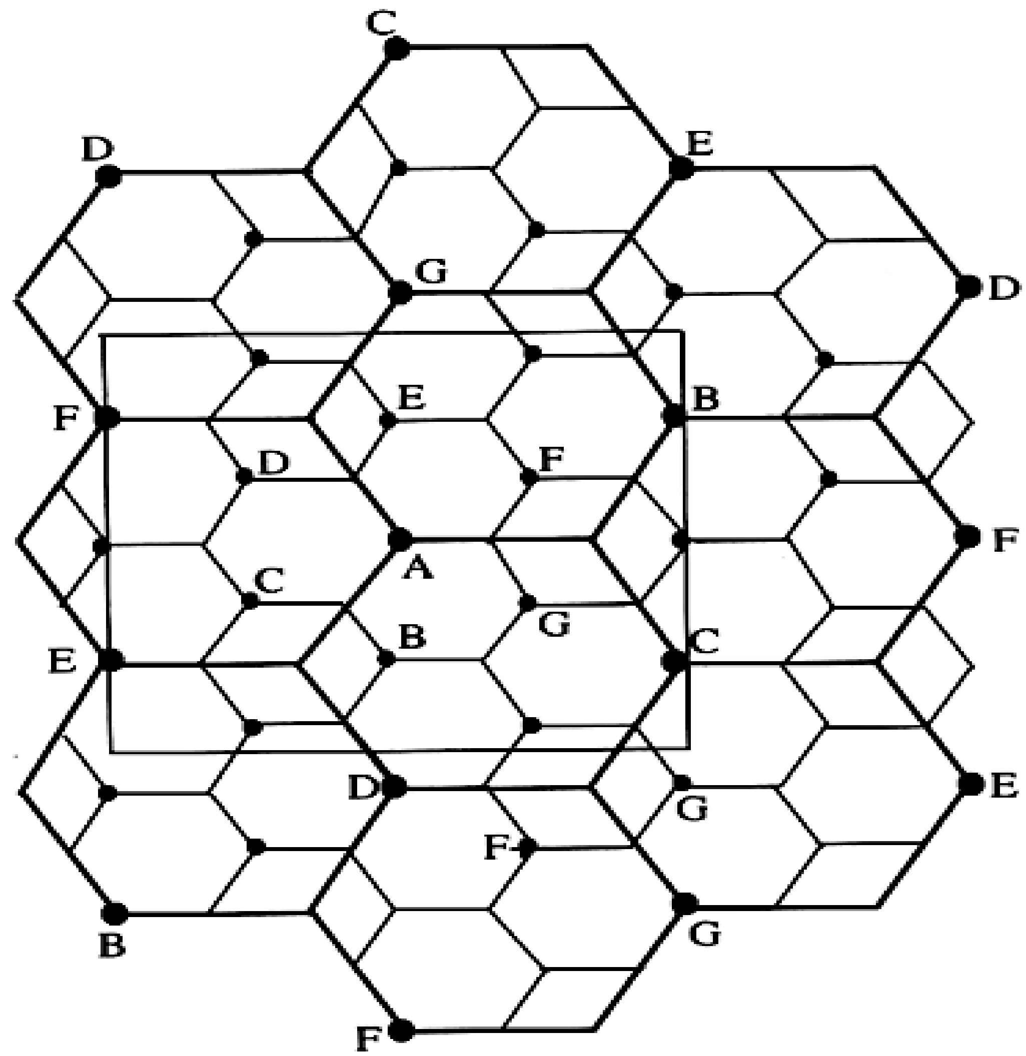
$$\text{Pr [at new cell boundary]} = \text{Pt2} (R/2)^{-n}$$

- where Pt1 and Pt2 are the transmit powers of the larger and smaller cell base stations & n is the path loss exponent.
- So, $\mathbf{Pt2 = Pt1 / 2^n}$
- If we take n=3 and the received powers equal to each other, then

$$\text{Pt2} = \text{Pt1} / 8$$

- 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



Overcome – Handoff

- 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 minimum & 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 & other for larger cell
  – The larger cell is dedicated to high speed traffic so that handoffs occur less frequently
  – Initially, small power group has less channels & large power group has large no of channels but at maturity of the system large power group does not have any channel

Topic 10

Sectoring

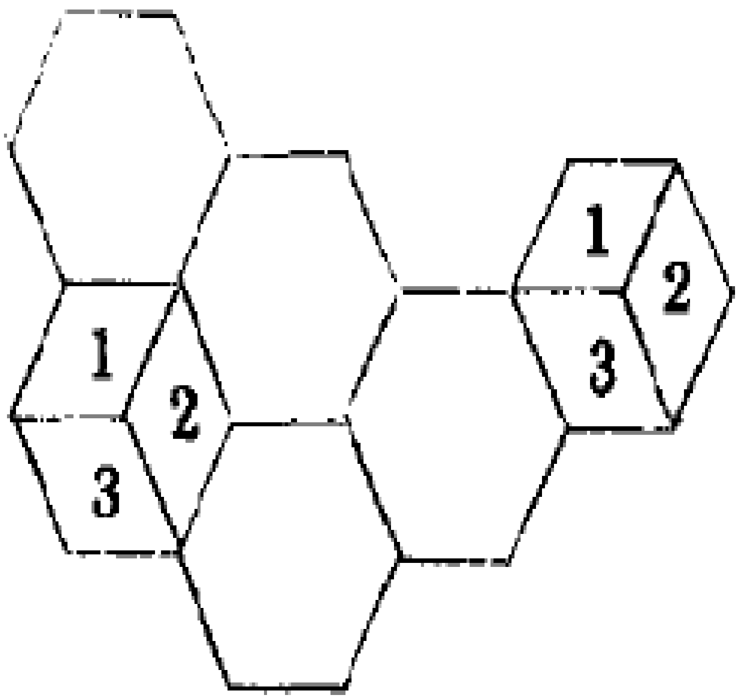
Introduction

- Cell splitting achieves capacity improvement by rescaling the system.
- By decreasing the cell radius *R* & keeping the co-channel reuse ratio *D*/*R* unchanged, cell splitting increases the number of channels per unit area.
- Another way to increase capacity is to keep the cell radius unchanged & to decrease the *D*/*R* ratio.
- Sectoring increases SIR so that cluster size may be reduced.
- First the SIR is improved using directional antennas & then capacity improvement by reducing the number of cells in a cluster, thus increasing the frequency reuse.
- However, it is necessary to reduce the relative interference without decreasing the transmit power.

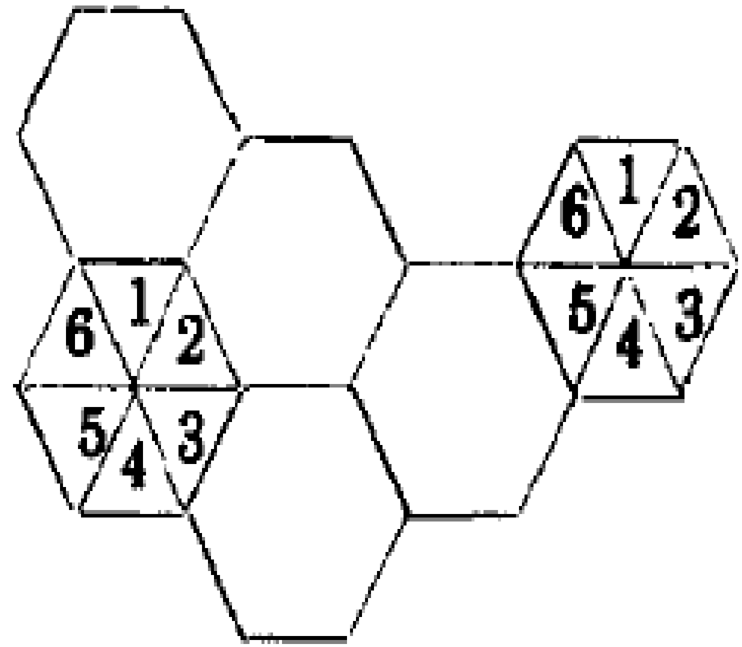
Reducing Co-channel Interference

- The co-channel interference may be decreased by replacing a single omnidirectional antenna at the base station by several directional antennas.
- By using directional antennas, a given cell will receive interference & transmit with only a fraction of the available co-channel cells.
- The technique for decreasing co-channel interference & increasing system performance by using directional antennas is called sectoring.
- The factor by which co-channel interference is reduced depends on the amount of sectoring used.
- A cell is normally partitioned into three 120° sectors or six 60° sectors as shown in Figure 1(a) and 1 (b).

Figure 1 - 120 & 60 degrees Sectoring



(a)

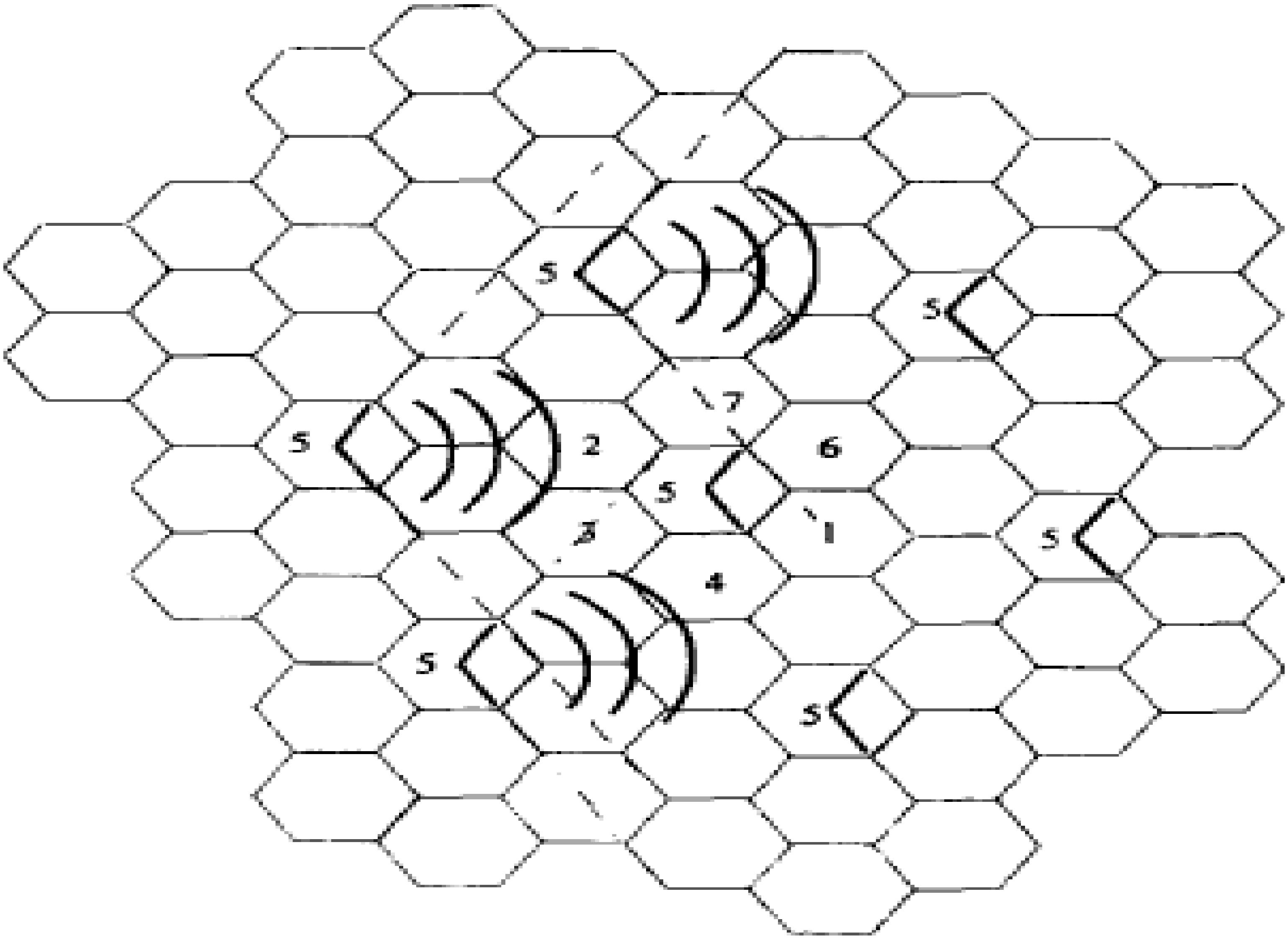


(b)

120 degree Sectoring reducing Interference

- In Figure 2, consider the interference experienced by a mobile located in the right-most sector in the center cell labeled "5".
- There are three co-channel cell sectors labeled "5" to the right of the center cell & three to the left of the center cell.
- Out of these six co-channel cells, only two cells have sectors with antenna patterns which radiate into the center cell.
- Hence a mobile in the center cell will experience interference on the forward link from only these two sectors.
- This *S/I* improvement allows to decrease the cluster size *N* in order to improve the frequency reuse & the system capacity

Figure 2 -120 degree Sectoring reducing Interference



Penalty for Improved S/I

- The penalty for improved *S/I* & the resulting capacity improvement is an increased number of antennas at each base station & decrease in trunking efficiency due to channel sectoring at the base station.
- Since sectoring reduces the coverage area of a particular group of channels, the number of handoffs also increases.
- Because sectoring uses more than one antenna per base station, the available channels in the cell must be subdivided & dedicated to a specific antenna.

Topic 11

Repeaters for Range Extension

Role of Repeaters

- A wireless operator needs to provide dedicated coverage for hard-to-reach areas, such as within buildings, or in valleys or tunnels.
- Radio re-transmitters, known as repeaters, are used to provide such range extension capabilities.
- Repeaters are bidirectional in nature & simultaneously send signals to and receive signals from a serving base station.
- Repeaters may be installed anywhere & capable of repeating an entire cellular band.
- Upon receiving signals from a base station, the repeater amplifies and reradiates the base station signals to the specific coverage region.
- Unfortunately, the received noise & interference is also reradiated by the repeater on both forward and reverse link.

Repeaters Vs System Capacity

- Care must be taken to properly place the repeaters & to adjust the various forward and reverse link amplifier levels and antenna patterns.
- In practice, directional antennas or distributed antenna systems (DAS) are connected to the inputs or outputs of repeaters for spot coverage, particularly in tunnels or buildings.
- By modifying the coverage of a serving cell, an operator can dedicate a certain amount of the base station's traffic for the areas covered by the repeater.
- However, the repeater does not add capacity to the system.
- Repeaters are being used to provide coverage into and around buildings, where coverage is weak .

Location of Repeaters

- Determining the proper location for repeaters & distributed antenna systems within buildings requires careful planning, to avoid re-radiation of interference into the building from the base station.
- Also, repeaters must be provisioned to match the available capacity from the serving base station.
- Software products, such as Site-Planner allow engineers to determine the best placements for repeaters & required DAS network while simultaneously computing the traffic and installation cost.

Topic 12

Microcell Zone Concept

Introduction

- The increased number of handoffs required during sectoring results in an increased load on the switching and control link elements of the mobile system.
- A solution to this problem is based on a microcell concept for seven cell reuse, as illustrated in Figure 1.
- In this scheme, each of the three zone sites represented as Tx/Rx in Figure 1 are connected to a single base station & share the same radio equipment.
- The zones are connected by coaxial cable, fiber-optic cable, or microwave link to the base station.
- Multiple zones & a single base station make up a cell.
- As a mobile travels within the cell, it is served by the zone with the strongest signal.

Time & Space Distribution

- As a mobile travels from one zone to another within the cell, it retains the same channel.
- Unlike in sectoring, a handoff is not required at the MSC when the mobile travels between zones within the cell.
- The base station simply switches the channel to a different zone site.
- Thus a given channel is active only in the particular zone in which the mobile traveling & hence the base station radiation is localized & interference is reduced.
- The channels are distributed in time & space by all three zones & reused in co-channel cells in the normal fashion.
- This technique is particularly useful along highways or along urban traffic corridors.

Advantage of Zone Cell Technique

- The advantage of this zone cell technique - while the cell maintains a particular coverage radius, the co-channel interference is reduced.
- And a large central base station is replaced by several lower powered transmitters.
- Decreased co-channel interference improves the signal quality & increase in capacity without degradation in trunking efficiency caused by sectoring.

Figure 1 – The Micro-cell Concept

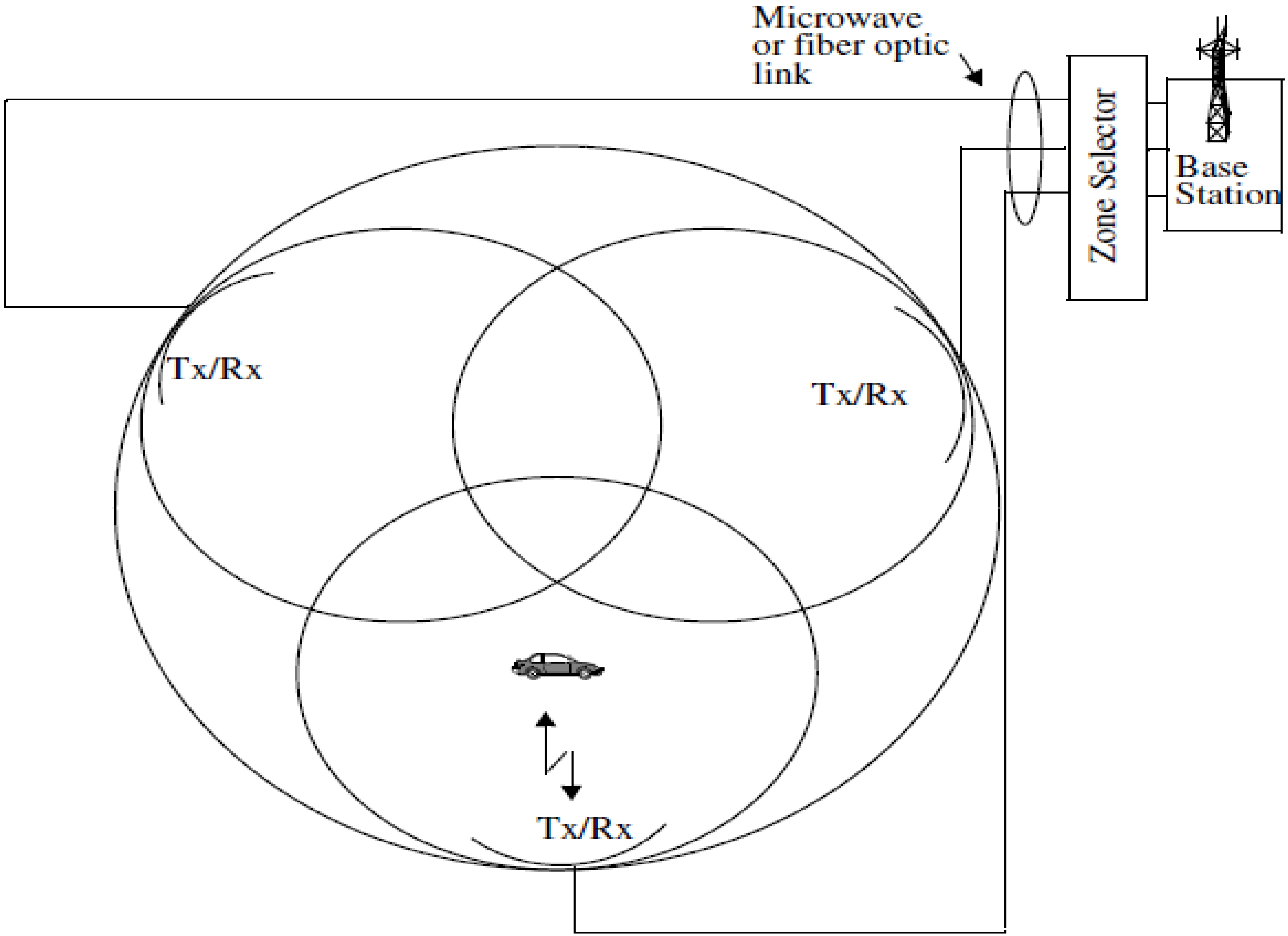
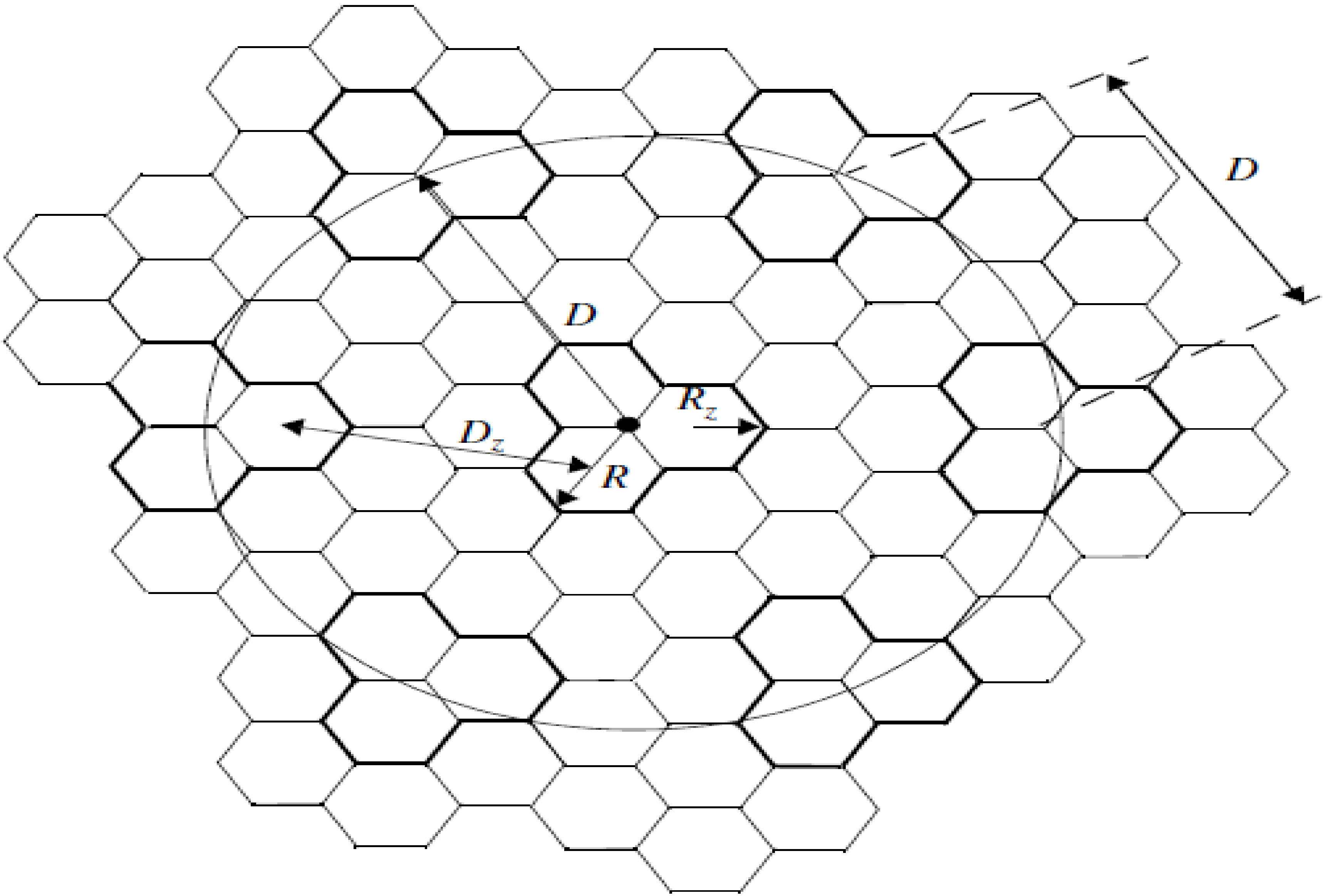


Figure 2 – Microcell Architecture with N = 7



Reduction in Cluster size

- In Figure 2, let each individual hexagon represents a zone, while each group of three hexagons represents a cell.
- The zone radius R_z is approximately equal to one hexagon radius.
- The capacity of the zone microcell system is related to the distance between co-channel cells & not zones. This distance is represented as *D.*
- For a D_z /R_z value = 4.6, the value of co-channel ratio - *D/R*, is equal to three, where *R* is the radius of the cell & equal to twice the length of the hexagon radius.
- D/*R* = 3 corresponds to a cluster size of *N* = 3.
- This reduction in the cluster size from *N* = 7 to *N* = 3 amounts to a 2.33 times increase in capacity for a system based on the zone microcell concept.

Applications

- In the worst case, the system provides a margin of 2 dB over the required signal-to-interference ratio while increasing the capacity by 2.33 times over a conventional seven-cell system using omni-directional antennas.

- No loss in trunking efficiency is experienced.

- Zone cell architectures are being adopted in many cellular & personal communication systems.

Model Question Bank

Unit - V

Part - A

- 1) What is frequency re-use?

  The design process of selecting & allocating channel groups for all the cellular base stations within a system is called frequency reuse or frequency planning.

2) Define cell in a wireless network.

A cell is a basic geographical unit of a cellular network & 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.

Part - A

- 3) Mention the factors which influence the co-channel interference in cellular networks.

  Co-channel interference is dependent on cluster size, large cluster size less interference and vice versa.

  4) What is channel assignment strategy?

  A scheme for increasing capacity and minimizing interference is required for effective utilization of radio spectrum. CAS can be classified as either fixed or dynamic. Choice of CAS impacts the performance of system for call management.

Part - A

- 5) What is called fixed channel assignment strategy?

  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.

  6)What is called dynamic channel assignment strategy?

  Voice channels are not allocated to different cells permanently. MSC only allocates a given frequency, not currently in use in the cell or any other cell which falls within the limiting reuse distance.

Part - A

- 7) Mention the advantages & disadvantages of dynamic channel assignment strategy.

  Advantage: Increased channel utilization and decreased probability of a blocked call.

  Disadvantage: Increases the storage and computational load on the system.

- 8) What is hand-off operation?

  Handoff operation involves identifying the new BS and allocation of voice and control signal to channels associated with new BS. It must be performed successfully, infrequently and impercitble to user.

Part - A

- 9) What is the safety margin required for hand-off operation?
- 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 insufficient time to complete handoff, so carefully chosen to meet the requirements.

Part - A

- 10) What is the role of a MSC in a cellular network?
- MSC no longer monitors RSS of all channels
  - reduces computational load considerably
  - enables much more rapid and efficient handoffs
  - imperceptible to user

- 11) What is soft-handoff operation?

  The ability to select between the instantaneous received signals from different Base Stations is called soft handoff.

Part - A

- 12) What is intersystem hand-off?

  If a mobile moves from one cellular system to another system controlled by a different MSC, an inter-system handoff is required. MSC engages in intersystem handoff when signal becomes weak in a given cell.

  13) Mention the practical considerations for hand-off operation.

- Problems occur because of a large range of mobile velocities
- Small cell sizes or micro-cells → larger handoffs
- MSC load is heavy when high speed users are passed between very small cells
- Umbrella Cells

Part - A

- 14) What are called Umbrella Cells?

  Cells which are meant to use different antenna heights & Transmitter power levels to provide large **and** small area coverage are called Umbrella cells.

- 15) Mention the sources of interference in a cellular network.

  Sources of interference include -

  - another mobile in the same cell
  - a call in progress in a neighboring cell
  - other base stations operating in same frequency band
  - any non-cellular system which leaks energy into band

Part - A

- 16) Mention the major types of cellular interferences.
- The two major types of cellular interference are Co-channel interference (CCI) & Adjacent channel interference (ACI).

- 17) Differentiate between CCI and 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.

Part - A

- 18) What are co-channel cells?
- Frequency reuse indicates that in a given coverage area there are several cells using the same set of frequencies. These cells are called co-channel cells

- 19) What is called near-far effect?
- If an adjacent channel user is transmitting in very close range to a subscriber's receiver, while the receiver attempts to receive a base station on the desired channel, then its is called as the near–far effect

Part - A

- 20) What is trunking?

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

- 21) Define Erlang.

  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

Part - A

- 22) What is grade of service (GOS) ?
- 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)”.**

- 23) What is 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

Part - A

- 24) What is called Sectoring?
- The technique for decreasing co-channel interference & increasing system performance by using directional antennas in a cellular network is called sectoring.

- 25) What is microcell concept?
- Base stations are decomposed into three or more zones connected by coaxial cable or fiber-optic cable to the base station.
- Multiple zones & a single base station make up a cell.
- The mobile is served by the zone with the strongest signal within the cell.

Part - B

- 1) Explain the concept of frequency re-use and the channel assignment strategies in detail.
- 2)Discuss in detail, the hand-off strategies implemented in a cellular network.
- 3) Explain the co-channel interference and adjacent channel interference in detail.
- 4) Describe about trunking and grade of service in a cellular network.
- 5)Write short notes on – (i) Cell Splitting (ii) Sectoring.
- 6) What is the concept of microcell zone? Explain it with an illustration in detail.