Unit I

Chapter 1

# Introduction to Wireless Channel

**Syllabus**

Introduction, Free space propagation model, Ground reflection scenario, Hata model and Receiver- Noise computation. Channel estimation techniques and Diversity in wireless communications.

**Chapter Contents**

## 1.1 Wireless Communication :

**Definition :**

- Wireless communication is defined as the communication by radio waves. The term wireless explains the communications other than the broadcast communication, between individuals who often use portable or mobile equipment.

**Wireless Communication Systems :**

- Some of the wireless communication systems are as follows :
  1. Wireless LAN.
  2. Cordless telephone.
  3. Walkie-Talkie.
  4. Pagers.
  5. AC remote control.
  6. TV remote control.
  7. Cellular phones.
  8. Satellite communication systems.
- Wireless communication is the fastest growing part of electronic communication. Wireless communication began with Hertz first experiment on radio in 1887. Then Marconi communicated across the English channel in 1899 and across the Atlantic ocean in 1901.
- The early radio transmitters were too bulky to be installed in vehicles. The first mobile radio system for police department was one way with only receiver in the police car.
- World War II provided a major breakthrough in the development of mobile and portable radio systems including the two way systems called as Walkie-talkies.
- In the post war era the branch of mobile communication grew at the fastest rate.
- In the wireless communication systems, the signal energy propagates in the form of electromagnetic waves over the wireless media or wireless channels. The examples of wireless media are radio waves, microwave and infrared light.
- The wireless media does not use a conductor or wire as a communication channel. Instead it uses the air or vacuum as medium to carry the information from transmitter to receiver.
- The transmitter first converts the data signal into electromagnetic waves and transmits them using a suitable antenna.
- The receiver receives the electromagnetic waves using a receiving antenna and converts them into data signal again.

### 1.1.1 Need of Wireless Communication :

- The communication systems can be classified into two broad categories as :
  1. Wired or guided communication systems.
  2. Wireless or unguided communication systems.
- The wired communication systems such as conventional telephone system use some kind of wired media such as coaxial cable or optical fiber cable to inter connect its end users.
- The **wireless systems** do not use wires as the transmission media. Instead air acts as the communication medium and communication takes place using electromagnetic (EM) waves.
- Examples of wireless communication systems are : satellite communication, mobile phones, wireless LAN and WAN, etc.
- The wireless communication is needed because of the reasons mentioned below :
  1. Long distance communication is difficult using wired media due to the length of wire, maintenance problems etc.
  2. One user to multiuser communication system becomes complicated using wired media. This becomes easy with wireless links.
  3. Broadcasting applications such as radio, TV etc are possible only through wireless communication due to a large number of users. Wired communication is not possible for such application.

4. It is easy to add new users without any additional wiring.
5. Wireless communication is possible even if the user is moving.
6. Using wireless LANs or wireless communication between computer and peripherals we can avoid wiring and improve reliability.

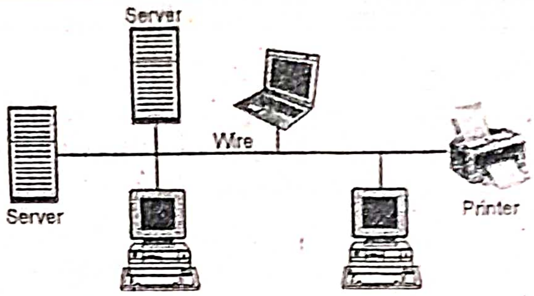
### 1.1.2 Wired and Wireless Networks :

**Communication channel :**

- In the computer networks such as the Internet the data needs to be transferred from a source to destination computer over a **communication channel.**
- A communication channel can be either a wired channel or a wireless channel.
- A communication channel is also called as **physical media such as** copper cables or optical fiber cables, whereas the examples of wireless communication media are : radio frequency waves, microwaves and infrared signals.

**A wired network :**

- A **network** is defined as the collection of computers, terminals, servers and various components connected to each other, to allow easy flow of data and use of resources.
- Fig. 1.1.1 shows a wired network in which various devices are interconnected with wires.



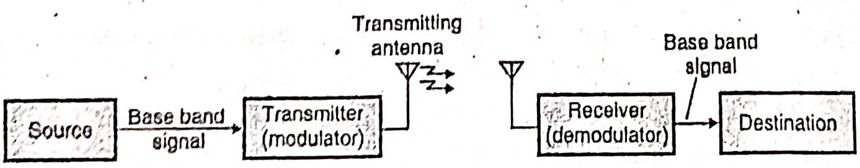

(O-921) Fig. 1.1.1 : A wired network

**A wireless network :**

- A wireless network is defined as the collection of computers, servers, terminals and various other components, connected to each other by **wireless links** instead of connecting wires.
- Wireless networks use **radio waves** to connect one device in the network to the others. All the devices in a wireless network can be moved within the **range** or **coverage** area of the network.
- This makes the wireless networks extremely portable. In wireless networks **air** is used as a **medium** to transfer the data.
- A computer needs to have the **wireless network card** to be a part of a wireless network. It will have the same functionality, as that of a wired computer but its speed will reduce.

### 1.1.3 Wireless Communication System :

- The most basic wireless system consists of a transmitter, a receiver and a channel which is usually a radio link as shown in Fig. 1.1.2.
- The radio waves cannot be used directly. Hence a modulator at the transmitter and a demodulator at the receiver are required to be used. The signal transmitted over the channel is a modulated signal.




(G-118(a)) Fig. 1.1.2 : Elements of a wireless communication system

- The signals transmitted by a transmitter will travel over a communication channel to the receiver. In the wireless radio communication, this channel is nothing but the free space.
- The process of signal travel from the transmitter to receiver can be divided into two parts :
  1. Radiation of the signal
  2. Propagation

**Radiation :**

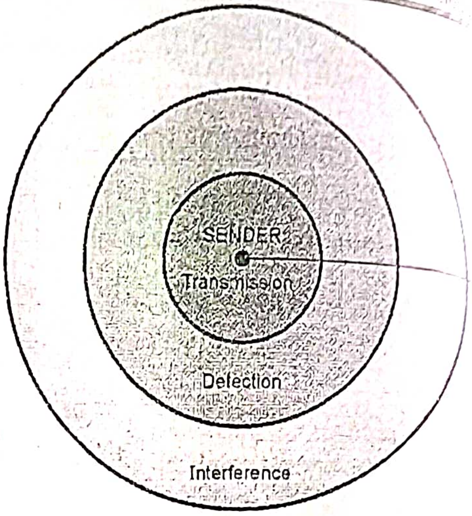
- Whenever a high frequency current flows through a conductor, the power measured on both the sides of the conductor is not same.
- A part of the power is dissipated in the resistance of the conductor and a part of it "escapes" into the free space.
- This escape of power is known as "radiation".

**Propagation of radio waves :**

- This "radiated" power then propagates in space in the form of electromagnetic (EM) waves.
- The radiation and propagation of the radio waves cannot be seen.
- The theory of electromagnetic radiation was propounded by the British physicist J.C. Maxwell in 1857.
- His theory and mathematical expressions explaining the behaviour of the electromagnetic waves is universally accepted and used.

### 1.1.4 Signal Transmission :

- Refer Fig. 1.1.3 to understand the concept of signal transmission. The sender transmits EM radio waves in all the directions.
- Depending on the distance from the sender we can divide total area into three concentric circles known as :
  1. Transmission range.
  2. Detection range.
  3. Interference range.




(G-2445)**Fig. 1.1.3 : Ranges of transmission, detec interference**

1. **Transmission range :**
   - This is the range in which transmission is p The receiver in this range receives the signal very small error rate. A receiver can also a sender in this range.
2. **Detection range :**
   - This is the range in which it is possible to the signal in the presence of backgroun but the error rate is too high. communication cannot be established.
3. **Interference range :**
   - Within the third (and the largest) radius, interference range, the sender can interfer the transmission from some other source.
   - However due to large background not, a re in this range cannot detect the signal.

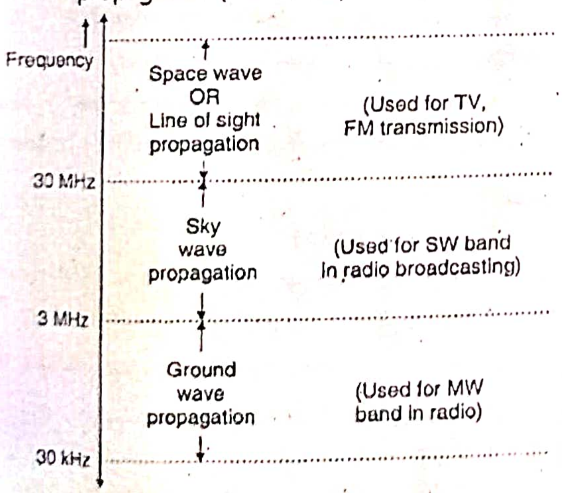
### 1.1.5 Path Loss of Radio Signals :

- The radio signals follow a straight path t the air from transmitter to receiver.
- While travelling the radio signals experi power loss called **free path loss.** Due to th the received power $P_r$ is always less tha transmitted power $P_t$.
- The path loss depends on the atmos conditions such as rain, fog, snow, smo particles present in the air etc.

- Path loss affects the reception quality for satellite communication and mobile communication.

### 1.1.6 Types of Wave Propagation :

- The radio waves can penetrate objects, buildings etc. if their frequency is low. But the high frequency radio waves (that are used for mobile communication) gets blocked even due to small objects such as trees.
- Once the signal leaves the antenna, (i.e. radiated) it can take any of the following three routes (paths). The type of propagation is decided by the route taken by the signal to reach the receiver from the transmitter.
- The three basic paths that a radio signal can take are :
  1. Along the surface of the earth **(Ground wave propagation)** : Used for AM radio, submarine communication etc. The frequencies involved are less than 3 MHz.
  2. Upto the layer called "ionosphere" and back **(Sky wave propagation)** : Used for SW radio, amateur radio etc. The frequency range for sky wave propagation is 3 to 30 MHz.
  3. From transmitter to receiver in a straight line **(Space wave propagation)** : Space wave propagation (> 30 MHz).

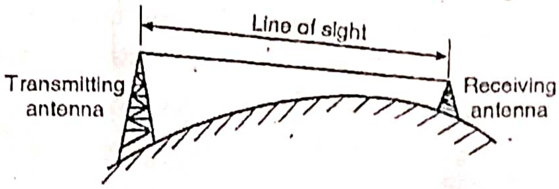



(D-718) **Fig. 1.1.4 : Relation between the type of propagation and frequency**

- Space wave propagation or **line of sight** (LOS) communication is used at frequencies above 30 MHz.
- The typical applications are TV broadcasting, mobile phones, satellite systems etc.

**Line of Sight (LOS) :**

- Line of sight in the space wave propagation is defined as the straight path between transmitting antenna and a receiving antenna, when unobstructed by the horizon as shown in Fig. 1.1.5.




(B-2976) **Fig. 1.1.5 : Concept of line of sight**

## 1.2 Mobile Radio Propagation :

- The mobile propagation takes place at frequencies that are much higher than 30 MHz.
- Therefore, it is not possible to use either ground wave propagation or sky wave propagation for mobile propagation.
- The only mode of propagation that is suitable for mobile propagation is the space wave propagation or line of sight **(LOS)** propagation.
- The mobile radio channel puts limitations on the best performance of a wireless communication system. The wired channels are stationary and predictable.
- On the other hand, mobile channels are random in their characteristics and difficult to analyze. Multiple factors such as speed of mobile station determine how rapidly the signal levels fade.
- Therefore modeling a mobile radio channel is a very difficult part of the mobile radio system design.

**Additional Signal Propagation Effects :**

- In real life we rarely have the line of sight communication, between a sender and receiver. Mobile phones are used inside tall building, or while driving a car, or on a hill etc.

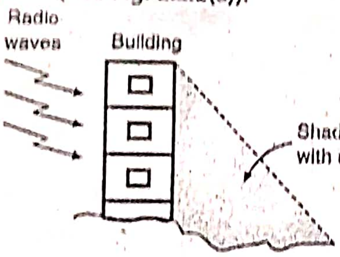
- Therefore we need to consider many more effects occurring in addition to the signal attenuation taking place only due to the path loss.
- Some of the important effects are as follows :
  1. Blocking or shadowing.
  2. Reflection.
  3. Refraction.
  4. Scattering.
  5. Diffraction.

### 1.2.1 Blocking or Shadowing :

- At very high frequencies the radio frequency signal behave like light. Hence small obstacles like walls, trees, cars etc. can block the signal.

**Definition :**

- Blocking or shadowing is defined as the extreme form of attenuation of radio signals due to large objects. (See Fig. 1.2.1(a)).




(G-2446)**Fig. 1.2.1(a) : Blocking or shadowing**

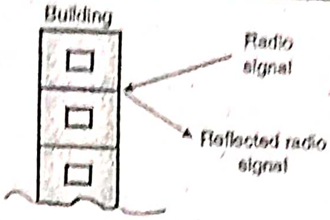
### 1.2.2 Reflection : SPPU : March 20

**University Questions**

**Q. 1** List and explain different radio propagation mechanism with suitable example.

**(In Sem. March 20, 6 Marks)**

- Another important effect is **reflection** of radio signals which takes place if the size of the obstacle (hill, building) is much larger than the wavelength of the radio signals (Fig. 1.2.1(b)).
- If a propagating radio wave hits an object the size of which is very large as compared to its wavelength then the wave gets reflected by the object.




(G-2446)**Fig. 1.2.1(b) : Reflection**

- The example of such a large object is a large building, furniture, wall, a hill etc. The phase shift between the incident and reflected wave is 180°.
- The reflected signal is not as strong as the original one because the object absorbs some energy.
- In big cities, the reflection helps signal transmission where no line of sight communication is possible.

### 1.2.3 Refraction : SPPU : March 20

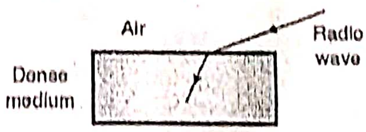
**University Questions**

**Q. 1** List and explain different radio propagation mechanism with suitable example.

**(In Sem. March 20, 6 Marks)**

**Definition :**

- It is defined as the change in direction of radio signal when it passes obliquely from a medium of lower density to the other medium of higher density. That is why radio signal bend towards earth.
- The refraction takes place when the two mediums involved have different densities. This is because the velocity of radio signals is inversely proportional to the density of medium.
- The principle of refraction is illustrated in Fig. 1.2.1(c).




(G-2447) **Fig. 1.2.1(c) : Refraction**

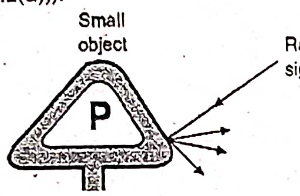
### 1.2.4 Scattering : SPPU : March 20

**University Questions**

**Q. 1** List and explain different radio propagation mechanism with suitable example.

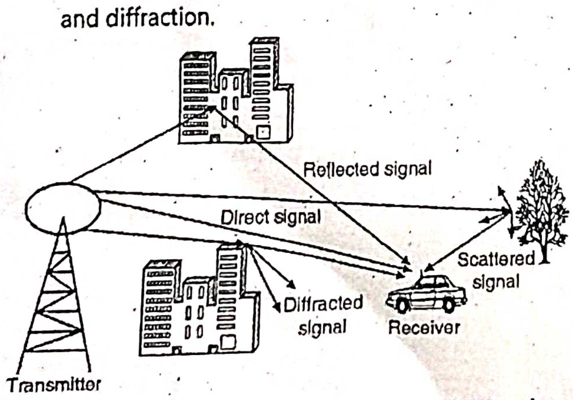
**(In Sem. March 20, 6 Marks)**

- Blocking and reflection happen when an obstacle is large in size.
- But scattering of a radio signal takes place if the object is small in size (typically equal to or smaller than the wavelength of the radio signal (See Fig. 1.2.1(d))).




(G-2447) **Fig. 1.2.1(d) : Scattering**

- The scattering of an EM wave takes place when the wave travels through a medium containing many objects which are smaller than the wavelength of the wave.
- The examples of such objects are lamp posts, street signs etc. Due to this phenomenon, the wave gets scattered in several weak outgoing signals.
- Scattering is also produced by rough surfaces, small objects, or other irregularities in the channel.
- In order to ensure a proper functioning of devices in such an environment, the radio network design must utilize the correct methods of deployment (placement and antenna selection) to minimize this effect.
- Fig. 1.2.2 illustrates the three propagation mechanisms for EM waves, reflection, refraction and diffraction.




(G-2095) **Fig. 1.2.2 : Reflection, refraction and scattering**

### 1.2.5 Diffraction :

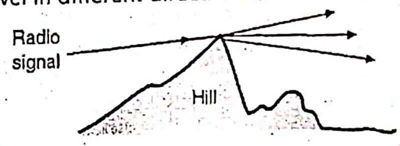
**SPPU : March 20**

**University Questions**

**Q. 1** List and explain different radio propagation mechanism with suitable example.

**(In Sem. March 20, 6 Marks)**

- Diffraction is very similar to scattering. As shown in Fig. 1.2.3, in diffraction, the radio waves get **deflected** at the edges of a large object and will travel in different directions.




(G-2448) **Fig. 1.2.3 : Diffraction**

- A propagating wave gets diffracted when it hits an object or surface which cannot be penetrated, and has sharp irregularities i.e. edges.
- Therefore it is very difficult to precisely predict the signal strength at any given point.
- At the edges of such object, the incident wave bends and starts propagating in different directions.
- This is known as diffraction. The diffracted waves are present throughout the space and even behind the obstacle.
- The diffraction of a wave takes place when the size of the object is comparable with the wavelength of the wave.
- Due to diffraction, a wave can reach places behind the object where it could not have otherwise reached.
- The amount of diffraction is dependent on the frequency of the wave being diffracted. It is more for low frequency waves.

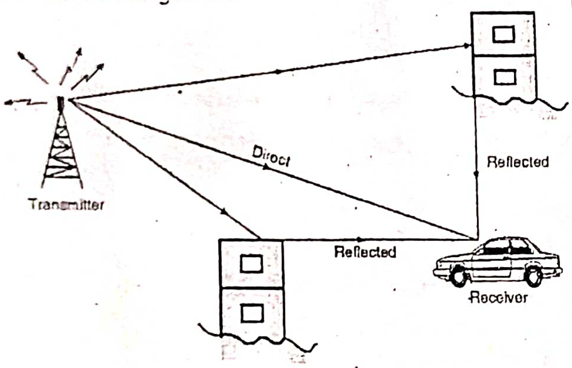
### 1.2.6 Signal Attenuation :

- The power of the signal received by a receiver is always less than the power of the signal transmitted by the transmitter.

- This reduction in the signal strength is known as **attenuation** and it is due to various factors that are discussed later on in this chapter.
- All the effects discussed so far are dependent on time and frequency and they take place simultaneously to affect the signal strength.

### 1.2.7 Multipath Propagation :

- In reality the radio signal received at the receiver is not just due to the direct signal transmitted by the transmitter, but also due to many reflected, refracted, scattered and diffracted radio signals as shown in Fig. 1.2.4.




(G-2449)**Fig. 1.2.4 : Multi-path propagation**

- This phenomenon is called as the **Multi-path Propagation.** Due to different path lengths of the direct and reflected rays they take different times to reach the receiver. This effect is called as the **Delay Spread.**
- Therefore the radio waves following different paths will undergo different phase shifts. The resultant signal strength at the receiver is equal to the vector sum of the signal strengths of all the signals.
- The typical value of **Delay Spread** in big cities is between 3 $\mu s$ and 12 $\mu s$. GSM can tolerate a delay spread upto 16 $\mu s$.

**Effect of delay spread : ISI :**

- Due to the delay spread, the shorter pulses will be **smeared out** into broader pulses and a single LOS pulse will result in multiple weaker pulses.
- Due to broadening of pulses at th... adjacent pulses will interfere with ea...
- If each pulse corresponds to a trans... then the adjacent symbols will interf... other.
- Such an interference is known as the I... Interference (ISI). We can use an equa... reducing the ISI.

### 1.2.8 Fading :

**Definition :**

- Fading is defined as the variations or flu... in the signal strength at the receiver. The... spreading and continuous movement... sender and receiver result in signal fading...
- The fading of any type, takes place du... interference between two waves whic... different paths to travel from transm... receiver.
- Thus fading takes place due to r... reception of the signal.
- Due to different path lengths, the two si... undergo different phase shifts.
- At the receiver the vector sum of them... place.
- Therefore alternate cancellation and reinf... will take place if the path difference is... as $\lambda/2$.
- Such fluctuations are therefore more... occur at lower wavelengths or higher fre...

**Types of fading :**

1. **Short term fading :**
   - The quick changes taking place in th... signal power is known as short term fadi...
   - The receiver has to continuously ada... changing signal strength.
2. **Long term fading :**
   - The variations in average received sig... over a long time is known as long term fa...

**Flat fading :**

- A received radio signal is said to have undergone flat fading if the channel bandwidth is greater than the signal bandwidth. Flat fading channels are also known as the **narrow band channels.**
- In flat fading all the frequency components in a signal fade in the same proportion simultaneously.
- Flat fading is also called as non-selective fading.

**Frequency selective fading :**

- In frequency selective fading, different frequency components in the received signal undergo unequal fading.
- If the channel bandwidth is less than the signal bandwidth then the frequency selective fading will take place.

**Coherence bandwidth :**

- Coherence bandwidth of a wireless channel is the frequency range over which its gain is constant and its phase response is linear.

**Different reasons for fading :**

1. The fading can take place due to interference between the lower and upper rays of the sky wave.
2. It can take place due to interference between waves arriving by different number of hops or paths.
3. Due to interference between the ground waves and sky waves.
4. Due to fluctuations of height or density in ionosphere layers.
5. As the fading is a frequency selective process, the signals very close to each other in the frequency domain will fade to a different extent.
6. The AM signal is very badly distorted due to such a frequency selective fading. The SSB signal is not affected to such an extent.
7. One way to counteract the problem of fading is to use space or frequency diversity reception system. The other way is to use the automatic gain control (AGC) for the receiver.

### 1.2.9 Diversity Reception :

- Diversity reception is used in order to minimize the effects of fading.
- The principle of diversity reception is based on the fact that the signal at different points on the earth or different frequency signals do not fade simultaneously.

### 1.2.10 Merits of Wireless Communication :

- There are many advantages of wireless communications, using wireless communications technology and wireless networking, as compared to wired communications and networks.
- Some of the major advantages of wireless communication include mobility, increased reliability, ease of installation, rapid disaster recovery and above all lower cost.
- Following are some of the important advantages of wireless communication over wired communication :

1. No wires are required to be used.
2. Wireless transmission has a larger coverage area than that of wired transmission.
3. Wireless media has large bandwidth.
4. It is easy install and easy to add new users to the existing network.
5. Wireless media does not need any maintenance.
6. Wireless transmission / media can be used when the number of users is huge. e.g. TV broadcasting, radio broadcasting, mobile phone network.
7. Mobility.
8. Increased reliability.
9. Rapid disaster recovery.
10. Lower cost.

### 1.2.11 Demerits of Wireless Communication :

- Along with the many advantages of wireless communications and technology, there are some disadvantages and limitations as well.
- The most important limitations are radio signal interference, security problems and health hazards.
  1. Small objects such as walls can obstruct the signal.
  2. Weather conditions such as rain, fog, moisture can increase signal attenuation and disrupt the communication.

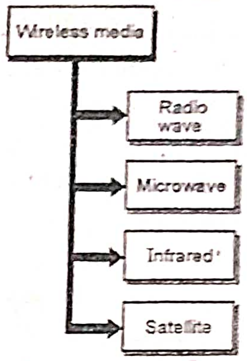
### 1.2.12 Applications of Wireless Communication :

- Some of the important applications of wireless communication are as follows :
  1. Vehicles.
  2. Emergencies.
  3. Business.
  4. Replacement of wired networks.
  5. Infotainment.
  6. Location dependent services.
  7. Mobile and wireless devices.

## 1.3 The Wireless Channel :

**Types of Wireless Channel :**

- In wireless communication mostly the earth's atmosphere is used as the physical path to carry information from sender to receiver.
- Wireless media/channel is used when it is not possible to use wired media due to distance or obstructions.
- There are four main types of wireless media/ channels :
  1. Radio wave
  2. Microwave
  3. Infrared
  4. Satellite




(G-119) Fig. 1.3.1 : Classification of wireless media

### 1.3.1 Radio Frequency Waves :

- It uses the radio frequency (RF) waves as links for transmission. This technology is more flexible, and it allows consumers to link appliances that are distributed throughout the house.
- The RF transmission is categorized as narrowband transmission or spread spectrum transmission.
- One of the examples of a narrowband technology is microwave transmissions which are high-frequency radio waves that can have a transmission range of up to 50 km.
- Thus the microwave technology cannot be used to set up local networks. But it could be used to connect local networks present in separate buildings.
- The low frequency bands of EM spectrum consists of the radio frequency (RF), microwaves, infrared and visible light portions. This portion of the spectrum can be used for **Information Transmission.**
- The higher frequency waves such as X-rays and gamma rays are not used for the information transmission.

### 1.3.2 Important Properties of RF Waves :

- On the other hand the radiofrequency (RF) waves are widely used in both indoor and outdoor communication because they possess the following properties :

1. They can propagate through the buildings.
2. They can travel long distances.
3. There is no need to physically align the transmitter and receiver as RF waves are omnidirectional.
4. Many characteristics of RF waves are dependent on their frequency.
5. The low frequency waves can pass through very easily but their power drops drastically with increased distance. Thus they cannot travel longer distances.
6. On the other hand the high frequency waves can travel longer distances but they are more prone to absorption due to raindrops or they get easily reflected by obstacles and the interference problem is grave.

### 1.3.3 Applications :

- Some of the important applications of radio transmission systems are :
  1. Cellular communication.
  2. Wireless LAN.
  3. Point to point and point to multipoint radio systems.
  4. Satellite communication.

## 1.4 Wireless Generations :

- The cellular systems are classified into different evolutionary generations from first generation (1G) to fifth generation (5G).
- The **first generation wireless networks** are based on analog technology and they are used only for analog voice services.
- The **second generation wireless systems (2G)** employ digital modulation and advanced call processing capabilities. Typical examples include Global System for Mobile (GSM), cordless telephone (CT2) etc.
- The **third generation wireless systems (3G)** are developed to provide universal access throughout the world.
- They have used broadband ISDN to provide access to information networks like internet, communications using Voice Over Internet Protocol (VoIP), voice-activated calls etc.
- The **fourth generation wireless systems (4G)** are currently under deployment but continue to evolve.
- The next generation cellular networks have been designed to support high speed data communications traffic in addition to the voice calls.
- The new technologies and standards are being implemented so that the wireless networks can replace the fiber optic or copper cables. The wireless networks are used as replacement for wires within offices, buildings, homes with the use of **Wireless Local Area Networks (WLANs).**
- The **Bluetooth** modem standard can connect several devices with invisible wireless connections within a person's personal workspace. It was conceived as a wireless alternative to RS232 cables.
- WLANs and Bluetooth use low power levels. They don't need a license for spectrum use.
- They are used for adhoc wireless communication of voice and data anywhere in the world.

### 1.4.1 First Generation : Analog Voice :

- The first generation of cellular telephony was suitable only for voice communication using analog signals. Now cellular technology is in the fourth generation.
- One of the important first generation mobile system used in North America is AMPS.
- The first generation of wireless mobile system was implemented in 1980's.
- The modulation scheme used was frequency modulation (FM).
- Long form of AMPS is Advanced Mobile Phone System. It is one of the leading analog cellular system in North America.

- It makes use of FDMA (Frequency Division Multiple Access) to separate channels in a link.

**Frequency bands :**

- AMPS uses the ISM 800-MHz band for its operation. It uses two separate channels for forward i.e. base station to mobile station and for reverse i.e. from mobile station to base station communication.
- The frequency bands allotted for the forward and reverse communication are as follows :
  1. Reverse Communication : 824 MHz to 849 MHz.
  2. Forward Communication : 869 MHz to 894 MHz.
- Each band has been divided into 832 channels. But two providers are allowed to share an area. That each provider is allowed to use 416 channels in each cell.
- Out of 416, 21 channels are used for control and the remaining 395 channels for information.

**Transmission :**

- AMPS makes use of FSK and FM systems for modulation. FM stands for frequency modulation while FSK is frequency shift keying.
- FM is used for the modulation of voice signals whereas FSK is used for the control channels.
- The coverage area of first generation systems was 2100 square km.
- The other 1G technologies developed to provide only analog voice communication were Nordic Mobile Telephone (NMT) and Total Access Communication System (TACS).
- 1G technology was developed only for providing the voice communication but **paging networks** also are considered as 1G technology.
- Pager system provides only one-way messaging.

**Features of First Generation :**

- Table 1.4.1 presents the features of first generation.

**Table 1.4.1 : Features of 1G ...**

| Sr. No. | Feature | Value |
|---|---|---|
| 1. | Generation | 1-G (197... |
| 2. | Technology | Analog ... |
| 3. | Standard | AMPS |
| 4. | Switching | Circuit sw... |
| 5. | Frequency band | 824-894 M... |
| 6. | Modulation | FM |
| 7. | Data speed | 2.4 kbps |
| 8. | Multiplexing | FDMA |
| 9. | Core network | PSTN |
| 10. | Service | Only voice ... |

**Drawbacks of 1-G Systems :**

1. Poor voice quality.
2. No security.

### 1.4.2 Second Generation : Digital V...

- The second generation of cellular te... developed in order to improve the communication.
- The second generation was designed ... voice.
- 2G networks began to emerge around ... their actual implementation started by ...
- The second generation mobile system... systems and it has the following developments :
  1. IS-54 (TDMA) in 1991.
  2. IS-95 (CDMA) in 1993.
  3. IS-136 in 1996.
  4. GSM (TDMA).
- Out of these the GSM (Global system ... communications) is by far the most co... standard. 2.5G and 2.75G are the ... versions of 2G.

**Services :**

- The 2G family of systems provides the following services :
  1. Digital voice.
  2. Web.
  3. E-mails.
  4. Browsing.

**Performance :**

- Although 2G systems provided a huge improvement over 1G and increased the number of subscribers the standards were poor.
- 2G systems were unable to handle complex data and they could not use the available bandwidth efficiently.

**Features of 2G Systems :**

- Some of the important features of the 2G-mobile systems are as follows :

**Table 1.4.2 : Features of 2G systems**

| Sr. No. | Feature | Value / Description |
|---|---|---|
| 1. | Generation | 2-G (1990) |
| 2. | Technology | Digital Cellular Technology |
| 3. | Standard | CDMA, TDMA and GSM |
| 4. | Switching | Circuit/ Packet switching |
| 5. | Frequency band | 850 - 1900 MHz (GSM) |
| 6. | Data speed | 9.6 kbps. |
| 7. | Multiplexing | CDMA, TDMA |
| 8. | Modulation | GMSK |
| 9. | Core network | PSTN |
| 10 | Services | Digital voice, data and SMS facility |
| 11 | Handoff | Horizontal |

### 1.4.3 Third Generation : Digital Voice and Data :

- The third generation of wireless mobile communication systems have been developed to meet the International Mobile Telecommunication - 2000 (IMT - 2000) specifications which are defined by International Telecommunications Union (ITU).
- The 3G systems have evolved due to the need for high speed, fast data transmission and better quality of service (QoS).
- The 3G systems were launched in 2001 and it provides the network for transporting rich **multimedia** contents.
- The 3G systems use circuit switching technology for voice calls / SMS facility, whereas they use the packet switching for the high speed data.
- The well known examples of 3G systems are :
  1. W – CDMA.
  2. CDMA – 2000.
  3. TD – SCDMA.
- 3G systems are compatible with the other cellular standards like CDMA, GSM and TDMA.
- The frequency range used by the 3G standards is 2100 MHz and it has a bandwidth of 15-20 MHz.
- 3G standards facilitate the users to use high speed internet services, as well as video chatting. The international roaming has become possible due to 3G standard.
- Universal Mobile Telecommunications System (UMTS) was adopted by Europe which uses W-CDMA as its standard.
- UMTS is based on the GSM infrastructure. Hence UMTS is the most popular 3G technology.

**Features of Third Generation :**

- Some of the important features of 3G mobile systems are as follows :

**Table 1.4.3 : Features of 3G systems**

| Sr. No. | Feature | Value / Description |
|---|---|---|
| 1. | Generation | 3G (2001) |
| 2. | Technology | Broadband/IP, FDD, TDD |
| 3. | Standards | CDMA, W-CDMA, UMTS. |
| 4. | Switching | Circuit/Packet switching |
| 5. | Frequency band | 1.6 GHz to 2.5 GHz |

| Sr. No. | Feature | Value / Description |
|---|---|---|
| 6. | Data speed | 2 Mbps |
| 7. | Multiplexing | CDMA |
| 8. | Core network | Packet network |
| 9. | Services | High speed data, voice, video |
| 10. | Handoff | Horizontal |

### 1.4.4 Fourth Generation (4G) :

- The 4G wireless systems were designed to fulfill the requirements of International Mobile Telecommunications Advanced (IMT-A) using IP (Internet Protocol) for all the services.

**Applications of 4G :**

- The 4G is developed to support the QoS and data rate requirements of the advanced applications such as :
  1. Wireless broadband access.
  2. Multimedia Messaging Service (MMS).
  3. Video chat.
  4. Mobile TV.
  5. HDTV.
  6. Digital Video Broadcasting (DVB).
  7. Voice and data.
  8. Other services which need large bandwidth.
- In 4G systems, an advanced radio interface is used with Orthogonal Frequency Division Multiplexing (OFDM), Multiple Input Multiple Output (MIMO) and the link adaptation technologies.
- 4G standards also includes **Long Term Evolution (LTE)** and IEEE 802.16 (Wi-Max).
- The 4G systems provide very high data rates as compared to 3G.
- But the major problem with 4G systems is security because of its IP address system.

**Features of 4G Systems :**

- The important features of 4G mobile systems are as follows :

**Table 1.4.4 : Features of 4G systems**

| Sr. No. | Feature | Value / Description |
|---|---|---|
| 1. | Generation | 4G (2010) |
| 2. | Technology | IP-Broadband, Wi-Fi, MIMO |
| 3. | Standard | Wi Max and LTE |
| 4. | Switching | Packet switching |
| 5. | Frequency band | 2 GHz – 8 GHz |
| 6. | Data speed | 50 Mbps |
| 7. | Multiplexing | MC-CDMA and OFDM |
| 8. | Core network | Internet |
| 9. | Service | Dynamic Information Access |
| 10. | Handoff | Vertical |

## 1.5 5G and Above Wireless Networks :

- The 4G technology has now been deployed and the research for the next generation named as 5G has already begun.
- It is considered to be the next major phase of mobile telecommunication standard after 4G.
- The 5G standard will be made commercially available by 2020.
- This standard is way beyond just the faster data speeds or faster mobile devices.
- 5G will provide an access to high and low speed data services.
- It will involve combination of existing and evolving systems.

### 1.5.1 Why 5G ?

- Fifth generation technology is useful because of the following reasons :
  1. It provides very High speed, high capacity, and low cost per bit.

2. It supports interactive multimedia, voice, video, Internet, and other broadband services, more effectively.
3. 5G technology offers Global access and service portability.
4. It can provide the high quality services due to high error tolerance.
5. 5G technology uses remote management so that user can get better and fast solution.
6. With the use of 5G technology the uploading and downloading speed will be very high.

### 1.5.2 Features of 5G :

- Following are the most important features of 5G :
1. Ubiquitous connectivity
2. It provides Speed up to 10 Gbit/s.
3. The 5G technology supports virtual private network.
4. The uploading and downloading speed of 5G technology is high.
5. 5G network is very fast and reliable.
6. Larger data volume per unit area (i.e. high system spectral efficiency).
7. High capacity to allow more devices connectivity concurrently and instantaneously.
8. Lower battery consumption.
9. It provides better connectivity irrespective of the geographic region.
10. Larger number of supporting devices.

### 1.5.3 Features of Fifth Generation :

Table 1.5.1 : Features of Fifth Generation

| Sr. No. | Feature | Value / Description |
|---|---|---|
| 1. | Generation | 5G (2020) |
| 2. | Technology | WWWW, IPv6 |
| 3. | Standard | Yet to be finalized |
| 4. | Switching | Packet |
| 5. | Frequency | 15 GHz |
| 6. | Data speed | > 1 Gbps |
| 7. | Multiplexing | MC-CDMA, LAS-CDMA, OFDM |
| 8. | Core network | Internet |
| 9. | Services | Interactive multimedia, Voice over IP, Virtual reality, Augmented reality, IOT etc. |
| 10. | Handoff | Horizontal and vertical |

### 1.5.4 Expectations in 5-G Network :

- In future, 5G will be necessary worldwide because of the increasing traffic rates of data, voice, and video streaming.
- 5G technology will have the capability to share the data everywhere, every time, by everyone.
- The 5G technology is expected to cater the following requirements :
1. 10-100 times higher data rate.
2. 10 times longer battery life for low power devices.
3. 10-100 times higher number of connected devices.
4. 5-times reduced end to end latency.
5. 1000 times higher mobile data volume per area.

### 1.5.5 Technologies of 5G :

- Major technologies included in 5G are :
1. MIMO (Multiple Input Multiple Output)
2. Ultra radio access design (RAN)
3. Flexible duplexing

### 1.5.6 Advantages of 5-G Technology :

- Following are the advantages of 5G :
1. 5G technology can gather all networks on one platform.

2. It is more effective and efficient.
3. 5G technology will provide a huge broadcasting data (in Gigabit), which will support more than 60,000 connections.
4. 5G is compatible with the previous generations.
5. It can offer uniform, uninterrupted, and consistent connectivity across the world.

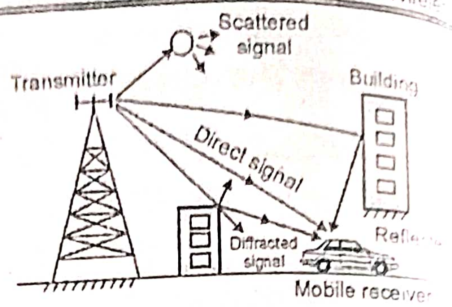
### 1.5.7 Applications of 5G :

- The 5G technology can be used in the following applications :
  1. Entertainment and multimedia
  2. Internet of Things – Connecting everything
  3. Smart Home
  4. Logistics and shipping
  5. Smart cities
  6. Smart farming
  7. Healthcare and mission critical applications
  8. Drone operation
  9. Security and surveillance

## 1.6 Multipath Fading :

**Multipath Propagation :**

- When the electromagnetic waves leave the transmission antenna, they do not only follow the direct path from transmitter to receiver.
- Instead, they undergo reflection, refraction and scattering from various objects such as tall buildings, hills etc, while travelling.
- Due to this, multiple copies of the same EM signal are produced which are small in strength and have different phase shifts as compared to the direct wave as shown in Fig. 1.6.1.
- Thus the transmitted signal gets propagated via multiple roots while travelling from transmitter to receiver. This is called as multipath propagation.

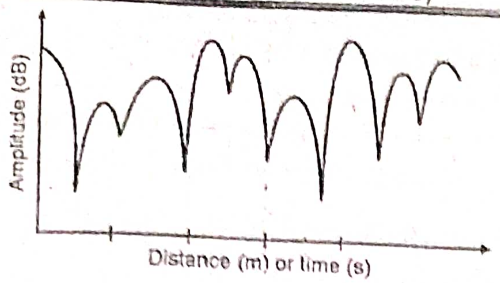



(O-903) **Fig. 1.6.1 : Concept of multipath prop...**

- The power of the signal received by a ... always less than the power of th... transmitted by the transmitter.
- This reduction in the signal strength is ... **attenuation** and it is due to various facto...
- The signal reaching a receiver follows ... paths instead of just the direct path be... transmitter and a receiver as shown in Fig...
- This is called as the multipath reception.
- It takes place when a receiver receives th... path transmitted signal along with the r... and scattered versions of the same signal.
- The reflection and scattering occur... buildings, trees, and other obstacles al... radio path.

**Multipath Fading :**

- Due to this the radio waves arrive at a receiver from many different direction... different time delays.
- Due to different path lengths, each... undergoes a different phase shift while ... the receiver.
- The net signal strength at the receiver is ... the vector sum of all these signals.
- With a moving receiver the signal streng... receiver fluctuates continuously.
- This is known as **multipath fading** as s... Fig. 1.6.2.
- The effects of multipath propagation ... reduced, by using some special pr... techniques such as equalization and ... diversity.




(G-2807) **Fig. 1.6.2 : Fading / Multipath**

## 1.7 Propagation Models for Wireless Channels :

**Need :**

- Since the received signal strength in mobile communication changes continuously and randomly, it is necessary to have a propagation model for predicting the average strength of the received signal.

**Types :**

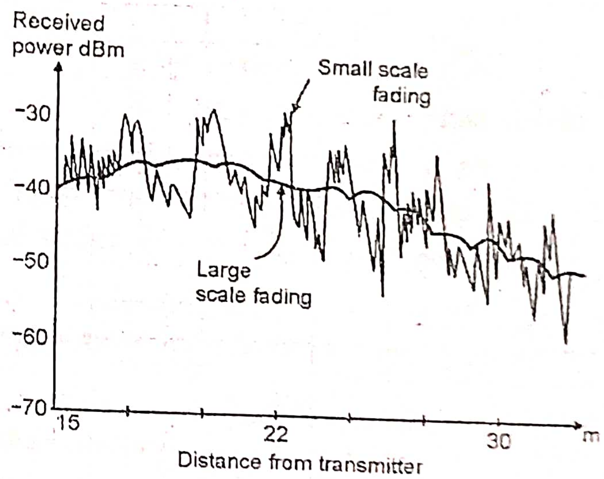
- There are two types of propagation models :
  1. Large scale models.
  2. Small scale or fading models.

**1. Large scale models :**

- The propagation models that predict the average signal strength at an arbitrary distance from the transmitter are called as large scale propagation models.
- These are useful in estimating the coverage area of the transmitter.
- They characterize the signal strength over large distances (several hundred kilometers) between a transmitter and receiver.

**2. Small scale or fading models :**

- The small scale or fading models are the models that characterize the rapid fluctuations of received signal strength over either very short distances or very short time durations.
- These models are useful for the mobile radio communications.
- A mobile station, when moves over a short distance, gives rise to the **small scale fading.**
- In the small scale fading the signal strength may vary by 30 to 40 dB when a receiver moves by a fraction of wavelength.
- We can use the small scale model to predict these signal fluctuation.
- As the MS (mobile station) moves away from the transmitter, over much larger distances, the average received signal decreases gradually.
- A large scale model can be used to predict the variations in the average strength of signal.
- Fig. 1.7.1 illustrates the small scale fading and the slower large scale variations for an indoor radio communication system.



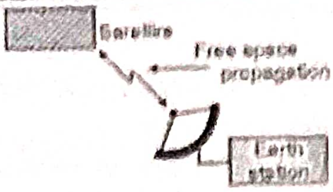

(G-2678) **Fig. 1.7.1 : Two types of fading**

**Conclusion :**

- From Fig. 1.7.1 we conclude that the signal fades quickly even with a small movement of the receiver but the average signal changes much slowly over a longer distance.
- In this chapter we will discuss the large scale propagation and different methods of predicting the received power.

## 1.8 Free Space Propagation Model :

- This model is used for predicting the received signal strength when the transmitter and receiver have a clear Line-Of-Sight (LOS) path between them as shown in Fig. 1.8.1.




(6-2632) Fig. 1.8.1 : Free space communication

- The examples of LOS communication are :
  1. Microwave communication
  2. Satellite communication

**Function of the model :**

- The function of the free-space model is to predict the received signal strength as a function of the separation (d) between the transmitter and receiver.

### 1.8.1 Friis Free Space Equation :

- The free space power received by a receiving antenna is given by **Friis frees space equation** as follows :

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

$$= \frac{P_t G_t G_r}{L} \left(\frac{\lambda}{4\pi d}\right)^2 \quad ...(1.8.1)$$

- Where,

  $P_r(d)$ = Received power,

  $P_t$ = Transmitted power

  $G_t, G_r$ = Transmitter and receiver antenna gains

  $d$ = T-R separation in m,

  $L$ = System loss factor not related to propagation

  $\lambda$ = Wavelength

- The value of L is greater than or equal to 1.
- The gain of an antenna is related to its effective area $A_e$ with the following expression,

$$G = \frac{4\pi A_e}{\lambda^2} \quad ...(1.8.2)$$

- Where $\lambda = \frac{C}{f}$ and f = Carrier frequency in Hz.
- The losses L ($L \ge 1$) are generally corresponding to the attenuation due to transmission line, filter losses, and antenna losses.
- If L = 1, there are no losses in the system.

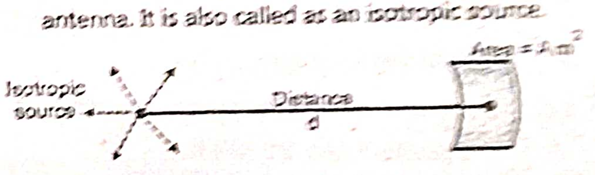
**Conclusion :**

- From the Friis equation we conclude that the received power is inversely proportional to the separation (d) between the transmitter and receiver.
- That means $P_r$ (d) decays at a rate of 20 dB / decade.

### 1.8.2 EIRP :

**Isotropic radiator :**

- If the transmitting antenna is assumed to be a point source which radiates equally in all the directions, then it is called as an **omnidirectional** antenna. It is also called as an isotropic source.




(6-2677) Fig. 1.8.2 : An isotropic source

**EIRP :**

- In practice we use a directional antenna having gain $G_t$.
- For a transmitter with output power $P_t$ driving a lossless antenna with gain $G_t$, the flux density in the direction of antenna boresight, at a distance "d" m is given by,

$$F = \frac{P_t G_t}{4\pi d^2} \text{ W/m}^2 \quad ...(1.8.3)$$

- The product $P_t G_t$ of Equation (1.8.3) is called as the **Effective Isotropically Radiated Power** or **EIRP**.
- It describes the combination of transmitter and antenna in terms of an equivalent isotropic source with power $P_t G_t$ watts radiating uniformly in all the directions.

$$\therefore \quad EIRP = P_t G_t \text{ watts} \quad ...(1.8.4)$$

- In other words, EIRP represents the maximum transmitted power in the direction of maximum antenna gain as compared to the isotropic radiator.

**ERP :**

- In practice we don't have isotropic radiators. Hence we need to use ERP (Effective Radiated Power) instead of EIRP.
- ERP denotes the maximum radiated power as compared to the half wave dipole antenna instead of an isotropic antenna.

### 1.8.3 Path Loss :

**Definition :**

- The free space path loss is defined as the loss of energy when EM wave propagates in a straight line through a vacuum with no absorption or reflection of energy.
- It takes place due to the spreading of energy associated with EM waves.
- Path loss PL represents the signal attenuation in "decibels" across the entire communication link.
- It is defined as the difference (in dB) between the transmitted signal power $P_t$ and received signal power $P_r$

$\therefore$ Path loss $PL = 10 \log_{10} [P_t / P_r]$

$$= -10 \log_{10} (G_t G_r) - 10 \log_{10} \left[\frac{\lambda}{4\pi d}\right]^2 \quad ...(1.8.5)$$

- The RHS of the above expression contains two terms.
- Their meaning is as follows :
  1. $-10 \log_{10}(G_t G_r)$ = Represents the gain
  2. $10 \log_{10} \left[\frac{\lambda}{4\pi d}\right]^2$ = Represents the free space loss.
- The free space loss increases in square proportion with the increase in distance "d".
- In order to keep this loss to a manageable value, we have to increase $\lambda$ (by reducing f) when the distance is increased.
- If the antenna gain are to be excluded, then the expression for path loss gets modified as follows :

$$P_{L\,(dB)} = -10 \log \left[\frac{\lambda^2}{(4\pi)^2 d^2}\right] \quad ...(1.8.6)$$

### 1.8.4 Validity of Friis Model :

- The Friis free space model is valid to predict the received power $P_r$ provided the value of "d" lies in the **far field** or **Fraun-hofer region,** of the transmitting antenna.

### 1.8.5 Fraun-hofer Region :

- The Fraun-hofer region of a transmitting antenna is defined as the region beyond the far field distance $d_f$.
- Where $d_f$ is given by,

$$d_f = \frac{2 D^2}{\lambda} \quad ...(1.8.7)$$

Where D = Largest physical dimension of the antenna

- The MR is said to be in the far, field region if the following conditions is satisfied.

$$d_f >> D \text{ and } d_f >> \lambda \quad ...(1.8.8)$$

### 1.8.6 Received Power in Terms of Reference Distance :

- The Friis free space expression is not true for d = 0.
- Hence we cannot use d = 0 as a reference point.
- Therefore a small distance $d_0$ is used as a received power reference point.
- Then the received power $P_r$ (d) at any distance $d > d_o$ is related to the received power $P_r$ at $d_o$.
- The reference distance $d_0$ should lie in the far-field region. That means,

$$d_o \geq d_f \quad ...(1.8.9)$$

- Then the received power at distance d which is greater than $d_o$ is given by,

$$P_r(d) = P_r(d_o)\left(\frac{d_o}{d}\right)^2 \quad ...d \geq d_o \geq d_f \quad ...(1.8.10)$$

- In mobile radio systems, it is very common that $P_r$ may fluctuate to a great extent over a typical area of many square kilometers.
- Due to large amount of signal strength fluctuations, the received power levels are expressed in dBm or dBW units.
- If we use the unit dBm to express the received power then Equation (1.8.10) gets modified as follows :

$$P_r(d)\ \text{dBm} = 10 \log\left[\frac{P_r(d_o)}{0.001\ W}\right] + 20 \log\left[\frac{d_o}{d}\right]$$

$$...d \geq d_o \geq d_f \quad ...(1.8.11)$$

- Where, $P_r(d_o)$ is expressed in Watts.

**Typical values of $d_o$ :**

- For the practical systems with low gain antennas operating in the 1-2 GHz frequency range, the typical the values of the reference distance $d_o$ are as follows :

| Sr. No. | Type of environment | Value of $d_o$ |
|---|---|---|
| 1. | Indoor | 1 m |
| 2. | Outdoor | 100 m to 1 km |

**Ex. 1.8.1 :** For a transmitting antenna with an operating frequency of 1 GHz and maximum dimension of 1 m, find the value of far-field distance.

**Soln. :**

**Given :** D = 1 m, f = 1 GHz.

**To find :** $d_f$

- We know that the far-field distance is given by,

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

- But $\lambda = \frac{C}{f}$

$$\therefore d_f = \frac{2D^2}{(C/f)} = \frac{2fD^2}{C}$$

$$\therefore d_f = \frac{2 \times 1 \times 10^9 \times (1)^2}{3 \times 10^8}$$

$$\therefore d_f = 6.67\ m$$ ...**Ans.**

**Ex. 1.8.2 :** Express the output power of 50 W of a ... in terms of dBm and dBW.

**Soln. :**

**Given :** $P_t$ = 50 W

**To find :** $P_t$ in dBm and dBW

1. **$P_t$ in dBm :**

- dBm is the decibel unit with respect to a ... level of 1 mW.

$$\therefore P_t(\text{dBm}) = 10 \log_{10}[P_t / 1\ \text{mW}]$$

$$= 10 \log_{10}\left[\frac{50 \times 10^3}{1}\right]$$

$$= 47\ \text{dBm}$$

2. **$P_t$ in dBW :**

- dBW is the decibel unit with respect to a ... power level of 1 W.

$$\therefore P_t(\text{dBW}) = 10 \log_{10}[P_t / 1\ W]$$

$$= 10 \log_{10}[50/1] = 17\ \text{dBW}$$

**Ex. 1.8.3 :** If the output power of 50 W is app... transmitting antenna of unity gain and carrier freq... 1 GHz, calculate the received power in dB m ... gain receiving antenna that is at a free space d... 90 m from the transmitter. Also find the valu... (10 km).

**Soln. :**

**Given :** $P_t$ = 50 W, $f_C$ = 1 GHz, $G_t = G_r = 1$, $d_1$ = ...

$d_2$ = 10 km, Assume L = 1

**To find :** $P_r$ (90 m) in dBm and $P_r$ (10 km)

1. **Find $P_r$ (90 m) :**

$$P_r(90\ m) = \frac{P_t G_t G_r \lambda^2}{(4\pi)^2 d^2 L}$$

$$\text{But } \lambda = \frac{C}{f_C} = \frac{3 \times 10^8}{1 \times 10^9} = 0.3\ m$$

$$\therefore P_r(90\ m) = \frac{50 \times 1 \times 1 \times (0.3)^2}{(4\pi)^2 \times (90)^2 \times 1}$$

$$= 3.518 \times 10^{-3}\ \text{mW}$$

$$\therefore P_r(90\ m)(\text{dBm}) = 10 \log_{10}\left[\frac{3.518 \times 10^{-3}}{1}\right]$$

$$= -24.54\ \text{dBm}$$

2. **Find $P_r$ (10 km) :**

- We know that

$$P_r(d)\ dBm = 10 \log_{10}\left[\frac{P_r(d_o)}{1\ mW}\right] + 20 \log_{10}\left[\frac{d_o}{d}\right]$$

- Here we will substitute d = 10 km and do = 90 m

$$P_r(10\ km)(dBm) = P_r(90\ m)(dBm) + 20 \log_{10}\left(\frac{90}{10 \times 10^3}\right) = -24.54 - 40.92$$

$$P_r(10\ km)(dBm) = -65.46\ dBm \quad ...\textbf{Ans.}$$

**Ex. 1.8.4 :** The received power at a distance of 100 km is 5 nW for a communication link. Determine the received power at a distance 200 km for the same link. Assume free space propagation mechanism.

**Soln. :**

**Given :** $P_{r1} = 5$ nW, $d_1 = 100$ km, Assume L = 1.

**To Find :** Received power $P_{r2}$ at a distance $d_2 = 200$ km

- The received power at 100 km is given by,

$$P_{r1} = \frac{P_t G_t G_r \lambda^2}{(4\pi)^2 d_1^2 L} = \frac{P_t G_t G_r \lambda^2}{(4\pi)^2 d_1^2}$$

$$5 \times 10^{-9} \times 10^{10} = \frac{P_t G_t G_r \lambda^2}{(4\pi)^2}$$

$$\frac{P_t G_t G_r \lambda^2}{(4\pi)^2} = 50 \quad ....(1)$$

**Received power $P_{r2}$ :**

- The received power at 200 km is given by,

$$\therefore P_{r2} = \frac{P_t G_t G_r \lambda^2}{(4\pi)^2 d_2^2} = 50 / (200 \times 10^5)^2$$

$$P_{r2} = 1.25 \times 10^{-13}\ W \quad ...\textbf{Ans.}$$

**Ex. 1.8.5 :** If a transmitter produces 50 W of power, express the transmit power in units of (i) dBm and (ii) dBW. If 50 W is applied to a unity gain antenna with a 900 MHz carrier frequency, find the received power in dBm at a free space distance of 100 m from the antenna. What is $P_r$(10 km) ? Assume unity gain for the receiver antenna.

**Soln. :**

**Given :** $P_t = 50$ W, $f_C = 900$ MHz, $G_t = G_r = 1$,

$d_1 = 100$ m, $d_2 = 10$ km, Assume L = 1

**To Find :**

1. $P_t$ in dBm
2. $P_t$ in dBW
3. $P_r$ (100 m)
4. $P_r$ (10 km)

- Refer Ex. 1.8.2 for Pt in dBm and Pt in dBW.

**Find $P_r$ (100 m) :**

- The received power at 100 km is given by,

$$P_r(100\ m) = \frac{P_t G_t G_r \lambda^2}{(4\pi)^2 d^2 L}$$

$$\text{But } \lambda = \frac{C}{f_C} = \frac{3 \times 10^8}{900 \times 10^6} = 0.33\ m$$

$$\therefore P_r(100\ m) = \frac{50 \times 1 \times 1 \times (0.33)^2}{(4\pi)^2 \times (100)^2 \times 1}$$

$$= 3.5 \times 10^{-3}\ mW \quad ...\textbf{Ans.}$$

$$\therefore P_r(100\ m)(dBm) = 10 \log_{10}\left[\frac{3.5 \times 10^{-3}}{1}\right]$$

$$= -24.5\ dBm \quad ...\textbf{Ans.}$$

**Find $P_r$ (10 km) :**

- We know that

$$P_r(d)\ dBm = 10 \log_{10}\left[\frac{P_r(d_o)}{1\ mW}\right] + 20 \log_{10}\left[\frac{d_o}{d}\right]$$

- Here we will substitute d = 10 km and $d_o$ = 100 m.

$$\therefore P_r(10\ km)(dBm) = P_r(100\ m)(dBm) + 20 \log_{10}\left(\frac{100}{10 \times 10^3}\right)$$

$$= -24.5 - 40$$

$$\therefore P_r(10\ km)(dBm) = -64.5\ dBm \quad ...\textbf{Ans.}$$

**Ex. 1.8.6 :** Assume a receiver is located 10 km from a 50 W transmitter. The carrier frequency is 6 GHz and free space propagation is assumed, $G_t = 1$ and $G_r = 1$. Find the power at the receiver in dBm.

**Soln. :**

**Given :** $P_t = 50$ W, $f_C = 6$ GHz, $G_t = G_r = 1$,

Assume L = 1

**To Find :** $P_r$ (10 km) in dBm

**Find $P_r$ (10 km) :**

- The received power at 10 km is given by,

$$P_r(10\ km) = \frac{P_t G_t G_r \lambda^2}{(4\pi)^2 d^2 L}$$

$$\text{But } \lambda = \frac{C}{f_C} = \frac{3 \times 10^8}{6 \times 10^9} = 0.05\ m$$

$$\therefore P_r(10\ km) = \frac{50 \times 1 \times 1 \times (0.05)^2}{(4\pi)^2 \times (10000)^2 \times 1}$$

$$\therefore P_r(10\ km) = 8 \times 10^{-12}\ W \quad ...\textbf{Ans.}$$

**Conversion to dBm :**

$$\therefore P_r (10\text{ km}) (\text{dBm}) = 10 \log_{10} [P_r / 1\text{ mW}]$$

$$\therefore P_r (10\text{ km}) (\text{dBm}) = 10 \log_{10}\left[\frac{8 \times 10^{-12}}{1 \times 10^{-3}}\right]$$

$$\therefore P_r (10\text{ km}) (\text{dBm}) = -81\text{ dBm} \quad \text{...Ans.}$$

**Ex. 1.8.7 :** A unit gain antenna with a maximum dimension of 1 m produces 50 W power at 900 MHz. Find (i) the transmit power in dBm and dBW, (ii) the received power at a free space distance of 5 m and 100 m using free space distance formula.

**Soln. :**

**Given :** $P_t = 50$ W, $f_C = 900$ MHz,

$G_t = G_r = 1$,

$d_1 = 5$ m, $d_2 = 100$ m,

Assume L = 1

**To Find :**

1. $P_t$ in dBm
2. $P_t$ in dBW
3. $P_r$ (5 m)
4. $P_r$ (100 m)

– Refer Ex. 1.8.5 for the transmit power in dBm and dBW and the received Power at a free space distance of 100 m.

**Find $P_r$ (5 m) :**

– Received Power at a free space distance of 5 m is given by,

$$P_r (5\text{ m}) = \frac{P_t G_t G_r \lambda^2}{(4\pi)^2 d^2 L}$$

$$\text{But } \lambda = \frac{C}{f_C} = \frac{3 \times 10^8}{900 \times 10^6}$$

$$= 0.33\text{ m}$$

$$\therefore P_r (5\text{ m}) = \frac{50 \times 1 \times 1 \times (0.33)^2}{(4\pi)^2 \times (5)^2 \times 1}$$

$$= 1.38\text{ mW} \quad \text{...Ans.}$$

$$\therefore P_r (5\text{ m}) (\text{dBm}) = 10 \log_{10}\left[\frac{1.38 \times 10^{-3}}{1 \times 10^{-3}}\right]$$

$$= 1.4\text{ dBm} \quad \text{...Ans.}$$

**Ex. 1.8.8 :** Assume a receiver located10 km from a 50 W transmitter The carrier frequency is 1900 MHz. Free space propagation is assumed.

$G_t = 1$ and $G_r = 2$.

Find :

1. The power at the receiver.
2. The magnitude of E field at the receiver antenna.
3. The rms voltage applied to the receiver input assuming that the receiver antenna has a purely real impedance of 50 Ω and is matched to the receiver.

**Soln. :**

**Given :** $P_t = 50$ W, $f_C = 1900$ MHz, $G_t = 1$, $G_r = 2$,

d = 10 km

**To Find :**

1. The power at the receiver.
2. The magnitude of E field at the receiver antenna.
3. The rms voltage applied to the receiver input.

**1. The power at the receiver :**

– The power received at the receiver is given by,

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

$$\text{But } \lambda = \frac{C}{f_C} = \frac{3 \times 10^8}{1900 \times 10^6} = 0.\text{ m}$$

$$\therefore P_r (d) = \frac{50 \times 1 \times 2 \times (0.157)^2}{(4\pi)^2 \times (10000)^2 \times 1}$$

$$= 1.56 \times 10^{-10}\text{ W} \quad \text{...Ans.}$$

$$\therefore P_r (\text{dBm}) = 10 \log_{10}\left[\frac{1.56 \times 10^{-10}}{1 \times 10^{-3}}\right]$$

$$= -68.06\text{ dBm} \quad \text{...Ans.}$$

**2. The magnitude of E field at the receiver antenna :**

– For a receiving antenna, the effective area is given by,

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

– And the received power in terms of the effective area and the magnitude of E field is given by,

$$P_r (d) = \frac{|E^2|}{120\,\pi} A_e$$

$$\therefore |E| = \sqrt{\frac{P_r (d) \times 120\,\pi}{G_r \lambda^2 / 4\pi}}$$

$$= \sqrt{\frac{1.56 \times 10^{-11} \times 120\pi}{2 \times (0.157)^2 / 4\pi}}$$

$$= \sqrt{\frac{1.56 \times 10^{-11} \times 120 \times \pi}{3.92 \times 10^{-3}}}$$

$$\therefore |E| = 3.872 \times 10^{-3} \text{ V/m} \qquad \text{...Ans.}$$

3. **Rms voltage at receiver input :**

- With antenna impedance of 50 Ω and matched to receiver, the rms voltage at the receiver input is ;

$$V_{rms} = \frac{(P_r(d) \cdot 50)^{1/2}}{2} = \frac{(1.56 \times 10^{-11} \cdot 50)^{1/2}}{2}$$

$$\therefore V_{rms} = 8.83 \times 10^{-5} \text{ V} \qquad \text{...Ans.}$$

---

**Ex. 1.8.9 :** Calculate the change in received signal power in a free-space propagation environment at two different points such that the distance of the second point is ten times the distance of the first point. Express your answer in dB.

**Soln. :**

**Given :** $d_2 = 10\, d_1$

**To Find :** change in received signal power

- The power received at a distance $d_1$ is given by,

$$P_{r1} = \frac{P_t G_t G_r \lambda^2}{(4\pi)^2 d_1^2 L} = \frac{k}{d_1^2} \qquad \text{...(1)}$$

- The power received at a distance $d_2$ is given by,

$$P_{r2} = \frac{P_t G_t G_r \lambda^2}{(4\pi)^2 d_2^2 L} = \frac{k}{d_2^2} \qquad \text{...(2)}$$

- But $d_2 = 10\, d_1$. Substituting this into Equation (2) we get,

$$P_{r2} = \frac{k}{100\, d_1^2}$$

$$\therefore P_{r2} = (k / d_1^2) / 100 \qquad \text{...(3)}$$

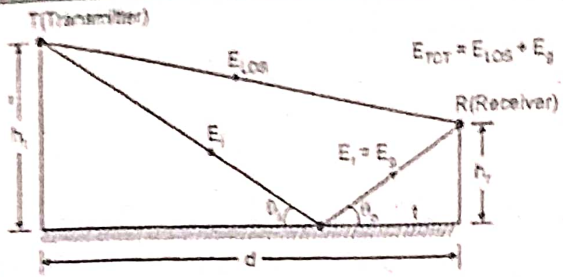
- Substituting Equation (1) into Equation (3) we get,

$$P_{r2} = \frac{(P_{r1})}{100} \qquad \text{...(4)}$$

- Thus with 10 fold increase in the distance, the received power reduces by 100 times.

## 1.9 Ground Reflection (Two Ray) Model :

- The two ray model is also called as ground reflection model or two ray ground reflection model and it is as shown in Fig. 1.9.1.




(6-2524) **Fig. 1.9.1 : Two ray ground reflection model**

- It considers the direct path as well as ground reflected path between the transmitter and receiver.
- This model gives accurate results in predicting large scale signal strength over long distances.

**Assumptions :**

1. The earth's surface is flat, and the maximum distance **d** between the transmitter and receiver (T – R) is only a few tens of km.
2. The total E-field at the receiver $E_{TOT}$ is vector sum of direct line-of-sight component $E_{LOS}$ and the ground reflected component $E_g$.
3. Let $h_t$ be the height of the transmitter and $h_r$ be the height of the receiver.

**Expression for total received E-field :**

- If the free space E-field is $E_0$ (V/m) at a distance $d_0$ from the transmitter then for $d > d_0$, the E-field is given by,

$$E(d, t) = \frac{E_0 d_0}{d} \cos\left(\omega_c \left(t - \frac{d}{c}\right)\right) \text{......} (d > d_0) \qquad \text{...(1.9.1)}$$

Where, $|E(d, t)| = \dfrac{E_0 d_0}{d}$ represents the envelop of E- field at a distance d from the transmitter.

- The direct wave travels a distance d′ and reflected wave that travels at a distance d″ before reaching the receiver.
- The E-field produced by the direct component at the receiver is given by,

$$E_{LOS}(d', t) = \frac{E_0 d_0}{d'} \cos\left(\omega_c \left(t - \frac{d'}{c}\right)\right) \qquad \text{...(1.9.2)}$$

- And the E-field produced by the ground reflected wave is given by,

$$E_g(d'',t) = \frac{\tau E_0 d_0}{d''} \cos\left(\omega_c\left(t - \frac{d''}{c}\right)\right) \quad ...(1.9.3)$$

- The laws of reflection in dielectrics states that,

$$\theta_i = \theta_0 \quad ...(1.9.4)$$

$$\text{and } E_g = \tau E_i \quad ...(1.9.5)$$

$$E_t = (1 + \tau) E_i \quad ...(1.9.6)$$

- Where $\tau$ is the reflection coefficient for ground.
- Assume that the E-field polarization is perfectly horizontal and a perfect ground reflection ($\tau_1 = -1$, $E_t = 0$), to obtain the total E- field $E_{TOT}(d, t)$ at the receiver as follows,

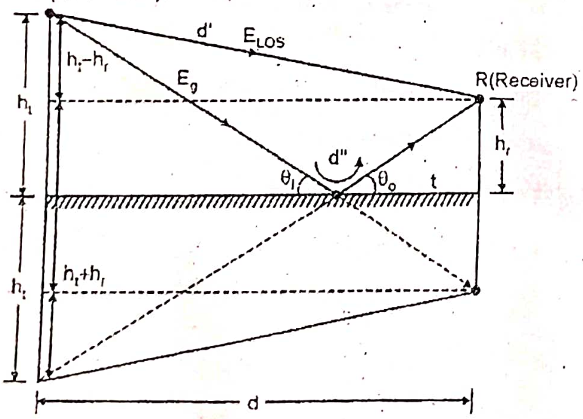
$$|E_{TOT}| = |E_{LOS} + E_g| \quad ...(1.9.7)$$

- Substituting values of $E_{LOS}$ and $E_g$ from Equations (1.9.2) and (1.9.3) we get,

$$E_{TOT}(d, t) = \frac{E_0 d_0}{d'} \cos\left(\omega_c\left(t - \frac{d'}{c}\right)\right) + (-1)\frac{E_0 d_0}{d''} \cos\left(\omega_c\left(t - \frac{d''}{c}\right)\right) \quad ...(1.9.8)$$

- The geometry of Fig. 1.9.2 shows the use of **method of images** to find out the path difference $\Delta$ between the direct and the ground reflected paths as follows :
- The path difference $\Delta$ is,

$$\Delta = d'' - d' = \sqrt{(h_t + h_r)^2 + d^2} - \sqrt{(h_t - h_r)^2 + d^2} \quad ...(1.9.9)$$




**(G-2813) Fig. 1.9.2 : Method of images to find the path difference between the line-of sight and ground reflected paths**

- If $d >> (h_t + h_r)$ then we can simplify the above expression using Taylor series approximation to get,

$$\Delta = d'' - d' = \frac{2h_t h_r}{d}$$

- Also the phase difference $\theta_\Delta$ be... E-field components is given by,

$$\theta_\Delta = \frac{2\pi\Delta}{\lambda} = \frac{\Delta\omega_c}{c}$$

- And the time delay $\tau_d$ between the ... two components is given by,

$$\tau_d = \frac{\Delta}{c} = \frac{\theta_\Delta}{2\pi f_c}$$

- For large values of distance d, the ... between the direct path distance d' ... reflected path d'' becomes very small.
- Therefore the amplitudes of $E_{LOS}$ ... virtually identical but there will be ... difference between them. That means,

$$\left|\frac{E_0 d_0}{d}\right| \approx \left|\frac{E_0 d_0}{d'}\right| \approx \left|\frac{E_0 d_0}{d''}\right|$$

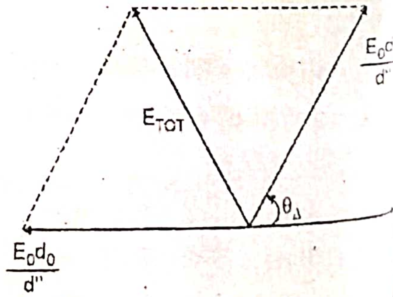
- The value of received electric field at tim... can be evaluated as,

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

$$E_{TOT}\left(d, t = \frac{d''}{c}\right) = \frac{E_0 d_0}{d'} \angle\theta_\Delta - \frac{E_0 d_0}{d''}$$

$$E_{TOT}\left(d, t = \frac{d''}{c}\right) \approx \frac{E_0 d_0}{d} [\angle\theta_\Delta - 1]$$

- Fig. 1.9.3 shows the phasor diagram th... how to combine the electric field comp... line-of-sight, ground reflected waves ... total received E-field.




**(G-2825) Fig. 1.9.3 : Phasor diagram**

- The electric field (at the receiver) at a distance d from the transmitter is,

$$|E_{TOT}(d)| = \sqrt{\left(\frac{E_0 d_0}{d}\right)^2 (\cos\theta_\Delta - 1)^2 + \left(\frac{E_0 d_0}{d}\right)^2 \sin^2\theta_\Delta} \quad ...(1.9.15)$$

$$|E_{TOT}(d)| = \frac{E_0 d_0}{d}\sqrt{2 - 2\cos\theta_\Delta} \quad ...(1.9.16)$$

- Solving using trigonometric identities we get,

$$|E_{TOT}(d)| = \frac{2 E_0 d_0}{d} \sin\left(\frac{\theta_\Delta}{2}\right) \quad ...(1.9.17)$$

- This is the exact expression for the total received E-field for the two ray ground reflection model.

**Approximate expression for $E_{TOT}$ (d) :**

- For the sufficiently large values of distance d, the phase difference $\theta_\Delta$ will be $\leq \pi$ and the E field received $E_{TOT}$ (d) will decrease asymptotically with increase in the distance.
- We can simplify Equation (1.9.17) when $\sin\left(\frac{\theta_\Delta}{2}\right) \approx \frac{\theta_\Delta}{2}$, which happens when $\frac{\theta_\Delta}{2} < 0.3$ radians.
- Use Equations (1.9.10) and (1.9.11) to write,

$$\frac{\theta_\Delta}{2} \approx \frac{2\pi h_t h_r}{\lambda d} < 0.3 \text{ rad} \quad ...(1.9.18)$$

- This implies that, Equation (1.9.17) will get simplified if,

$$d > \frac{20\pi h_t h_r}{3\lambda} \approx \frac{20 h_t h_r}{\lambda} \quad ...(1.9.19)$$

- Thus, if the value of d is such that it satisfies Equation (1.9.19), we can approximate the received E-Field as,

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

Where k : constant ...(1.9.20)

**Received power :**

- The expression for the received power at a distance d from the transmitter for a two ray ground reflection model is given by,

$$P_r = P_t G_t G_r \frac{h_t^2 h_r^2}{d^4} \quad ...(1.9.21)$$

**Conclusion :**

- We conclude from Equation (1.9.21), that at large distances $d >> \sqrt{h_t h_r}$, the received power is inversely proportional to $d^4$ and reduced at a rate of 40 dB/decade.
- This path loss is much more rapid than path loss in free space.
- For large values of d, the received power and path loss are independent of frequency.

**Path loss for two ray model :**

- The pass loss for two ray model is given by,

$$PL(dB) = 40 \log d - (10 \log G_t + 10 \log G_r + 20 \log h_t + 20 \log h_r) \quad ...(1.9.22)$$

### 1.9.1 Advantages of Two Ray Model :

- The major advantages of the two ray model are as given below :
  1. It is a useful propagation model, because it considers both the direct path and the ground reflected propagation path between the transmitter and receiver to calculate the path loss.
  2. It can predict the large scale signal strength for large values of d in the mobile systems and for the LOS microwave channels.

### 1.9.2 Disadvantage of Two Ray Model :

- The major disadvantage of the two ray model is given below :
  1. This is an oversimplified model and errors are introduced due to the fact that the effects of factors like buildings, terrain profile etc. are not considered while calculating the signal strength.

**Ex. 1.9.1 :** In the following cases, tell whether the two-ray model could be applied, and explain why or why not :

Case 1 : $h_t$ = 35 m, $h_r$ = 3 m, d = 250 m.

Case 2 : $h_t$ = 30 m, $h_r$ = 1.5 m, d = 450 m.

**Soln. :**

- We can apply the two ray model only if the following condition is satisfied.

$$d > 10\,(h_t + h_r)$$

**Case-1 :**

$$h_t = 35 \text{ m}, h_r = 3 \text{ m}, d = 250 \text{ m}.$$

Here, $10\,(h_t + h_r) = 10\,(35 + 3) = 380$ m.

- Thus the condition is not satisfied. Hence, we cannot apply the two ray model.

**Case-2 :**

$$h_t = 30 \text{ m}, h_r = 1.5 \text{ m}, d = 450 \text{ m}.$$

Here, $10\,(h_t + h_r) = 10\,(30 + 1.5) = 315$ m.

- Thus, the condition is satisfied. Hence, we can apply the two ray model.

**Ex. 1.9.2 :** In a cellular radio system, a mobile receiver is located 5 Km from the base station. It uses an antenna with gain 2.55 dB. The electric field at 1 Km from the transmitter is $10^{-3}$ V/m. If carrier frequency is 900 MHz, then find the electric field at the mobile receiver using the 2 ray ground reflection model. The heights of the transmitting antenna and receiving antenna are 50 m and 1.5 m respectively.

**Soln. :**

**Given :** $d = 5$ Km, $E_0\,(1 \text{ Km}) = 10^{-3}$ V/m, $f = 900$ MHz.

$d_0 = 1$ Km, $h_t = 50$ m, $h_r = 1.5$ m

**To find :** The electric field at the mobile.

**Step 1 : Find the wavelength :**

$$\lambda = \frac{c}{f} = \frac{3 \times 10^8}{900 \times 10^6} = \frac{1}{3} \text{ m}$$

**Step 2 : Find the electric field at the mobile :**

Since, $d >> \sqrt{h_t h_r}$, the electric field is given by,

$$E_R(d) \approx \frac{2E_0\, d_0}{d} \cdot \frac{2\pi h_t\, h_r}{\lambda d}$$

$$\therefore E_R(d) \approx \frac{2 \times 10^{-3} \times 1 \times 10^3}{5 \times 10^3} \times \frac{2\pi \times 50 \times 1.5}{\frac{1}{3} \times 5 \times 10^3}$$

$$E_R(d) = 113.098 \times 10^{-6} \text{ V/m.} \qquad \text{...Ans.}$$

**Ex. 1.9.3 :** In a two-ray ground reflection model, the phase difference is required to be kept below 6.261 radians. The receiver antenna height is 2 m, carrier frequency as 900 MHz and the angel of incidence must be less than 5°. Find the minimum transmitter-receiver separation distance and the height of the transmitter antenna.

**Soln. :**

**Given :** $h_r = 2$ m, $\theta_\Delta = 6.261$, $\theta_i < 5°$. $f = 900$ MHz

Assume $d >> h_t + h_r$

**To find :** $d_{min}$ and $h_{t\,(min)}$

**Step 1 : Find $h_{t\,(min)}$ :**

- The wavelength is given by,

$$\lambda = \frac{c}{f} = \frac{3 \times 10^8}{900 \times 10^6} = 0.333 \text{ m}$$

- We know that,

$$\theta_\Delta = \frac{2\pi}{\lambda} \cdot \frac{2h_t\, h_r}{d} = \frac{4\pi}{\lambda} \cdot \frac{h_t h_r}{d} \qquad \text{...(1)}$$

$$\tan \theta_I = \frac{h_t + h_r}{d} < \tan 5 \qquad \text{...(2)}$$

- Substituting for d we get,

$$\frac{h_t + h_r}{\frac{4\pi}{\lambda} \frac{h_t \cdot h_r}{\theta_\Delta}} < \tan 5$$

$$\therefore \frac{h_t\left(1 + \frac{h_r}{h_t}\right)}{h_t \cdot \frac{4\pi}{\lambda} \cdot \frac{h_r}{\theta_\Delta}} < \tan 5$$

$$\therefore \frac{1 + \frac{h_r}{h_t}}{\frac{4\pi}{\lambda} \cdot \frac{h_r}{\theta_\Delta}} < \tan 5$$

- Substituting the values we get,

$$\frac{1 + \frac{2}{h_t}}{\frac{4\pi}{0.33} \times \frac{2}{6.261}} < \tan 5$$

$$\frac{1 + \frac{2}{h_t}}{12.03} < 0.0874$$

$$\therefore 1 + \frac{2}{h_t} < 1.05368$$

$$\therefore \frac{2}{h_t} < 0.05368$$

$\therefore h_{t\,(min)} = 37.26$ m ...**Ans.**

**Step 2 : Find $d_{min}$ :**

- Consider Equation (2) and substitute the values to get,

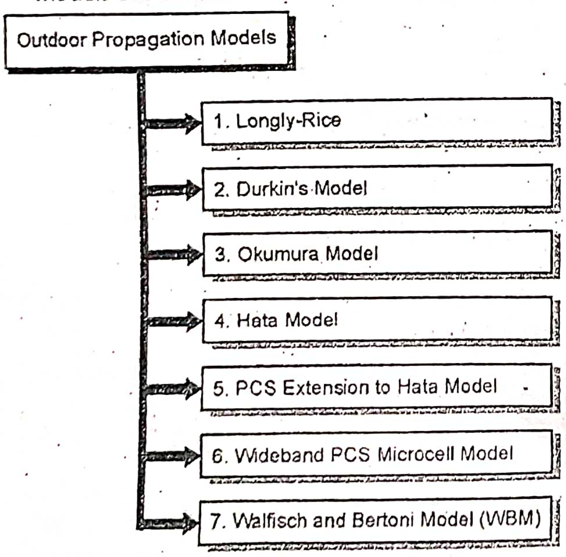
$$\frac{37.26 + 2}{d} < 0.0874$$

$$\therefore d > \frac{39.26}{0.0874}$$

$\therefore$ dmin = 449.2 m ...**Ans.**

## 1.10 Outdoor Propagation Models :

- The transmission of radio waves in mobile communication generally takes place over irregular terrain.
- Hence we need to take in to consideration the terrain profile of a particular area to calculate the path loss.
- The outdoor terrain profile can vary to a great extent. Therefore a number of outdoor propagation models have been developed to predict path loss over irregular terrain.
- The aim of all these models is to predict signal strength at a particular receiving point or in a specific local area (called a sector).
- However they use different methods that vary widely in their approach, complexity and accuracy to achieve their goal.
- Some of the commonly used outdoor propagation models are as follows :




(G-2830) **Fig. 1.10.1 : Outdoor propagation models**

- Radio propagation models are empirical in nature, that is, they are developed based on large collections of measured data for the specific wireless communication environment.
- It is necessary to have sufficiently large collection of data to provide enough likeliness to all kinds of situations that can happen in that specific environment.

### 1.10.1 Okumura Propagation Model :

- The Okumura propagation model is suitable for large cell coverage with distances up to 100 km in urban areas, and it can extrapolate predictions up to 3 GHz.
- We can use this model for effective base-station antenna heights in the range from 30 m to 1000 m, whereas the effective mobile receiver antenna height is taken as 3 m.
- The Okumura propagation model is very accurate in its predictions and is used by computer simulation tools.
- A simplified version of the Okumura path loss model, for propagation in an urban mobile environment, is expressed as follows :

$$L_{PO}\,(dB) = L_f\,(dB) + \alpha_m\,(f_c, r) - \alpha_t - \alpha_r - \Sigma\,\alpha_c \quad ...(1.10.1)$$

- where $L_f$ is the free-space propagation path loss expressed in dB
- $\alpha_m$ represents the median attenuation relative to free space, and is a function of $f_c$ and r.
- $\alpha_t$ is the effective base station antenna height ($h_t$) gain factor, which varies at a rate of 20 dB/decade, and expressed mathematically as follows :

$$\alpha_t = 20 \log (0.005 \times h_t) \quad ...(1.10.2)$$

- Note that the above expression is valid for the range 1000 m $> h_t >$ 30 m.
- Next, $\alpha_r$ is the effective mobile receiver antenna height ($h_r$) gain factor, which varies at a rate of 10 dB/decade for heights less than 3 m, and it is mathematically expressed as follows :

$$\alpha_r = 20 \log (0.33 \times h_r) \text{ for } 10\text{ m} > h_r > 3\text{ m} \quad ...(1.10.3)$$

And $$\alpha_r = 10 \log (0.33 \times h_r) \text{ for } h_r \le 3\text{ m} \quad ...(1.10.4)$$

- $\alpha_c$ is the correction factor gain which depends on the type of environment (suburban area, open area), water surfaces, isolated, obstacle, etc.
- The Okumura model prepared based on the data collected in different terrains with specified system parameters.
- The standard deviation between the measured path loss and predicted path loss using this model is about 10-14 dB.
- This model is ideally suitable for use in cities with many urban structures but not many tall building structures.
- The Hata propagation model is base on the Okumara model.

**Features of Okumura model :**

- Some of the important features of this model are as follows :
  1. It is suitable for large cell coverage up to 100 km.
  2. It is suitable for urban areas
  3. This model can be used for effective base-station antenna heights from 30 m to 1000 m, and effective mobile receiver antenna height of 3 m.
  4. The standard deviation for this model is 10-14 dB.
  5. The Okumura propagation model is very accurate.

**Ex. 1.10.1 :** Find median path loss using Okumura's model for d = 50 km $h_{te}$ = 100 m, $h_{re}$ = 10 m. If EIRP from base station is 1kW at 900 MHz, find received power. Take $A_{mu}$(900 Mhz (50 km)) = 43 dB and $G_{AREA}$ = 9 dB.

**Soln. :**

**Given :** Okumura's model, d=50 km $h_{te}$=100 m, $h_{re}$=10 m, EIRP= 1 kW, f = 900 MHz

**To find :** Received power

- The path loss is given by,

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

- Where,

$L_F$ : free space propagation loss

$L_{50}$ : $50^{th}$ percentile (median) value of propagation path loss

$A_{mu}$ : median attenuation relative to free s...

$G(h_{te})$ : base station antenna height gain fac...

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

$G_{Area}$ : gain because of type of environment

1. **The free space path loss :**

- The free space path loss is given by,

$$L_F = 10 \log \left[ \frac{\lambda^2}{(4\pi)^2 d^2} \right]$$

- But $\lambda = c/f$ and d = 50 km.

$$\therefore L_F = 10 \log \left[ \frac{\left( \frac{3 \times 10^8}{900 \times 10^6} \right)^2}{(4\pi)^2 \times (50 \times 10^3)^2} \right]$$

$$\therefore L_F = 125.5 \text{ dB}$$

2. **Find $G(h_{te})$ and $G(h_{re})$ :**

$A_{mu}$ (900 MHz (50 Km)) = 43 dB, $h_{te}$ = 10 m

$G_{AREA}$ = 9 dB and $h_{te}$ = 100 m

- We know that,

$$G(h_{te}) = 20 \log \left( \frac{h_{te}}{200} \right) = 20 \log \left( \frac{100}{200} \right)$$

$$\therefore G(h_{te}) = -6 \text{ dB}$$

- And,

$$G(h_{re}) = 20 \log \left( \frac{h_{re}}{3} \right) = 20 \log \left( \frac{10}{3} \right)$$

$$\therefore G(h_{re}) = 10.46 \text{ dB}$$

3. **The total path loss :**

- For Okumura model the total path loss is give...

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

$$L_{50}\,(dB) = 125.5 + 43 - (-6) - 10.46 - 9$$

$$\therefore L_{50}\,(dB) = 155.04 \text{ dB}$$

4. **The median received power :**

- The median received power is given by,

$$P_r(d) = EIRP\,(dB_m) - L_{50}\,(dB) + G_r\,(dB)$$

$$EIRP = 1\text{ KW} = 20 \log (1 \times 10^3) = 60 \text{ dB}$$

$$\therefore P_r(d) = 60 \text{ dBm} - 155.04 \text{ dB} + 0 \text{ dB}$$

$$\therefore P_r(d) = -95.04 \text{ dBm}$$

## 1.10.2 Hata Model :

- The Hata model is an empirical formulation of the graphical path loss data obtained from the Okumura model.
- It is valid in the frequency range from 150 - 1500 MHz only.
- In this model Hata presented the propagation loss in the urban area in the form of a standard formula and provided correction equations for its application to other situations.
- The standard formula for median path loss in urban areas is given by the following equation.

$$L\,(\text{urban})\,(\text{dB}) = 69.55 + 26.16 \log f_c - 13.82 \log h_{te} - a\,(h_{re}) + (44.9 - 6.55 \log h_{te}) \log d \quad ...(1.10.5)$$

Where,

$f_c$ = Frequency in (MHz) from 150 MHz to 1500 MHz

$h_{te}$ = Effective transmitter (base station) antenna height ranging from 30 m to 200 m.

$h_{re}$ = Effective receiver (mobile) antenna height ranging from 1 m to 10 m.

d = Tx – Rx separation distance in km.

$a\,(h_{re})$ = Correction factor for effective mobile antenna height that is a function of the size of the coverage area.

- The mobile antenna correction factor $a\,(h_{re})$ for small to medium city is given by,

$$a\,(h_{re}) = (1.1 \log f_c - 0.7)\, h_{re} - (1.56 \log f_c - 0.8)\ \text{dB} \quad ...(1.10.6)$$

- And the value of $a\,(h_{re})$ for large city is,

$$a\,(h_{re}) = 8.29\,(\log 1.54\, h_{re})^2 - 1.1\ \text{dB} \quad \text{for } f_c \le 300\ \text{MHz}$$

$$a\,(h_{re}) = 3.2\,(\log 11.75\, h_{re})^2 - 4.97\ \text{dB for } f_c \ge 300\ \text{MHz} \quad ...(1.10.7)$$

- We can modify the standard Hata formula of Equation (1.10.5) as follows to calculate the path loss in suburban area.

$$L\,(\text{dB}) = L\,(\text{urban}) - 2 \log \left(\frac{f_c}{28}\right)^2 - 5.4 \quad ...(1.10.8)$$

- For path loss in open rural areas, the standard Hata formula is modified as follows.

$$L\,(\text{dB}) = L\,(\text{urban}) - 4.78 \log f_c^2 + 18.33 \log f_c - 40.94 \quad ...(1.10.9)$$

**Features of Hata Model :**

- The important features of this model are :

1. In Hata model there are no path specific corrections.
2. The data loss predicted by this model is very close to that predicted by the Okumura model provided d is greater than 1 km.
3. This model works well for the mobile systems with large sized cells.
4. It is not suitable for the personal communication systems (PCS) which have smaller cell size.

**Ex. 1.10.2 :** For a large city, compute the median loss using Hata model at a distance d = 8 km, fc = 2.1 GHz, hre = 2 m and hte = 40 m.

**Soln. :**

**Given :** d = 8 km, fc = 2.1 GHz = 2100 MHz,

hre = 2 m, hte = 40 m.

**To find :** $L_{(curban)}$

**Step 1 : Find a (hre) :**

- a (hre) is the correction factor for effective mobile antenna. For a large city and fc ≥ 300 MHz it is given by,

$$a\,(h_{re}) = 3.2\,(\log 11.75\ \text{hre})2 - 4.97 \quad ...(1)$$

$$\therefore\ a\,(h_{re}) = 3.2\,(\log 11.75 \times 2)2 - 4.97$$

$$\therefore\ a\,(h_{re}) = 1.04\ \text{dB} \quad ...(2)$$

**Step 2 : Find the urban loss :**

- According to Hata model,

$$L_{(urban)} = 69.55 + 26.16 \log fc - 13.82 \log h_{te} - a\,(h_{re}) + (44.9 - 6.55 \log h_{te}) \log d \quad ...(3)$$

$$\therefore\ L_{(urban)} = 69.55 + 26.16 \log 2100 - 13.82 \log 2 - 1.04 + (44.9 - 6.55 \log 40) \log 8$$

$$\therefore\ L_{(urban)} = 69.55 + 86.9 - 1.04 - 22.14 + 31.07$$

$$\therefore\ L_{(urban)} = 164.34\ \text{dB}$$ ...Ans.

## 1.11 Receiver-Noise Computation :

- As the noise at the receiver arises due to thermal effects, it is known as thermal noise.
- It is necessary to accurately characterize noise power for computing the signal-to-noise power ratio and the bit-error rate at the receiver.
- The noise Power Spectral Density (PSD) $\eta_0$ denotes the noise power per hertz of bandwidth.
- Hence, the total noise power is given as,

  Noise power = $\eta_0 \times B$
- Where, B is the bandwidth of the noise signal.
- Further, we can derive the noise power spectral density $\eta_0$ as,

$$\eta_0 = kTF \quad \text{... (1.11.1)}$$

- Where, $k = 1.38 \times 10^{-23}$ is the Boltzmann constant, T is the temperature in Kelvin, and F is the noise figure.
- The following example would clarify this idea.

**Ex. 1.11.1 :** Calculate the noise power spectral density $\eta_0$ and the noise power if noise figure F = 5 dB, T = 293 k and the bandwidth B = 30 kHz.

**Soln. :**

**Given :** F = 5 dB, T = 293 k, B = 30 kHz

**To find :** 1. $\eta_0$ 2. $P_n$

**Step 1 : Find $\eta$0 :**

- Given F = 5 dB. Hence the linear value of the noise figure is given by,

$$F = 10^{0.5}$$

- Now, we know that

$$\eta_0 = kTF$$
$$= 1.38 \times 10 -23 \times 293 \times 100.5$$
$$\therefore \eta_0 = 1.28 \times 10 -20$$

- Therefore, the value of $\eta$0 in decibels is,

$$\eta_0 \text{ dB} = 10 \log_{10} \eta_0$$
$$= 10 \log_{10} (1.28 \times 10 -20)$$
$$= -199 \text{ dBW/Hz} \quad \text{...Ans.}$$

**Step 2 : Find noise power Pn :**

- The noise power is given by,

$$P_n = \eta_0 B$$
$$= 1.28 \times 10^{-20} \times 30 \times 10^3$$
$$\therefore P_n = 3.84 \times 10^{-16} \text{ W}$$
$$\therefore P_n \text{ (dB)} = 10 \log_{10} (3.84 \times 10^{-16})$$
$$= -154 \text{ dB} \quad \text{...Ans.}$$

## 1.12 Channel Estimation in Wireless Systems :

- Consider the wireless channel model given in Equation 1.12.1, where h is the flat-fading channel coefficient.

$$y(k) = hx(k) + n(k) \quad \text{... (1.12.1)}$$

- In this expression, y(k) represents the output or response of the channel, x(k) is its input and n(k) is the channel noise.
- We can obtain the estimate $\hat{x}(k)$ of the symbol x(k) from y(k) simply as $\hat{x}(k) = \frac{1}{h} y(k)$. This is known as the **zero-forcing receiver** in wireless system.
- This shows that in order to detect the transmitted symbol x(k) at the receiver, we must know the **channel coefficient "h".**

**Definition of channel estimation :**

- The channel estimation is defined as the process of computing the channel coefficient " h" at the wireless receiver which is an important procedure in every wireless communication system.
- A popular scheme for estimating the wireless channel is with the help of transmission of pilot or training symbols.
- Pilot symbols are predetermined fixed symbols which are transmitted over the wireless channel. The pilot symbols are known to the wireless receiver.
- The receiver observes the outputs corresponding to the transmitted pilot symbols and with the help of knowledge of the transmitted pilot symbols, estimates the unknown fading channel coefficient.
- This procedure for pilot-based channel estimation is as follows :

- Let the transmitted $L^{(p)}$ pilot symbols be denoted as $x^{(p)}(1), x^{(p)}(2), \ldots, x^{(p)}(L^{(p)})$ for the purpose of channel estimation.
- Let the corresponding received outputs be $y^{(p)}(1), y^{(p)}(2), \ldots, y^{(p)}(L^{(p)})$, i.e., each $y^{(p)}(k)$, $1 \le k \le L^{(p)}$ is the output corresponding to the transmitted pilot symbol $x^{(p)}(k)$.
- The channel model for these received pilot symbols is given as follows :

$$y^{(p)}(k) = hx^{(p)}(k) + n(k)$$

- In order to simplify the derivation, let us assume that all the quantities $y^{(p)}(k)$, $x^{(p)}(k)$, $n(k)$ and the channel coefficient h are real.
- Due to the presence of the noise term n (k) in the above system, it is clear that $y(k) \neq hx(k)$ for any k.
- Thus, we have to determine an estimate of h from the noisy observation samples y (k).
- Intuitively then, a reasonable estimate $\hat{h}$ of h can be derived as a minimizer of the cost function as follows :

$$\hat{h} = \arg\min_h \{(y^{(p)}(1) - hx(p)(1))^2 + (y^{(p)}(2) - hx^{(p)}(2))^2 + \ldots + (y^{(p)}(L^{(p)}) - hx^{(p)}(L^{(p)})^2\}$$

$$= \underbrace{\sum_{k=1}^{L} (y^{(p)}(k) - hx^{(p)}(k))^2}_{\xi(h)}$$

- The above minimization is aimed at finding the best estimate of h which corresponds to the lowest observation error $\xi(h)$ and therefore it is termed as the least-squares estimate.
- The most convenient way to minimize the error function $\xi(h)$, is to differentiate it and set it equal to zero.
- Differentiate the error function to get,

$$\frac{d\xi(h)}{dh} = \sum_{k=1}^{L} 2\,(y^{(p)}(k) - hx^{(p)}(k)\,(x^{(p)}(k))$$

- Equate the differentiated error function to zero to get,

$$0 = \sum_{k=1}^{L} x^{(p)}(k)\,(y^{(p)}(k) - \hat{h}\,x^{(p)}(k))$$

$$\Rightarrow \hat{h} = \frac{\sum_{k=1}^{L} y^{(p)}(k)\,x^{(p)}(k)}{\sum_{k=1}^{L} (x^{(p)}(k))^2} \quad \ldots(1.12.2)$$

- In this way, we can compute the channel estimate $\hat{h}$ of the fading channel coefficient h.
- This is the desired expression for the channel coefficient estimate.

**Matrix based derivation :**

- Let us now derive a matrix-based framework to derive the above result.
- The vector model for the pilot-symbol transmission reception is given as follows :

$$\underbrace{\begin{bmatrix} y^{(p)}(1) \\ y^{(p)}(2) \\ \vdots \\ y^{(p)}(L^{(p)}) \end{bmatrix}}_{y^{(p)}} = h \underbrace{\begin{bmatrix} x^{(p)}(1) \\ x^{(p)}(2) \\ \vdots \\ x^{(p)}(L^{(p)}) \end{bmatrix}}_{x^{(p)}} + \underbrace{\begin{bmatrix} n(1) \\ n(2) \\ \vdots \\ n(L^{(p)}) \end{bmatrix}}_{n}$$

(O-1723)

- Hence, we can write the vector model for the above system as,

$$y^{(p)} = h\,x^{(p)} + n$$

- where, $y^{(p)}$, $x^{(p)}$, n are $L^{(p)}$ dimensional vectors. The least-squares estimate of the channel coefficient $\hat{h}$ given as

$$C = \arg\min_h \| y^{(p)} - hx^{(p)} \|^2$$

$$= \arg\min_h \{(y^{(p)} - hx^{(p)})^T (y^{(p)} - hx^{(p)})\}$$

$$= \arg\min_h \Big\{ \underbrace{(y^{(p)})^T y^{(p)} - 2\big((y^{(p)})^T y^{(p)}\big) h + \big((x^{(p)})^T x^{(p)}\big) h^2}_{\xi(h)} \Big\}$$

(O-1724)

- As stated previously, in order to minimize the observation error, we can differentiate the above cost function $\xi(h)$ and set it equal to zero, to obtain the estimate $\hat{h}$ which is identical to the expression derived above in Equation (1.12.2).
- Taking the derivative and equating it to zero we get,

$$\frac{d\xi(\hat{h})}{dh} = -2\left((x^{(p)})^T y^{(p)}\right) + 2\left((x^{(p)})^T x^{(p)}\right)\hat{h}$$

$$\Rightarrow \quad 0 = -2\left((x^{(p)})^T y^{(p)}\right) + 2\left((x^{(p)})^T x^{(p)}\right)\hat{h}$$

$$\therefore \quad \hat{h} = \frac{(x^{(p)})^T y^{(p)}}{(x^{(p)})^T x^{(p)}}$$

$$\therefore \quad \hat{h} = \frac{\Sigma_{k=1}^{L} y^{(p)}(k)\, x^{(p)}(k)}{\Sigma_{k=1}^{L} (x^{(p)}(k))^2}$$

- Similarly we can derive the expression for the channel estimation for complex numbers h, $x^{(p)}(k)$, $y^{(p)}(k)$ by simply replacing the transpose operator above with the Hermitian operator.
- Hence, the general expression for the channel estimate $\hat{h}$ when the various quantities are complex numbers is given as,

$$\hat{h} = \frac{(x^{(p)})^H y^{(p)}}{(x^{(p)})^H x^{(p)}} = \frac{(x^{(p)})^H y^{(p)}}{\| x^{(p)} \|^2} \quad \ldots(1.12.3)$$

- This is the desired expression.

## 1.13 Diversity in Wireless Communication :

- Diversity reception is used in order to minimize the effects of fading.
- The theory of diversity lies at the heart of all modern wireless communication theory and technologies.
- It is by far the best tool available to combat the effects of multipath fading in a wireless channel and thereby ensure reliable communication.
- Diversity techniques can be employed in such scenarios to substantially improve the reliability of wireless communication, while reducing the BER.
- The principle of diversity reception is based on the fact that the signal at different points on the earth or different frequency signals do not fade simultaneously.
- There are two fundamental types of diversity reception systems :
  1. Space diversity system
  2. Frequency diversity system

**1. Space diversity :**

- In this system two or more receiving antennas are used. They are placed at points which are separated by about nine or more wavelengths.
- Receivers equal to the number of antennas employed. The output stage of all the receivers made common.
- As all the receivers receive the signal, the AGC from the receiver with the strongest signal at the moment is used to cut off all the other receivers.
- Thus, only the signal from the strongest receiver passed to the common output stage.

**2. Frequency diversity :**

- This system works on the similar principle of the space diversity. The signal is transmitted simultaneously at two or three different frequencies.
- Out of the signals received by different receivers which are tuned to different frequencies, only the strongest signal at a particular frequency is selected.
- Due to the use of two or three frequencies for transmitting the same signal more bandwidth is required and the frequency spectrum is wasted.
- Therefore frequency diversity system is used only when it is not possible to use the space diversity.

## 1.14 Diversity Techniques :

**Concept :**

- Diversity techniques provide wireless link improvement at low cost. It is a powerful communication receiver technique.
- Diversity requires no training overhead because the transmitter does not require training sequence. There are a wide range of diversity implementations.
- Many diversity implementations are very practical and they provide significant link improvement with some additional cost.
- Diversity techniques exploit the random nature of radio propagation by searching independent or at least highly uncorrelated signal paths for communication.
- Practically, the receiver makes diversity decisions and that decisions are unknown to the transmitter.
- If one radio path experiences a deep fade, another independent path can have a strong signal.
- On order to select one path from more than one paths, both the instantaneous and average SNRs at the receiver can be improved.

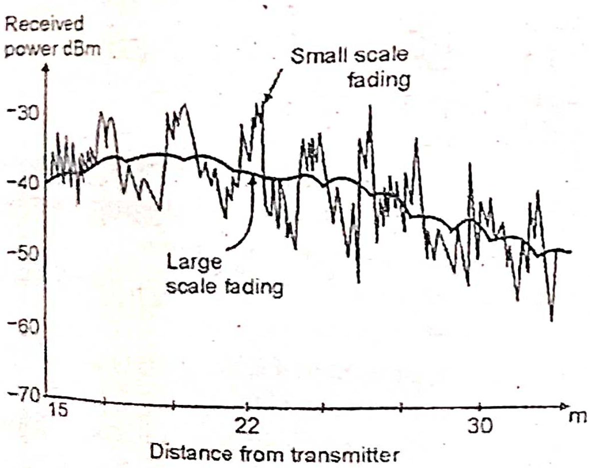
- They can be always improved by as much as 20 dB to 30 dB.
- We have already seen the two types of fading-small-scale and large-scale fading.

**Types of Diversity :**

- There are two types of diversity techniques :
  1. Microscopic diversity
  2. Macroscopic diversity

### 1.14.1 Microscopic Diversity :

- The small scale or fading models are the models that characterize the rapid fluctuations of received signal strength over either very short distances or very short time durations.
- These models are useful for the mobile radio communications.
- A mobile station, when moves over a short distance, gives rise to the **small scale fading.**
- Main cause of small scale fades is multiple reflections from the surroundings in the area of the mobile.
- Small-scale fading for narrowband signals results in a Rayleigh fading distribution of signal strength over small distances.
- The microscopic diversity techniques can be used to exploit the rapidly changing signal in order to prevent the occurrence of deep fades.
- The small-scale fading in Fig. 1.14.1 reveals that if two antennas are separated by a small part of a meter, one can receive a null signal while other receives a strong signal.

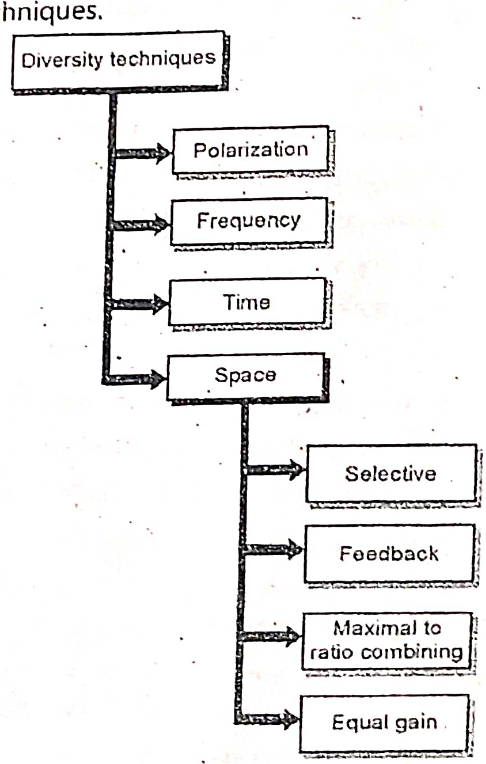



(G-2678) **Fig. 1.14.1 : Two types of fading**

- A receiver can mitigate small scale fading effects by choosing the best signal at all times, this is known as antenna or space diversity.

### 1.14.2 Macroscopic Diversity :

- Large scale fading is caused by shadowing. The shadowing occurs due to variations in both the terrain profile and the nature of surroundings.
- The received signal in deeply shadowed conditions, can improve the average signal-to-noise ratio on the forward link.
- This type of diversity is known as called macroscopic diversity.
- In the macroscopic diversity technique, the mobile takes the advantage of large separations between the serving base stations.
- This technique is useful at the base station receiver. The base station can improve the reverse link with the. use of the base station antennas separated in space.
- In order to improve the reverse link, a base station selects the antenna with the strongest signal from the mobile.
- Fig. 1.14.2 shows the types of the Diversity techniques.




(G-2828) **Fig. 1.14.2 : Types of Diversity Techniques**

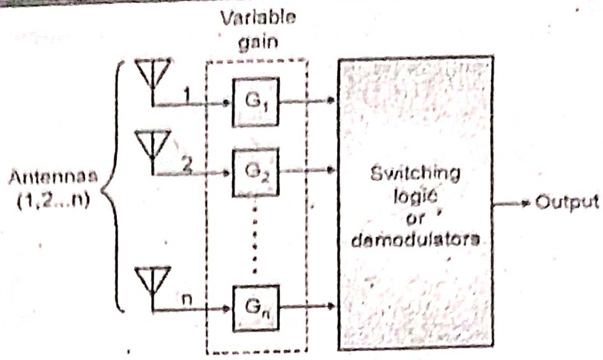
- The functionality of each diversity method is different.
- A common goal of all diversity techniques is to decrease the large scale fading effects observed in the multipath receiver circuits.

### 1.14.3 Space Diversity :

- The space diversity technique is also known as antenna diversity.
- This is one of the most popular diversity technique used in the wireless systems.
- Conventional wireless communication systems include an elevated base station antenna and a mobile antenna close to the ground.
- In the conventional system, there is no guarantee of a direct path between the transmitter and the receiver.
- There is possibility of a number of scatterers in the surrounding area of the mobile that occurs a Rayleigh fading signal.
- The received signals from spatially separated antennas on the mobile will have basically uncorrelated envelopes for antenna separations of one half wavelength or more.
- Antenna space diversity technique is used in the design of base station.
- In order to provide diversity reception, multiple base station receiving antennas are used at each cell site.
- The scatterers are generally occurs on the ground in the surrounding area of the mobile.
- Hence, the base station antennas are considerably spaced far apart in order to achieve decorrelation.
- The base stations are separated in the order of several tens of wavelengths.
- Thus the space diversity can be used at either the base or mobile station or both.

**Block diagram :**

- Fig. 1.14.3 shows the block diagram of a space diversity technique.




(G-2829) **Fig. 1.14.3 : Block diagram of space diversity**

- The block diagram consists of 'n' number of antennas with separate gain values $G_1$, $G_2$, $G_3$, ...$G_n$ and a set of demodulators.
- The demodulators are used to generate the required output.

#### 1.14.3.1 Space Diversity Reception Methods :

- The Space diversity reception methods can be classified into the following four categories :
  1. Selection diversity
  2. Feedback or scanning diversity
  3. Maximal ratio combining
  4. Equal gain diversity

**1. Selection Diversity :**

- In this method the branches having the strongest received signal will be selected.

**2. Feedback or Scanning Diversity :**

- In this method 'n' signals are scanned in a proper sequence and monitored to pick up a signal in the sequence that is above the predetermined threshold value.

**3. Maximal Ratio Combining :**

- In this method, the signals from all of the 'n' branches are weighted.
- The signals are weighted according to their individual signal voltage to noise power ratios and then the signals are combined.

**Advantages :**

1. It generates an acceptable SNR value.
2. High accuracy.
3. Best reduction of fading.

4. **Equal Gain Combining :**

- In this method, all the diversity branches are added with the same weighing factor.
- The signals from each diversity branches are co-phased that provides equal gain factor.
- The disadvantage of this technique is, it degrades the SNR value by 0.5 dB at the output of the combiner if two branches are involved.

#### 1.14.3.2 Advantages of Space Diversity :

- Following are some of the advantages of Space diversity technique :
  1. A number of diversity branches are allowed in space diversity.
  2. It is applicable to the macroscopic diversity.
  3. No need of extra bandwidth or power.

#### 1.14.3.3 Disadvantages Space Diversity :

- Following are some of the disadvantages of space diversity technique :
  1. Large hardware size is required for space diversity.
  2. Larger antenna spacing is needed at the base station in microscopic diversity.

### 1.14.4 Polarization Diversity :

- Polarization diversity uses antennas of different polarizations i.e. horizontal and vertical.
- Two uncorrelated fading signals will be received if a signal is transmitted by a pair of polarized antennas and received by another pair of antennas.
- This is due to fading variations by horizontal and vertical polarizations and different reflection coefficient values of the tall building walls.

**Advantage :**

1. No need of additional space and bandwidth.

**Disadvantages :**

1. Polarization diversity required 3 dB extra power.
2. Only two diversity branches are allowed.

### 1.14.5 Frequency Diversity :

- An information in this diversity technique is transmitted on more than one carrier frequency.
- The frequencies are separated by more than the coherence bandwidth of the mobile channel.
- These will be uncorrelated with each other and will not experience the same fades.
- In case of uncorrelated channels are, the occupancy of simultaneous fading will be the multiple of the individual fading probabilities.
- Frequency diversity technique is applied in the microwave fields whenever line-of-sight links are used. In LOS links, they carry several channels in a frequency division multiplex mode (FDM).
- There can be deep fading in frequency diversity due to tropospheric propagation and resulting refractions of the signal.
- A radio licensee provides 1 : N protection switching. In 1 : N protection switching, one frequency is idle.
- An idle frequency is available on a stand-by basis in order to provide frequency diversity switching for any one of the N other carriers being used on the same link.
- Each frequency (carrier) carries independent traffic.
- The appropriate traffic is switched to the backup frequency when diversity is required.

**Advantage :**

1. It allows several diversity branches.

**Disadvantages :**

1. It needs extra bandwidth.
2. It requires many receivers due to use of multiple channels.

### 1.14.6 Time Diversity :

- In the time diversity technique, the information is transmitted repeatedly at exact time spacings that would exceed the coherence time of the mobile channel.
- This leads in the repetition of signals for several times with independent fading conditions.
- Hence it is possible to achieve the diversity branch signals, when same information is transmitted for different time slots.

- The time diversity technique is used in the spread spectrum CDMA systems where RAKE receiver is used for the reception.
- The RAKE receiver can align the replicas in time by demodulating multiple replicas of the transmitted CDMA signal.
- Here, each replica experiences a particular multipath delay.
- As the RAKE receiver can align the replicas in time, it can better estimate the original signal formed at the receiver.

**Advantages :**

1. Simple hardware is needed.
2. Multiple diversity branches can be used.

**Disadvantages :**

1. More frequency spectrum is required depending on the number of diversity branches.
2. In case of small diversity frequency, larger buffer memory is required.

## Review Questions

Q. 1 Define wireless communication.

Q. 2 State some examples of wireless communication systems.

Q. 3 Explain the need of wireless communication.

Q. 4 Write a short note on : a wireless network.

Q. 5 Define and explain the following :

(a) Path loss

(b) RF signal interference

(c) Fading

Q. 6 Explain the term blocking or shadowing.

Q. 7 What is LOS communication ?

Q. 8 Define reflection and refraction of radio waves.

Q. 9 Explain the multipath propagation and its effects.

Q. 10 What is fading ? What are its types ?

Q. 11 State and explain different reasons for fading.

Q. 12 State advantages, disadvantages and applications of wireless communication.

Q. 13 What are different wireless media ?

Q. 14 State and explain various properties of RF waves.

Q. 15 Explain the principle of cellular net...

Q. 16 What is MSC ?

Q. 17 Define cell and cluster.

Q. 18 Explain different generations ... systems.

Q. 19 Explain the evolution of cel... highlighting 1G/2G/3G.

Q. 20 Explain the 1G cellular system a... features and drawbacks.

Q. 21 Explain the 2G cellular system a... features.

Q. 22 Explain the 2G cellular system is bette... 1G system.

Q. 23 Write a note on : the 3G cellular syste...

Q. 24 Explain the 4G cellular system and ... features.

Q. 25 Write a note on : the 5G cellular system

Q. 26 State the features of 5G cellular system

Q. 27 What are the advantages and limitatio... cellular system.

Q. 28 Describe the term multipath fading.

Q. 29 Explain the free space propagation mod...

Q. 30 Explain the ground reflection model.

Q. 31 State advantages and disadvantages ... model.

Q. 32 State various outdoor propagation mode...

Q. 33 Write a note on : Hata model.

Q. 34 With the help derivation explain the c... channel estimation in wireless systems.

Q. 35 Explain the concept of diversity rece... wireless systems.

Q. 36 State and explain different techniques of di... reception in wireless systems.

Q. 37 Explain the concept of microscopic div... reception in wireless systems.

Q. 38 Explain the concept of macroscopic div... reception in wireless systems.

Q. 39 Explain the concept of space diversity recepti... wireless systems.

Q. 40 Explain the concept of frequency diversity rece... in wireless systems.

Q. 41 Explain the concept of time diversity recepti... wireless systems.

Unit II

Chapter 2

# Orthogonal Frequency Division Multiplexing

**Syllabus**

Introduction, Motivation and Multicarrier basics, OFDM example, Bit error rate for OFDM. **Multiple-Input Multiple-Output Wireless Communications :** Introduction to MIMO wireless communications, MIMO system model and MIMO-OFDM.

Chapter Contents

## 2.1 Introduction to OFDM :

- Orthogonal Frequency Division Multiplexing (OFDM) technique is used in 4G wireless cellular systems such as Long-Term Evolution (LTE) and WiMAX (Worldwide Interoperability for Microwave Access).
- It is a key broadband wireless technology and it supports data rates larger than 100 Mbps.
- Similar to LTA and WiMax, the wireless local area (LAN) standards such as 802.11 a/g/n are also based on OFDM.

## 2.2 Motivation and Multicarrier Basics :

**Single-carrier communication system :**

- In a single carrier communication system, a single radio frequency carrier is used to carry the information. Hence information in the form of bits is carried by only one single RF carrier.
- This system uses a single carrier for the entire baseband bandwidth of B.
- Therefore, the symbols are transmitted as symbol X(0) from $0 \le t < T$, symbol X(1) from $T \le t < 2T$, X(2) from $2T \le t < 3T$ and so on, i.e., a single symbol transmitted every $T = 1 / B$ seconds.

**Symbol time T :**

- If a bandwidth B = 2W available for communication, where W is the one-sided bandwidth, or the maximum frequency, then the symbol time T for a single carrier communication system, is given by,

$$T = 1/B$$

**Symbol rate :**

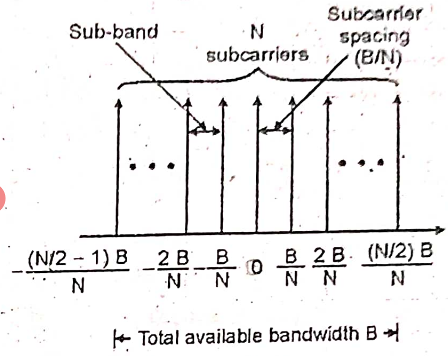
- If the symbols can be transmitted at intervals of 1/B seconds each. Then, the symbol rate is given by,

$$\text{Symbol Rate} = \left[\frac{1}{1/B}\right] = B \qquad ...(2.2.1)$$

- Such a system is called as a **single-carrier communication system.**

**Multi-carrier communication system :**

- Multi-carrier communication system is a method of transmitting data by splitting it into several components, and sending each of these components over separate carrier signals.
- Thus this system uses more than one carriers.
- Fig. 2.2.1 shows the concept of Multi-carrier communication system.




(Q-1686) **Fig. 2.2.1 : Multi-carrier concept**

- As shown in Fig. 2.2.1, the total bandwidth B is divided into N sub-bands each of bandwidth B/N.
- Each sub-band is represented by a subcarrier.
- As shown in Fig. 2.2.1, the subcarriers are placed at frequencies (..., – B/N, 0, B/N, ... ).

**Example :**

- If the bandwidth B = 256 kHz with N = 64 subcarriers then the bandwidth per sub-band is equal to 256 / 64 = 4 kHz.
- The frequency spacing between the subcarriers is also 4 kHz.

**Implementation of multi-carrier transmission system :**

- Consider the $i^{th}$ subcarrier at the frequency $f_i = i\left(\frac{B}{N}\right)$ with $-\left(\frac{N}{2}-1\right) \le i \le \left(\frac{N}{2}\right)$.
- If $X_i$ is the data transmitted on the $i^{th}$ subcarrier, then the signal $s_i(t)$ corresponding to the $i^{th}$ subcarrier is given by,

$$s_i(t) = X_i e^{j2\pi f_i t} = X_i e^{j2\pi i (B/N) t} \qquad ...(2.2.2)$$

- Where,

  $s_i(t)$ = $i^{th}$ subcarrier signal

  $X_i$ = data transmitted on the $i^{th}$ subcarrier

  $f_i$ = $i^{th}$ subcarrier centre frequency

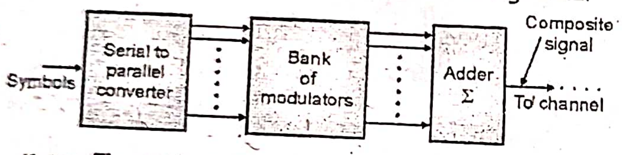
  $e^{j2\pi f_i t}$ = $i^{th}$ subcarrier

- Equation (2.2.2) shows the process of data modulation over the $i^{th}$ subcarrier.
- There are a total N data streams and the N different data symbols $X_i$ are modulated over the N different subcarriers with centre frequencies $f_i$.

### 2.2.1 Multicarrier Transmission :

**MCM Transmitter :**

- The block diagram of MCM (Multicarrier modulation) transmitter is as shown in Fig. 2.2.2.




(O-1587)**Fig. 2.2.2 : Multicarrier modulation transmitter**

- MCM transmitter consists of a serial to parallel converter, bank of modulators and an adder.
- Serial to parallel conversion is used to transmit N information symbols in parallel. Thus there are N numbers of data streams.
- The modulator modulates $i^{th}$ data stream onto the $i^{th}$ subcarrier.
- Adder will make the sum all the modulated subcarriers.
- Sum of all such subcarriers forms a composite signal which then would be transmitted on a channel.

**Modulation Process :**

- Consider the different modulated signals $s_i(t)$ corresponding to the N different subcarriers.
- The composite signal s(t) is formed by superposing modulated signals at the transmitter and is given by,

$$s(t) = \sum_i s_i(t) \qquad ...(2.2.3)$$

- Substitute the value of $s_i(t)$ from equation (2.2.2) we get,

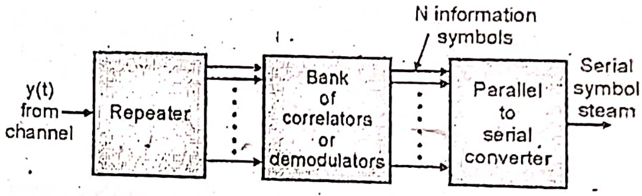
$$s(t) = \sum_i X_i e^{j2\pi f_i t}$$

$$s(t) = \sum_i X_i e^{j2\pi i(B/N)t} \qquad ...(2.2.4)$$

- This composite signal s(t) is then transmitted over the wireless channels.
- Thus, in the multicarrier system, N different data streams are transmitted over N subcarriers in parallel.

**MCM Receiver :**

- The block diagram MCM receiver is as shown in Fig. 2.2.3.




(O-1688)**Fig. 2.2.3 : Multicarrier modulation receiver**

- It consists of a repeater, bank of demodulators and parallel to serial converter. The received signal y(t) is applied to a repeater stage.
- At the receiver end composite signals are amplified first.
- Repeater is an antenna that simultaneously receives, amplifies, and transmits a signal.
- It is passed on to the bank of demodulators or correlators and the data is converted back to serial from parallel, forming a symbol stream.

**Demodulation Process :**

- At the receiver, the individual data streams are isolated from the composite signal s (t).
- The receiver receives the signal y(t) as ,

$$y(t) = s(t) = \sum_i X_i e^{j2\pi f_i t}$$

- At receiver, for simplicity of demodulation process, we assume that the noise is absent.
- It can be seen that the right-hand side of equation (2.2.4) is indeed the Fourier series representation s(t), corresponding to the

fundamental frequency $f_0 = (B)N$ and the various $X_i$ representing the Fourier coefficients.

- All the frequencies $i\left(\frac{B}{N}\right)$ are multiples of the fundamental frequency $f_0 = \left(\frac{1}{T_0}\right) = \left(\frac{B}{N}\right)$.
- To extract $X_l$ (Fourier coefficient corresponding to the frequency $f_l = l f_0$) follow the process similar to calculate the Fourier series as,

$$f_0 \int_0^{T_0} y(t)\,(e^{j2\pi l f_0 t})^*\,dt = \frac{B}{N}\int_0^{N/B} \left(\sum_i X_i\, e^{j2\pi i (B/N) t}\right) e^{-j2\pi l (B/N)}\,dt$$

$$= \frac{B}{N}\sum_i \int_0^{N/B} X_i\, e^{j2\pi (i-l) f_0 t}\,dt$$

$$= \underbrace{\frac{B}{N}\int_0^{\frac{N}{B}} X_l\,dt}_{i=l} + \frac{B}{N}\sum_{i\neq l}\int_0^{N/B} X_i e^{j2\pi(i-l)f_0 t}\,dt$$

$$= X_l + \frac{B}{N}\sum_{i\neq l} X_i \underbrace{\int_0^{N/B} e^{j2\pi(i-l)f_0 t}\,dt}_{=0}$$

$$= X_l \qquad \text{(O-1668)}$$

- We have used $\int_0^{T_0} e^{j2\pi(i-l)f_0 t}\,dt = 0$ for $i \neq l$, because this is basically integrating a sinusoid of frequency $(i - l)f_0$, which is a multiple of the fundamental frequency $f_0$ over the time period $T_0$.
- As there are an integer number of cycles of the sinusoid of frequency $(i - l)\,f_0$, this integral is 0.
- This basically means that the different sinusoids $e^{j2\pi i f_0 t}$ and $e^{j2\pi l f_0 t}$ are **orthogonal.**
- This property of orthogonality helps to extract the different streams $X_i$ modulated over the different subcarriers.
- This property of orthogonality can be summarized as follows,

$$\int_0^{N/B} e^{j2\pi(i-l)(B/N)t} = \begin{cases} 0 & i \neq l \\ \frac{N}{B} & i = l \end{cases}$$

- Therefore, all the subcarriers other than the $i^{th}$ subcarrier are orthogonal to the $l^{th}$ subcarrier.
- A coherent demodulation is multiplying the term with $(e^{j2\pi f l t})^*$ and integrating it.
- The coherent demodulation is the demodulati... with the carrier matched to the subcarr... frequency $f_l = l\left(\frac{B}{N}\right)$.
- Thus, the data modulated on the diffe... subcarriers $X_l$ can be easily recovered coherently demoudulating with each of ... subcarriers corresponding to $l = -\left(\frac{N}{2}-1\right), \ldots$
- This transmission on multiple orthog... subcarriers and the associated data recov... the receiver is called as Multi Carrier Modula... (MCM).
- The window of time associated with detectio... this multicarrier signal is given by,

$$\left(\frac{N}{B}\right) = \left(\frac{1}{f_0}\right) = T_0$$

- This is basically the time period of integration.

**Symbol rate :**

- Hence, MCM mainly transmits N symbols usin... subcarriers in a time period of $\left(\frac{N}{B}\right)$.
- Therefore, the symbol rate of MCM is given b...

$$\text{Symbol Rate} = \left[\frac{N}{N/B}\right] = B \qquad \ldots$$

- From equation (2.2.5), we can say that the ... symbol rate in single carrier versus mult... systems is unchanged.
- From Equations (2.2.1) and (2.2.5), it is cle... the symbol rate in both single-carrier and ... carrier communication systems is exactly ide... i.e. B.
- The single-carrier system transmits each sym... time 1/B whereas the MCM system transm... symbols in parallel in time N/B.

**Advantages of MCM system :**

- Consider a transmission bandwidth B = 1024 kHz. This bandwidth B is much gr... than the coherence bandwidth $B_c$ wh... typically around 250 kHz.

- The single-carrier system experiences frequency-selective fading and inter-symbol interference as the transmission bandwidth $B >> B_C$.
- Consider an OFDM system that uses N = 256 subcarriers in the same bandwidth.
- The bandwidth per subcarrier is,

  $B_s = 1024 / 256 = 4$ kHz.
- That means the subcarrier bandwidth of 4 kHz is significantly lower than the coherence bandwidth of 250 kHz.
- Each subcarrier in OFDM experiences flat fading, since $\left(\frac{B}{N}\right) << B_C$.
- There is no inter-symbol interference in the data transmitted on any of the subcarriers in OFDM.
- MCM eliminates the Inter-Symbol interference (ISI) through parallel transmission by using multiple narrowband subcarriers.
- This results in avoiding distortion of the received symbols.
- We may summarize the advantages of MCM system as follows :
  1. Each OFDM subcarrier experiences flat fading
  2. ISI is eliminated
  3. Signal distortion is avoided.

**Disadvantage :**

- MCM system suffers from a significant disadvantage. Implementation of the bank of N modulators and N demodulators with closely spaced subcarrier frequencies is a challenging task.
- To overcome this problem, data transmission by Frequency Division Multiplexing using the Discrete Fourier Transform is used.
- This technique, where the MCM signal is generated by using the IFFT (Inverse FFT) operation is known as Orthogonal Frequency Division Multiplexing or OFDM.

## 2.3 Orthogonal Frequency Division Multiplexing (OFDM) :

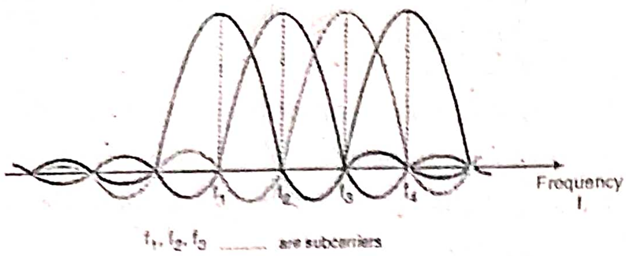
Short

- OFDM stands for Orthogonal Frequency Division Modulation.
- It is a wideband wireless digital communication technique.
- OFDM is a digital modulation scheme which can be used for high speed video communication and audio communication without any inter symbol interference (ISI).
- It has a high spectral efficiency. That means it can accommodate a large number of users.
- It is a multiplexing / multiple access scheme which has advanced features suitable for the fourth generation of wireless communication systems.
- It is mainly based on the DSP techniques.

### 2.3.1 Orthogonality :

**Definition :**

- Two signals are said to be orthogonal if they are independent of each other in a specified time interval and do not interact with each other.
- We can transmit a number of orthogonal signals over a common channel without interference and detect them on the receiving end without interference.
- In FDM we have different channels (signals) occupying different frequency bands with a guard band in between to avoid any interference between the adjacent channels. But this makes FDM a bandwidth inefficient system.
- The bandwidth efficiency improves considerably if we use OFDM technique instead of the simple FDM.
- In the orthogonal FDM (OFDM) the subcarriers $f_1, f_2, f_3$ ...... etc.
- Are placed as close as they can be placed theoretically in the frequency domain. This is shown in Fig. 2.3.1.

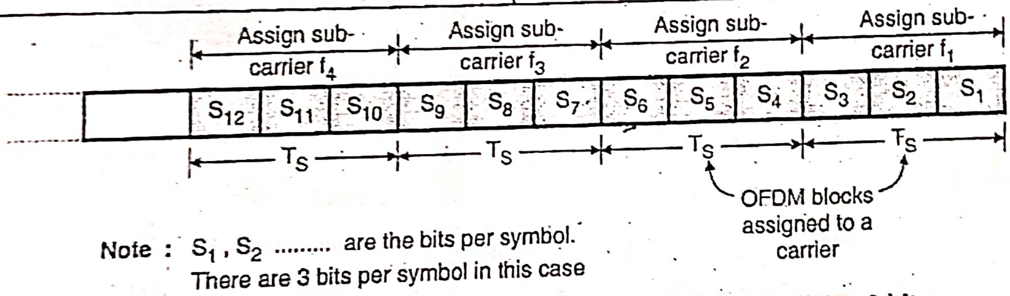



(E-1334) **Fig. 2.3.1 : Orthogonal signals in frequency domain (principle of OFDM)**

- Note that the subcarriers $f_1$, $f_2$ ......etc are placed at the null points of all the other subcarriers.
- This automatically eliminates the interference among the adjacent subcarriers.
- Due to this type of placement of subcarriers, the total bandwidth of the OFDM system is much less than that of the conventional FDM system and we can accommodate more number of users.

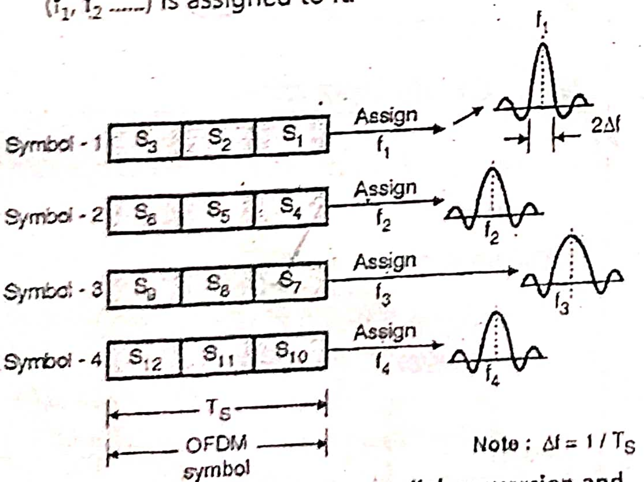
### 2.3.2 Assigning the Subcarriers :

- In OFDM, single information stream or frame is split into multiple symbols and a separate carrier is assigned to each symbol or a group of symbols.
- All this information is transmitted simultaneously through these multiple carriers.
- There are two ways of assigning the subcarriers, as follows :
- Consider one OFDM frame. Then read the first group of bits/symbol and assign one subcarrier to it.
- Then read another group of bits / symbol and assign another subcarrier to it, and continue.
- Note that all these subcarriers are orthogonal to each other.
- $T_s$ represents the duration of each symbol. This is as shown in Fig. 2.3.2(a).




(E-1335) **Fig. 2.3.2(a) : Assigning subcarriers to each symbol containing 3 bits**

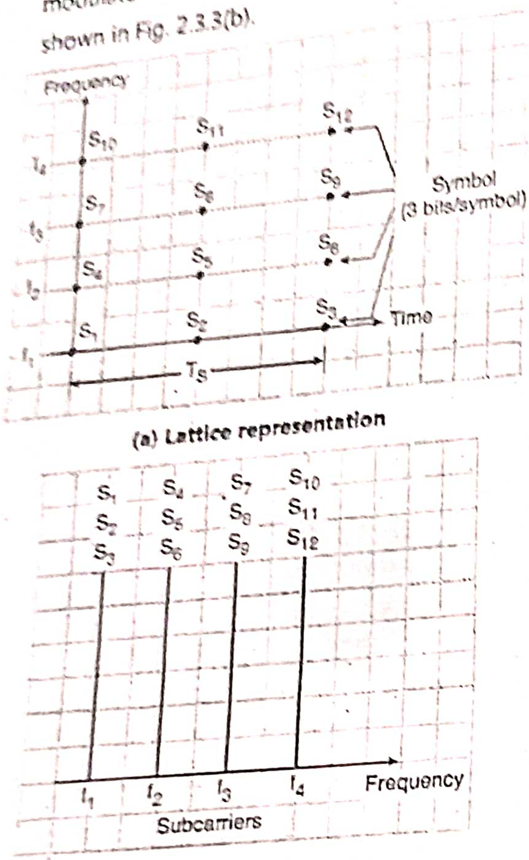
- All the symbols are then arranged in parallel as shown in Fig. 2.3.2(b) and an orthogonal subcarrier ($f_1$, $f_2$ ......) is assigned to it.




(E-1336) **Fig. 2.3.2(b) : Serial to parallel conversion and mapping into frequency domain components after modulation in OFDM**

- In the second method of assigning the subcarriers the bits/symbol of the whole OFDM frame are read and then a matrix is formed in which each element represents a symbol (or word).
- The whole frame is then represented as a time versus frequency plot as shown in Fig. 2.3.3(a).
- Note that each point in this lattice represents a symbol (word).
- Thus $f_1$ is assigned to the first symbol consisting of bits $S_1$, $S_2$, $S_3$.
- Then $f_2$ is assigned to the second symbol consisting of bits $S_4$, $S_5$, $S_6$ and so on.

- The symbols (group of bits) are then used to modulate different orthogonal subcarriers as shown in Fig. 2.3.3(b).

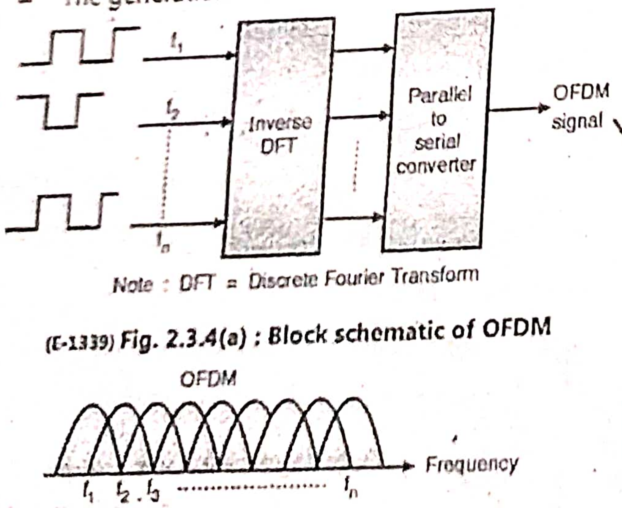



(b) Subcarrier assignment

(E-1337) Fig. 2.3.3 : Second method of carrier assignment

### 2.3.3 Generation of OFDM Signals :

- The generation of OFDM is as shown in Fig. 2.3.4.




(b) Frequency spectrum

(E-1339) Fig. 2.3.4 : Principle of OFDM

- The symbols will first modulate different orthogonal carriers $f_1, f_2 ........ f_n$.
- Then they are applied to the inverse DFT block.
- The output of IDFT block is then applied to the parallel to serial converter to produce the OFDM signal.

### 2.3.4 OFDM-PAPR (OFDM-Peak-to-peak Average Power Ratio) :

**Definition :**

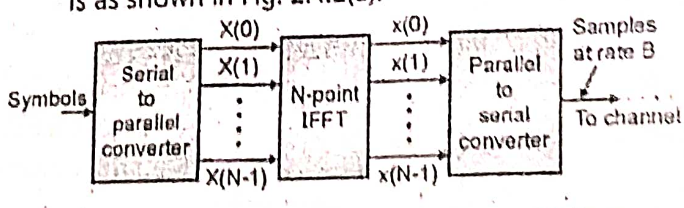
- Peak-to-peak average power ratio (PAPR) is defined as the ratio of peak power to the average power of a signal. It is measured in decibels (dB).
- It is observed that PAPR occurs, in conditions where in a multicarrier system, the different sub-carriers are out of phase with each other.
- The sub-carriers are different at every time instant with respect to each other and have different phase values.
- If all the subcarriers attain the maximum value simultaneously, then the output envelope shoots up suddenly. This causes a 'peak' to appear in the output envelope.
- Similar to the OFDM system there are a large number of independently modulated subcarriers, the peak value of the system may be very high as compared to the average value of the complete system.
- In LTE system, the value of OFDM signal PAPR is approx. 12 dB.

## 2.4 OFDM Operation :

- Fig. 2.4.1 illustrates the process of a typical OFDM system

**OFDM transmitter with IFFT :**

- The block diagram of OFDM transmitter with IFFT is as shown in Fig. 2.4.1(a).




(O-1689) Fig. 2.4.1(a) : OFDM transmitter with IFFT

- The bank of modulators in MCM is replaced by IFFT block in OFDM.
- The information symbols at the input are converted from serial stream into parallel stream.
- Since we assumed that there are N subcarriers allowed for the OFDM transmission, we name them from 0 to N-1.
- The serial to parallel converter takes the serial stream of input bits and outputs N parallel streams (indexed from 0 to N-1).
- The N point IFFT modulates parallel streams in a baseband fashion.
- The output of IFFT block is then applied to the parallel to serial converter to produce the OFDM signal.
- Let s(t) is the MCM transmit signal. It is band-limited to the total bandwidth B.

  $\therefore$ Nyquist sampling rate = B and

  Associated sampling time is $T_s = 1/B$
- Consider now the composite MCM signal $\sum_i X_i e^{j2\pi i(B/N)t}$
- The $\mu^{th}$ sample at time instant $\mu T_s = \mu / B$ is given by,

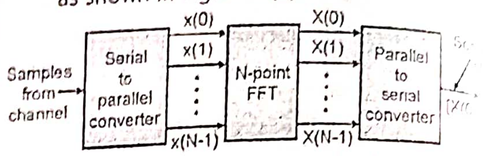
$$s(\mu T_s) = x(\mu) \sum_i X_i e^{j2\pi i (B/N)(\mu/B)}$$

$$x(\mu) = \underbrace{\sum_i X_i e^{j2\pi (i\mu/N)}}_{\text{DFT}} \quad ...(2.4.1)$$

- Equation (2.4.1) shows that the sample $x(\mu)$ is basically the Inverse Discrete Fourier Transform (IDFT) coefficient of the information symbols X(0), X(1), . . . , X (N – 1) at the $\mu^{th}$ time point.
- In order to generate the sampled MCM signal, the Inverse Fast Fourier Transform (IFFT) can be easily used.
- This method of generating the composite transmit signal through IFFT or IDFT reduces the complexity of implementing an OFDM system.
- This method with IDFT reduces complexity of the system as it eliminates the need for the bank of modulators corresponding to the subcarrier frequencies.
- The generation of the MCM signal using ... operation is called as Orthogonal Fr... Division Multiplexing **(OFDM).**

**OFDM receiver with FFT :**

- The block diagram of OFDM receiver wi... as shown in Fig. 2.4.1(b).




(O-1690)**Fig. 2.4.1(b) : OFDM receiver with FFT**

- The OFDM receiver performs the inverse pr... of the transmitter.
- In order to recover the information symb... FFT operation is used at the receiver.
- A fast Fourier transform (FFT) is performed ... samples received from channel to produ... series of symbols.

### 2.4.1 Cyclic Prefix in OFDM :

- The cyclic prefix is an important componen... OFDM system.
- A Cyclic Prefix (CP) is inserted between O... symbols.
- The CP is formed by adding the trailing ... samples of an OFDM symbol before the O... symbol start.
- An N point FFT recovers the original informat... symbols.
- Consider a frequency-selective channel mode... with channel taps h(0), h(1), . . . , h(L – 1).
- The received symbol (y) at a given time instant can be given by the following expression,

$$y(n) = h(0)\,x(n) + \underbrace{h(1)\,x(n-1) + \ldots + h(L-1)\,x(n-L+...)}_{\text{ISI component}}$$

(O-1669) ...(2.4.2)

- From Equation (2.4.2), it is clear that the receive... symbol y(n) at the time instant n experiences inte... symbol interference from the previous ... transmitted symbols.

- Consider two OFDM symbols as follows :
- Let $x(0), x(1), x(2), \ldots, x(N-1)$ are the IFFT samples of the modulated symbols $X(0), X(1), \ldots, X(N-1)$, and $\tilde{x}(0), \tilde{x}(1), \ldots, \tilde{x}(N-1)$ are the IFFT samples of the previous modulated symbol block $\tilde{X}(0), \tilde{X}(1), \ldots, \tilde{X}(N-1)$.
- Therefore, the samples related to these two blocks of OFDM symbols are transmitted sequentially as

(O-1670)

$$\underbrace{\tilde{x}(0), \tilde{x}(1), \ldots, \tilde{x}(N-1)}_{\text{Previous block}} \; \underbrace{x(0), x(1), \ldots, x(N-1)}_{\text{Current block}}$$

- The received symbol y(0) corresponding to the transmission of x(0) can be expressed as follows,

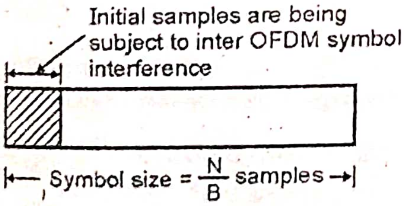
(O-1671)

$$y(0) = h(0)\,x(0) + \underbrace{h(1)\,\tilde{x}(N-1) + \ldots + h(L-1)\,\tilde{x}(N-L+1)}_{\text{ISI from previous OFDM symbol}} \quad \ldots(2.4.3)$$

- Equation (2.4.3) shows that the received symbol y(0) experiences inter-symbol interference from the previous OFDM block symbols $\tilde{x}(N-1), \tilde{x}(N-2), \ldots\ldots, \tilde{x}(N-(L-1))$.
- There is inter-OFDM symbol interference in this new OFDM system.

**Inter-OFDM symbol interference :**

- Fig. 2.4.2 shows the concept of inter-OFDM symbol interference.




(O-1708)**Fig. 2.4.2 : Inter-OFDM symbol interference**

- As shown in Fig. 2.4.2, the initial samples of the current OFDM symbol block are being subjected to interference from the N – 1 samples of the previous OFDM block.
- Similarly, the received symbol y (1) is given as,

(O-1672)

$$y(1) = h(0)\,x(1) + \underbrace{h(1)\,x(0)\,h(0)\,\tilde{x}(N-1) + \ldots + h(L-1)\,\tilde{x}(N-L+2)}_{\text{ISI from previous OFDM symbol}} \quad \ldots(2.4.4)$$

- Equation (2.4.4) shows that the received symbol y(1) experiences inter-symbol interference from the previous OFDM block symbols $\tilde{x}(N-1), \tilde{x}(N-2), \ldots, \tilde{x}(N-L+2)$.

**OFDM with cyclic prefix :**

- Now consider a modified transmission scheme in which the padding of $L_c$ symbols is done at the end of each transmitted OFDM sample stream and the transmitted stream is given by,

(O-1673)

$$\underbrace{\tilde{x}(0), \ldots, \tilde{x}(N-1)}_{\text{Previous block}}, \underbrace{x(N-L_c), x(N-L_c+1), \ldots, x(N-1)}_{\text{Cyclic prefix}} \underbrace{x(0), \ldots, x(N-1)}_{\text{Current block}} \quad \ldots(2.4.5)$$

- As shown in the Equation (2.4.5), the prefix is added before the current block.
- The transmitted sample block $x(0), x(1), \ldots, x(N-1)$ of the current block is prefixed with the $L_c$ samples $x(N-L_c), x(N-L_c+1), \ldots, x(N-1)$.
- The nature of this prefix is cyclic, because the same samples from the end of the block are being cycled towards the beginning. Therefore, this is known as the cyclic prefix.
- The received symbol y(0) corresponding to x(0) is given by,

(O-1674)

$$y(0) = h(0)\,x(0) + \underbrace{h(1)\,x(N-1) + \ldots + h(L-1)\,x(N-L+1)}_{\text{ISI from previous OFDM symbol}} \quad \ldots(2.4.6)$$

**How to avoid ISI :**

- If $L_c \geq (L-1)$, then inter-symbol interference can be seen to be from $x(N-1), x(N-2), \ldots, x(N-L+1)$.
- Inter-OFDM symbol interference can be avoided with the cyclic prefix of appropriate length, i.e., $L_c \geq (L-1)$, and inter-symbol interference is restricted to samples from the same OFDM symbol.

- The samples y(0), y(1), . . . , y(N – 1) are given as,

$$y(0) = h(0)x(0) + h(1)\,x(N-1) + \ldots + h(L-1)\,x(N-L+1)$$

$$y(1) = h(0)x(1) + h(1)\,x(0) + \ldots + h(L-1)\,x(N-L+2)$$

$$\vdots$$

$$y(N-1) = h(0)x(N-1) + h(1)\,x(N-2) + \ldots + h(L-1)\,x(N-L)$$

- From the above equations it is clear that, the output y(n) is a circular convolution between the channel filter h (n) and the input x(n).
- Hence this can be expressed as follows,

Received samples [y(0), y(1),…,y(N – 1)]

$$= [h(0), h(1),\ldots,h(L-1),0,\ldots,0] *_N [x(0),x(1),\ldots,x(N-1)]$$

- Where $*N$ indicates the circular convolution of modulo N .
- Therefore, the output Y can be given by,

$$Y = h * Nx$$

- Taking the DFT of y(n) at the output, we get,

$$Y(k) = H(k)X(k),\ 0 \le k \le (N-1) \qquad \ldots(2.4.7)$$

- Where,

$Y(k)$ = N-point DFT of y(n)

$X(k)$ = N-point DFT of x(n)

$x(n)$ = IDFT of X(n)

- Therefore, the DFT of the samples x(n) gives back the original transmitted symbols X(n).
- The coefficients H(k) indicates the DFT of the zero-padded channel filter,

$$h(0), h(1),\ldots,h(L-1), \underbrace{0,\ldots,0}_{(N-L)}$$

- Thus, Equation (2.4.7) represents the flat-fading channel across the $k^{th}$ subcarrier in the OFDM system.
- Here Y(k) indicates the output symbol, while H(k) indicates the equivalent flat-fading channel coefficient.
- This is true for each subcarrier k, i.e., for $0 \le k \le (N-1)$.
- Thus in OFDM the conversion of the frequency-selective fading channel into a group of narrowband flat-fading channels takes place.
- If a single carrier communication system is used and the symbols X(0), X(1),..., X(N – 1) are directly transmitted then the received symbol y(n) can be given by,

$$y(n) = h(0)X(n) + h(1)X(n-1) + \ldots + h(L-1)\,X(n-L+1)$$

- Each symbol X(n) will experience inter-symbol interference of (L – 1) past symbols.
- Therefore, using OFDM, it is possible to eliminate the inter-symbol interference due to frequency-selective nature of the channel.
- The set of parallel flat-fading channels can be summarized as ,

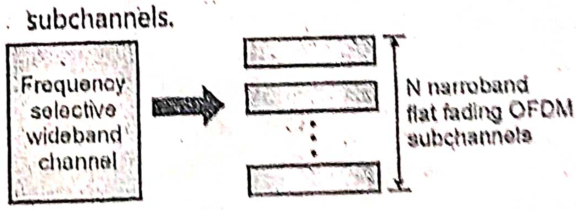
$$Y(0) = H(0)\,X(0)$$

$$Y(1) = H(1)\,X(1)$$

$$\vdots$$

$$Y(N-1) = H(N-1)X(N-1)$$

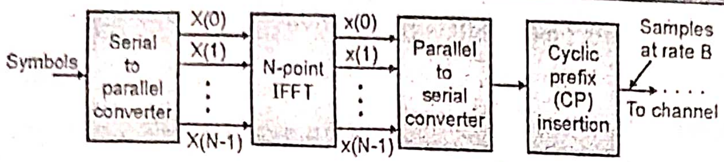
- Fig. 2.4.3 shows schematic representation of conversion of the frequency-selective wideband channel into N narrowband flat-fading subchannels.




(0-1709)Fig. 2.4.3 : OFDM parallel sub-channels

### 2.4.2 OFDM Transmitter with Cyclic Prefix :

- Fig. 2.4.4 shows the OFDM transmitter with Cyclic prefix.

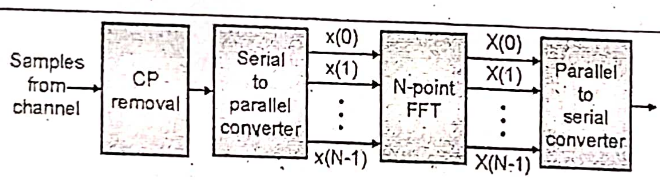



(O-1710)**Fig. 2.4.4 : OFDM transmitter with Cyclic prefix**

- The information symbols are parallelized in N different sub-streams by using serial to parallel converter.
- Each sub-stream will modulate a separate carrier through the N-point IFFT modulation block.
- A cyclic prefix is inserted which eliminates the inter-symbol (ISI) and inter-block interference (IBI).
- This cyclic prefix of length $L_c$ is a circular extension of the IFFT-modulated symbol and it is obtained by copying the last $L_c$ samples of the symbol in front of it.
- The information symbols are back-serial converted, forming an OFDM symbol that will modulate a high-frequency carrier before its transmission through the channel.

### 2.4.3 OFDM receiver with Cyclic Prefix :

- Fig. 2.4.5 shows the OFDM transmitter with Cyclic prefix. The inverse operations are performed at the receiver.




(O-1711)**Fig. 2.4.5 : OFDM receiver with Cyclic prefix**

- The information symbols are down-converted to the baseband and the cyclic prefix is removed. The coherent FFT demodulator will ideally retrieve the exact form of transmitted symbols.
- Finally, the parallel to serial block converts this parallel data into a serial stream to recover the original input data.
- By considering the noise at the receiver, the received symbol Y(k) can be expressed as,

$$Y(k) = H(k)X(k) + N(k) \quad ...(2.4.8)$$

- Where N(k) is the noise across the $k^{th}$ subcarrier.
- The zero-forcing detector for the subcarrier is a simple detection scheme for X(k) and is given by,

$$\hat{X}(k) = \frac{1}{H(k)} Y(k) = X(k) + \underbrace{\frac{N(k)}{H(k)}}_{\tilde{N}(k)}$$

- For a basic modulated transmission like BPSK or QPSK, the coherent or matched filter detector can be obtained by multiplying with the complex conjugate of H (k) i.e. H*(k) and is given by,

$$H^*(k)Y(k) = |H(k)|^2 X(k) + \underbrace{H^*(k)N(k)}_{\tilde{N}(k)}$$

- Minimum mean square error (MMSE) detector can also be used for this purpose.
- The equation for the MMSE receiver across the $k^{th}$ subcarrier in OFDM system is given by,

$$\hat{X}_{MMSE}(k) = \frac{H^*(k)}{|H(k)|^2 + \sigma_n^2} Y(k)$$

### 2.4.4 Impact of Cyclic Prefix on Data Rate :

- The transmitted samples x(n) with the cyclic prefix is given by,

$$\underbrace{x(N-L_c),\, x(N-L_c+1),\, \ldots,\, x(N-1)}_{\text{Cyclic prefix}}\ \underbrace{x(0),\, x(1),\, \ldots,\, x(N-1)}_{\text{Current block}}$$

(0-1675)

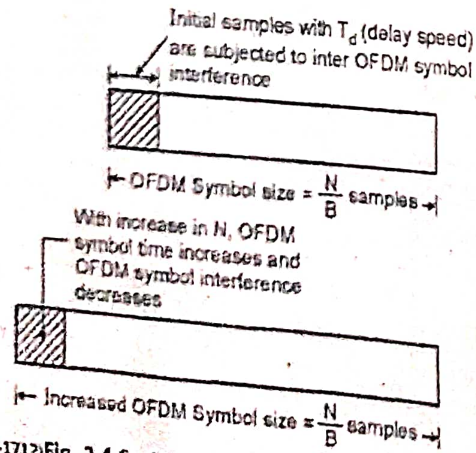
- The minimum length of the cyclic prefix is L – 1.
- As L – 1 is the delay spread of the wireless channel it follows that the length of the cyclic prefix should be greater than the delay spread of the wireless channel.
- However, since the samples in the end, i.e., x(N – L), x(N – L + 1), . . . , x(N – 1) are repeated in the beginning, they do not contain any additional information.
- Hence, the effect of the insertion of a long CP is lost in the throughput of the system.
- The loss in efficiency can be calculated as,

$$\text{Loss in efficiency} = \frac{\text{Cyclic prefix(CP)}}{\text{Total OFDM symbol length}} = \frac{L-1}{N+L-1}$$

- Due to very large block length N, we have,

$$\lim_{N \to \infty} \frac{L-1}{N+L-1} = 0$$

- Thus, with increase in the number of subcarriers N, the loss in throughput becomes 0 for a fixed length of the delay spread L.
- With increase in the number of subcarriers N, the symbol time N/B increases. This is shown in Fig. 2.4.6.




(0-1712)Fig. 2.4.6 : Inter OFDM symbol interference with increasing OFDM symbol time

- Increase in the number of subcarriers N re... increasing the symbol time of OFDM symb... restricts the ISI to a small fraction of the... symbol block, i.e., the fraction L / ... progressively smaller.
- With increase in the block length N, the de... delay at the receiver increases because one ... wait for arrival of the complete block ... samples before it can be demodulated.
- Hence, there is a trade-off between increa... versus decoding delay.
- We have seen that the duration of the cycl... should be greater than the delay ... Therefore, we need,

$$L_c \times T_s \geq T_d$$

- Where $T_s$ is the sample time and $T_d$ is the ... spread.

$$\text{Sample time } T_s = 1/B$$

- Where B is the total bandwidth of the system ... $T_d = 1/B_c$, where $B_c$ is the coherence ban... of the system.
- Substituting these values in Equation (2.4...) get,

$$L_c \geq \frac{T_d}{T_s} = \frac{B}{B_c}$$

- Combining Equation (2.4.10) with the con... $N >> L_c$ for efficiency in terms of the ef... data rate, we get,

$$N >> L_c \geq \frac{B}{B_c}$$

- This expression can be rearranged as $B_c >> ...$
- This is the same condition for frequen... fading across each subcarrier.
- This means the subcarrier bandwidth (B... required to be much less than the coh... bandwidth $B_c$.
- Therefore, the properly designed OFDM ... converts a frequency-selective fading cha... a set of parallel narrowband flat-fading ... across the subcarriers.

## 2.5 OFDM Design Example :

- In this section, we will illustrate an OFDM system design example
- Let us consider a practical WiMAX example to illustrate the effect of the various parameters in the design of a OFDM system.

**Various parameters in the design of a OFDM system :**

- We know that, WiMAX is a well-known 4G wireless standard.
- WiMax has total number of subcarriers N = 256, with a bandwidth of 15.625 kHz per subcarrier.

$$\therefore \left(\frac{B}{N}\right) = 15.625 \text{ kHz}$$

$$\therefore B = N \times 15.625 = 256 \times 15.625$$

$$\therefore B = 4 \text{ MHz}$$

- The subcarrier bandwidth is less than the coherence bandwidth, i.e., $B_S$ = 15.625 kHz << $B_C$ = 250 kHz.
- So each subcarrier experiences frequency flat fading.

**OFDM symbol time without CP :**

- The OFDM symbol time without CP is given by,

$$\left(\frac{N}{B}\right) = \left(\frac{256}{4 \times 10^6}\right) = 64 \text{ µs}$$

- The OFDM symbol time corresponding to the N = 256 IFFT samples is 64 µs.

**OFDM symbol time with cyclic prefix :**

- The cyclic prefix used in the WiMAX is 12.5 % of the symbol time.

$$\therefore \text{Duration of cyclic prefix} = 12.5\% \times \text{Symbol time}$$

$$= \frac{12.5}{100} \times 64 \text{ µs}$$

$$= 8 \text{ µs}$$

- ∴ Total transmitted OFDM symbol duration with cyclic prefix is 64 µs + 8 µs = 72 µs.

**Number of samples in the CP :**

- The number of samples in the CP is given by,

$$\text{Samples in CP} = \frac{\text{CP duration}}{\text{Sample time}}$$

$$= \frac{8 \text{ µs}}{1/B}$$

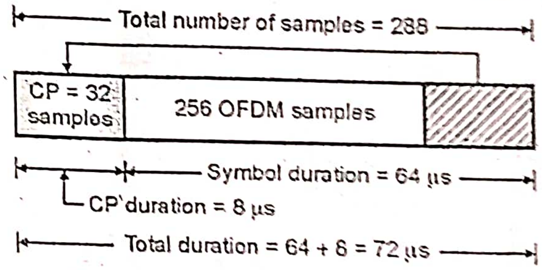
$$= 8 \times 10^{-6} \times 4 \times 10^6$$

$$= 32$$

∴ Length of the cyclic prefix $L_c$ = 32 samples

∴ Total number of samples = 256 + 32 = 288

- WiMAX OFDM symbol in terms of the regular samples and cyclic prefix is as shown in Fig. 2.5.1.




(O-1713)**Fig. 2.5.1 : WiMAX OFDM symbol with cyclic prefix**

**Loss in spectral efficiency :**

- The loss in spectral efficiency is given by,

$$\text{Loss in spectral efficiency} = \frac{\text{Length of the cyclic prefix } L_c}{\text{Total number of samples}}$$

$$= \frac{32}{288} = 11.1\%$$

- This loss in spectral efficiency is due to the insertion of the cyclic prefix.

### 2.5.1 Bit-Error Rate (BER) for OFDM :

- The OFDM subcarrier system model given in Equation (2.5.1) is as follows,

$$Y(k) = H(k)X(k) + N(k) \quad \quad ...(2.5.1)$$

- Here N(k) denotes the subcarrier noise obtained from the FFT of the noise samples at the output of the receiver.
- The subcarrier noise is given by,

$$N(k) = \sum_{m=0}^{N-1} n(m)\, e^{-j2\pi(km/N)}$$

- Where, N is the number of subcarriers, and n(0), n(1), . . . , n(N – 1) are additive noise samples for each of the output samples y(0), y(1) . . . . , y(N – 1).

- Now we will deduce the statistical properties of these noise samples N(k) required to characterize the Bit Error Rate(BER) performance of the OFDM system.
- The noise N(k) is Gaussian in nature as it is the linear combination of Gaussian noise samples n(0), n(1),..., n(N – 1).
- The mean or expected value of N(k) is given by,

$$E\{N(k)\} = E\left\{\sum_{m=0}^{N-1} n(m)\, e^{-j2\pi(km/N)}\right\}$$

$$= \sum_{m=0}^{N-1} E\{n(m)\}\, e^{-j2\pi(km/N)}$$

- The variance $\sigma_N^2$ of the noise sample N(k) is given by,

$$\sigma_N^2 = E\{|N(k)|^2\}$$

$$= E\left\{\left(\sum_{m=0}^{N-1} n(m)\, e^{-j2\pi(km/N)}\right)\left(\sum_{l=0}^{N-1} n(l)\, e^{-j2\pi(kl/N)}\right)^*\right\}$$

$$= E\left\{\sum_{m=0}^{N-1}\sum_{l=0}^{N-1} n(m)\, n^*(l)\, e^{-j2\pi(m-1)(k/N)}\right\} \quad ...(2.5.2)$$

- As the noise samples n(m) are independent identically distributed Gaussian of variance $\sigma_N^2$, it follows that $E\{n(m)\, n^*(l)\} = 0$ if $m \neq l$ and $\sigma_N^2$ if $m = l$.
- Thus the Equation (2.5.2) for the noise variance can be modified as,

$$\sigma_N^2 = \sum_{m=0}^{N-1}\sum_{l=0}^{N-1} E\{n(m)\, n^*(l)\}\, e^{-j2\pi(m-1)(k/N)}$$

$$\sigma_N^2 = \sum_{m=0}^{N-1} \sigma_n^2 = N\sigma_n^2$$

- Now assume that the nature of each of the channel taps h(0), h(1), ..., h(L – 1) is Rayleigh fading.
- That means it has a complex symmetric Gaussian distribution of mean 0 and variance 1.
- Thus, the channel coefficient across the $k^{th}$ subcarrier is given by,

$$H(k) = \sum_{m=0}^{N-1} h(m)\, e^{-j2\pi(km/N)} \quad ...(2.5.3)$$

- H(k) in Equation (2.5.3) is a linear combination of Gaussian random variables h(k), $0 \leq k \leq (L-1)$.
- Hence, H(k) is complex Gaussian. That means it has a Rayleigh fading envelope.
- H(k) has a zero mean as each h(k) is zero mean.
- Similar to the development of the noise variance above, it follows on similar lines that the channel power gain $E(|H(k)|^2)$ is given by,

$$E(|H(k)|^2) = E\left(\left|\sum_{m=0}^{L-1} h(m)\, e^{-j2\pi(km/N)}\right|^2\right)$$

$$= \sum_{m=0}^{L-1} E(|h(m)|^2)\, |e^{-j2\pi(km/N)}|^2$$

$$= L$$

- The system model in Equation (2.5.1) represents a standard Rayleigh fading channel of power gain L with receiver noise N(k) of variance $N\sigma_n^2$.
- So, the average Signal to Noise Ratio (SNR) is $\dfrac{LP}{N\sigma_n^2}$.
- The expression for BER for that of a Rayleigh fading wireless channel is given by,

$$BER_{OFDM} = \frac{1}{2}\left(1 - \sqrt{\frac{(LP/N\sigma_n^2)}{2 + (LP/N\sigma_n^2)}}\right)$$

### 2.5.2 Advantages of OFDM :

- The advantages of OFDM are as follows :
  1. OFDM makes efficient use of the spectrum by allowing overlap.
  2. OFDM divides the channel into narrowband flat fading sub-channels, it is more resistant to frequency selective fading as compared to single carrier systems.
  3. OFDM eliminates ISI and IFI with the use of a cyclic prefix.
  4. Due to the frequency selectivity of the channel, one can recover the lost symbols by using adequate channel coding and interleaving.

5. Channel equalization in OFDM becomes simpler as compared to single carrier systems that uses adaptive equalization techniques.
6. It is possible to use maximum likelihood decoding with reasonable complexity.
7. OFDM becomes efficient to implement the modulation and demodulation functions by using FFT techniques.
8. As compared to single carrier systems, OFDM is less sensitive to sample timing offsets.
9. It provides good protection against co-channel interference and impulsive parasitic noise.

### 2.5.3 Disadvantages of OFDM :

- The disadvantages of OFDM are as follows :
  1. OFDM requires RF power amplifiers with a high peak to average power ratio because it has a noise like amplitude with a very large dynamic range.
  2. OFDM system is more sensitive to carrier frequency offset and drift due to leakage of the DFT.
  3. It is sensitive to Doppler shift.
  4. It needs linear transmitter circuitry, which suffers from poor power efficiency.
  5. It suffers loss of efficiency caused due to cyclic prefix.

## 2.6 Introduction to Multi-antenna Technologies :

- Usually there is one input and one output providing connection between the network and mobile for a radio channel.
- In the mobile antenna systems, an extra antenna is added on the base station uplink for macro deployment.
- Macro deployment is obtained through a cross polarized antenna i.e. one antenna and two inputs/outputs.
- In order to obtain better resistance against fading on the uplink, the base station connects transmitter to one port and receiver to other port.
- The base station does the micro-diversity processing to improve the quality of signal by using algorithms like maximal ratio combining.
- To maximize the throughput over the radio link,the signals are combined from scattering and multipath in 4G systems.
- Multi-antenna techniques are used to improve the capacity of mobile communication systems without increasing the spectrum.
- To achieve this, Multi-antenna system uses smart antenna systems and multiple input multiple output (MIMO) .

## 2.7 Smart Antennas / Intelligent Antennas :

**Definition :**

- Smart antennas are arrays of antenna elements that change their antenna pattern dynamically in order to adjust to the noise, interference in the channel that affects the signal of interest.
- It is a system which involves multiple antenna elements and a digital signal processor to adjust the radiation.
- Smart antenna dynamically reacts to its environment to provide better signals and frequency usage for wireless communications.
- A smart antenna is basically a combination of multiple antenna elements (also called as antenna array).
- With smart antennas it is possible to optimize the radiation / reception pattern according to need of the application.

**Purpose of smart antennas :**

- Smart antennas can be used for the following purposes :
  1. Increase of coverage
  2. Increase of capacity

5. Channel equalization in OFDM becomes simpler as compared to single carrier systems that uses adaptive equalization techniques.
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**Purpose of smart antennas :**

- Smart antennas can be used for the following purposes :
  1. Increase of coverage
  2. Increase of capacity

3. Improvement of user position estimation
4. Improvement of link quality
5. Reduction in delay dispersion

### 2.7.1 Principle of Smart Antenna :

- Fig. 2.7.1 shows the principle of smart antenna.

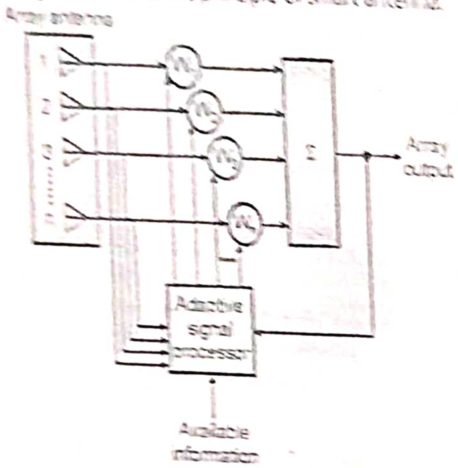



Fig. 2.7.1 : Smart antenna system

- In smart antennas, the signals received at the different antenna elements are multiplied with their complex weights W.
- The antenna selects the summed up weights adaptively.
- The smart antenna is also known as adaptive array elements.
- In order to transmit and receive the data adaptively, smart antennas combine an antenna array with digital signal processing ability.
- To adjust to the noise interference in the channel, smart antennas dynamically modify their antenna pattern.
- Smart antennas combinesarray gain, diversity gain and interference suppression to improve the capacity of the wireless systems.
- Improved capacity results in higher data rate.
- In order to reduce the multipath fading problems, smart antennas use multipath wave propagation.
- Smart antennas work by using two antennas and a signal processor.
- Smart antennas can focus on individual signa... comparing the signal strengths received by ... antennas.
- In mobile communication systems, the ... station plays the role of the listener and ... mobile equipment plays the role of signal sou...
- The function of a digital signal proce... equipped with an antenna array is to ad... various system parameters and to focus on ... required signal while cancelling out ... interferences.
- The smart antenna systems can electroni... adapt to the RF environment. Multi... propagation is obtained through scattering a... reflection.

### 2.7.2 Functions of Smart Antenna :

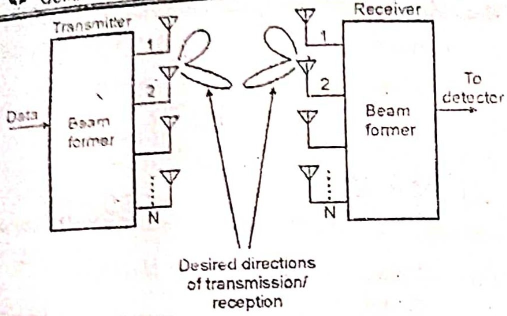
- Main two functions of a smart antenna are follows :

1. **Estimation of Direction of arrival (DOA) :**

- The smart antenna system computes the direc... of arrival of the signal.
- DOA is estimated using techniques like MU... (Multiple Signal Classification), estimation ... signal parameters through rotational invaria... techniques (ESPRIT) algorithms, Matrix Pe... method or one of their derivatives.
- They involve finding a spatial spectrum of t... antenna/sensor array, and calculating the D... from the peaks of this spectrum.

2. **Beamforming Method :**

- Fig. 2.7.2 shows the concept of beamforming.
- This method is used to create the radiat... pattern of the antenna array.
- They create antenna array by addi... constructively the phases of the signals in t... direction of the desired targets/mobiles and nullify the pattern of the targets/mobiles that ... undesired/interfering targets.




(G-2733) **Fig. 2.7.2 : Concept of beamforming**

### 2.7.3 Types of Smart Antenna Systems :

- There are two major configurations of smart antennas :
  1. Switched beam antenna
  2. Adaptive array antenna

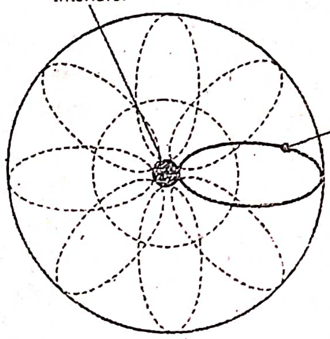
**1. Switched beam antenna :**

**Definition :**

- The antennas which form the multiple fixed beams with heightened sensitivity in some particular directions are known as Switched beam antennas.
- It is extension of cell sectoring as each sector is subdivided into smaller sectors.
- In this configuration of smart antenna, a finite number of fixed, predefined patterns or combining schemes (sectors) are available.

**Working :**

- The switched beam antenna systems detect signal strength; select from one of several predetermined, fixed beams and switch from one beam to other as the cellular phone (mobile) moves throughout the sector.
- The switched beam antennas combine the outputs of multiple antennas in such a way that they form directional beams with high spatial selectivity.
- To focus on an individual subscriber, switched beam antenna system use some predefined radiation patterns.
- After detecting signal strength, smart beam antenna system switches between thousands of predetermined patterns to match the best communication link.
- As the subscriber moves, the radiation pattern is switched and the best is selected.
- Fig. 2.7.3 shows the basic mechanism of a switched beam antenna system. Individual subscriber is denoted by S.




(G-2718) **Fig. 2.7.3 : Switched beam system**

- In a splitting system, macrocells are divided into a few microcells.
- Each microcell is equipped with different types of preset radiation patterns.
- When a subscriber enters a macrocell, the microcells with the strongest signals are determined and the corresponding beam is used for the maximum output power.
- As shown in Fig. 2.7.3, the sector is filled with predetermined patterns.
- When the subscriber enters into a specific area, only the corresponding pattern is selected.
- The system continuously monitors the subscriber and switches from beam to beam for the best output.

**Advantages of SBAs :**

1. Single or multiple fixed directional beams.
2. Simple algorithms are used for beam selection.

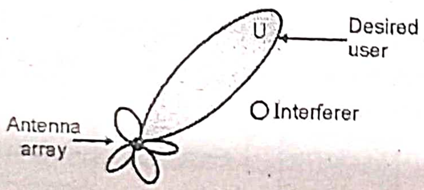
3. Significant increase in coverage and capacity.
4. Lower installation costs and less complexity.

**Disadvantages of SBAs :**

1. These antennas have non uniform gain with respect to angle.
2. Locking into the wrong beam due to multi path or interference.
3. Limited interference suppression.

2. **Adaptive array antenna :**

- Adaptive array antennas are the most advanced smart antenna approach as on date.
- In this system, multiple antennas are used both in the transmitting and receiving side of a communication link to adaptively optimize the transmission over the channel.
- An AAS system focus its transmit energy towards a receiver, and while receiving, it can focus towards the transmitter.
- Beamforming technique is used in AAS.
- Fig. 2.7.4 shows the basic principle of Adaptive array antenna system.




(G-2719) **Fig. 2.7.4 : Adaptive array antenna**

- Beam forming allows directional signal transmission or reception without manually steering the antennas.
- In the beam forming, several transmitters are set apart from each other.
- All transmitters transmit the same signal with different phase difference and delay.
- The interference occurred in all the transmitters can be used to guide a signal to a specific direction.
- The signal processing algorithms are used to locate and track the different types of signals, to reduce the interference and maximize the required signal reception.
- In an AAS, signals can be focused simultaneously on many remote devices.
- ASS controls the shape of these beams in such a way that the signal between the transmitter and receiver is always maximum.
- This system can increase link quality by combining the effects of multipath propagation and exploiting different data streams from different antennas.

**Advantages of AAS :**

1. Increased coverage
2. Increased capacity
3. Cost reduction
4. Improved link quality and reliability
5. Increased Spectral efficiency

**Disadvantages of AAS :**

1. Complex transceiver mechanism
2. Need of resource management
3. Physical size of the antennas

### 2.7.4 Features of Smart Antennas :

- The important features of the smart antennas (antenna arrays) are as follows :

1. Optimized radiation pattern.
2. They can be used for beam forming (extremely directional antenna).
3. They are adaptable to changes in signal power, transmission conditions and many other signal propagation effects.
4. Smart antennas can provide the required coverage.
5. Smart antennas reduce multipath fading and other multipath propagation effects.
6. Smart antennas are power efficient because the inputs are combined to multiple elements in order to optimize the available processing gain in the downlink.
7. It improves the signal to interference ratio of the received signals.

8. With the help of smart antennas, space division multiple access adopts to the radio environment.

- The handset antennas of today's mobile phone are omnidirectional in nature.

### 2.7.5 Advantages of Smart Antenna Systems :

- The advantages of the smart antennas (antenna arrays) are as follows :
  1. In smart antennas, focus on the energy sent out into the cell increases base station range and coverage.
  2. Lower power requirements also allows a greater battery life and smaller/lighter handset size.
  3. A Smart antenna can reduce the effective delay spread of the channel, enabling higher bit rates to be supported without the use of an equalizer, improved bit error rate.
  4. Smart antennas improves the capacity by precise control of signal nulls quality and mitigation of interference combine to frequency reuse reduce distance (or cluster size).
  5. A smart antenna lowers amplifier costs, power consumption.
  6. Smart antennas are highly reliable.

### 2.7.6 Disadvantages of Smart Antenna Systems :

- The disadvantages of the smart antennas (antenna arrays) are as follows :
  1. **Cost :** The cost of such a device will be more, not only in the electronics section, but also in the power.
  2. **Size :** To make this method to be efficient large base stations are required. This will increase the size.
  3. **Diversity :** diversity becomes a big problem when multiple mitigation is needed. The terminals and base stations should have multiple antennas.

### 2.7.7 Applications of Smart Antenna Systems :

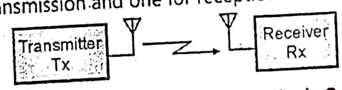
- Smart antenna technologies can be used to improve most wireless applications containing:
  1. Wi-Fi a/b/g access points and clients
  2. Mobile video
  3. Mobile broadband/gaming
  4. Satellite/digital radio
  5. GPS
  6. 3G Wireless
  7. WiMax
  8. RFID

## 2.8 Multi-antenna Techniques :

- Following are the types of Multi-antennas :
  1. SISO (Single-input Single-output)
  2. SIMO (Single-input Multiple-output)
  3. MISO (Multiple-input Single-output)
  4. MIMO (Multiple-input Multiple-output)

**Single Input Single Output (SISO) :**

- SISO stands for Single Input and Single Output. As shown in Fig. 2.8.1, it consists of one antenna for transmission and one for reception.

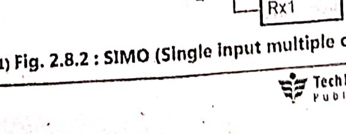



(G-2720) Fig. 2.8.1 : SISO (Single Input Single Output)

- SISO is a conventional radio system where neither the transmitter nor receiver has multiple antenna.

**Single Input Multiple Output(SIMO) :**

- SIMO stands for Single Input and multiple Outputs. It consists of one antenna for transmission and multiple antennas for reception.
- Here one signal is transmitted and two or more are received.
- A typical SIMO structure is shown in Fig. 2.8.2.

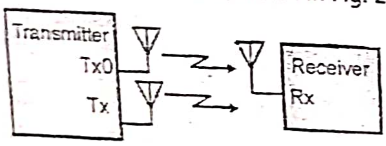



(G-2721) Fig. 2.8.2 : SIMO (Single Input multiple output)

- Receive diversity is used in the SIMO antenna technique.
- While receiving a signal, the antenna can either select the strongest signal or can join all the signals received in different antennas is known as receive diversity.
- As compared to SISO systems SIMO systems provide more throughput with micro-diversity.

**Multiple Input Single Output (MISO) :**

- In the MISO (Multiple-input Single-output) antenna technique, multiple antennas are used in the transmitter while a single antenna is used in the receiver.
- This is a comparatively new technology. MISO has been a favorite as only multiple antennas need to be installed in the base station (BS).
- A typical MISO structure is shown in Fig. 2.8.3.



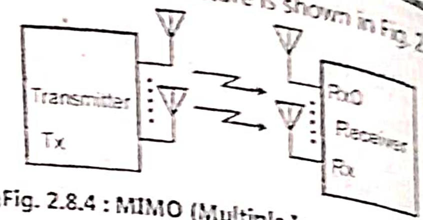

(G-2722) **Fig. 2.8.3 : MISO (Multiple input single output)**

- Transmit diversity is used in the MISO antenna technique.
- Transmit antenna diversity is a controlled diversity technique which provides spatial repetition of transmitted signals through different antennas.
- A method known as STC (Space Time Coding) is implemented at the transmitter with multiple antennas.
- STC allows the transmitter to transmit signals simultaneously in time and space, which means the data can be transmitted by multiple antennas at different times repeatedly.

**Multiple Input Multiple Output (MIMO) :**

- MIMO consists of multiple antennas in both the transmitter and the receiver.
- They have capability of combining the SIMO and MISO technologies, MIMO increase capacity by using Spatial Multiplexing (SM).

- A typical MIMO structure is shown in Fig. 2.8.4




(G-2723) **Fig. 2.8.4 : MIMO (Multiple Input Multiple Ou...**

## 2.9 MIMO (Multiple Input Multiple Output) Systems :

**Principle :**

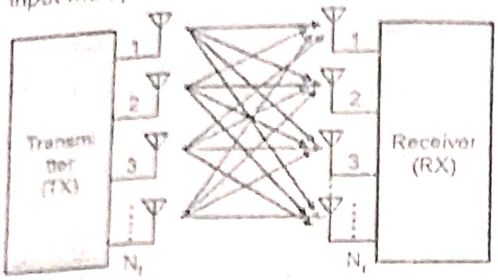
- The Multiple-Input Multiple-Output (M... system uses multiple antennas on both transmitter and receiver.
- They have dual capability of combining the S... and MISO technologies.
- They can also increase capacity by using Sp... Multiplexing (SM).
- The MIMO method has some clear advanta... over Single-input Single-output (SISO) metho...
- The fading is greatly eliminated by sp... diversity, and low power is required as compa... to other techniques in MIMO.
- MIMO systems are used to obtain high sp... and throughput.

**Types of MIMO :**

- The Multiple Input multiple Output (MI... method can be divided into various ty... depending on uses.
- MIMO is basically the combination of all multiple antenna techniques such as SISO, SI... and MISO.
- It can use the beam forming or the sp... Multiplexing methods.
- MIMO can be categorized into the following types :
  1. Multi-antenna types and
  2. Multi-user types
- Multi-antenna types are as follows : SISO (Si... input Single-output), SIMO (Single-input Mu... output) and MISO (Multiple-input Single-ou...

**Block diagram :**

- Fig. 2.9.1 shows the block diagram of multiple-input multiple-output system.

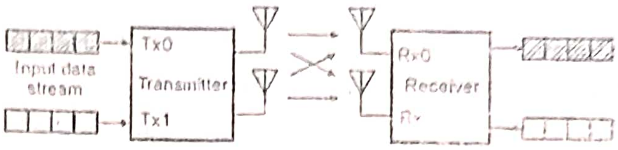



(G-2736) **Fig. 2.9.1 : Block diagram of a multiple-input multiple-output system**

- It consists of a transmitter with $N_t$ number of transmitting antennas and a receiver with $N_r$ number of receiving antennas as shown.
- The data stream at the transmitter (Tx ) enters an encoder, and the encoded outputs are applied to $N_t$ transmitting antennas.
- Multiple transmitting antennas transmit the signal through the wireless propagation channel, which is assumed to be **quasi-static** and **frequency-flat**.
- The meaning of the term quasi-static is that the coherence time of the channel is extremely long due to which "a large number" of bits can be transmitted within this time.

### 2.9.1 A 2 x 2 MIMO :

- Refer Fig. 2.9.2. In a MIMO system, "Input" and "output" are the variables that describe the transmission medium or channel between the transmitter and the receiver.
- These two words are being used with respect to the transmission medium.
- That means, a base station with two transmitting antennas would give the channels MI (Multiple Input) and at the receiver with two antennas receives two outputs from the channel to constitute the MO (Multiple Output).
- The data streams transmitted and received here are assumed to mutually independent.
- The MIMO in Fig. 2.9.2 is known as a 2 x 2 MIMO as two transmitting and two receiving antennas are used.




(G-2737)**Fig. 2.9.2 : A 2 x 2 MIMO with two transmitters and two receivers with high speed independent data streams**

- The multiple parallel streams provided by a MIMO system are decoded by scattering produced by cluster.
- Channel estimation methods are used to separate the individual channels at the receiver end.
- Redundant data required for control or error control purpose is transmitted on the channels with diversity MIMO systems like **STBC** (Space Time Block Code) and **SFBC** (Space Frequency Block Code).
- With two antennas at all the antenna sites, the typical MIMO is a 2 x 2 MIMO which is suitable for 4G indoor system.
- The data speed can be doubled if the scattering is perfect with no correlation between the signal paths.
- However practically it is not possible to double the data speed because of interferences in buildings.

**Performance of MIMO :**

- MIMO systems provide better comparison compared to SISO (Single Input Single Output) systems.
- In open areas MIMO indoor performance can be increased by 30% as compared to SISO systems and in high scattering regions the MIMO systems indoor performance can be around 100 %.

- Thus, we can obtain **high throughput** with MIMO.
- If the order of MIMO is increased, to say 4 x 4 MIMO then it would require four antennas on the system and mobile.
- This would be practically difficult. It would need strong scattering environment covering multiple paths. and increasing the system capacity or coverage.
- The STBC and STTC (Space Time Trellis Code) processing is used in the 4G systems so as to improve the signal quality diversity.

### 2.9.2 Parameters for Maximum Throughput :

- The systems can be optimized to obtain maximum throughput by considering the following parameters :

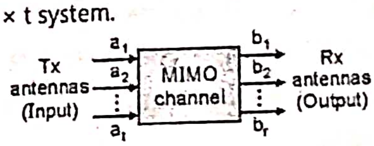
1. **Signal quality :**
   - On the MIMO paths, the signal to noise ratio (S/N) should be high enough for maintaining high modulation performance of 64 QAM.
2. **Low noise factor on uplink :**
   - We need to have a system with good uplink performance and low noise factor for indoor applications.
   - This keeps the mobile transmit power low.
3. **Ease of installation :**
   - The systems should be deployed to provide maximum throughput.
   - It is possible to obtain 85% performance with implementation in 95% of buildings and 95% performance with implementation in 10 % buildings.
4. **Uniform coverage :**
   - The system should provide uniform coverage in order to obtain maximum performance.

### 2.9.3 Space Time Codes (STCs) :

- We need to use the Space time codes **(STCs)** to maximize diversity, coding gain and throughput in order to compensate for the channel fading and decrease the bit error rate.
- There are following two types of space time codes used in MIMO systems :
  1. Space time block code **(STBC)** and
  2. Space time trellis code **(STTC)**
- The space time block codes **(STBC)** are transmitted using a block structure.
- It supports a simple decoding at the receiver end.
- With STBC the system can transmit multiple copies of the data over a number of antennas in order to improve the data transfer reliability.
- The space time trellis codes **(STTEs)** are the codes that transmit multiple redundant copies of convolutional or trellis code distributed over time and a number of transmit antennas.
- The receiving antenna would reconstruct the original transmitted data using the multiple redundant copies.
- The space time trellis code provides both diversity and coding gain as compared to the space time block codes.
- The STTCs have a good bit-error performance. However their encoding and decoding methods are complex.
- They require a virterbi decoder at the receiver end.

## 2.10 MIMO Model :

- Fig. 2.10.1 shows a MIMO wireless system which consists of t transmit antennas and r receive antennas. Such a MIMO system is also referred as an r × t system.




(0-1658)**Fig. 2.10.1 : MIMO system input-output schematic**

- Let $a_1, a_2 ......a_t$ are the t symbols transmitted from the t transmit antennas in the MIMO system, i.e. $a_i$

- The $a_i$ denotes the symbol transmitted from the $i^{th}$ transmit antenna with $1 \le i \le t$.
- The t-dimensional vector is formed by stacking of transmit symbols. It is also called as the transmit vector and is given by,

$$a = \begin{bmatrix} a_1 \\ a_2 \\ \vdots \\ a_t \end{bmatrix}$$

(O-1656)

- Let $b_1, b_2 \ldots b_r$ are the r received symbols across the r receive antennas, which can be stacked as the r-dimensional receive symbol vector and is given by,

$$b = \begin{bmatrix} b_1 \\ b_2 \\ \vdots \\ b_r \end{bmatrix}$$

(O-1657)

- Let $h_{ij}$ is the complex coefficient representing the fading channel coefficient between the $i^{th}$ receive antenna and the $j^{th}$ transmit antenna.
- There are rt channel coefficients available in this wireless scenario that correspond to all possible combinations of the r receive antennas, and t transmit antennas.
- The r × t channel coefficients are arranged in a matrix form as follows :

$$H = \begin{bmatrix} h_{11} & h_{12} & \cdots & h_{1t} \\ h_{21} & h_{22} & \cdots & h_{2t} \\ \vdots & \vdots & \ddots & \vdots \\ h_{r1} & h_{r2} & \cdots & h_{rt} \end{bmatrix}$$

(O-1659)

- Here the r × t dimensional matrix H is called as the MIMO channel matrix.
- Let $n$ is the additive noise at the receive antenna and it is denoted by $n_i$ i.e., $n_1, n_2 \ldots, n_r$.
- The vector form representation of the net MIMO input output system model is :

$$\underbrace{\begin{bmatrix} b_1 \\ b_2 \\ \vdots \\ b_r \end{bmatrix}}_{b} = \underbrace{\begin{bmatrix} h_{11} & h_{12} & \cdots & h_{1t} \\ h_{21} & h_{22} & \cdots & h_{2t} \\ \vdots & \vdots & \ddots & \vdots \\ h_{r1} & h_{r2} & \cdots & h_{rt} \end{bmatrix}}_{H} \underbrace{\begin{bmatrix} a_1 \\ a_2 \\ \vdots \\ a_t \end{bmatrix}}_{a} + \underbrace{\begin{bmatrix} n_1 \\ n_2 \\ \vdots \\ n_r \end{bmatrix}}_{n}$$

(O-1660)

...(2.10.1)

- This can be represented using matrix notation as,

$$b = H \cdot a + n$$

- From Equation (2.10.1), the receive symbol $b_1$ is given as,

$$b_1 = h_{11}a_1 + h_{12}a_2 + \ldots h_{1t}a_t + n_1 \quad \ldots(2.10.2)$$

- From Equation (2.10.2) it can be seen that all the symbols $a_1, a_2, \ldots, a_t$ interfere at $b_1$ received at the receive antenna 1.
- Similarly, the receive symbol $b_2$ is given by,

$$b_2 = h_{21}a_1 + h_{22}a_2 + \ldots + h_{2t}a_t + n_2 \quad \ldots(2.10.3)$$

- This is true for all the receive antennas, that means at each receive antenna i, the receive symbol $b_i$ is a linear sum of all the transmit symbols $a_1, a_2, \ldots, a_t$ from the t transmit antennas, observed in additive noise $n_i$.

### 2.10.1 SIMO System Model :

- In case of a single transmit antenna (i.e. t=1) and multiple receive antennas, it is a Single-Input Multiple-Output (SIMO) system or the receive diversity system.
- The system model of SIMO is given by,

$$\underbrace{\begin{bmatrix} b_1 \\ b_2 \\ \vdots \\ b_r \end{bmatrix}}_{b} = \underbrace{\begin{bmatrix} h_1 \\ h_2 \\ \vdots \\ h_r \end{bmatrix}}_{h} a + \underbrace{\begin{bmatrix} n_1 \\ n_2 \\ \vdots \\ n_r \end{bmatrix}}_{n}$$

(O-1661)

### 2.10.2 MISO System Model :

- In case of a single receive antenna (i.e., r = 1) and multiple transmit antennas, it is a Multiple-Input Single-Output (MISO) system model or a transmit diversity system.
- The system model for MISO is given by :

$$b = \underbrace{\begin{bmatrix} h_1 & h_2 & \cdots & h_t \end{bmatrix}}_{h^T} \underbrace{\begin{bmatrix} a_1 \\ a_2 \\ \vdots \\ a_t \end{bmatrix}}_{a} + n$$

(O-1662)

### 2.10.3 SISO System Model :

- In case of a single receive and transmit antenna (i.e. r = t = 1) it reduces to the single-input single-output (SISO) system.
- The system model for SISO is given as :

$$b = ha + n$$

### 2.10.4 MIMO System Model :

- The covariance matrix of the noise $R_n$ of the noise vector n is defined as,

$$R_n = E\{nn^H\}$$

$$= E\left\{\begin{bmatrix} n_1 \\ n_2 \\ \vdots \\ n_r \end{bmatrix}\begin{bmatrix} n_1^* & n_2^* & \cdots & n_r^* \end{bmatrix}\right\}$$

(G-1443)

$$= \begin{bmatrix} E\{|n_1|^2\} & E\{n_1n_2^*\} & \cdots & E\{n_1n_r^*\} \\ E\{n_2n_1^*\} & E\{|n_2|^2\} & \cdots & E\{n_2n_r^*\} \\ \vdots & \vdots & \ddots & \vdots \\ E\{n_rn_1^*\} & E\{n_rn_2^*\} & \cdots & E\{|n_r|^2\} \end{bmatrix}$$

$$= \begin{bmatrix} \sigma_n^2 & 0 & 0 & \cdots & 0 \\ 0 & \sigma_n^2 & 0 & \cdots & 0 \\ \vdots & & & \ddots & \vdots \\ 0 & 0 & 0 & \cdots & \sigma_n^2 \end{bmatrix}$$

(G-1444)

$$= \sigma_n^2 I$$

- The noise vector n with the covariance structure above is a spatially uncorrelated additive noise, because the noise samples at the different antennas i, j are independent, i.e., $E\{n_in_j^*\} = 0$ if $i \neq j$.
- In order to denote the transmission and reception across different time instants, add the time index k to the MIMO system model to frame the net model as,

(G-1445)

$$\underbrace{\begin{bmatrix} b_1(k) \\ b_2(k) \\ \vdots \\ b_r(k) \end{bmatrix}}_{b(k)} = \underbrace{\begin{bmatrix} h_{11} & h_{12} & \cdots & h_{1t} \\ h_{21} & h_{22} & \cdots & h_{2t} \\ \vdots & \vdots & \ddots & \vdots \\ h_{r1} & h_{r2} & \cdots & h_{rt} \end{bmatrix}}_{H} \underbrace{\begin{bmatrix} a_1(k) \\ a_2(k) \\ \vdots \\ a_t(k) \end{bmatrix}}_{a(k)} + \underbrace{\begin{bmatrix} n_1(k) \\ n_2(k) \\ \vdots \\ n_r(k) \end{bmatrix}}_{n(k)}$$

- The vectors b(k), a(k), n(k) are the ... transmit, and noise vectors of the MIMO ... communication system at the time ins... respectively.
- We have assumed the channel matrix H ... constant or not dependent on the time ins... This is known as a slow fading or quasi... channel matrix.
- This matrix indicates that the channel coeff... are constant over the block of transmitted ... vectors.
- At last, assume that any two noise samples a... two different time instants are uncorre... i.e., $E\{n_i(k)\, n_j^*(l)\} = 0$ if $k \neq l$.
- Hence, the noise covariance matrix is given a...

$$E\{n(k)\, n(l)^H\} = \sigma^2\, \delta(k-l)\, I$$

- Where the delta function $\delta(k-l) = 1$ if ... otherwise it is 0.
- This noise process, that is uncorrelated a... different antennas and time instants is kno... spatio-temporally uncorrelated noise.

### 2.10.5 Advantages of MIMO :

- Following are some of the advantages of MIM...
  1. Increased uplink/downlink throughput
  2. High QoS (Quality of Service) with incre... spectral efficiency
  3. Increases the spatial diversity ... multiplexing gain
  4. Minimizes the fading effects on ... transmitted signal traveling to re... antenna
  5. Better Signal to Noise Ratio(SNR)
  6. Reduction in BER (Bit Error Rate)
  7. Higher speed and throughput

### 2.10.6 Disadvantages of MIMO :

- Following are some of the advantages of MIMO :
  1. Each antenna requires individual RF units to process the radio signal.
  2. Device battery drains quickly as it has to process complex signal processing algorithms
  3. Higher hardware complexity

### 2.10.7 Applications of MIMO :

- WLAN (Wi-Fi) uses MIMO with 802.11 n standard.
- This is possible because, multiple small antennas are present in modem devices like laptops, data cards, mobiles, tablets.
- The HSPA uses MIMO in commercial networks.
- But it is difficult to install two antennas in mobile devices considering the mobile hardware limitations.
- Some mobile devices do support dual antennas that operate for MIMO. Both these antennas are cross-polarized.

## 2.11 MIMO-OFDM :

- MIMO-OFDM is a combination of the Multiple-Input Multiple-Output (MIMO) and OFDM system.
- In this system multiple number of transmitters at one point and multiple number of receivers at other end and are effectively combined in order to improve the channel capacity of wireless system.
- It also highly improves the spectrum efficiency, reliability of system and coverage area.
- MIMO OFDM system will increase the data rate in broadband multi-antenna wireless systems.
- Just like OFDM system, MIMO-OFDM converts a frequency-selective MIMO channel into multiple parallel flat fading MIMO channels.
- MIMO-OFDM simplifies baseband receive processing by eliminating the need for a complex MIMO equalizer.
- The SISO frequency-selective channel is modeled as an FIR channel filter, with the output y(n) at time instant n and is given by,

(O-1676)

$$y(n) = \sum_{l=0}^{L-1} h(l)\, x(n-l) + \omega(n)$$

$$= h(0)\, x(n) + \underbrace{h(1)\, x(n-1) + \ldots + h(L-1)\, x(n-L+1)}_{\text{ISI from previous symbols}} + \omega(n)$$

- Where ω(n) indicates the noise.
- A MIMO frequency-selective channel can be modeled as a MIMO FIR filter, with the output y(n) at time instant n and is given by,

$$y(n) = \sum_{l=0}^{L-1} H(l)\, x(n-l) + \omega(n)$$

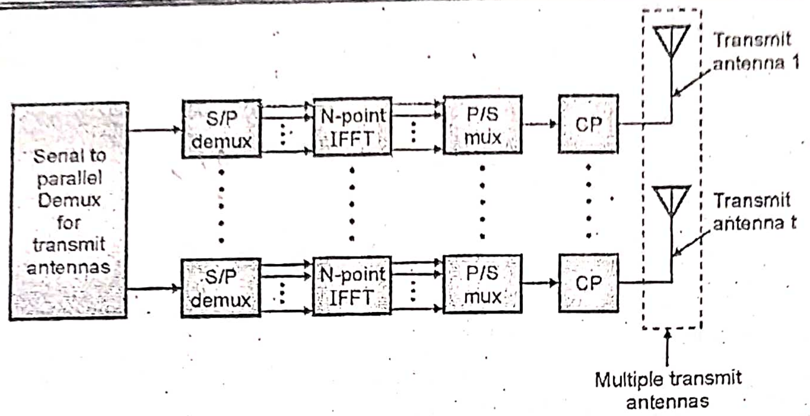
$$= H(0)\, x(n) + \underbrace{H(1)\, x(n-1) + \ldots + H(L-1)\, x(n-L+1)}_{\text{ISI from previous symbol vectors}} + \omega(n)$$

(O-1677)

- The symbol vector y(n) at the time instant n is affected by inter-symbol vector interference from x(n − 1) , x(n − 2) ....,x(n − L + 1) and this is an L-tap frequency-selective MIMO channel.
- In a MIMO frequency-selective channel, the inter-symbol vector interference takes place between current and previous transmit symbol vectors.
- In a MIMO-OFDM system, it is necessary to perform the IFFT or IDFT operation at each transmit antenna.

### 2.11.1 MIMO OFDM Transmitter :

- Fig. 2.11.1 shows the processing at the transmitter of the MIMO-OFDM system.

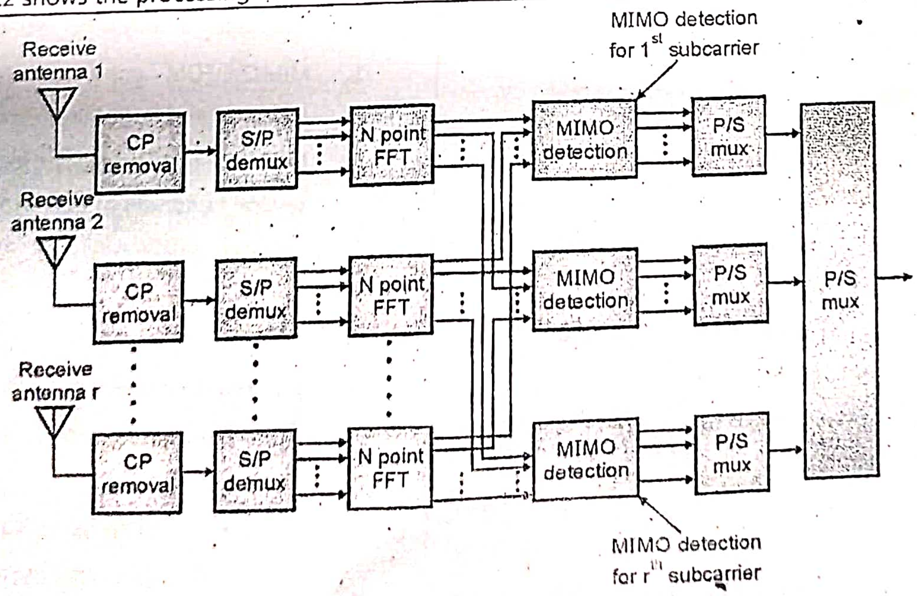



(O-1714)Fig. 2.11.1 : MIMO OFDM transmitter

- MIMO OFDM transmitter consists of Serial to parallel demux block for transmit antennas, N-point IFFT, parallel to serial mux and Cyclic Prefix(CP).
- On each transmit antenna again S/P demux operation is performed.
- Each information symbol is passed through a serial to parallel (S/P) converter and becomes parallel data.
- On the parallel data, the IFFT operation is performed.
- Time domain symbols are parallel to serial (P/S) converted and then a cyclic prefix (CP) is added.
- CP is added to eliminate ISI and ICI (inter-carrier interference).
- Finally, the amplified modulated signals are transmitted.

### 2.11.2 MIMO OFDM Receiver :

- Fig. 2.11.2 shows the processing at the receiver of the MIMO-OFDM system.




(O-1715)Fig. 2.11.2 : MIMO OFDM receiver

- At the receiver, Cyclic prefix (CP) and IFFT is removed at each receive antenna.
- MIMO detection is performed across each subcarrier.
- For the first subcarrier take the output from the first subcarrier at every receive antenna.
- For the second subcarrier take the output from the second subcarrier at every receive antenna and perform the MIMO detection for all subcarriers.
- After MIMO detection of all subcarriers, convert these subcarriers from parallel to serial.
- Again all these parallel streams are converted into serial streams by using parallel to serial mux.
- With the use of MIMO-OFDM, the MIMO frequency-selective channel can be converted into a set of parallel flat-fading MIMO channels.
- These channels can be described as follows,

$$\tilde{y}(0) = \tilde{H}(0)\,\tilde{x}(0)$$

$$\tilde{y}(1) = \tilde{H}(1)\,\tilde{x}(1)$$

$$\vdots$$

$$\tilde{y}(N-1) = \tilde{H}(N-1)\,\tilde{x}(N-1)$$

- The model across the $k^{th}$ subcarrier is given by,

$$\tilde{y}(k) = \tilde{H}(k)\,\tilde{x}(k)$$

- Where,

$\tilde{y}(k)$ = Received symbol vectors corresponding to the $k^{th}$ subcarrier.

$\tilde{x}(k)$ = Transmitted symbol vectors corresponding to the $k^{th}$ subcarrier.

$\tilde{H}(k)$ = Flat-fading channel matrix corresponding to the subcarrier k.

- Each of the received symbol vectors $\tilde{y}(0), \tilde{y}(1), \ldots, \tilde{y}(N-1)$ can be processed by a simple MIMO zero-forcing receiver or a MIMO-MMSE receiver in order to detect the symbol vectors $\tilde{x}(0), \tilde{x}(1), \ldots, \tilde{x}(N-1)$.
- The zero forcing MIMO receiver for the subcarrier k of the MIMO-OFDM system is given by,

$$\hat{\tilde{x}}_{ZF}(k) = (\tilde{H}(k))^{\dagger}\,\tilde{y}(k)$$

$$= (\tilde{H}^{H}(k)\,\tilde{H}(k))^{-1}\,\tilde{H}^{H}(k)\,\tilde{y}(k)$$

- The MMSE receiver for the subcarrier k of the MIMO-OFDM system is given as,

$$\hat{\tilde{x}}_{MMSE}(k) = (\tilde{H}(k))^{\dagger}\,\tilde{y}(k)$$

$$= P_d\,(P_d\,\tilde{H}^{H}(k)\,\tilde{H}(k) + \sigma_{\omega}^{2}\,I)^{-1}\,\tilde{H}^{H}(k)\,\tilde{y}(k)$$

- Where, $P_d$ is the data power.
- Let $h_{\mu,v}(k)$, $\tilde{h}_{\mu,v}(k)$ indicates the $(\mu, v)^{th}$ entries of the matrices H(k) and $\tilde{H}(k)$ respectively.
- The $\tilde{h}_{\mu,v}(k)$ is the N -point DFT of the zero-padded coefficients $h_{\mu,v}(0), h_{\mu,v}(1), \ldots, h_{\mu,v}(L-1)$.
- The channel matrix $\tilde{H}(k)$ is the $k^{th}$ frequency point corresponding to the N-point FFT of the zero padded channel matrices $[H(0), H(1), \ldots, H(L-1), 0_{r \times t}, \ldots, 0_{r \times t}]$.
- The $\tilde{H}_{\mu,v}(k)$ is the N-point DFT of the zero-padded coefficients $H_{\mu,v}(0), H_{\mu,v}(1), \ldots, H_{\mu,v}(L-1)$.

### 2.11.3 Advantages of MIMO-OFDM :

- The advantages of MIMO-OFDM are as follows :

1. MIMO-OFDM enables support for more antennas and larger bandwidth.
2. MIMO-OFDM increases the data rates up to several hundreds of M bits/sec. and achieves spectral efficiencies of several tens of bits/Hz/s.
3. It increases spectral efficiency of the system.
4. It improves reliability of link.
5. It has low sensitivity to time synchronization error.
6. It has extra resistance to fading.
7. It has high bandwidth spectral efficiency.
8. The complexity for FFT and IFFT becomes low.

### 2.11.4 Disadvantages of MIMO-OFDM :

- The disadvantages of MIMO-OFDM are as follows :
  1. MIMO-OFDM needs multiple antennas.
  2. An implementation cost is high.
  3. Accuracy of synchronization must be very high.
  4. High power consumption.

### 2.11.5 Applications of MIMO-OFDM :

- MIMO-OFDM is used in the following applications :
  1. Worldwide Interoperability for Microwave Access (WIMAX)
  2. Digital Video Broadcasting (DVB)
  3. Digital Audio Broadcasting (DAB)
  4. High Definition TV and Digital Television
  5. Long Term Evolution (LTE)
  6. In wireless ATM transmission system
  7. Wireless Fidelity (WIFI)

## Review Questions

Q. 1 Explain the concept of Smart Antennas.

Q. 2 State and explain the types of Smart Antenna Systems.

Q. 3 State the features of Smart Antennas.

Q. 4 Write a short note on : Multiantenna techniques.

Q. 5 Explain concept of MIMO w.r.t. 4G technology.

Q. 6 How do we use space-time block code (STBC) and space time trellis code (STTC) ?

Q. 7 Explain single-carrier communication system and multi-carrier communication system.

Q. 8 Write a short note on multicarrier transmission.

Q. 9 What are the advantages and disadvantages of MCM system ?

Q. 10 Write a short note on Orthogonal Frequency Division Multiplexing (OFDM).

Q. 11 Define and explain orthogonality.

Q. 12 Define and explain OFDM-PAPR.

Q. 13 Explain OFDM with IFFT.

Q. 14 How to avoid ISI ?

Q. 15 Explain OFDM transmitter with cyclic prefix.

Q. 16 What is the impact of cyclic prefix on data rate

Q. 17 What are the advantages of OFDM ?

Q. 18 What are the disadvantages of OFDM ?

Q. 19 Define smart antenna.

Q. 20 Write a short note on functions of smart antenna

Q. 21 What are the types of smart antenna explain any one.

Q. 22 What are the advantages and disadvantages of switched beam system ?

Q. 23 What are the advantages and disadvantages of AAS ?

Q. 24 What are the features of smart antennas ?

Q. 25 What are the advantages of smart antenna systems ?

Q. 26 What are the disadvantages of smart antenna systems ?

Q. 27 What are the applications of smart antenna systems ?

Q. 28 What are the different types of multi-antenna techniques ?

Q. 29 Write a short note on MIMO system model.

Q. 30 Write a short note on applications of MIMO.

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