Wireless Communication

MCA -4th sem
Sub Code-MCA406C
Sub Name-WCMC

Course Information

Recommended Textbooks

- Theodore Rappaport, **Wireless Communications: Principles and Practice**, Second Edition, Prentice Hall, December 2001.

Outline

- Introduction
  - What is wireless and mobile networking
  - History of Wireless
  - Challenges of Mobile and Wireless Communication
  - What is Personal Communications Systems
  - Overview of Wireless Technologies and Systems

Outline

- Cellular concepts
  - Frequency reuse,
  - Handoff
  - Interference and system capacity,
  - Sectoring
  - Cell splitting

Outline

- Wireless Link Characteristics
  - Radio Propagation
  - Short and Long wave properties
  - Attenuation
  - Interference
  - Fading and Multi-path Fading
  - Transmit power and range
  - Bit Error Rate and Models

Outline

- Modulation Techniques
- Multiple Access (TDMA , FDMA and CDMA)
- GSM in detail

What is Wireless Communication

- Transmitting voice and data using electromagnetic waves in open space
- Electromagnetic waves
  - Travel at speed of light ($c = 3x10^8$ m/s)
  - Has a frequency (f) and wavelength (λ)
    - $c = f \times \lambda$
  - Higher frequency means higher energy photons
  - The higher the energy photon the more penetrating is the radiation

Why Wireless?

- Freedom from wires

  No cost of installing the wires, No bunches of wires running around e.g. Bluetooth , Wi-Fi

- Global coverage

  where wires communication is not feasible or costly e.g. rural areas, battle field and outer space.

- Stay Connected

  Anywhere any time

- Flexibility

  Connect to multiple devices simultaneously

Wireless History

- Ancient Systems: Smoke Signals, Carrier Pigeons…
- Using light and flags for wireless communication remained important for the navy until radio transmission was introduced. Even today a sailor has to know some codes represented by flags if all other means of wireless communication fail.
- James C Maxwell (1831- 1879) laying the theoretical foundation for EM fields with his famous equations
- Heinrich Hertz (1857- 1894) was the first to demonstrate the wave character of electrical transmission through space (1886).(Note Today the unit Hz reminds us of this discovery).

Wireless History cont…

- Radio invented in the 1880s by Marconi
- The first transatlantic transmission followed in 1901.
- WARC – World Administration Radio Conference took place ,coordinating world wide use of radio frequencies
- The 1st radio broadcast took place in 1906 when Reginald A Fessenden transmitted voice and music for Christmas.
- The invention of electronic vacuum tube in 1906 by Lee De Forest (1873- 1961) &Robert Von Lieben (1878 – 1913)Helped to reduce the size of sender and receiver .
- One of the 1st mobile transmitter was on board at Zeppelin in 1911

Wireless History cont…

- In 1915 , the first wireless voice transmission was set up between New York and San Francisco
- The 1st commercial radio station started in 1920
  - –Note Sender & Receiver still needed huge antennas High transmission power.
- In **1926**, the first telephone in a train was available on the Berlin – Hamburg line
- **1928** was the year of many field trials for TV broadcasting. John L Baird (1888 – 1946) transmitted TV across Atlantic and demonstrated color TV
- Until **1932** , all wireless communication used AM which offered relatively poor quality due to interference.

Wireless History cont…

- Invention of FM in 1933 by Edwin H Armstrong [1890 - 1954] .
- Both the modulation schemes are still used for todays radio broadcasting with FM having much better quality.
- 1946, Public Mobile in 25 US cities, high power transmitter on large tower. Covers distance of 50 Km. Push to talk, uses 120khz of RF bandwidth.1950 channels doubled and BW 60k, 1960 4times increase, BW 30khz
- After 2nd world war (in 1958) ,a network in Germany was build namely the analog A- Netz using a carrier frequency of 160 Mhz.
- Connection setup was only possible from the mobile station and no handover was possible

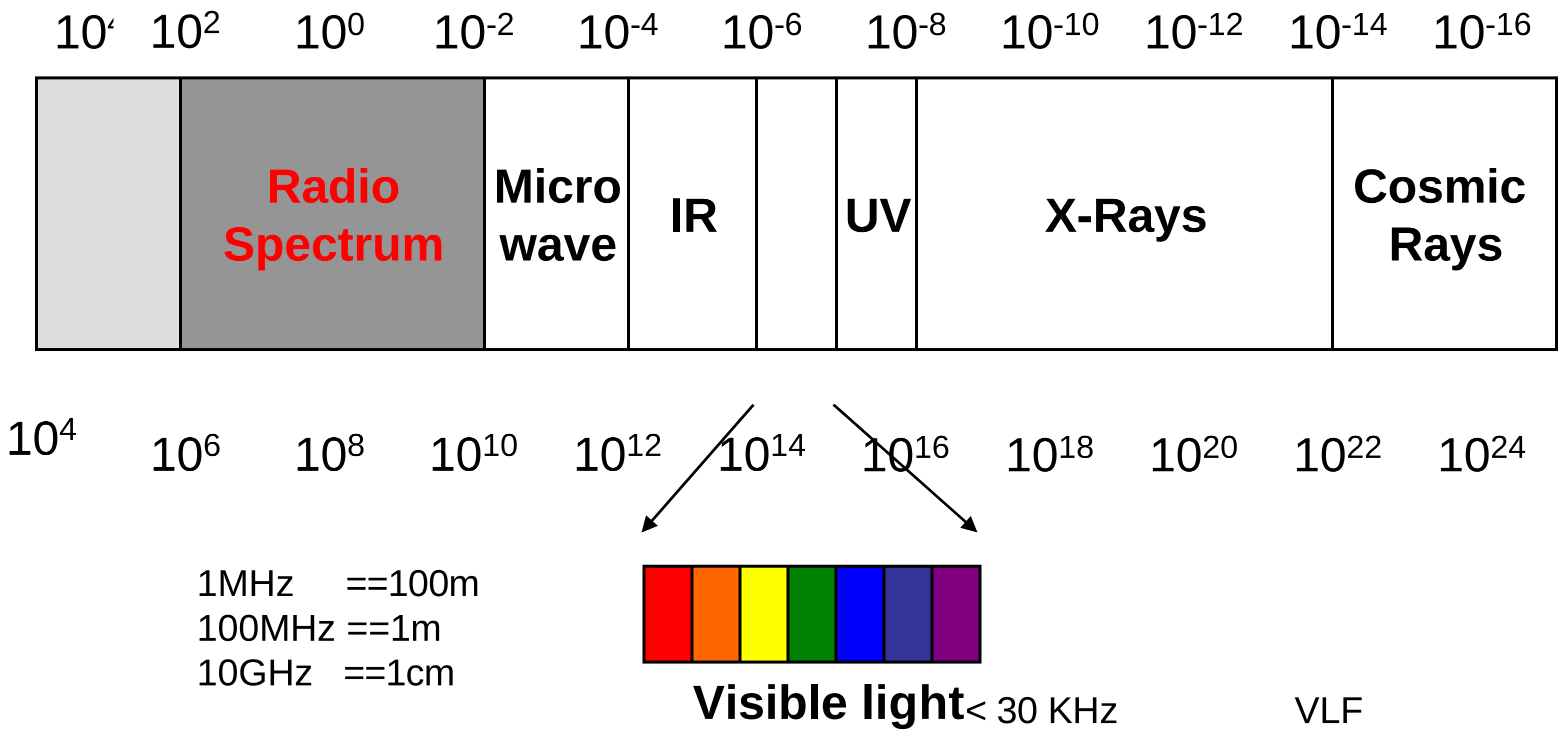
Wireless History cont…

- 1982: ***Groupe Spéciale Mobile*** was launched to develop standards for pan-European mobile network
- GSM now stands for ***Global System for Mobile Communications***
- 1992 Official commercial launch of GSM in Europe
- 1995 GSM specifications ported to PCS 1900
- 1997 - Wireless LANs
- 1998 - Specification for next generation CDMA starts
  Qualcomm starts work on wideband CDMA spec.
- 2000 - Bluetooth with 1Mbit/s specification, single cell
  Later work on 10Mbit/s spec with multi cell capability
- In 2002 Camera phones are first introduced in the U.S. market.

Wireless History cont…

- In 2005 mobile phone subscribers exceed fixed phone subscriber.
- iTunes Application Store (July) and Android Market (October) open in 2008
- In 2010 First 4G handset is introduced at International CTIA WIRELESS show.
- In 2010 Apple introduced the iPad, another revolution in portable “tablet” computing.
- In 2010 FCC proposes National Broadband Plan, recommending 500MHz of spectrum be allocated for commercial use by 2020.
- In 2012 the number of subscriber reaches 1 million.

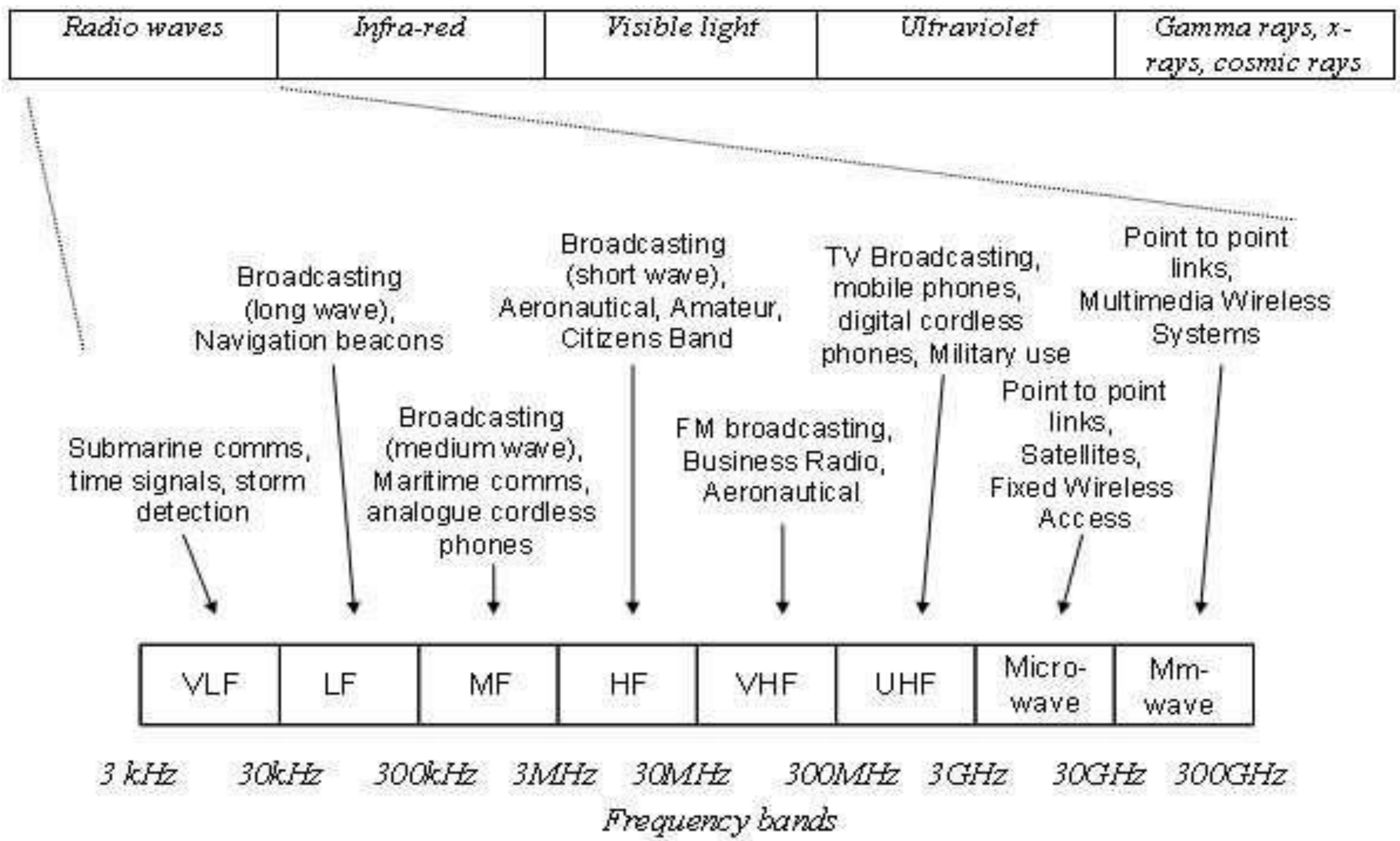
Electromagnetic Spectrum



1MHz ==100m
100MHz ==1m
10GHz ==1cm

< 30 KHz	VLF
30-300KHz	LF
300KHz – 3MHz	MF
3 MHz – 30MHz	HF
30MHz – 300MHz	VHF
300 MHz – 3GHz	UHF
3-30GHz	SHF
> 30 GHz	EHF

Electromagnetic Spectrum



Wavelength of Some Technologies

- GSM Phones:
  - frequency ~= 900 Mhz
  - wavelength ~= 33cm
- PCS Phones
  - frequency ~= 1.8 Ghz
  - wavelength ~= 17.5 cm
- Bluetooth:
  - frequency ~= 2.4Gz
  - wavelength ~= 12.5cm
  - Federal Communications Commission(FCC)
  - PTA

Frequency Carries/Channels

- The information from sender to receiver is carrier over a well defined frequency band.
  - This is called a channel
- Each channel has a fixed frequency bandwidth (in KHz) and Capacity (bit-rate)
- Different frequency bands (channels) can be used to transmit information in parallel and independently.

Wireless Com Sys Examples

- Cellular Telephony
- Wide Area Wireless Data Systems
- High Speed Local and Personal Area Networks
- Paging Messaging Systems
- Satellite Based Mobile System

Simplex Communication

- Normally, on a channel, a station can transmit only in one way.
  - This is called simplex transmision
- To enable two-way communication (called full-duplex communication)
  - We can use Frequency Division Multiplexing
  - We can use Time Division Multiplexing

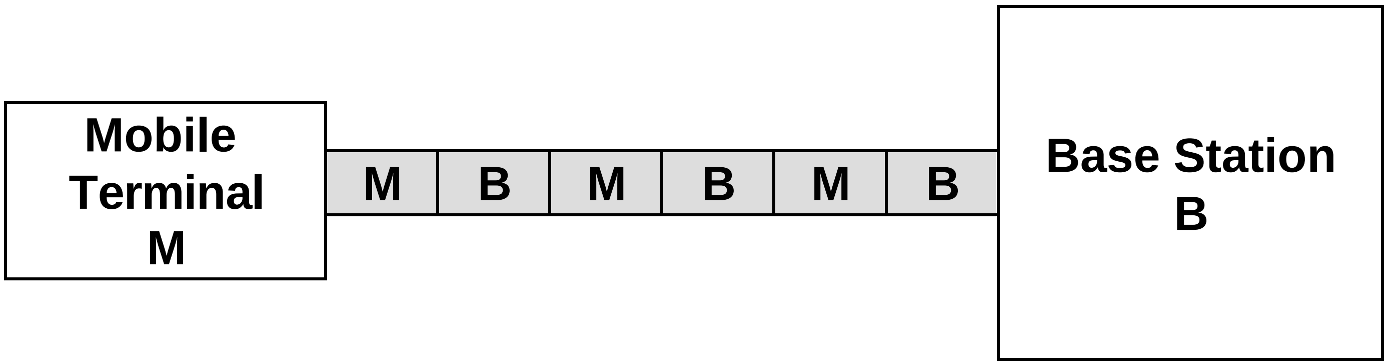
Duplex Communication - FDD

- FDD: Frequency Division Duplex

Forward Channel and Reverse Channel use different frequency bands

Duplex Communication - TDD

- TDD: Time Division Duplex



A singe frequency channel is used. The channel is divided into time slots. Mobile station and base station transmits on the time slots alternately.

Several PCS systems

- AMPS-USDC(NADC)IS-54 and 154
- IS-95 CDMA One System
  - CDMA based multiple access
- GSM: Global System for Mobile Communications
  - The mobile telephony system that we are using
- IS-136
  - USA digital cellular mobile telephony system
  - TDMA based multiple access
- Residential, business and public cordless access applications and systems

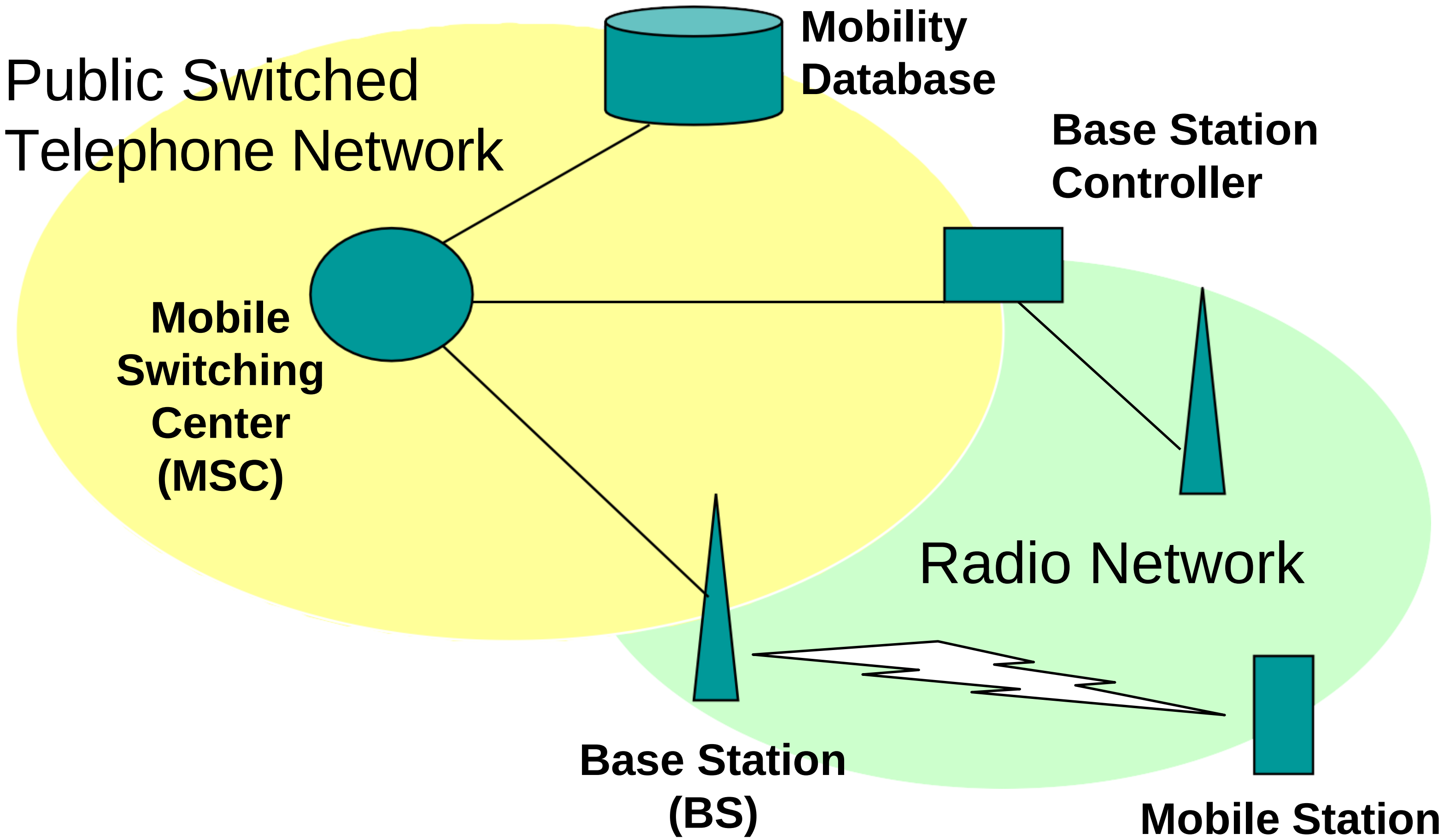
Several PCS systems

- Wideband wireless systems
  - For Internet access and multimedia transfer
    - Cdma2000
    - W-CDMA, proposed by Europe
    - SCDMA, proposed by China/Europe
- Other PCS Systems
  - Special data systems
    - CDPD: Cellular Digital Packet Data
  - Paging Systems
  - Mobile Satellite Systems
  - ISM band systems: Bluetooth, 802.11, etc

PCS Problems

- How to integrate mobile and wireless users to the Public Switched Telephone Network (PSTN) (Voice Network)
  - Cellular mobile telephony system
- How to integrate mobile and wireless users to the Internet (Data Network)
  - Mobile IP, DHCP.
- How to integrate all of them together and also add multimedia services (3G Systems)

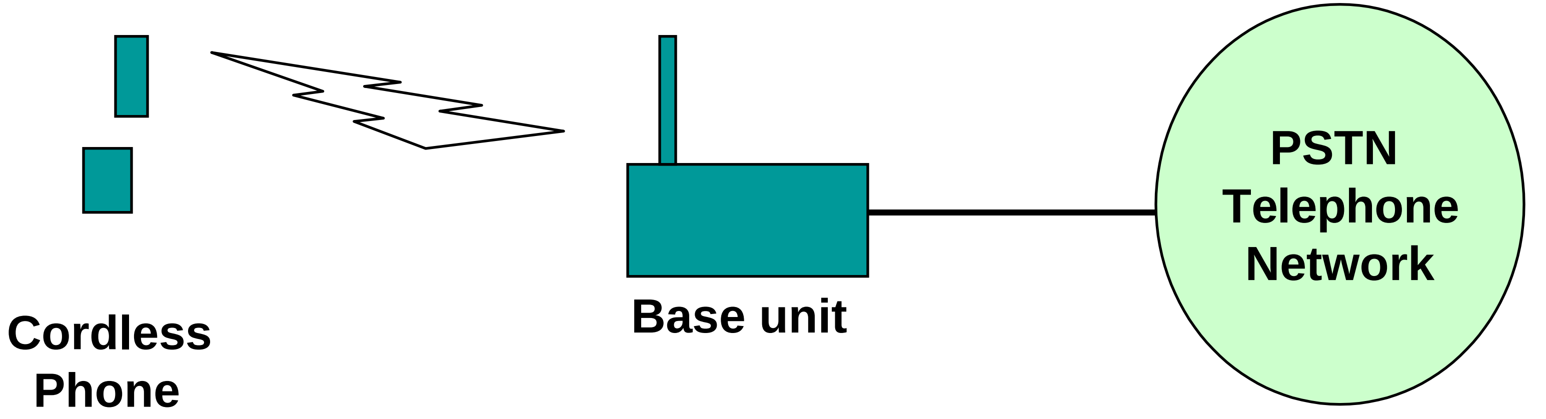
Very Basic Cellular/PCS Architecture



PCS Systems Classification

- Cordless Telephones
- Cellular Telephony
- Wide Area Wireless Data Systems
- High Speed Local and Personal Area Networks
- Paging Messaging Systems
- Satellite Based Mobile Systems
- 3G Systems

Cordless Telephones



Cordless Telephones

- Characterized by
  - Low mobility (in terms of range and speed)
  - Low power consumption
  - Two-way voice communication
  - High circuit quality
  - Low cost equipment, small form factor and long talk-time
  - No handoffs between base units
- Usage
  - At homes and at public places where cordless phone base units are available
- Design Choices
  - Few users per MHz
  - Few users per base unit

Cordless Phone

- Some more features
  - 32 Kb/s adaptive differential pulse code modulation (ADPCM) digital speech encoding
  - Tx power <= 10 mW
  - Low-complexity radio signal processing
    - No forward error correction (FEC) or whatsoever.
  - Low transmission delay < 50ms
  - Simple Frequency Shift Modulation (FSK)
  - Time Division Duplex (TDD)

Paging Systems

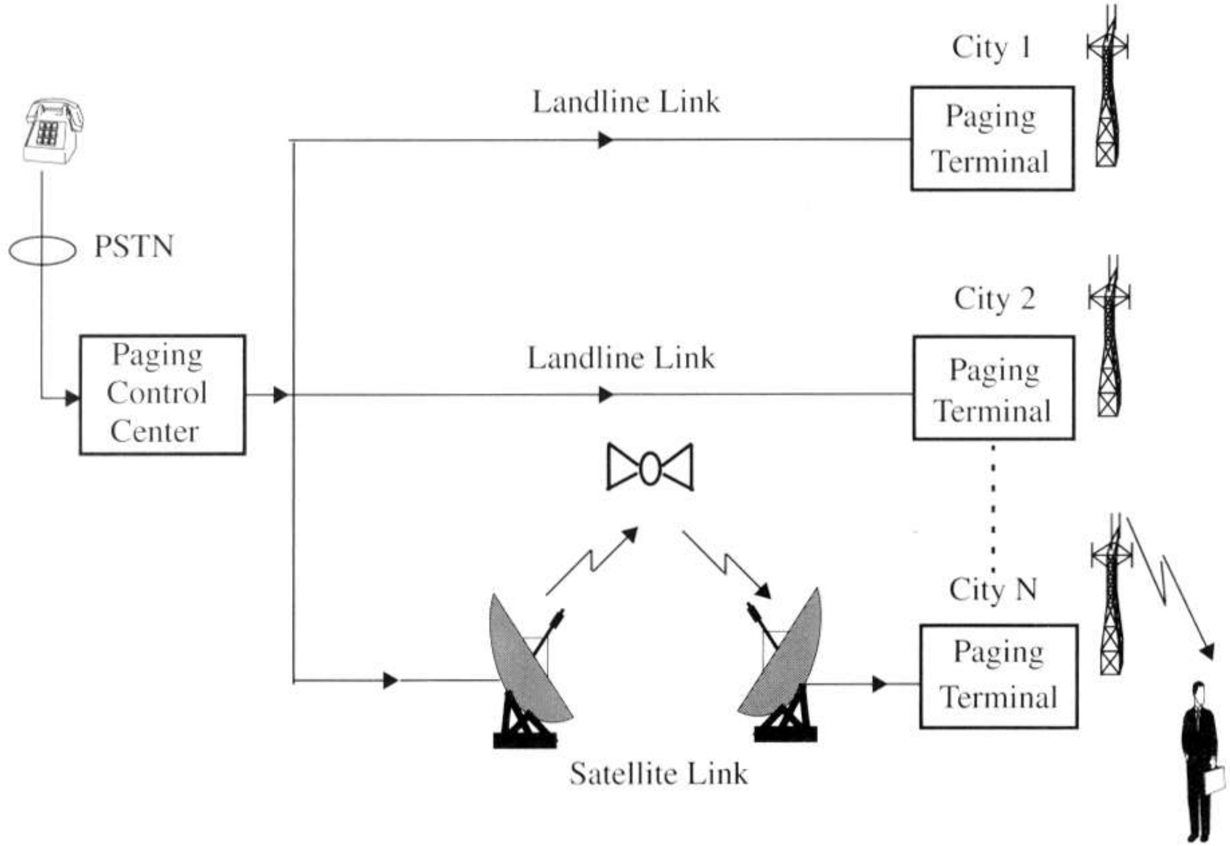
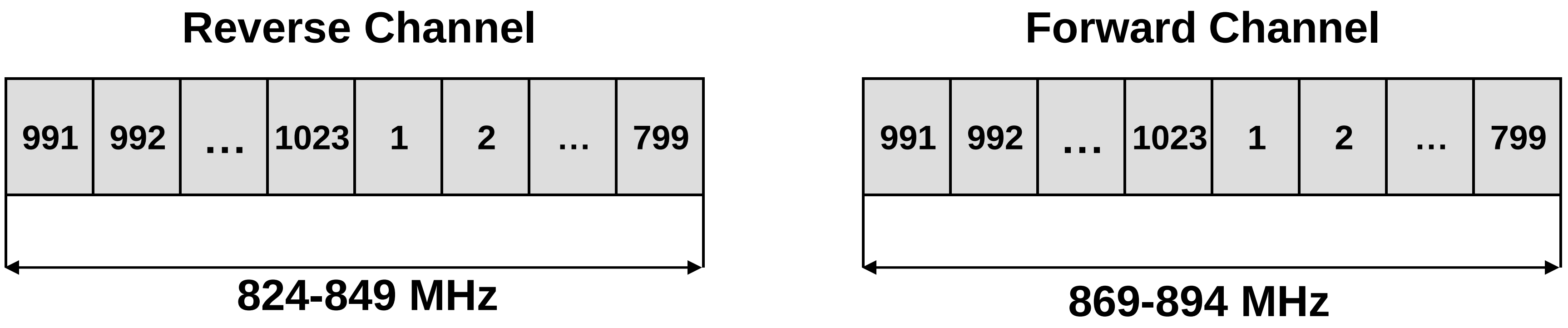


Figure 1.3 A wide area paging system. The paging control center dispatches pages received from the PSTN throughout several cities at the same time.

Example - Frequency Spectrum Allocation in U.S. Cellular Radio Service



	Channel Number	Center Frequency (MHz)
Reverse Channel	1 <=N <= 799	0.030N + 825.0
	991 <= N <= 1023	0.030(N-1023) + 825.0
Forward Channel	1 <=N <= 799	0.030N + 870.0
	991 <= N <= 1023	0.030(N-1023) + 870.0

(Channels 800-990 are unused)

Fwd & Rev Channel in each duplex pair is 45 MHz apart

Major Mobile Radio Standards

Standard	Type	Year Intro	Multiple Access	Frequency Band (MHz)	Modulation	Channel BW (KHz)
AMPS	Cellular	1983	FDMA	824-894	FM	30
USDC IS- 54 IS-136	Cellular	1991	TDMA	824-894	DQPSK	30 3 users in 30 and 6
IS-95	Cellular/PCS	1993	CDMA	824-894 1800-2000	QPSK/BPSK	1250
FLEX	Paging	1993	Simplex	Several	4-FSK	15
DCS-1900 (GSM)	PCS	1994	TDMA	1850-1990	GMSK	200
PACS	Cordless/PCS	1994	TDMA/FDMA	1850-1990	DQPSK	300

Major Mobile Radio Standards - Europe

Standard	Type	Year Intro	Multiple Access	Frequency Band (MHz)	Modulation	Channel BW (KHz)
ETACS	Cellular	1985	FDMA	900	FM	25
NMT-450/900	Cellular	1981/ 1986	FDMA	450-470 890-960	FM FM	25 12.5
GSM	Cellular/PCS	1990	TDMA	890-960	GMSK	200KHz
C-450	Cellular	1985	FDMA	450-465	FM	20-10
ERMES	Paging	1993	FDMA4	Several	4-FSK	25
CT2	Cordless	1989	FDMA	864-868	GFSK	100
DECT	Cordless	1993	TDMA	1880-1900	GFSK	1728
DCS-1800	Cordless/PCS	1993	TDMA	1710-1880	GMSK	200

Wireless System Definitions

- Mobile Station
  - A station in the cellular radio service intended for use while in motion at unspecified locations. They can be either hand-held personal units (portables e.g. a walkie-talkie or cordless) or cell phone in fast moving vehicles (mobiles)
- Base station
  - A fixed station in a mobile radio system used for radio communication with the mobile stations. Base stations are located at the center or edge of a coverage region. They consists of radio channels and transmitter and receiver antennas mounted on top of a tower.

Wireless System Definitions

- Mobile Switching Center
  - Switching center which coordinates the routing of calls in a large service area. In a cellular radio system, the MSC connections the cellular base stations and the mobiles to the PSTN (telephone network). It is also called Mobile Telephone Switching Office (MTSO)
- Subscriber
  - A user who pays subscription charges for using a mobile communication system
- Transceiver
- A device capable of simultaneously transmitting and receiving radio signals

Wireless System Definitions

- Control Channel
  - Radio channel used for transmission of call setup, call request, call initiation and other beacon and control purposes.
- Forward Channel
  - Radio channel used for transmission of information from the base station to the mobile
- Reverse Channel
  - Radio channel used for transmission of information from mobile to base station

Wireless System Definitions

- Simplex Systems
  - Communication systems which provide only one-way communication
  - Pagers
- Half Duplex Systems
  - Communication Systems which allow two-way communication by using the same radio channel for both transmission and reception. At any given time, the user can either transmit or receive information.
  - Push-to-talk and release-to-listen systems
- Full Duplex Systems
  - Communication systems which allow simultaneous two-way communication. Transmission and reception is typically on two different channels (FDD).

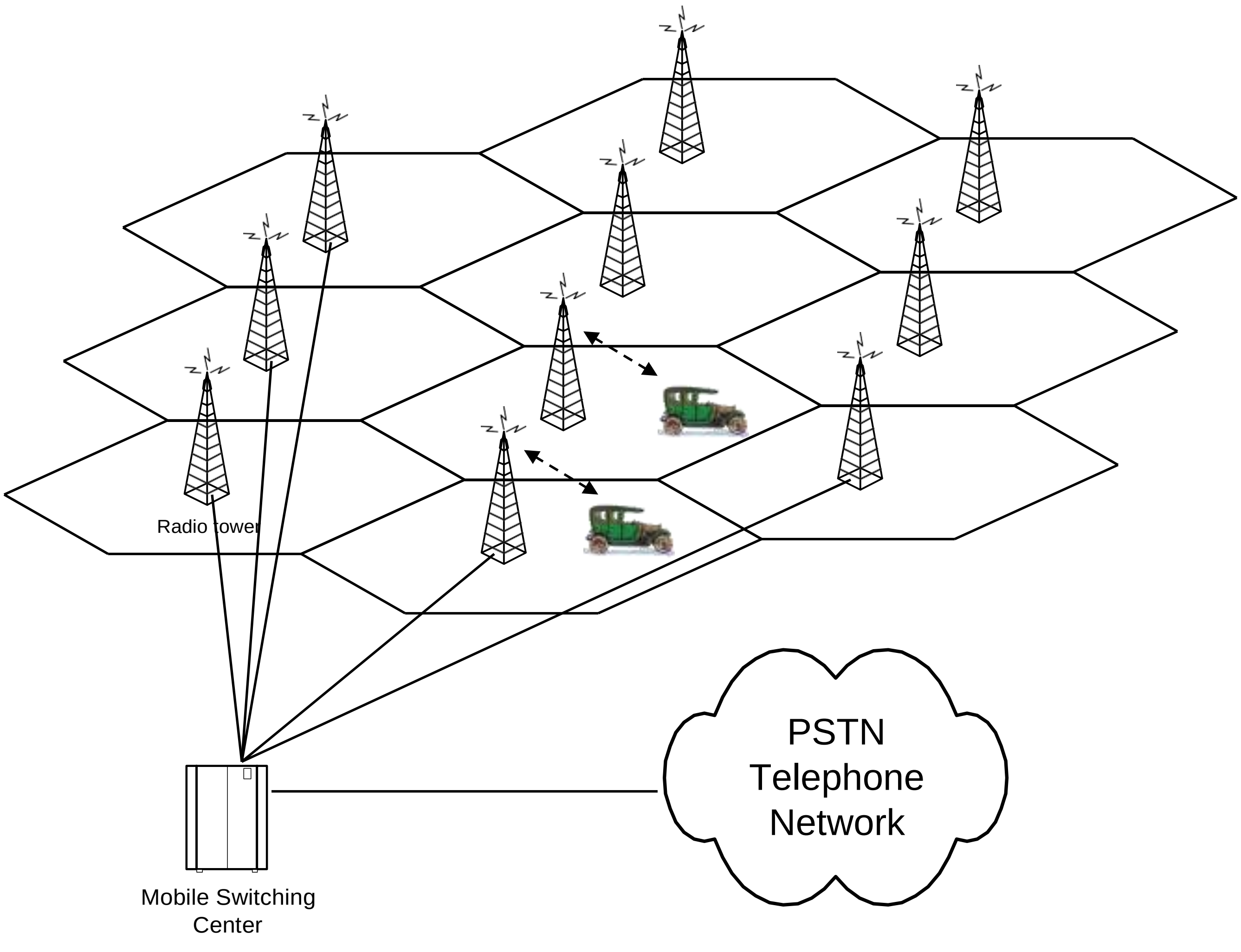
Wireless System Definitions

- Handoff
  - The process of transferring a mobile station from one channel or base station to an other.
- Roamer
  - A mobile station which operates in a service area (market) other than that from which service has been subscribed.
- Page
  - A brief message which is broadcast over the entire service area, usually in simulcast fashion by many base stations at the same time.

Cellular Telephony

- Characterized by
  - High mobility provision
  - Wide-range
  - Two-way voice communication
  - Handoff and roaming support
  - Integrated with sophisticated public switched telephone network (PSTN)
  - When mobile is turned on and not engaged in a call monitors the control channel for strongest BS.

Cellular Telephony - Architecture



Cellular Telephony Systems

- Mobile users and handsets
  - Very complex circuitry and design
- Base stations
  - Provides gateway functionality between wireless and wire line links
- Mobile switching centers
  - Connect cellular system to the terrestrial telephone network

Call to Mobile Initiated by PSTN

MSC		Receives call from PSTN. Sends the requested MIN to all base station.			Verifies that the mobile has a vaild MIN, ESN pair.	Requests BS to move mobile to unused voice channel pair.		Connects the mobile with the calling party on the PSTN.
Base Station	FCC		Transmits page (MIN) for specified user.				Transmits data message for mobile to move to specific voice channel.	
	RCC			Receives MIN, ESN, Station Class Mark and passes to MSC.				
	FVC							Begin voice transmission.
	RVC							Begin voice reception.
Mobile	FCC		Receives page and matches the MIN with its own MIN.				Receives data messages to move to specified voice channel.	
	RCC			Acknowledges receipt of MIN and sends ESN and Station Class Mark.				
	FVC							Begin voice reception.
	RVC							Begin voice transmission.

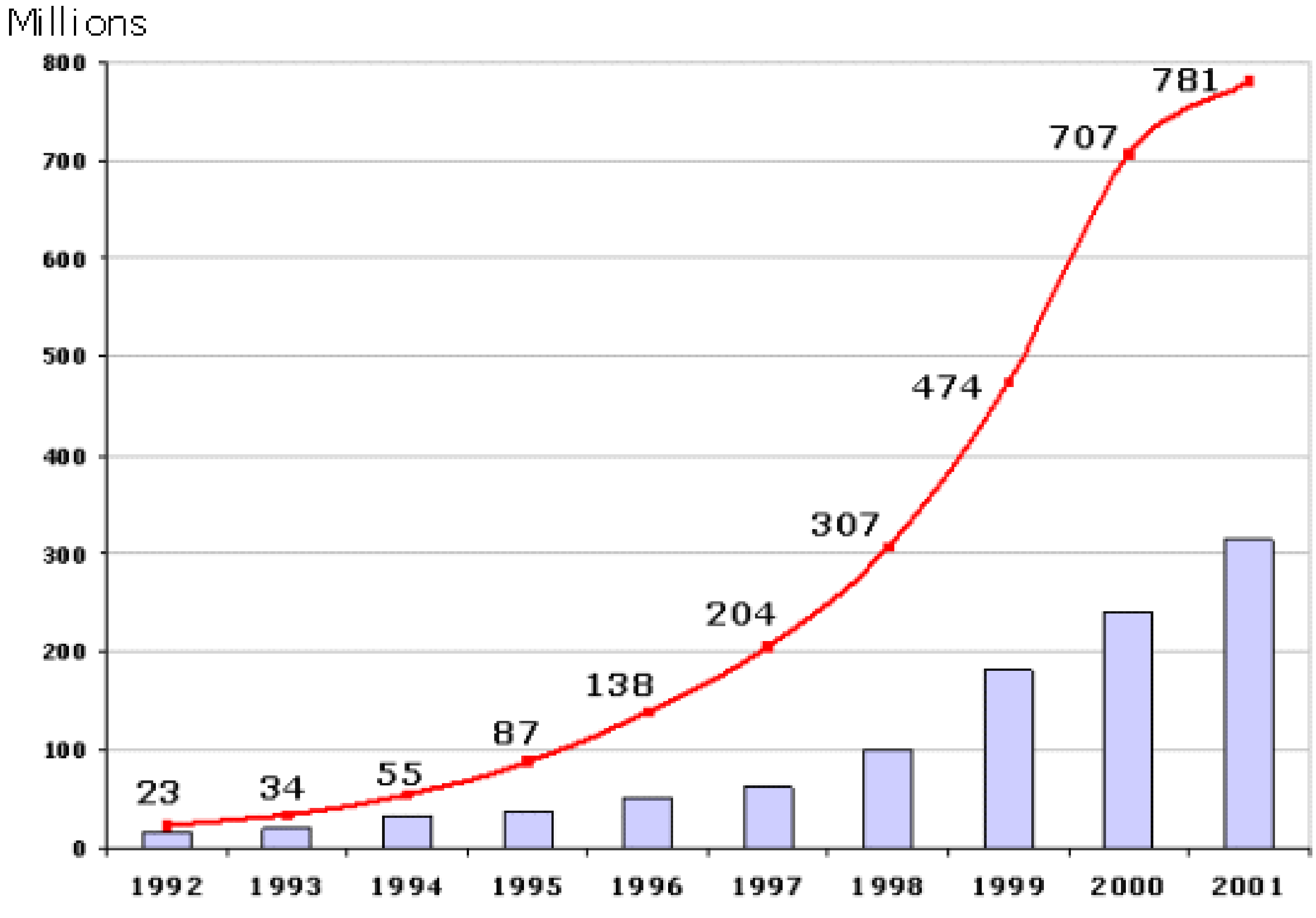
time →

Mobile initiated Call

MSC			Receives call initiation request from base station and verifies that the mobile has a vaild MIN, ESN pair.	Instructs FCC of originating base station to move mobile to a pair of voice channels.		Connects the mobile with the called party on the PSTN.	
Base Station	FCC				Page for called mobile, instructing the mobile to move to voice channel.		
	RCC	Receives call initiation request. and MIN, ESN, Station Class Mark.					
	FVC						Begin voice transmission.
	RVC						Begin voice reception.
Mobile	FCC				Receives page and matches the MIN with its own MIN. Receives instruction to move to voice channel.		
	RCC	Sends a call initiation request along with subscriber MIN and number of called party.					
	FVC						Begin voice reception.
	RVC						Begin voice transmission.

time →

World Cellular Subscriber Growth



Cellular Networks

- First Generation
  - Analog Systems
  - Analog Modulation, mostly FM
  - AMPS
  - Voice Traffic
  - FDMA/FDD multiple access
- Second Generation (2G)
  - Digital Systems
  - Digital Modulation
  - Voice Traffic
  - TDMA/FDD and CDMA/FDD multiple access
- 2.5G
  - Digital Systems
  - Voice + Low-datarate Data
- Third Generation
  - Digital
  - Voice + High data rate DATA
  - Multimedia Transmission also

2nd Generation Cellular Networks

- 2 G networks include 3 TDMA and 1 CDMA based standards.
- GSM:
  - 8 time slotted users for each 200kHz channel
  - Deployed in cellular and PCS bands(Europe, Asia, Australia and South America)
- IS-136(USDC/NADC):
  - Supports 3 time slotted users in each 30 kHz channel
  - Deployed in cellular and PCS bands(North and South America and Australia)
- PDC: Japanese digital standard similar to IS136
- IS-95(cdma One):
  - Supports 64 orthogonally coded users on 1.25MHz channel

2nd Generation Cellular Networks

- 2G standards were first to rely on digital modulation on air interface and sophisticated DSP both in handsets and BS.
- 2G networks were deployed for conventional mobile telephony.
- In 2001 major carriers decided in favor of 3G systems based on TDMA based GSM platform instead of IS136 and PDC.

2G Technologies

	cdmaOne (IS-95)	GSM, DCS-1900	IS-54/IS-136 PDC
Uplink Frequencies (MHz)	824-849 (Cellular) 1850-1910 (US PCS)	890-915 MHz (Eurpe) 1850-1910 (US PCS)	800 MHz, 1500 Mhz (Japan) 1850-1910 (US PCS)
Downlink Frequencies	869-894 MHz (US Cellular) 1930-1990 MHz (US PCS)	935-960 (Europa) 1930-1990 (US PCS)	869-894 MHz (Cellular) 1930-1990 (US PCS) 800 MHz, 1500 MHz (Japan)
Deplexing	FDD	FDD	FDD
Multiple Access	CDMA	TDMA	TDMA
Modulation	BPSK with Quadrature Spreading	GMSK with BT=0.3	$\pi/4$ DQPSK
Carrier Seperation	1.25 MHz	200 KHz	30 KHz (IS-136) (25 KHz PDC)
Channel Data Rate	1.2288 Mchips/sec	270.833 Kbps	48.6 Kbps (IS-136) 42 Kbps (PDC)
Voice Channels per carrier	64	8	3

2G and Data

- 2G is developed for voice communications
- Data sent using Circuit switching
- Provides data rates in the order of ~9.6 Kbps
- Increased data rates are required for internet application
- This requires evolution towards new systems: 2.5 G

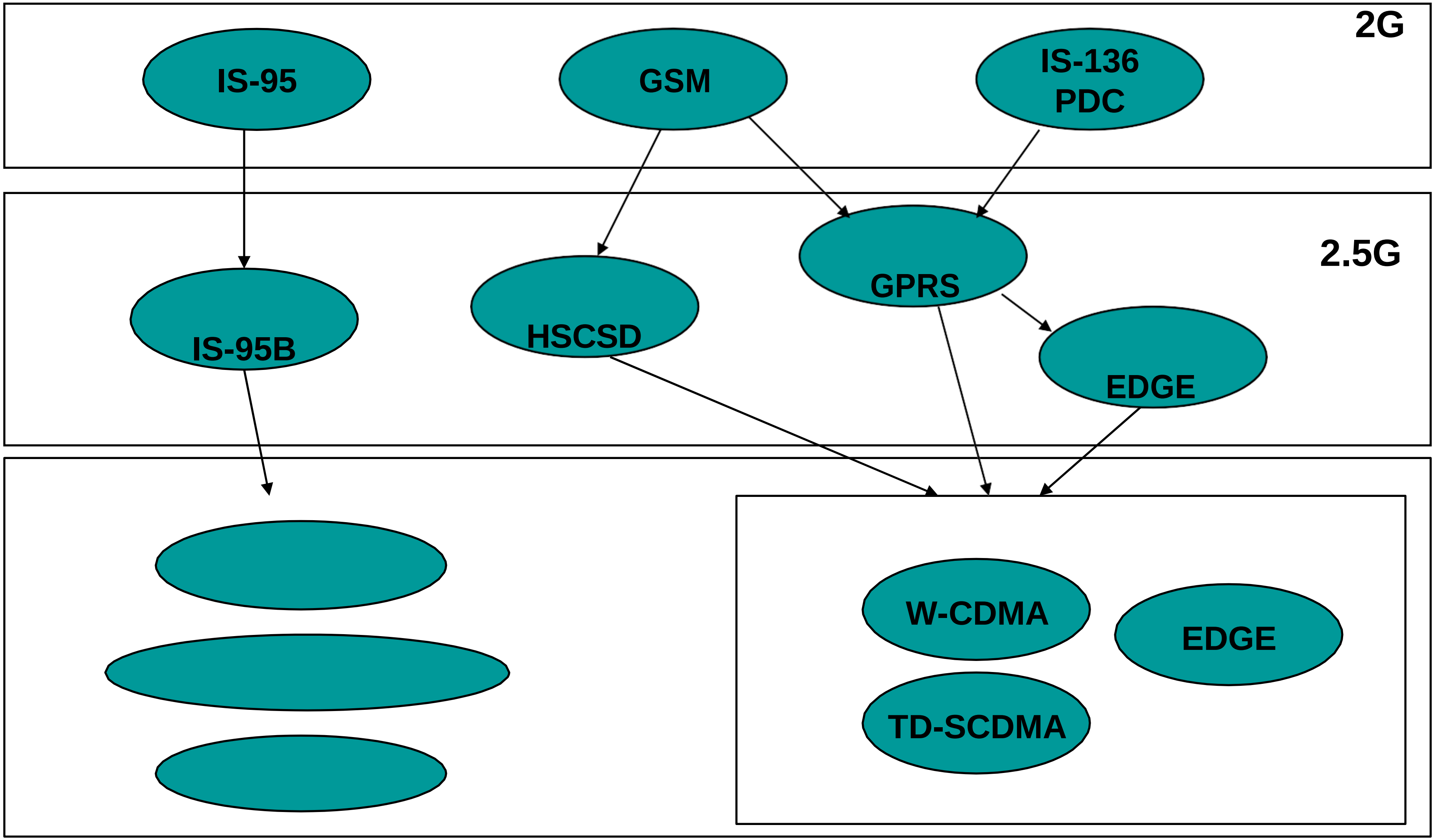
Evolution to 2.5G Mobile Networks

- The 2G deployed before the widespread use of Internet.
- limited Internet browsing and short messaging capability using CS approach.
- In effort to provide increased data-rates, new data centric standards have been developed and overlaid over existing 2G equipments.
- Existing systems were supplemented with hardware and software upgrade to support high data rates for web browsing, email, m-commerce and LBS.

2.5 Technologies

- Evolution of TDMA Systems
  - HSCSD for 2.5G GSM
    - Up to 57.6 Kbps data-rate
  - GPRS for GSM and IS-136
    - Up to 171.2 Kbps data-rate
  - EDGE for 2.5G GSM and IS-136
    - Up to 384 Kbps data-rate
- Evolution of CDMA Systems
  - IS-95B
    - Up to 64 Kbps

Upgrade Paths for 2G Technologies



3G

cdma200-1xRTT

cdma2000-1xEV,DV,DO

cdma200-3xRTT

2.5 Technologies

- HSCSD for 2.5G GSM
  - Allows a user to use consecutive time slots(TS) in GSM to obtain high data-rates.
  - Relaxes error control algorithms and increases data rate to 14.4kbps as compared to 9.6kbps for GSM.
  - Using 4 consecutive TS, HSCSD provides a raw tx-ion rate of 57.6kbps.
  - Requires a software upgrade at the GSM BS.
- GPRS for GSM and IS-136
  - General Packet Radio System is Packet based data networks.
  - Well suited for internet usage.
  - Supports multi-user network sharing of individual radio channel and time slot

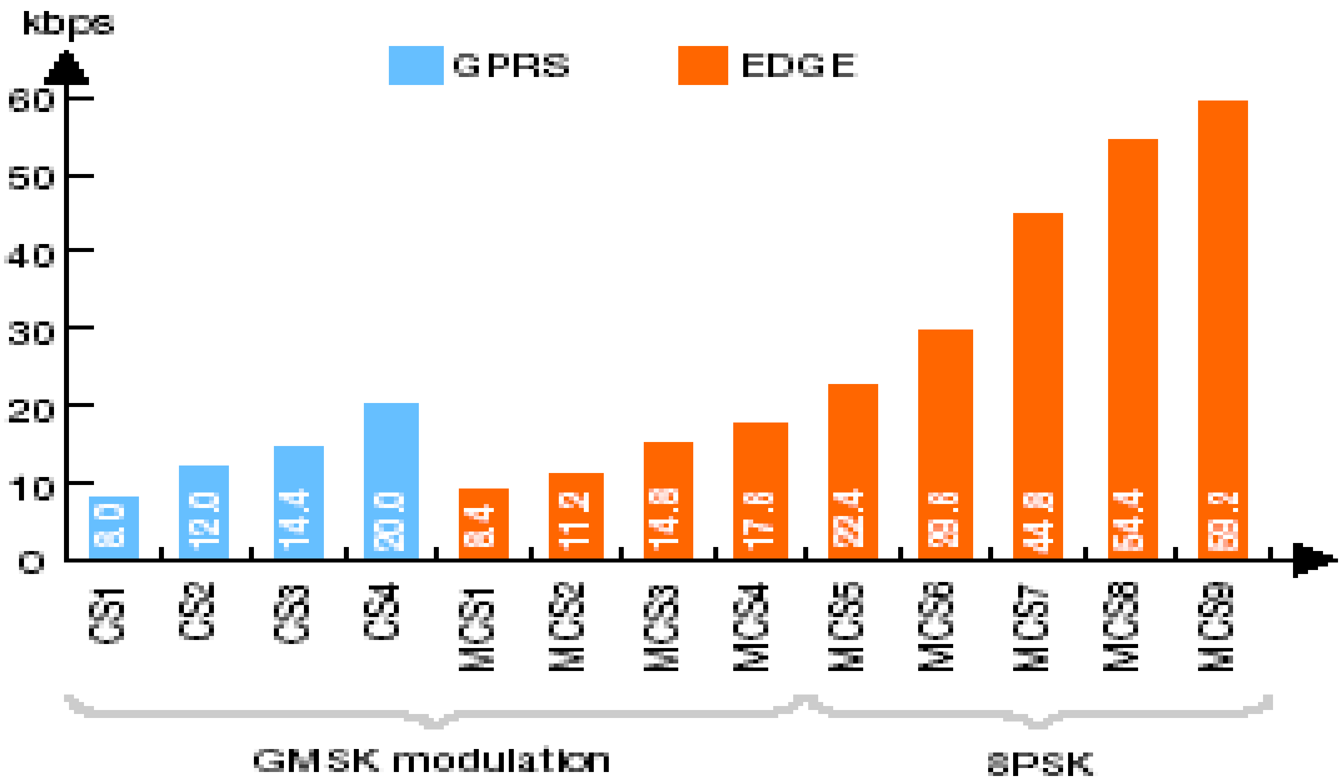
2.5 Technologies

- GPRS for GSM and IS-136
  - Retains the modulation format specified in 2G standard, but uses completely redefined air interface
  - With all the time slots dedicated for a GPRS user its able to achieve data rate of 171.2 kbps(where each slot provides 21.4 kbps raw un-coded date)
  - Applications are required to provide there own error correction schemes.
  - Merely requires new routers and internet gateways at the BS, and software upgrade to redefine BS air interface.

2.5 Technologies

- EDGE for 2.5G GSM and IS-136
  - Enhanced Data rate for GSM evolution.
  - Requires new hardware and software upgrade at BSs.
  - Uses 8PSK digital Modulation in addition to GMSK used for GSM
  - 9 different autonomously selectable air interface format, Multiple Modulation and Coding Schemes(MCS), with varying degree off error control protections.
  - Each MCS state may use GMSK or 8 PSK for network access, depending on instantaneous demand of network and operating conditions.
  - ***User connection may adaptively determine best MCS settings for particular radio propagation conditions, selecting best air interface is called incremental redundancy.***
  - Radio data rate per time slot – 69.2kbps *8=547.2 per channel

2.5 Technologies



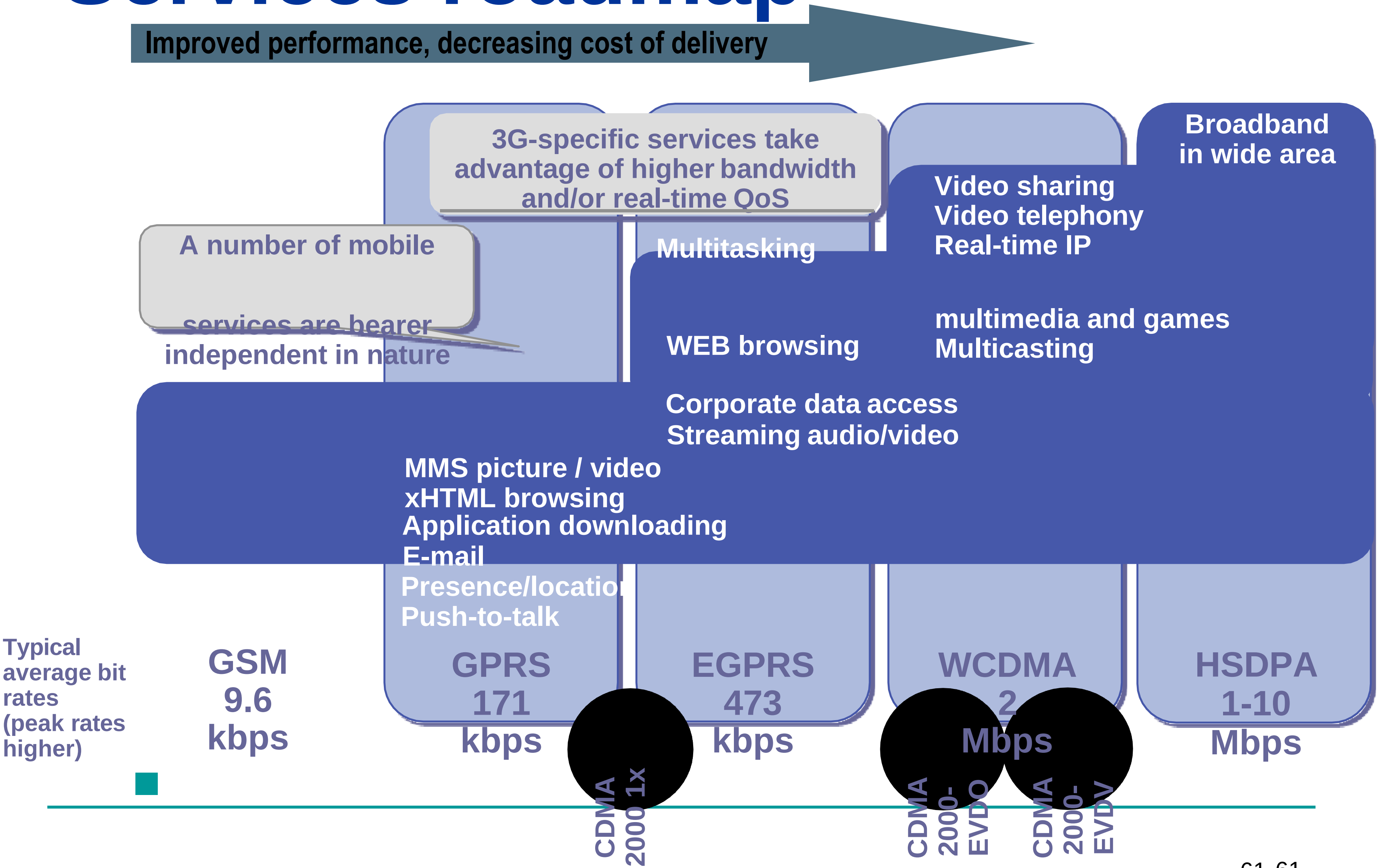
2.5 Technologies

- Evolution of CDMA Systems
  - IS-95B
    - Support *medium data rate(MDR)* service by allowing user to command 8 Walsh codes simultaneously to provide data rate of 115.2kbps (8*14.4kbps)
    - In reality only 64kbps is available to a user due to slotting techniques of the air interface.

2.5 Technologies

Wireless Data Tech	Channel BW	Duplex	Infrastructure Change	Requires New Spectrum	Requires New Handsets
HS CSD	200 KHz	FDD	Requires Software Upgrade at base station	No	Yes, New HSCS D handsets provide 57 .6 Kbps on HS CSD n/w and 9 .6 Kbps on GSM n/w with dual mode phones. GSM only phones will not work in HSCSD N/w.
GPRS	200 KHz	FDD	Requires new packet overlay including routers and gateways	No	Yes, New GPRS handsets work on GPRS n/w at 171 .2 Kbps, 9 .6 Kbps on GSM n/w with dual mode phones. GSM only phones will not work in GPR S n/w.
EDGE	200 KHz	FDD	Requires new transceivers at base station. Also, software upgrade to the BSC & BTS	No	Yes, New handsets work on EDGE n/w at 384 Kbps, GPRS n/w at 144 Kbps, and GSM n/w at 9 .6 Kbps with tri- mode phones. GSM and GPRS -only phones will not work in EDGE n/w.
W -CDMA	5 M Hz	FDD	Requires completely new base stations	Yes	Yes, New W-CDMA handsets will work on W -CDMA at 2Mbps, EDGE n/w at 384 Kbps, GPRS n/w at 144 Kbps. GSM n/w at 9.9 Kbps. Older handsets will not work in W -CDMA.

Services roadmap

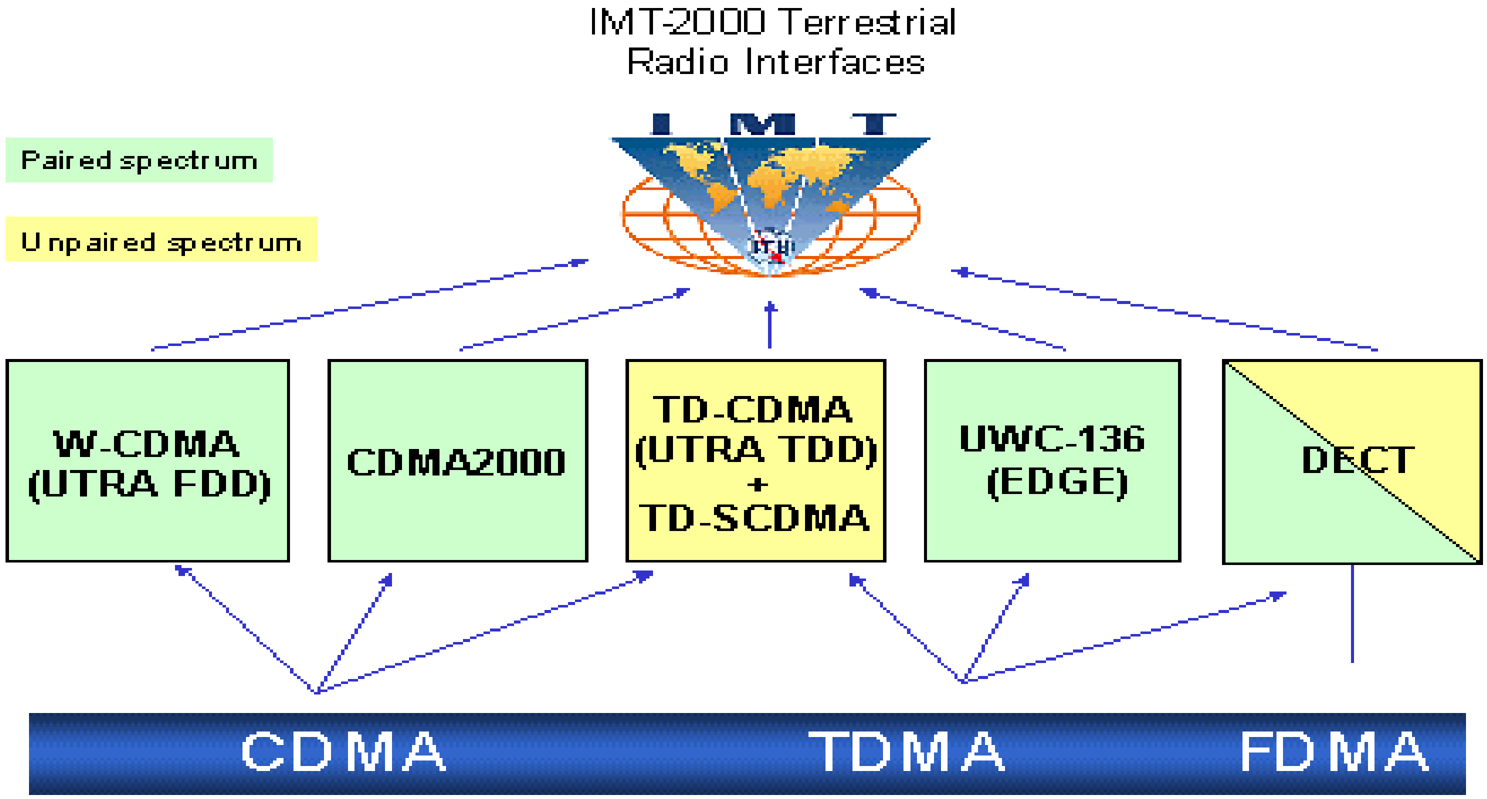


3G Systems

- Goals
  - Voice and Data Transmission
    - Simultanous voice and data access
  - Multi-megabit Internet access
    - Interactive web sessions
    - Communication using VoIP
  - Multimedia Content
    - Live music

3G Standards

- 3G Standard is created by ITU-T and is called as **IMT-2000.**
- The aim of IMT-2000 is to harmonize worldwide 3G systems to provide **Global Roaming**.



3G Systems

- Evolution of CDMA Systems
  - CDMA system evolved to CDMA2000
    - CDMA2000-1xRTT: Upto 307 Kbps
    - CDMA2000-1xEV: Evolutionary(Proprietary high data rate)
    - CDMA2000-1xEVDO: upto 2.4 Mbps(radio channels with data only)
    - CDMA2000-1xEVDV: 144 Kbps datarate (radio channels with data and voice)
  - GSM, IS-136 and PDC evolved to W-CDMA (Wideband CDMA) (also called UMTS)
    - Up to 2.048 Mbps data-rates
    - Future systems 8Mbps
    - Expected to be fully deployed by 2010-2015

3G W-CDMA(UMTS)

- UMTS is the European vision of 3G.
- UMTS is an upgrade from GSM via GPRS or EDGE.
- The standardization work for UMTS is carried out by Third Generation Partnership Project (3GPP).
- Data rates of UMTS are:
  - 144 kbps for rural
  - 384 kbps for urban outdoor
  - 2048 kbps for indoor and low range outdoor
- Virtual Home Environment (VHE)
- Wide band CDMA technology is selected for UTRAN air interface.
- New spectrum is allocated for these technologies i.e. 2500 to 2690, 1710-1885 and 806-960 MHz both for CDMA and UMTS standards.

3G CDMA 2000

- Seamless and evolutionary high data rate for 2G and 2.5 G CDMA, around 1.25 MHz radio channel.
- The standardization work for 3G CDMA 2000 is carried out by Third Generation Partnership Project 2(3GPP2).
- First air interface **CDMA 2000 1X RTT** (1X, 1 time original CDMA channel bandwidth, RTT, Radio Transmission Technology)
- Supports data rate up-to 307kbps
- CDMA2000-3xRTT
  - 3 adjacent (single 3.75 MHz)radio channels used together to provide data throughput in excess of 2 Mbps, ***Requires new RF HW at BS***
  - 3 non adjacent channels may be operated as simultaneously in parallel as 1.25 MHz each
- 3G TD-SCDMA (Radio Channel 1.6MHz)
  - Chinese's standard for 3G, evolution o GSM, adds high data rate equipment at BS, data only overlay on GSM using TDMA and TDD

3G CDMA 2000

Wireless Data Tech.	Channel BW	Duplex	Infrastructure Change	Requires New Spectrum	Requires New Handsets
IS-95B	1.25MHz	FDD	Requires new software in BSC	No	Yes, New handsets will work on IS-95B at 64 Kbps and IS-95A at 14.4 Kbps. CdmaOne phones can work in IS-95B at 14.4 Kbps
Cdma2000 1xRTT	1.25MHz	FDD	Requires new s/w in backbone and new channel cards at base stations. Also need to build a new packet service node.	No	Yes, New handsets will work on 1xRTT at 144 Kbps, IS-95B at 64 Kbps, IS-95A at 14.4 Kbps. Older handsets can work in 1xRTT but at lower speeds.
Cdma2000 1xEV (DO & DV)	1.25MHz	FDD	Requires s/w and digital card upgrade on 1xRTT networks	No	Yes,New handsets can work on 1xEV at 2.4 Mbps, 1xRTT at 144 Kbps, IS-95B at 64 Kbps, IS-95A at 14.4 Kbps. Older handsets can work in 1xEV but at lower speeds.
Cdma2000 3xRTT	3.75MHz	FDD	Requires backbone modifications and new channel cards at base stations.	Maybe	Yes, New handsets will work on 95A at 14.4 Kbps, 95B at 64 Kbps, 1xRTT at 144 Kbps, 3xRTT at 2 Mbps. Older handsets can work in 3X but at lower speeds.

The Cellular Concept

Cellular Systems-Basic Concepts

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

Cellular Systems-Basic Concepts

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

Frequency Reuse

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

Frequency Reuse

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

Frequency Reuse

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

Frequency Reuse

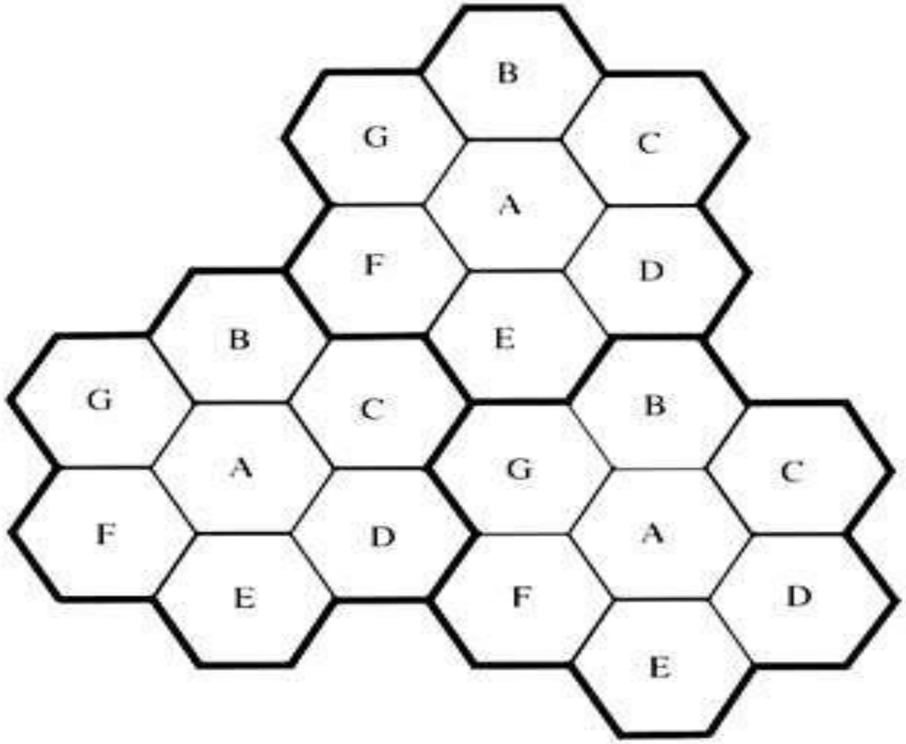


Figure 3.1 Illustration of the cellular frequency reuse concept. Cells with the same letter use the same set of frequencies. A cell cluster is outlined in bold and replicated over the coverage area. In this example, the cluster size, *N*, is equal to seven, and the frequency reuse factor is 1/7 since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

Frequency Reuse

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

Frequency Reuse

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

$$C=MkN=MS$$

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

Frequency Reuse

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

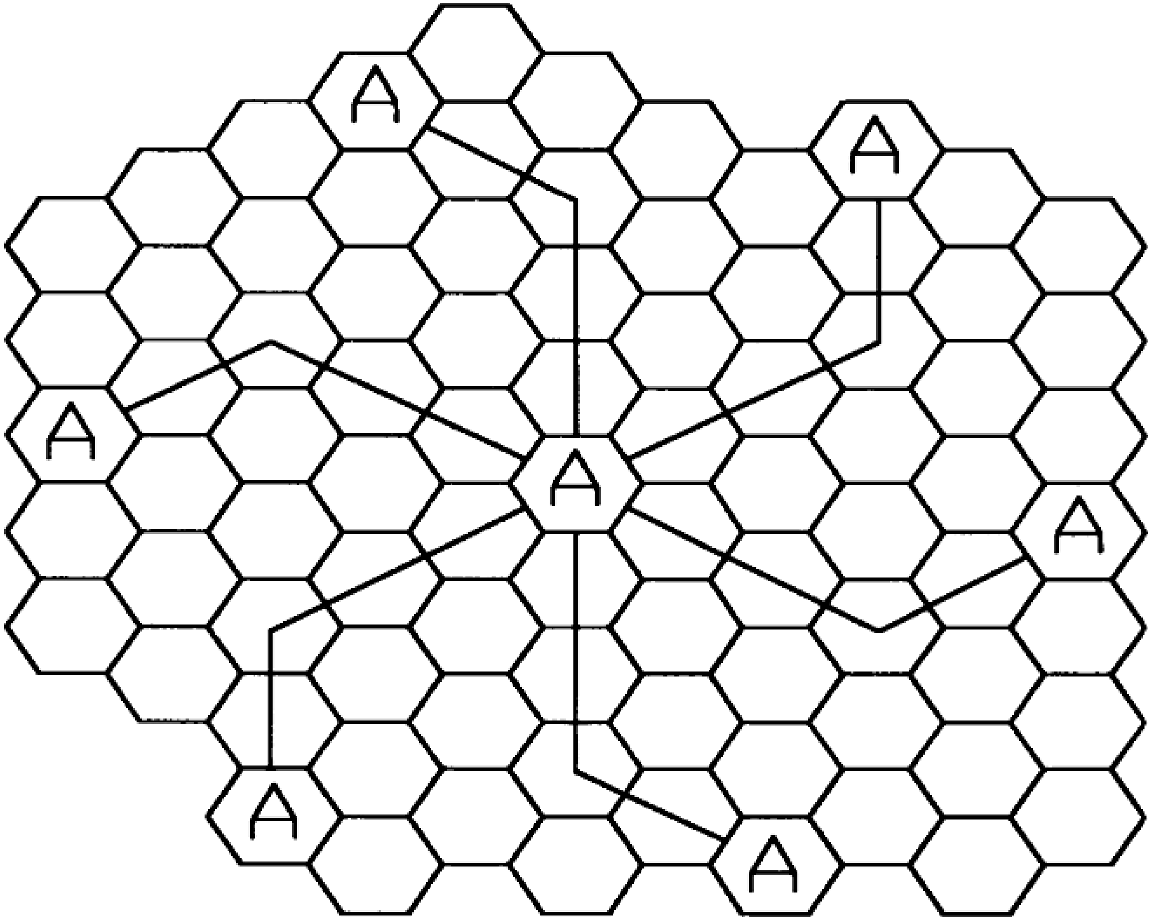
$$N=i^2+ij+j^2$$

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

In GSM normally N =7 is used.

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

Locating co-channel Cell



Channel Assignment Strategies

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

Dynamic Channel Assignment

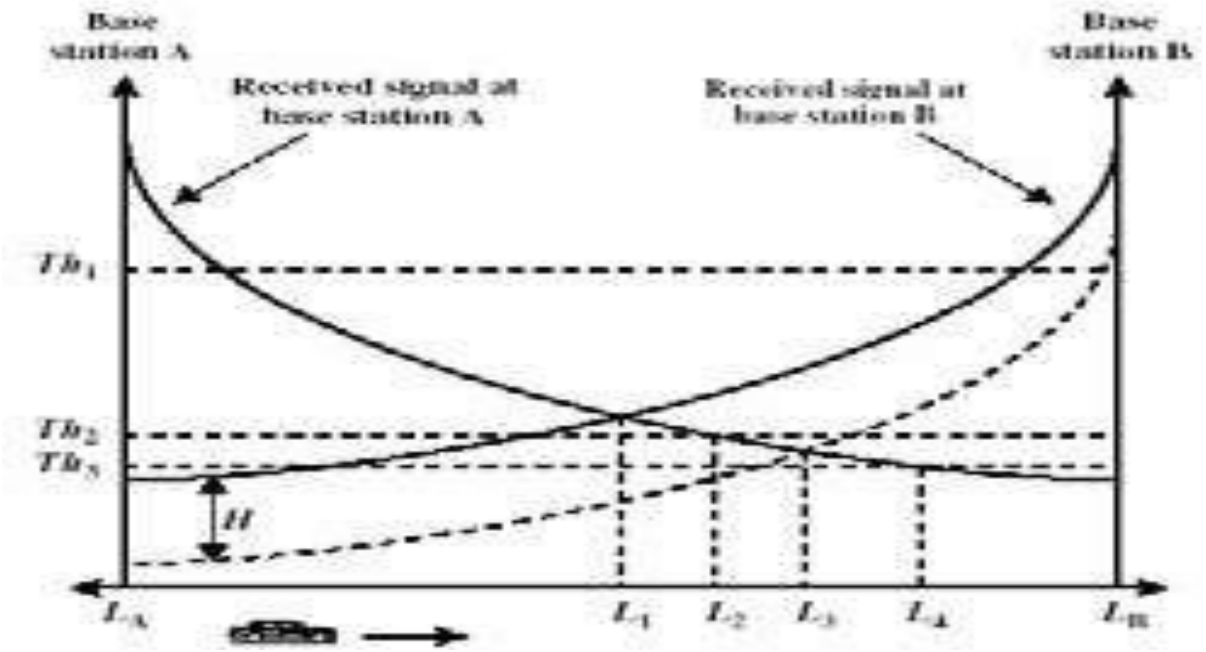
- Voice channels are not allocated to different cells *permanently*.
- Each time a call request is made, the *BS request* a channel from the MSC.
- MSC allocates a channel to the requesting cell using an algorithm that takes into account
  - likelihood of future blocking
  - The reuse distance of the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

Hand-off

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

Handoff

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



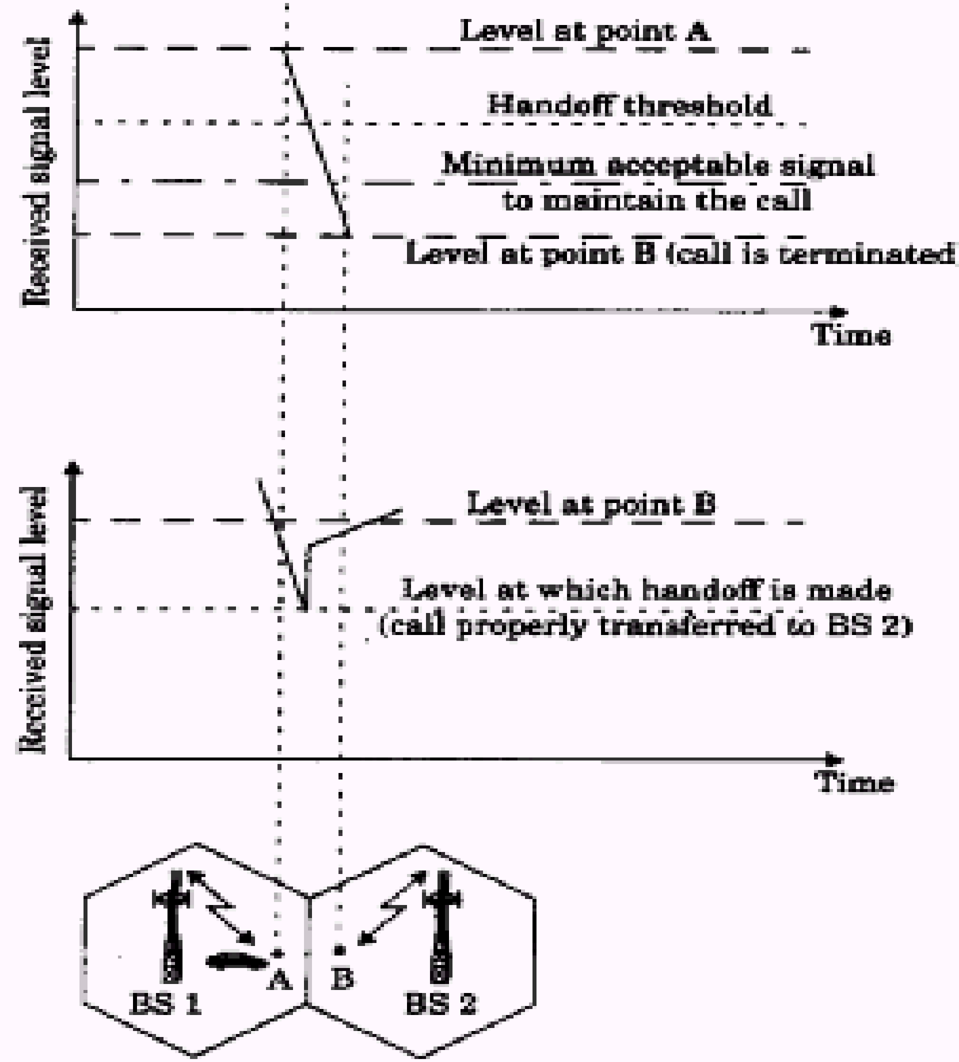


Figure 2.3
Illustration of a handoff scenario at cell boundary.

Hand-off strategies

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

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

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

Hand-off

- In deciding when to handoff , it is important to ensure that the drop in signal level is not due to momentary fading.
- In order to ensure this the BS monitors the signal for a certain period of time before initiating a handoff
- The length of time needed to decide if handoff is necessary depends on the speed at which the mobile is moving

Hand-off strategies

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

Hand-off strategies

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

Soft Handoff

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

Inter system Handoff

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

Prioritizing Handoffs

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

Prioritizing Handoffs

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

Practical Handoff Considerations

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

Umbrella Cells

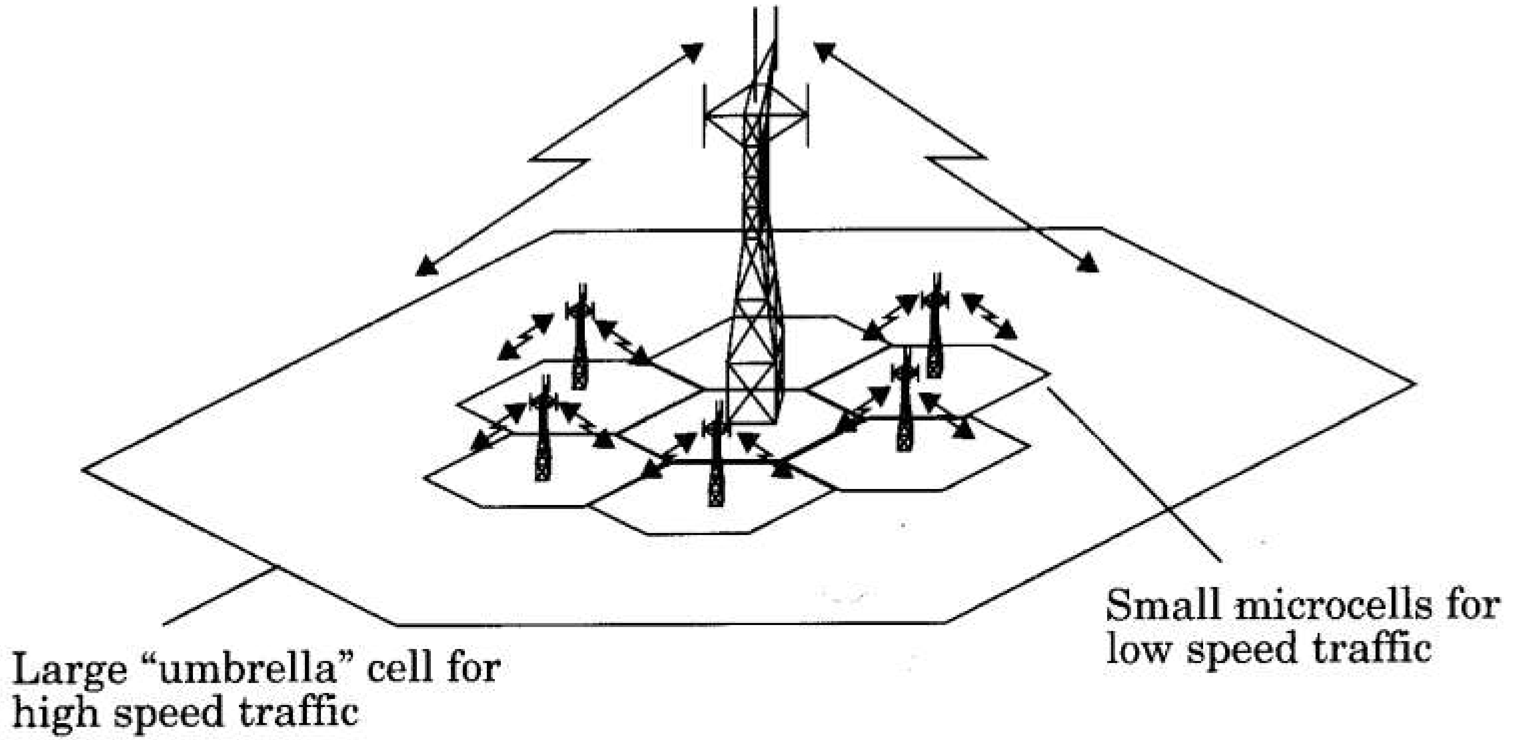


Figure 3.4 The umbrella cell approach.

Typical handoff parameters

- Analog cellular (1st generation)
  - threshold margin $\Delta \approx$ 6 to 12 dB
  - total time to complete handoff ≈ 8 to 10 sec
- Digital cellular (2nd generation)
  - total time to complete handoff ≈ 1 to 2 sec
  - lower necessary threshold margin $\Delta \approx$ 0 to 6 dB
  - enabled by mobile assisted handoff

Reuse Ratio:

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

Interference

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

Interference

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

Effects of Interference

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

Interference

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

Co-channel Interference

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

Co-channel Interference

- co-channel interference depends on:
  - *R* : cell radius
  - *D* : distance to base station of nearest co-channel cell where $D=R(\sqrt{3N})$
- if *D/R* ↑ then spatial separation relative to cell coverage area ↑
  - improved isolation from co-channel RF energy
- $Q = D / R$: co-channel reuse ratio
  - hexagonal cells → $Q = D/R = \sqrt{3N}$
- Smaller value of Q provides larger capacity, but higher CCI
- Hence there is tradeoff between capacity and interference.
  - small Q → small cluster size → more frequency reuse → larger system capacity
  - small Q → small cell separation → increased CCI

Signal to Interference ratio S/I

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

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

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

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

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

Signal to Interference ratio S/I

- The S/I for mobile is given by

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

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

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

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

Signal to Interference ratio S/I

- The MS is at cell boundary

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

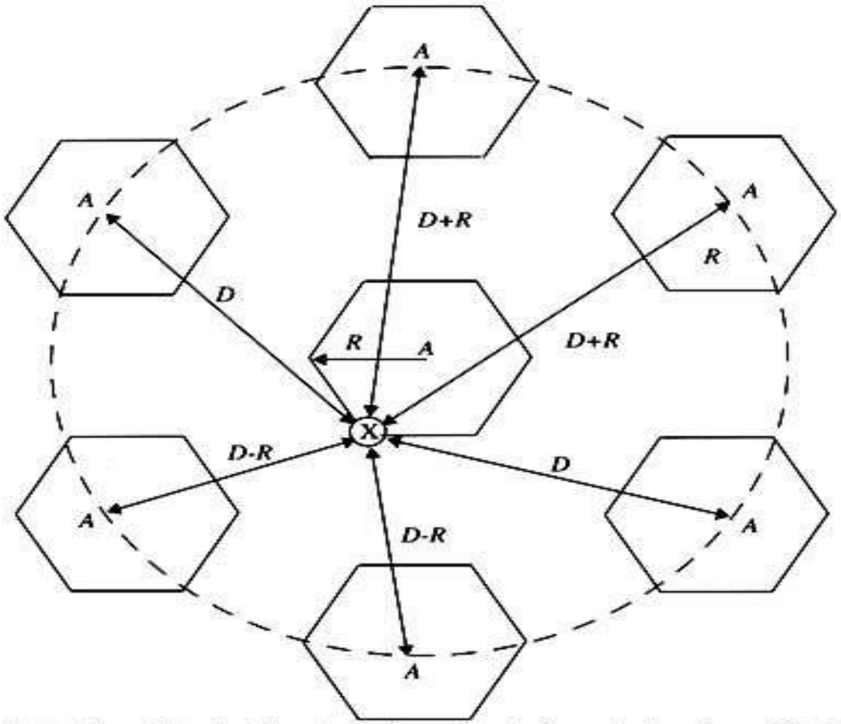


Figure 3.5 Illustration of the first tier of co-channel cells for a cluster size of $N = 7$. An approximation of the exact geometry is shown here, whereas the exact geometry is given in [Lee86]. When the mobile is at the cell boundary (point X), it experiences worst case co-channel interference on the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

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

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

Example S/I

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

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

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

Example S/I

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

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

Adjacent Channel Interference

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

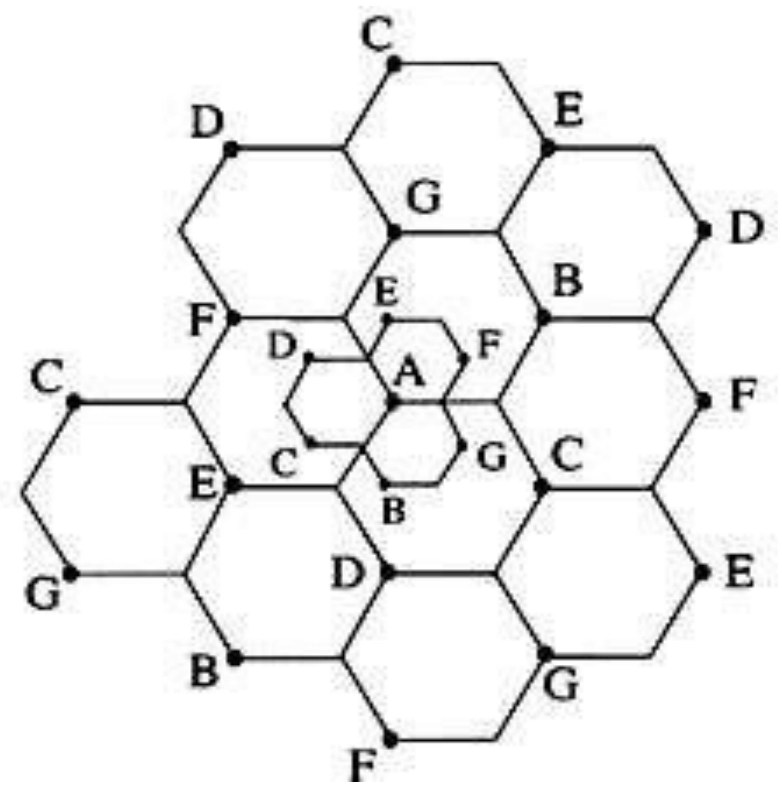
Improving Capacity

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

Cell Splitting

- Cell splitting is the process of subdividing a congested cell into smaller cells with
  - their own BS
  - a corresponding reduction in antenna height
  - a corresponding reduction in transmit power
- Splitting the cell reduces the cell size and thus more number of cells have to be used
- For the new cells to be smaller in size the transmit power of these cells must be reduced.
- Idea is to keep Q=D/R constant while decreasing R
- More number of cells ► more number of clusters ► more channels ►high capacity

Cells are split to add channels with no new spectrum usage



Example S/I

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

- cluster size N=7
- path loss exponent n=3
- Q=sqrt(3N)=4.582576
- number of neighboring cells io= 6, # of sides of hexagon
- signal to interference ratio=S/I= $(D/R)^{\wedge n} / i_o$ =73.334
- convert to dB, S/I=10log(S/I)=18.65dB
- S/I is less than required, it will work!

Cell Splitting-Power Issues

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

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

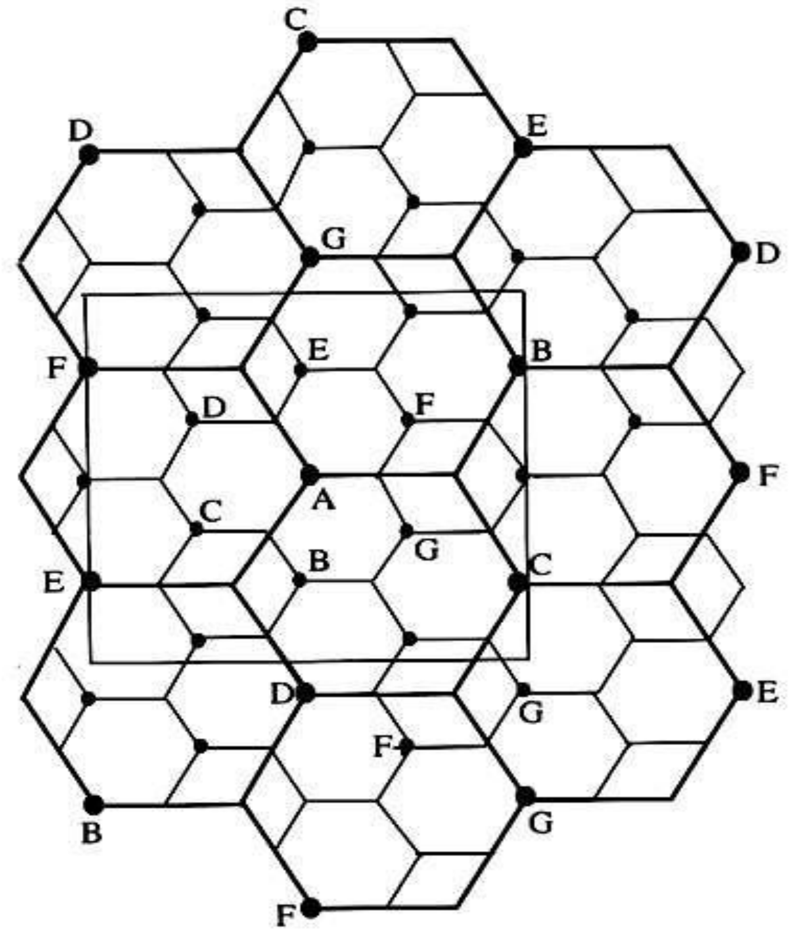
$$Pr[\text{at new cell boundary}] = Pt2 (R/2)^{-n}$$

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

$$Pt2 = Pt1/8$$

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

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



Cell Splitting

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

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

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

Umbrella Cells

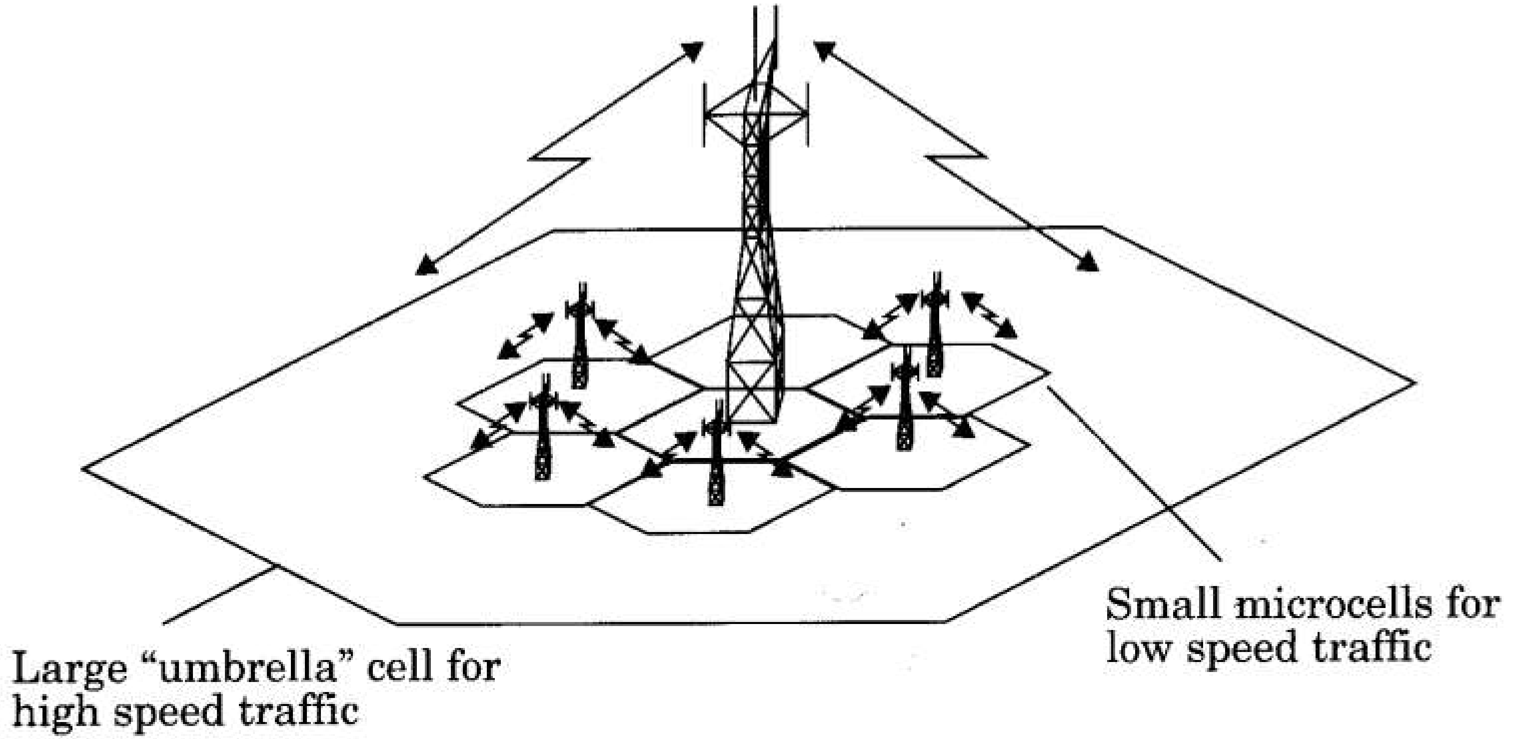
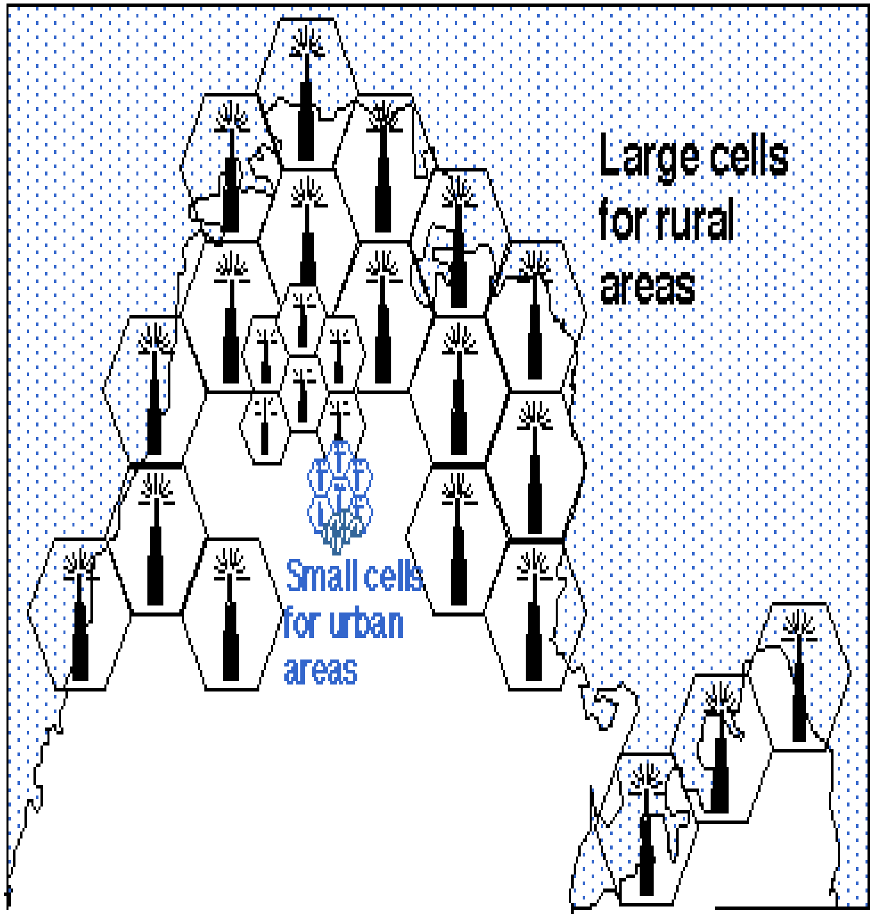
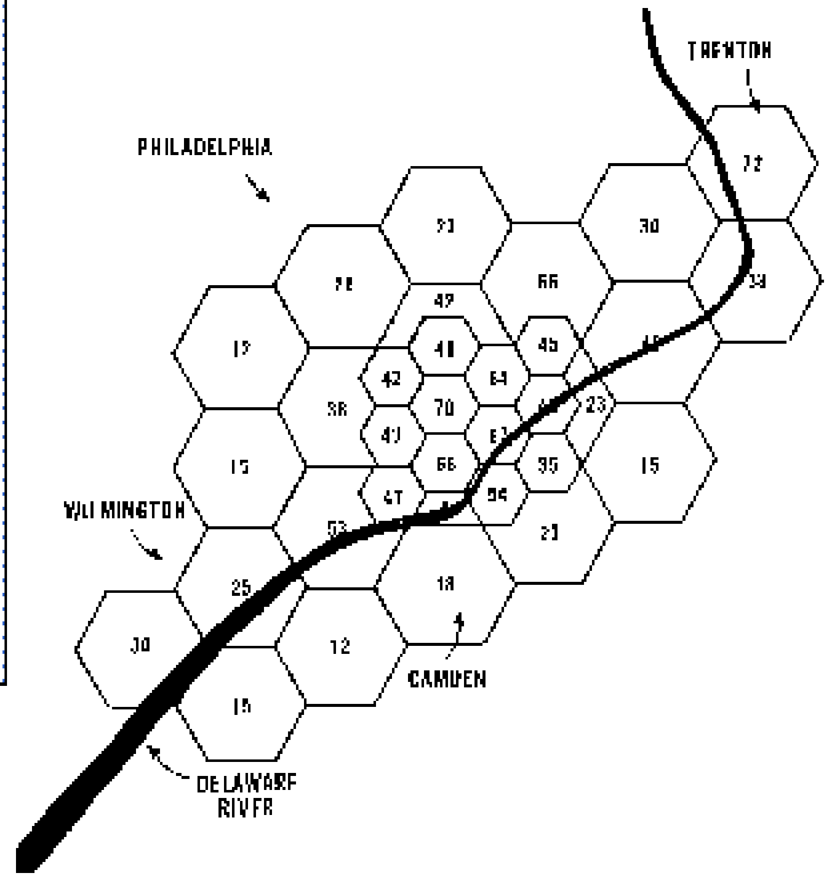


Figure 3.4 The umbrella cell approach.


Large cells
for rural
areas
Small cells
for urban
areas


TRENTON
PHILADELPHIA
WILMINGTON
CAMDEN
DELAWARE
RIVER

Sectoring

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

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

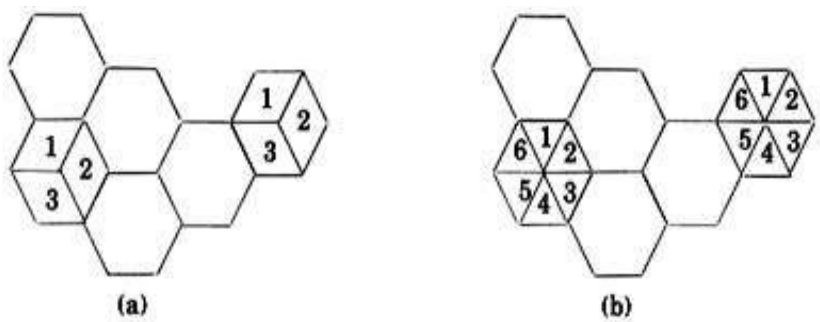


Figure 3.10 (a) 120° sectoring; (b) 60° sectoring.

Sectoring

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

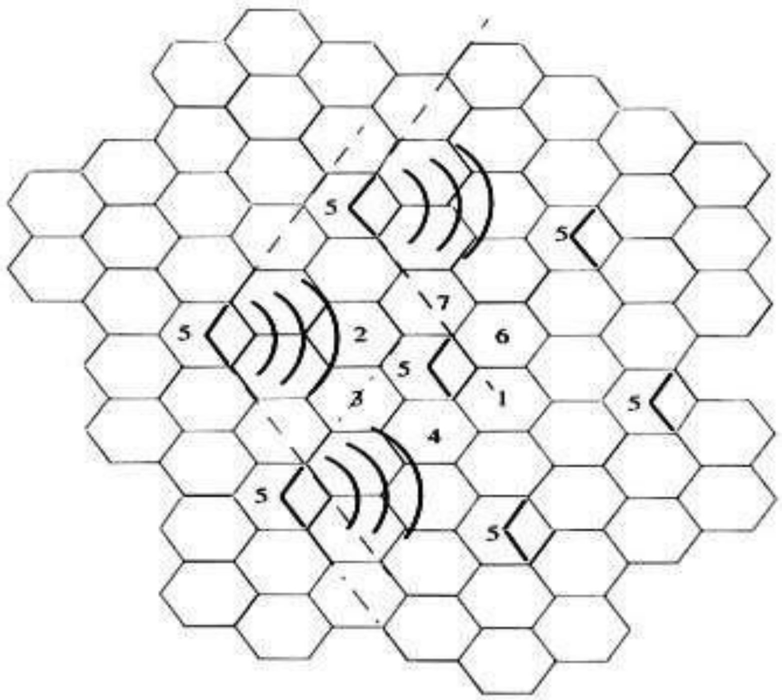


Figure 3.11 Illustration of how 120° sectoring reduces interference from co-channel cells. Out of the 6 co-channel cells in the first tier, only two of them interfere with the center cell. If omnidirectional antennas were used at each base station, all six co-channel cells would interfere with the center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

Problems with Sectoring

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

Microcell Zone Concept

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

Micro Zone Cell Concept

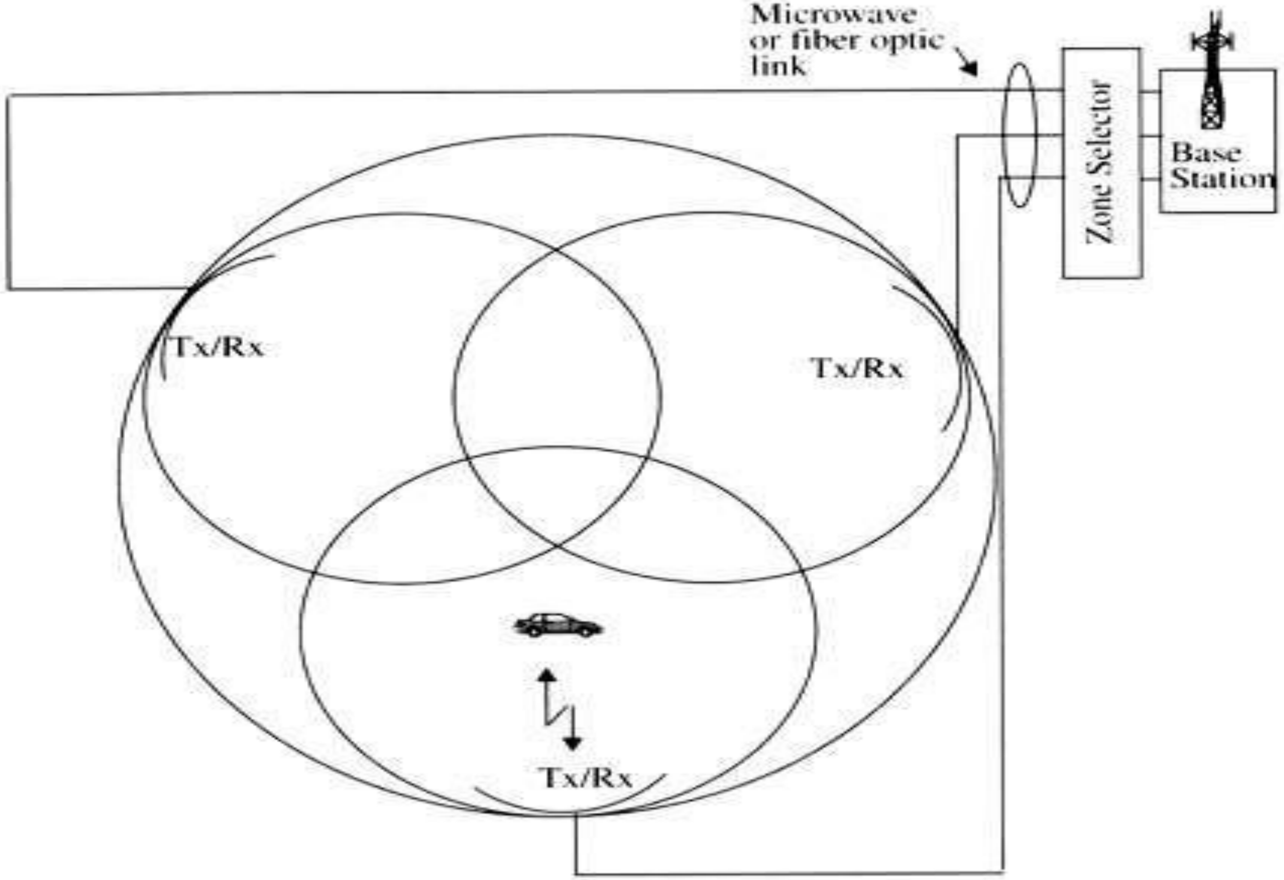


Figure 3.13 The microcell concept [adapted from [Lee91b] © IEEE].

Microcell Zone Concept

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

Repeaters for Range Extension

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

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

Mobile Radio Propagation

Large-scale Path loss

Wireless Communication

Chapter 3

Introduction

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

Properties of Radio Waves

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

Properties of Radio Waves

- Frequency dependence
  - Behave more like light at high frequencies
    - Difficulty in passing obstacle
    - Follow direct paths
    - Absorbed by rain
  - Behave more like radio at lower frequencies
    - Can pass obstacles
    - Power falls off sharply with distance from source
- Subject to interference from other radio waves

Propagation Models

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

- They are tools used for:
  - Predicting the average signal strength at a given distance from the transmitter
  - Estimating the variability of the signal strength in close spatial proximity to a particular locations

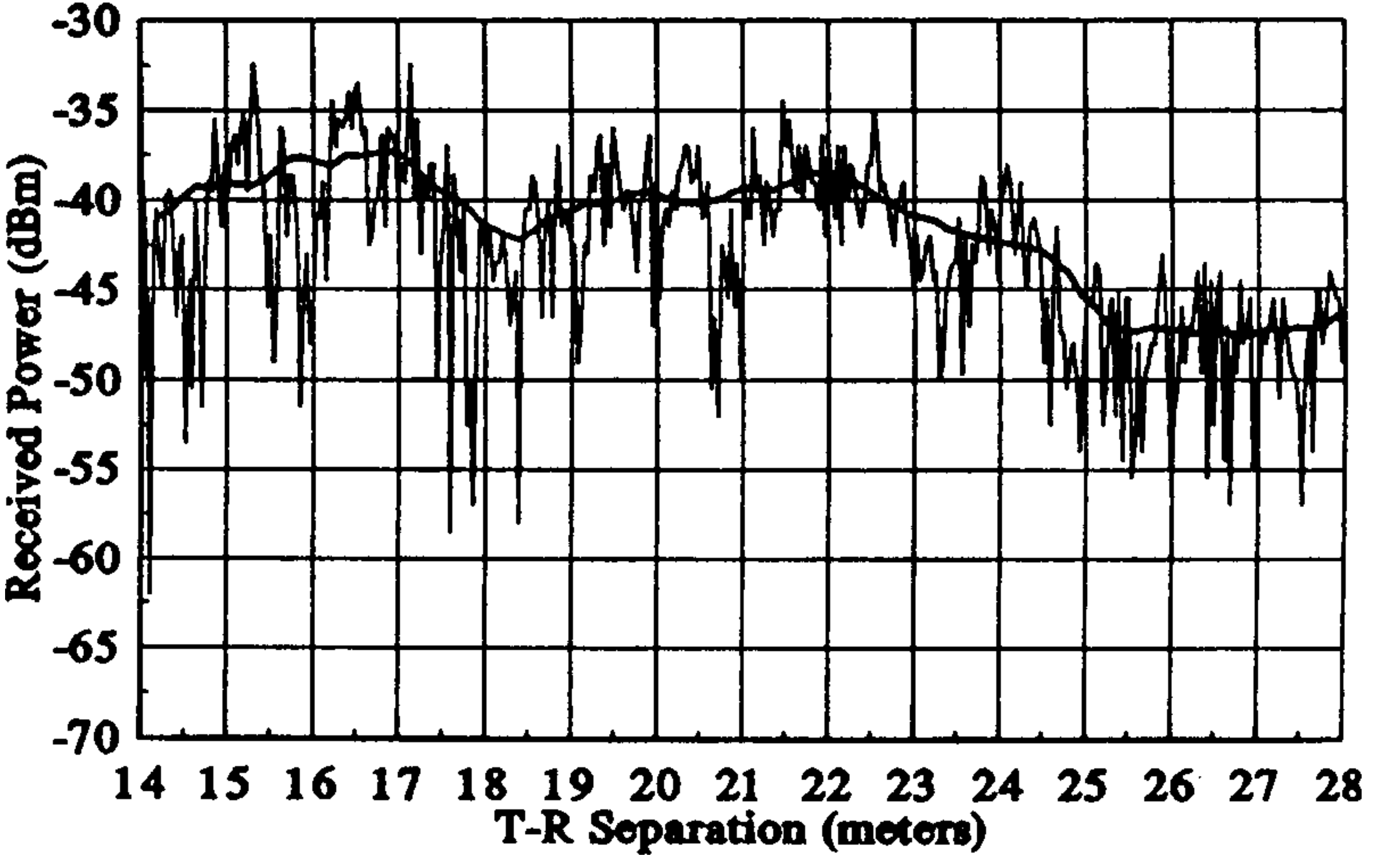
Propagation Models

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

Propagation Models

- Small Scale or Fading Models:
  - Characterize rapid fluctuations of received signal strength over
    - Very short travel distances(a few wavelengths)
    - Short time durations(on the order of seconds)

Small-scale and large-scale fading



Free Space Propagation Model

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

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

- Given by Friis free space eqn:

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

'L' is the system loss factor

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

L = 1 indicates no loss in the system hardware

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

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

Free Space Propagation Model

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

$$\lambda = c/f.$$

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

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

- Effective Isotropic Radiated Power (EIRP) is defined as

$$EIRP = P_t G_t$$

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

Free Space Propagation Model

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

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

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

  ERP=EIRP-2.15(dB)

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

Free Space Propagation Model

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

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

= -10 log {GtGr λ^2/(4π)^2d^2}

- Without antenna gains (with unit antenna gains)

PL = - 10 log { λ^2/(4π)^2d^2}

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

Free Space Propagation Model

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

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

Pr with reference to 1 mW is represented as

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

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

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

Example

- What will be the far-field distance for a Base station antenna with
- Largest dimension D=0.5m
- Frequency of operation fc=900MHz,1800MHz

- For 900MHz
- *λ =3*10^8/900*10^6)=0.33m*
- *df= 2D^2/ λ =2(0.5)^2/0.33=1.5m*

Example

- If a transmitter produces 50 watts of power, express the transmit power in units of (a) dBm, and (b) dBW. If 50 watts 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.

solution

Given:
Transmitter power, $P_t = 50$ W.
Carrier frequency, $f_c = 900$ MHz

Using equation (3.9),
(a) Transmitter power,

$$P_t(\text{dBm}) = 10\log[P_t(\text{mW})/(1\text{ mW})]$$
$$= 10\log[50 \times 10^3] = 47.0 \text{ dBm}.$$

(b) Transmitter power,

$$P_t(\text{dBW}) = 10\log[P_t(\text{W})/(1\text{ W})]$$
$$= 10\log[50] = 17.0 \text{ dBW}.$$

The received power can be determined using equation (3.1).

$$P_r = \frac{P_t G_t G_r \lambda^2}{(4\pi)^2 d^2 L} = \frac{50(1)(1)(1/3)^2}{(4\pi)^2(100)^2(1)} = 3.5 \times 10^{-6} \text{ W} = 3.5 \times 10^{-3} \text{ mW}$$

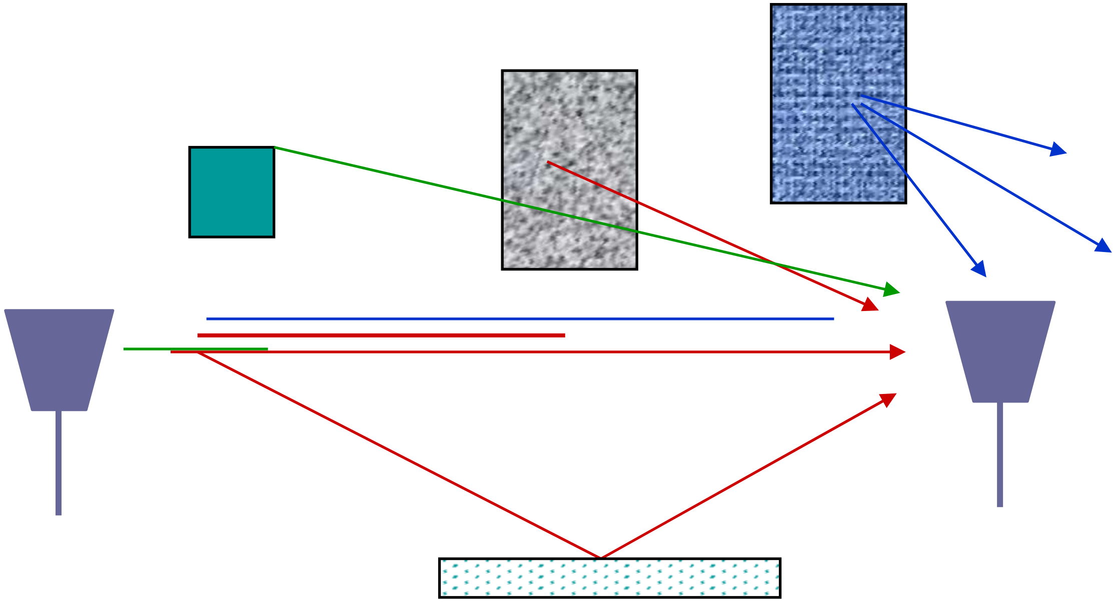
$$P_r(\text{dBm}) = 10\log P_r(\text{mW}) = 10\log\left(3.5 \times 10^{-3}\text{ mW}\right) = -24.5 \text{ dBm}.$$

The received power at 10 km can be expressed in terms of dBm using equation (3.9), where $d_0 = 100$ m and $d = 10$ km

$$P_r(10\text{ km}) = P_r(100) + 20\log\left[\frac{100}{10000}\right] = -24.5 \text{ dBm} - 40 \text{ dB}$$
$$= -64.5 \text{ dBm}.$$

Propagation Mechanisms

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



Propagation Mechanisms

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

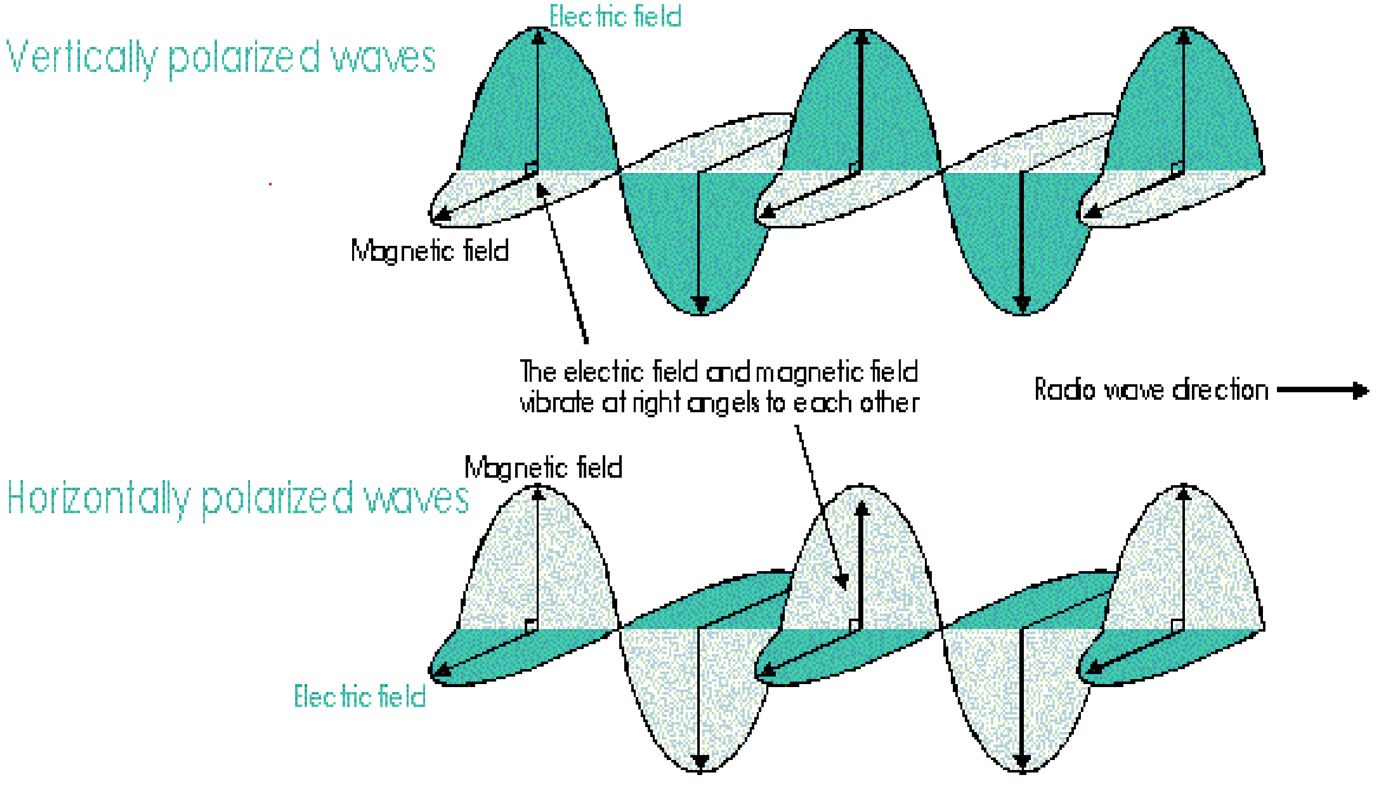
- Diffraction occurs when the radio path between the transmitter and receiver is obstructed by a surface that has sharp irregularities(edges)
  - Explains how radio signals can travel urban and rural environments without a line of sight path

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

Reflection

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

Vertical and Horizontal polarization



Reflection- Dielectrics

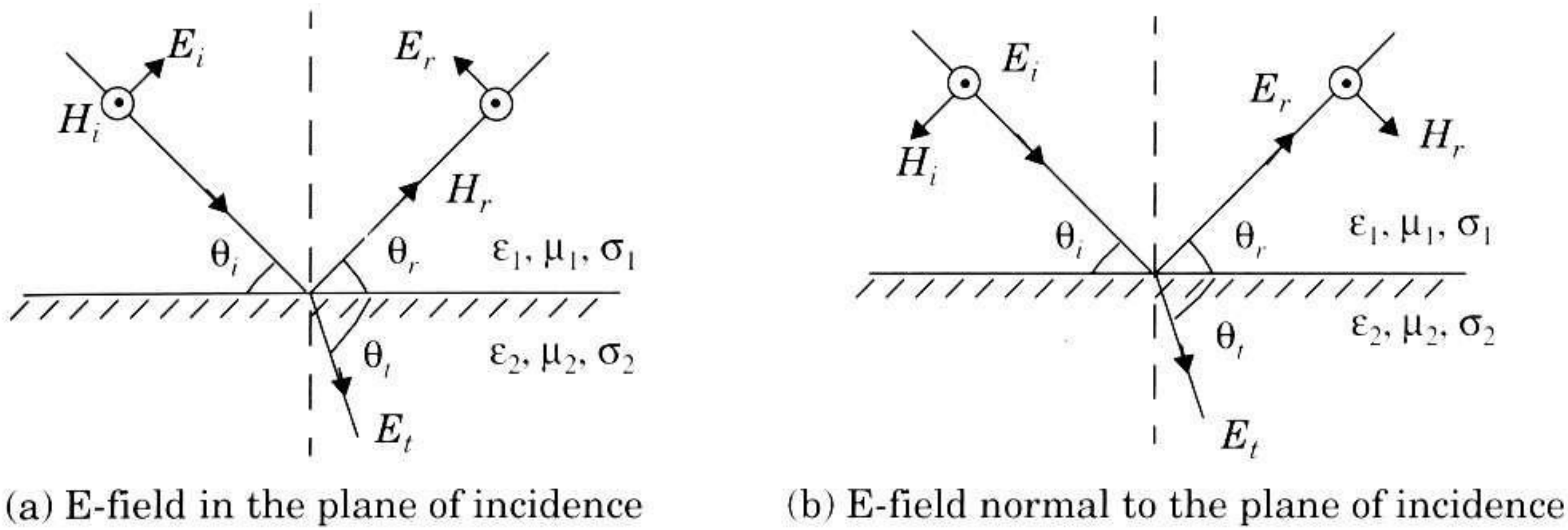


Figure 4.4 Geometry for calculating the reflection coefficients between two dielectrics.

Reflection

$E_i \quad \eta_1 \sin\theta_t + \eta_1 \sin\theta_i$

-

- $\Gamma(\perp) = \frac{E_r}{E_i} = \frac{\eta_2 \sin\theta_i - \eta_1 \sin\theta_t}{\eta_1 \sin\theta_i + \eta_1 \sin\theta_t}$ (Perpendicular E-field polarization)
- These expressions express ratio of reflected electric fields to the incident electric field and depend on impedance of media and on angles
- η is the intrinsic impedance given by $\sqrt{(\mu/\varepsilon)}$
- μ=permeability, ε=permittivity

Reflection-Perfect Conductor

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

Reflection - Brewster Angle

- that the reflection coefficient Γ(parallel) is equal to zero.
- It is given in terms of θ_B as given below

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

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

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

- Brewster angle only occur for parallel polarization

Ground Reflection(Two Ray) Model

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

Ground Reflection(Two Ray) Model

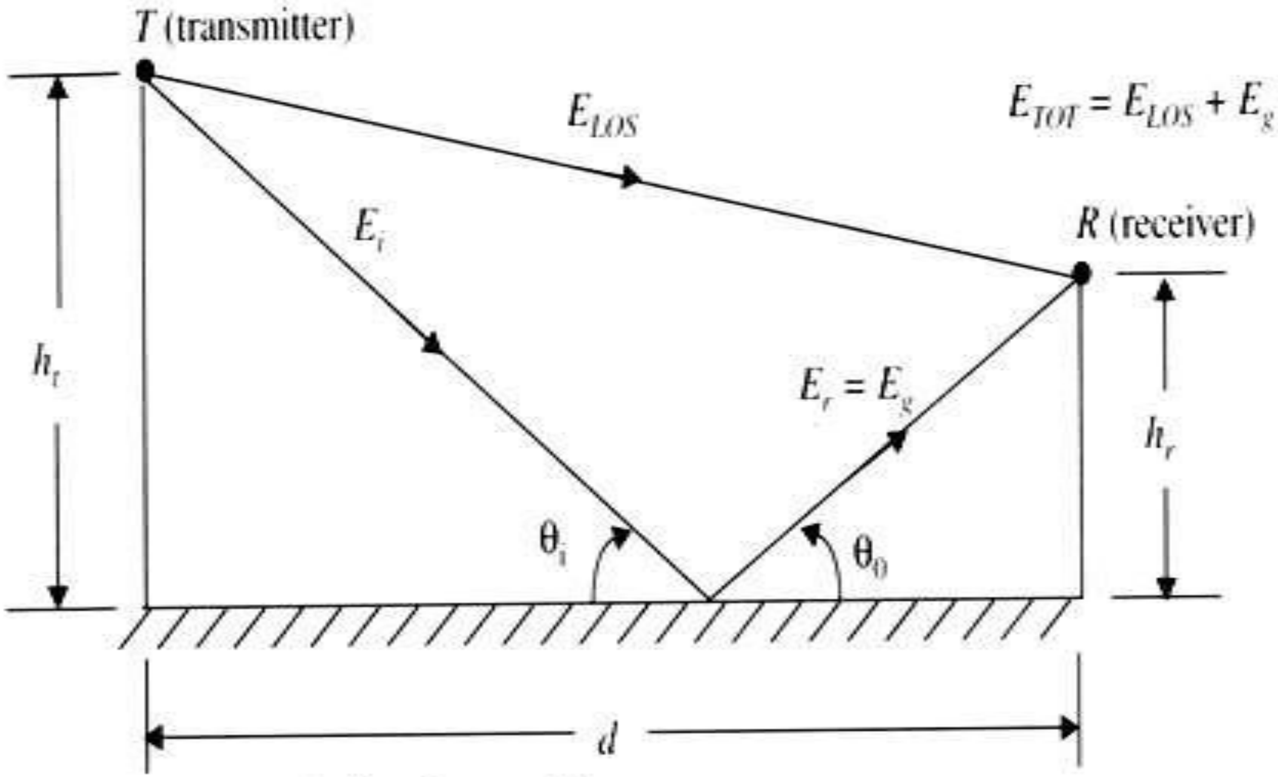


Figure 4.7 Two-ray ground reflection model.

Ground Reflection(Two Ray) Model

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

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

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

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

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

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

Ground Reflection(Two Ray) Model

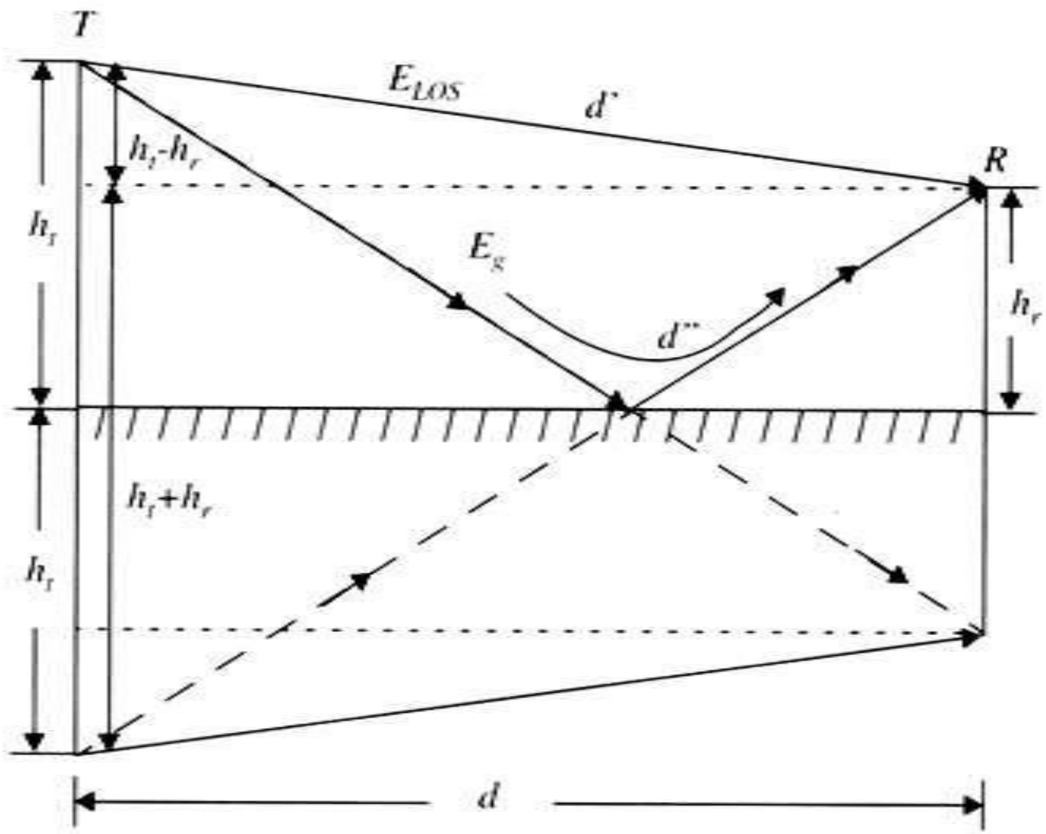


Figure 4.8 The method of images is used to find the path difference between the line-of-sight and the ground reflected paths.

Path Difference

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

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

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

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

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

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

Phase difference

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

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

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

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

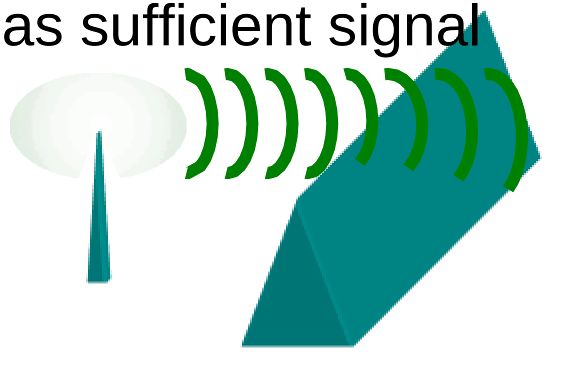
$$d^4$$

Diffraction

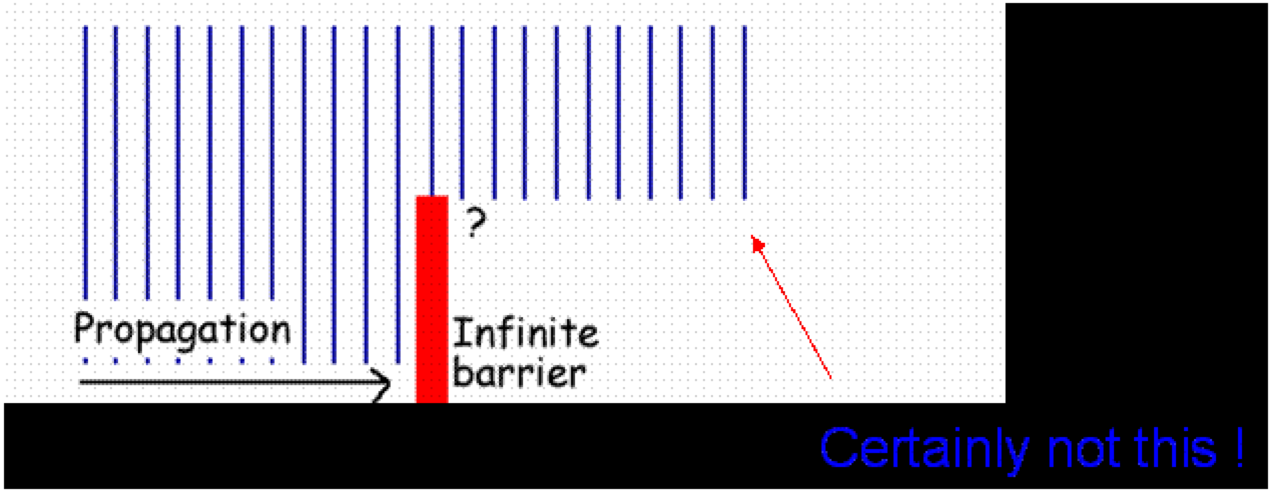
- Diffraction is the bending of wave fronts around obstacles.

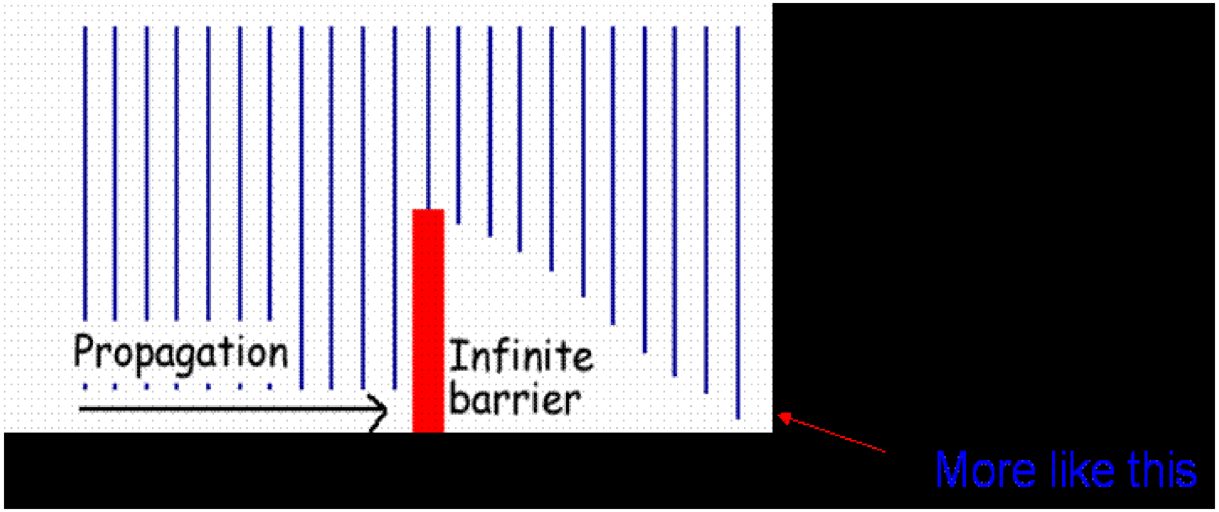
- Diffraction allows radio signals to propagate behind obstructions and is thus one of the factors why we receive signals at locations where there is no line-of-sight from base stations

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



Diffraction





Knife-edge Diffraction Model

- Estimating the signal attenuation caused by diffraction of radio waves over hills and buildings is essential in predicting the field strength in a given service area.
- As a starting point, the limiting case of propagation over a knife edge gives good in sight into the order of magnitude diffraction loss.
- When shadowing is caused by a single object such as a building, the attenuation caused by diffraction can be estimated by treating the obstruction as a diffracting knife edge

Knife-edge Diffraction Model

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

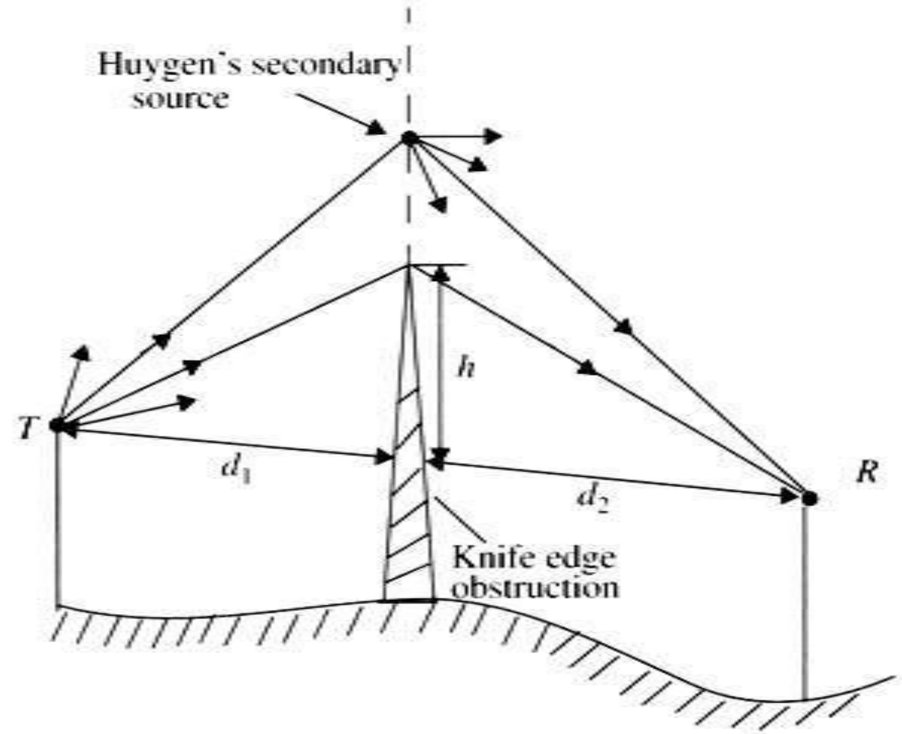


Figure 4.13 Illustration of knife-edge diffraction geometry. The receiver *R* is located in the shadow region.

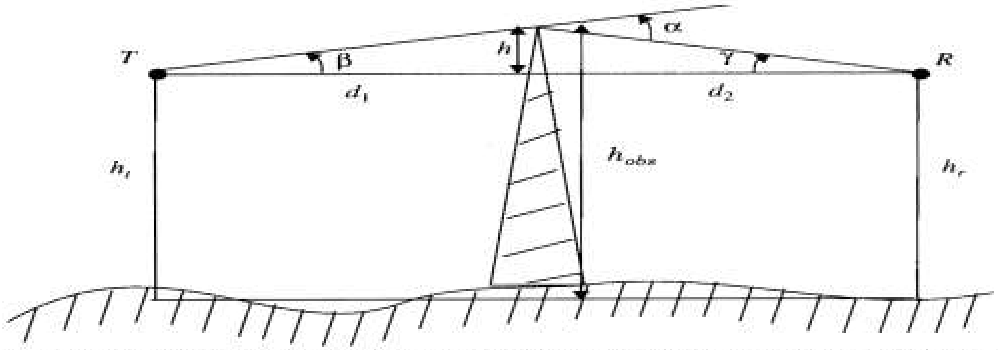
Knife-edge Diffraction Model

- The corresponding pha $\Delta \approx \frac{h^2}{2}\frac{(d_1 + d_2)}{d_1 d_2}$

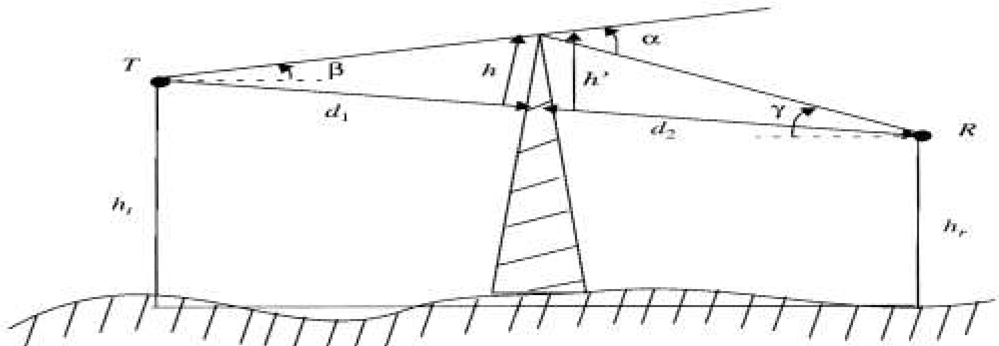
- *Fresnel-Kirchoff* diff $\phi = \frac{2\pi\Delta}{\lambda} \approx \frac{2\pi}{\lambda}\frac{h^2}{2}\frac{(d_1 + d_2)}{d_1 d_2}$ to normalize the phased term and gi

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

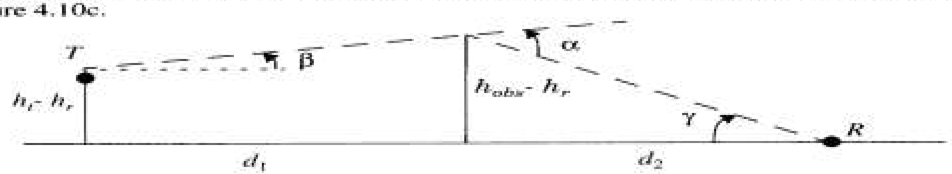
Knife-edge Diffraction Model



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



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



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

Figure 4.10 Diagrams of knife-edge geometry.

Fresnel zones

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

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

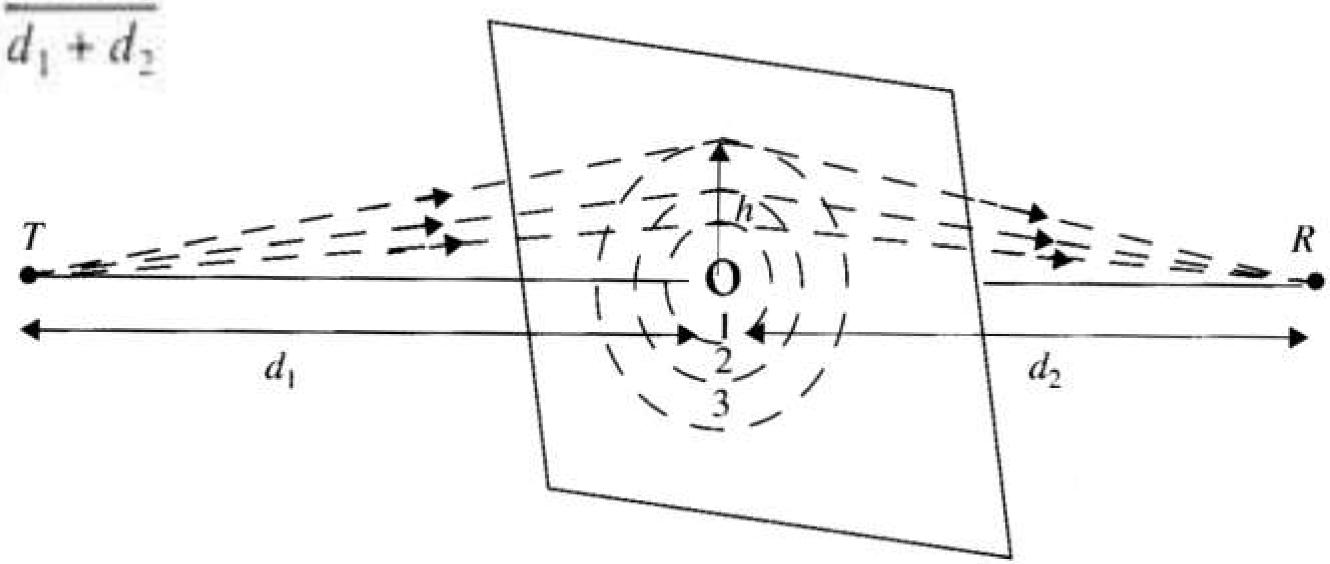
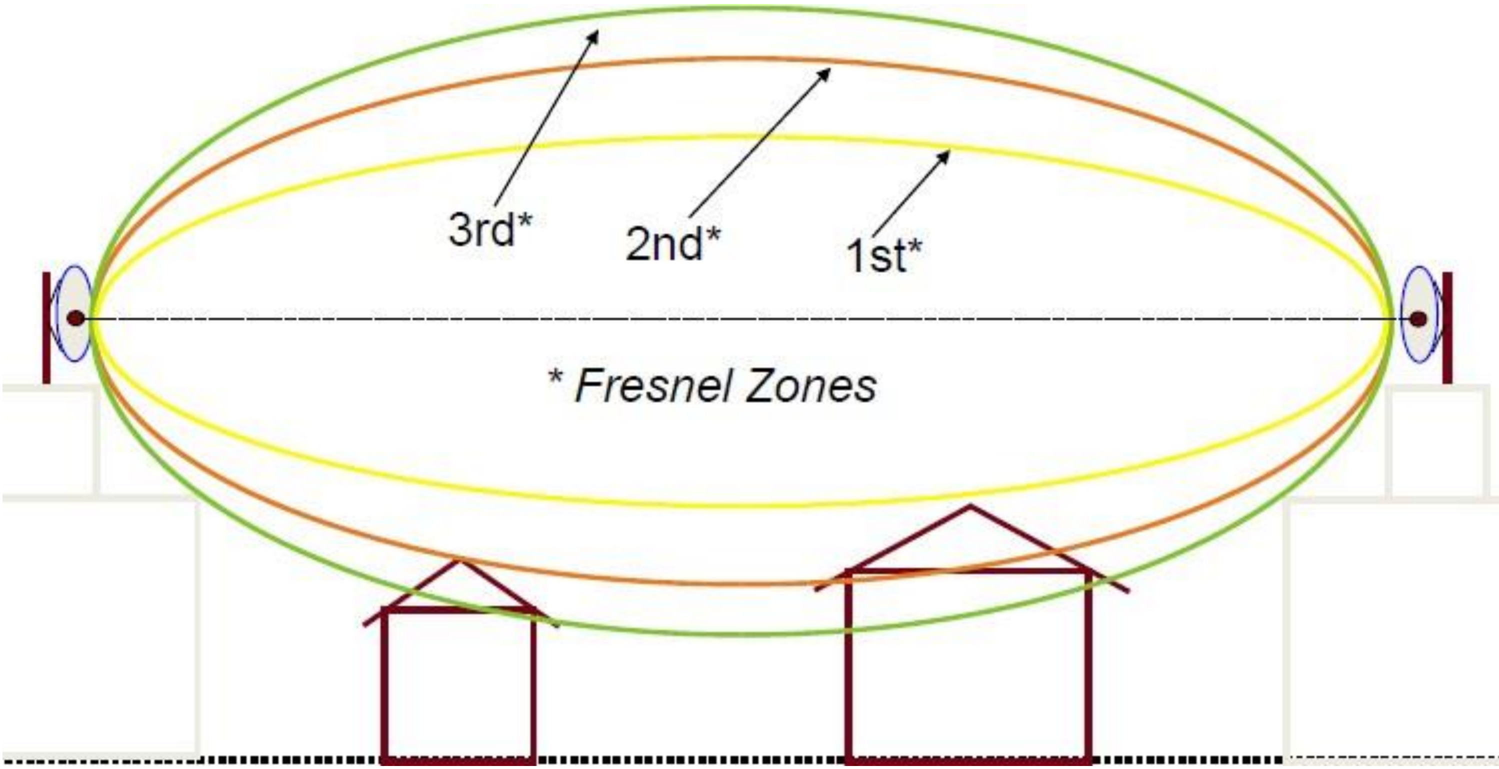


Figure 4.11 Concentric circles which define the boundaries of successive Fresnel zones.

Fresnel zones



Diffraction gain

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

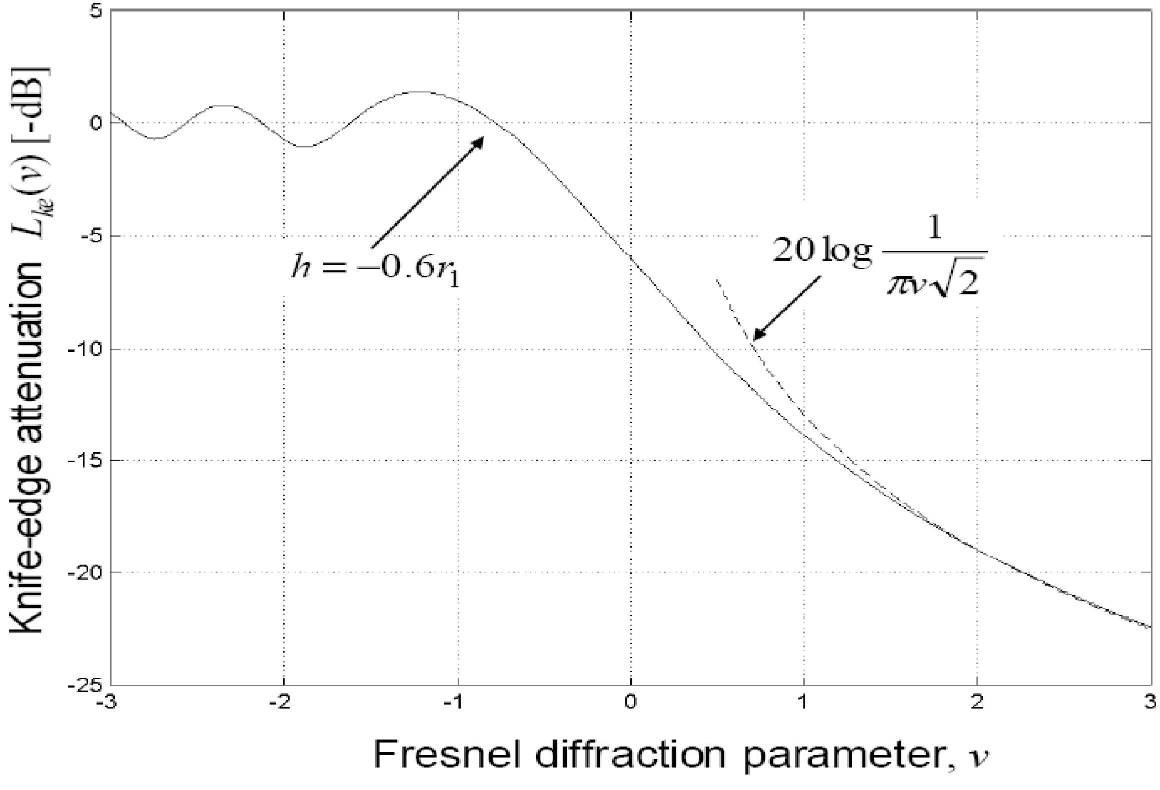
$$G_d(\text{dB}) = 20\log|F(v)|$$

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

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

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

Graphical Calculation of diffraction attenuation



Numerical solution

- An approximate numerical solution for equation

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

- Can be found using set of equations given below for different values of v

$G_d(dB)$	v
0	≤ -1
$20\log(0.5-0.62v)$	[-1,0]
$20\log(0.5\, e^{-0.95v})$	[0,1]
$20\log(0.4-(0.1184-(0.38-0.1v)^2)^{1/2})$	[1, 2.4]
$20\log(0.225/v)$	> 2.4

Example

Example 4.7

Compute the diffraction loss for the three cases shown in Figure 4.12. Assume $\lambda = 1/3$ m, $d_1 = 1$km, $d_2 = 1$ km, and (a) h = 25 m, (b) $h = 0$, (c) h = −25 m. Compare your answers using values from Figure 4.14, as well as the approximate solution given by Equation (4.61.a)–(4.61.e). For each of these cases, identify the Fresnel zone within which the tip of the obstruction lies.

Given:

$\lambda = 1/3$ m

$d_1 = 1$ km

$d_2 = 1$ km

(a)h = 25 m

Using Equation (4.56), the Fresnel diffraction parameter is obtained as

$$v = h\sqrt{\frac{2(d_1 + d_2)}{\lambda d_1 d_2}} = 25\sqrt{\frac{2(1000 + 1000)}{(1/3) \times 1000 \times 1000}} = 2.74.$$

From Figure 4.14, the diffraction loss is obtained as 22 dB.

Using the numerical approximation in Equation (4.61.e), the diffraction loss is equal to 21.7 dB.

The path length difference between the direct and diffracted rays is given by Equation (4.54) as

$$\Delta \approx \frac{h^2}{2}\frac{(d_1 + d_2)}{d_1 d_2} = \frac{25^2}{2}\frac{(1000 + 1000)}{1000 \times 1000} = 0.625 \text{ m}.$$

To find the Fresnel zone in which the tip of the obstruction lies, we need to compute n which satisfies the relation $\Delta = n\lambda/2$. For $\lambda = 1/3$ m, and $\Delta = 0/625$ m, we obtain

$$n = \frac{2\Delta}{\lambda} = \frac{2 \times 0.625}{0.3333} = 3.75.$$

Therefore, the tip of the obstruction completely blocks the first three Fresnel zones.

(b) $h = 0$ m

Therefore, the Fresnel diffraction parameter $v = 0$.

From Figure 4.14, the diffraction loss is obtained as 6 dB.

Using the numerical approximation in Equation (4.61.b), the diffraction loss is equal to 6 dB.

For this case, since $h = 0$, we have $\Delta = 0$, and the tip of the obstruction lies in the middle of the first Fresnel zone.

(c) $h = -25$ m

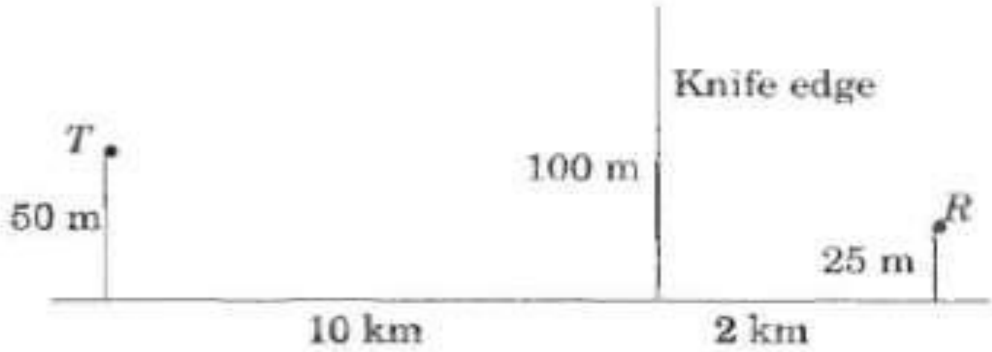
Using Equation (4.56), the Fresnel diffraction parameter is obtained as −2.74.

From Figure 4.14, the diffraction loss is approximately equal to 1 dB.

Using the numerical approximation in Equation (4.61.a), the diffraction loss is equal to 0 dB.

Example

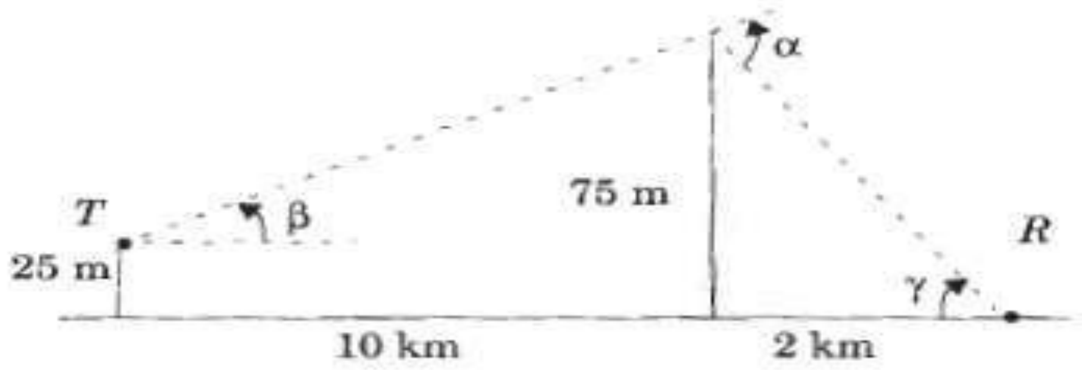
Example 4.8
Given the following geometry, determine (a) the loss due to knife-edge diffraction, and (b) the height of the obstacle required to induce 6 dB diffraction loss. Assume $f = 900$ MHz.



Solution

(a) The wavelength $\lambda = \frac{c}{f} = \frac{3 \times 10^8}{900 \times 10^6} = \frac{1}{3}$ m.

Redraw the geometry by subtracting the height of the smallest structure.



$$\beta = \tan^{-1}\left(\frac{75 - 25}{10000}\right) = 0.2865^\circ$$

$$\gamma = \tan^{-1}\left(\frac{75}{2000}\right) = 2.15^\circ$$

and

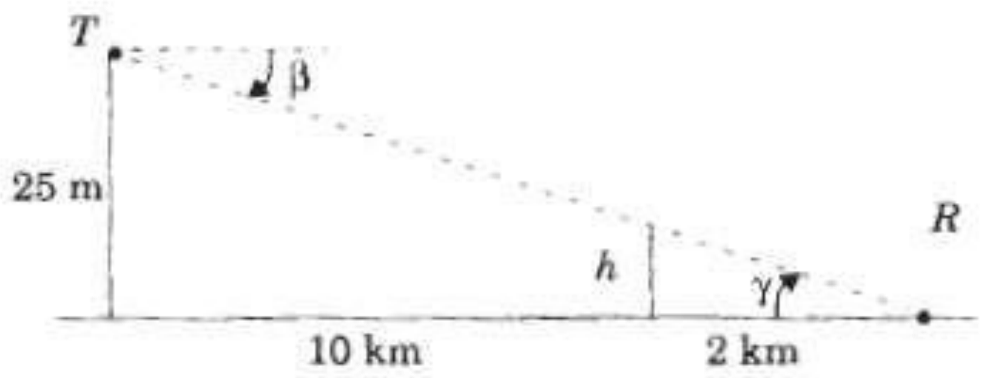
$$\alpha = \beta + \gamma = 2.434^\circ = 0.0424 \text{ rad}$$

Then using Equation (4.56)

$$v = 0.0424\sqrt{\frac{2 \times 10000 \times 2000}{(1/3) \times (10000 + 2000)}} = 4.24.$$

From Figure 4.14 or (4.61.e), the diffraction loss is 25.5 dB.

(b) For 6 dB diffraction loss, $v = 0$. The obstruction height h may be found using similar triangles ($\beta = \gamma$), as shown below.



It follows that $\frac{h}{2000} = \frac{25}{12000}$, thus $h = 4.16$ m.

Multiple Knife Edge Diffraction

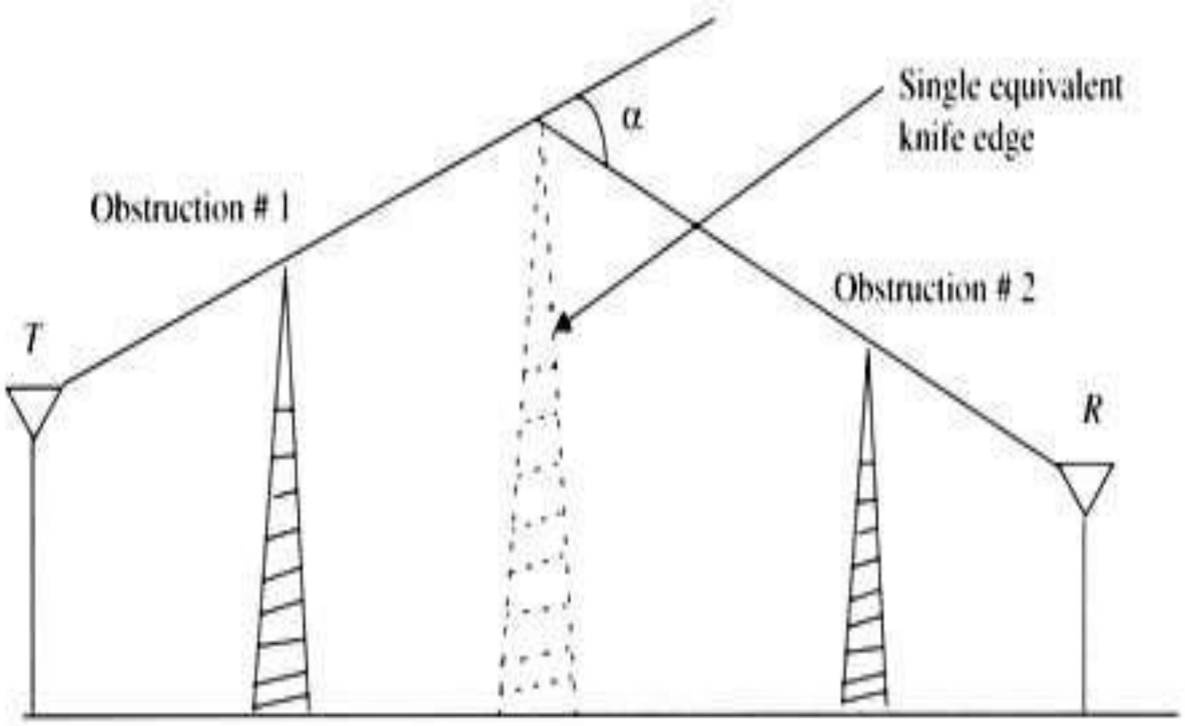


Figure 4.15 Bullington's construction of an equivalent knife edge [from [Bul47] © IEEE].

Scattering

- Scattering occurs when the medium through which the wave travels consists of objects with dimensions that are small compared to the wavelength, and where the number of obstacles per unit volume is large.

- Scattered waves are produced by
  - rough surfaces,
  - small objects,
  - or by other irregularities in the channel.

- Scattering is caused by trees, lamp posts, towers, etc.

Scattering

- Received signal strength is often stronger than that predicted by reflection/diffraction models alone
- The EM wave incident upon a rough or complex surface is **scattered** in **many** directions and provides more energy at a receiver
  - energy that would have been absorbed is instead reflected to the Rx.
- flat surface → EM reflection (one direction)
- rough surface → EM scattering (many directions)

Scattering

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

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

- Scattering path loss factor ρ_s is given by

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

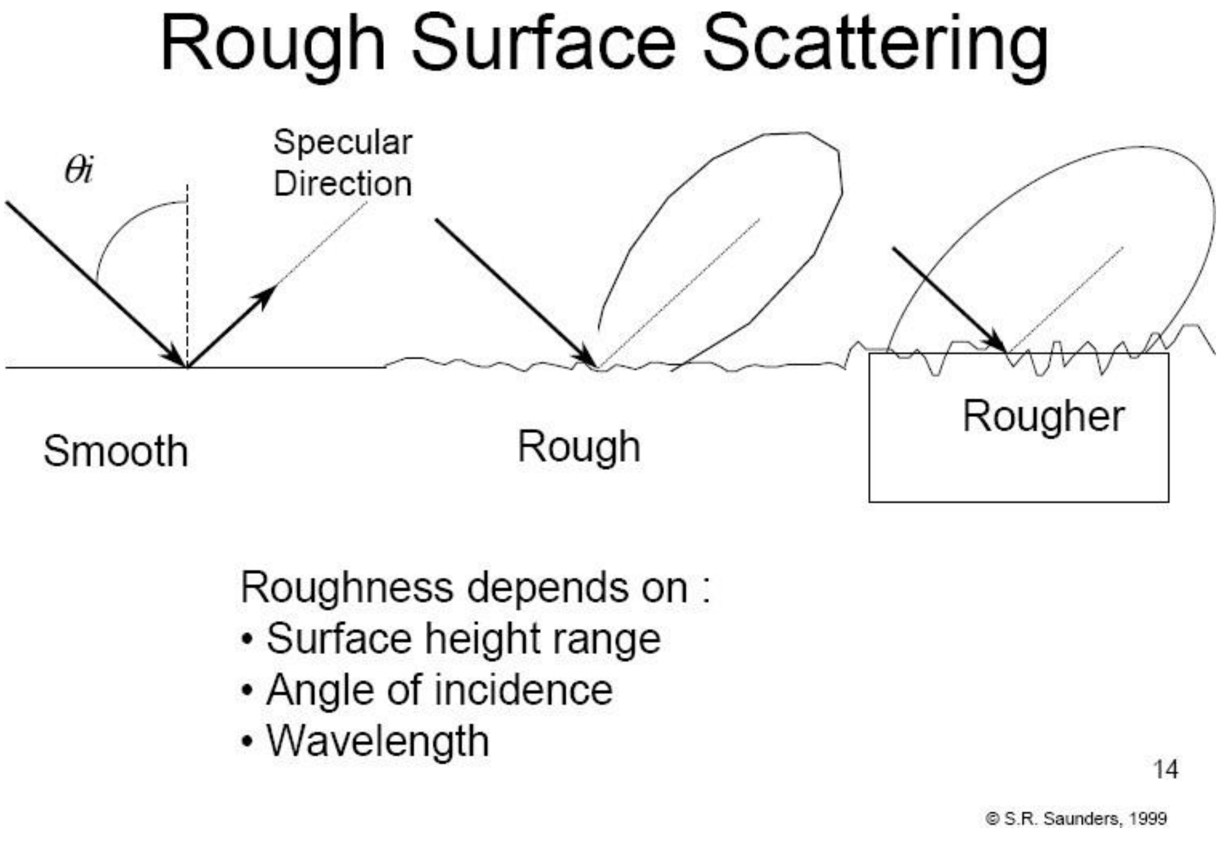
Where h is surface height and σ_h is standard deviation of surface height about mean surface height.

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

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

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

Scattering


Rough Surface Scattering
θi
Specular
Direction
Smooth
Rough
Rougher
Roughness depends on :
• Surface height range
• Angle of incidence
• Wavelength
14
© S.R. Saunders, 1999

Outdoor propagation Environment

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

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

Outdoor propagation Environment

Macrocells versus Microcells

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

Outdoor propagation Models

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

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

- Some common models used are
  - Longley Rice Model
  - Okumura Model
  - Hatta model

Longley Rice Model

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

Longley Rice Model

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

Okumura Model

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

Okumura Model

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

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

Okumura Model

- **Estimating path loss using Okumura Model**

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

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

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

L_F = free space propagation loss

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

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

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

G_{AREA} = gain due to environment

59

Okumura Model

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

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

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

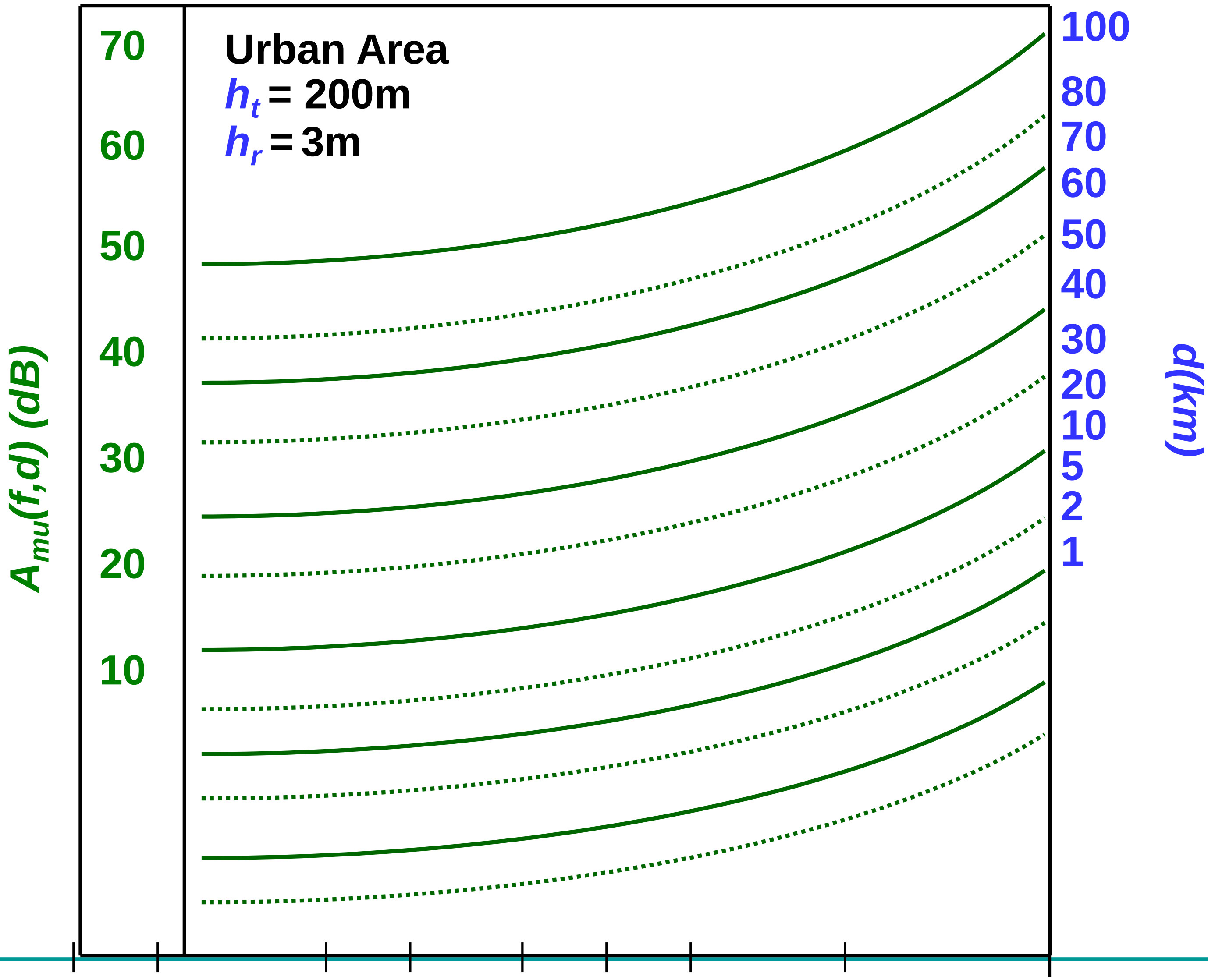
$$G(h_{re}) = 20\log\frac{h_{re}}{3} \qquad 3m < h_{re} < 10m$$

- **model corrected** for

Δh = terrain undulation height, isolated ridge height

average terrain slope and mixed land/sea parameter

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



100 200 300 500 700 1000 2000 3000 *f* (MHz)

Correction Factor G_{AREA}

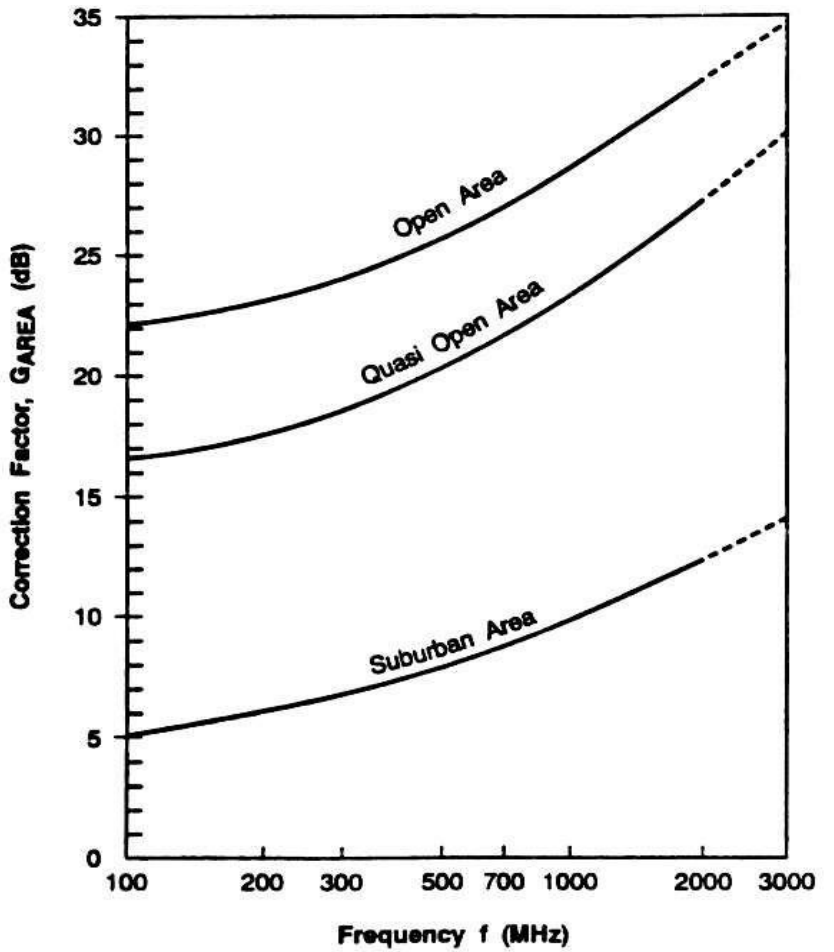


Figure 4.24 Correction factor, G_{AREA}, for different types of terrain [from [Oku68] © IEEE].

Example

Find the median path loss using Okumura's model for $d = 50$ km, $h_{te} = 100$ m, $h_{re} = 10$ m in a suburban environment. If the base station transmitter radiates an EIRP of 1 kW at a carrier frequency of 900 MHz, find the power at the receiver (assume a unity gain receiving antenna).

Solution to Example 3.10

The free space path loss L_F can be calculated using equation (3.6) as

$$L_F = 10\log\left[\frac{\lambda^2}{(4\pi)^2 d^2}\right] = 10\log\left[\frac{(3\times10^8/900\times10^6)^2}{(4\pi)^2\times(50\times10^3)^2}\right] = 125.5 \text{ dB}.$$

From the Okumura curves

$$A_{mu}(900\text{ MHz}(50\text{ km})) = 43 \text{ dB}$$

and

$$G_{AREA} = 9 \text{ dB}$$

$$G(h_{te}) = 20\log\left(\frac{h_{te}}{200}\right) = 20\log\left(\frac{100}{200}\right) = -6 \text{ dB}.$$

$$G(h_{re}) = 20\log\left(\frac{h_{re}}{3}\right) = 20\log\left(\frac{10}{3}\right) = 10.46 \text{ dB}.$$

Using equation (3.80) the total mean path loss is

$$\begin{aligned} L_{50}(\text{dB}) &= L_F + A_{mu}(f,d) - G(h_{te}) - G(h_{re}) - G_{AREA} \\ &= 125.5\text{ dB} + 43\text{ dB} - (-6)\text{ dB} - 10.46\text{ dB} - 9\text{ dB} \\ &= 155.04\text{ dB}. \end{aligned}$$

Therefore, the median received power is

$$\begin{aligned} P_r(d) &= EIRP(\text{dBm}) - L_{50}(\text{dB}) + G_r(\text{dB}) \\ &= 60\text{ dBm} - 155.04\text{ dB} + 0\text{ dB} = -95.04\text{ dBm}. \end{aligned}$$

Hata Model

- Most widely used model in Radio frequency.
- Predicting the behavior of cellular communication in built up areas.
- Applicable to the transmission inside cities.
- Suited for point to point and broadcast transmission.
- 150 MHz to 1.5 GHz, Transmission height up to 200m and link distance less than 20 Km.

Hata Model

- Hata transformed Okumura's graphical model into an analytical framework.
- The Hata model for urban areas is given by the empirical formula:

$L50_{,\ urban} = 69.55\ dB + 26.16 \log(f_c) - 3.82 \log(h_t) - a(h_r) + (44.9 - 6.55 \log(h_t)) \log(d)$

- Where $L50_{,\ urban}$ is the median path loss in dB.
- The formula is valid for

  150 MHz $\le f_c \le$ 1.5GHz,

  1 m $\le h_r \le$ 10m, 30m $\le h_t \le$ 200m,

  1km < d < 20km

Hata Model

- The correction factor $a(h_r)$ for mobile antenna height hr for a small or medium-sized city is given by:

$$a(h_r) = (1.1 \log f_c - 0.7)h_r - (1.56 \log(f_c) - 0.8) \text{ dB}$$

- For a large city it is given by

$$a(h_r) = 8.29[\log(1.54h_r)]^2 - 1.10 \text{ dB} \qquad \text{for } f_c <= 300 \text{ MHz}$$

$$3.20[\log(11.75h_r)]^2 - 4.97 \text{ dB} \qquad \text{for } f_c >= 300 \text{ MHz}$$

- To obtain path loss for suburban area the standard Hata model is modified as

$$L_{50} = L_{50}(\text{urban}) - 2[\log(f_c/28)]^2 - 5.4$$

- For rural areas

$$L_{50} = L_{50}(\text{urban}) - 4.78\log(f_c)^2 - 18.33\log f_c - 40.98$$

Indoor Models

- Indoor Channels are different from traditional channels in two ways

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

- Propagation inside a building is influenced by:

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

Indoor Models

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

  - Reflection, Diffraction and scattering

- Conditions are much more variable

  - Doors/Windows open or not

  - Antenna mounting : desk ceiling etc

  - The levels of floor

- Indoor models are classifies as

  - Line of sight (LOS)

  - Obstructed (OBS) with varying degree of clutter

Indoor Models

- Portable receiver usually experience

  - Rayleigh fading for OBS propagation paths

  - Ricean fading for LOS propagation path

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

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

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

Partition losses (same floor)

- Two types of partitions

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

- Partitions vary widely in their Physical and electrical properties.

- Path loss depend upon the types of partitions

Partition losses (same floor)

Partition Losses (Same Floor)

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

Partitions losses (between floors)

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

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

Partitions losses (between floors)

Table 4.4 Total Floor Attenuation Factor and Standard Deviation σ (dB) for Three Buildings. Each Point Represents the Average Path Loss Over a 20λ Measurement Track [Sei92a]

Building	915 MHz FAF (dB)	σ (dB)	Number of locations	1900 MHz FAF (dB)	σ (dB)	Number of locations
Walnut Creek						
One Floor	33.6	3.2	25	31.3	4.6	110
Two Floors	44.0	4.8	39	38.5	4.0	29
SF PacBell						
One Floor	13.2	9.2	16	26.2	10.5	21
Two Floors	18.1	8.0	10	33.4	9.9	21
Three Floors	24.0	5.6	10	35.2	5.9	20
Four Floors	27.0	6.8	10	38.4	3.4	20
Five Floors	27.1	6.3	10	46.4	3.9	17
San Ramon						
One Floor	29.1	5.8	93	35.4	6.4	74
Two Floors	36.6	6.0	81	35.6	5.9	41
Three Floors	39.6	6.0	70	35.2	3.9	27

Log distance path loss model

- Path loss can be given as

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

where n is path loss exponent and σ is standard deviation

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

Log distance path loss model

Table 4.6 Path Loss Exponent and Standard Deviation Measured in Different Buildings [And94]

Building	Frequency (MHz)	n	σ (dB)
Retail Stores	914	2.2	8.7
Grocery Store	914	1.8	5.2
Office, hard partition	1500	3.0	7.0
Office, soft partition	900	2.4	9.6
Office, soft partition	1900	2.6	14.1
Factory LOS			
Textile/Chemical	1300	2.0	3.0
Textile/Chemical	4000	2.1	7.0
Paper/Cereals	1300	1.8	6.0
Metalworking	1300	1.6	5.8
Suburban Home			
Indoor Street	900	3.0	7.0
Factory OBS			
Textile/Chemical	4000	2.1	9.7
Metalworking	1300	3.3	6.8

Ericsson Multiple Break Point Model

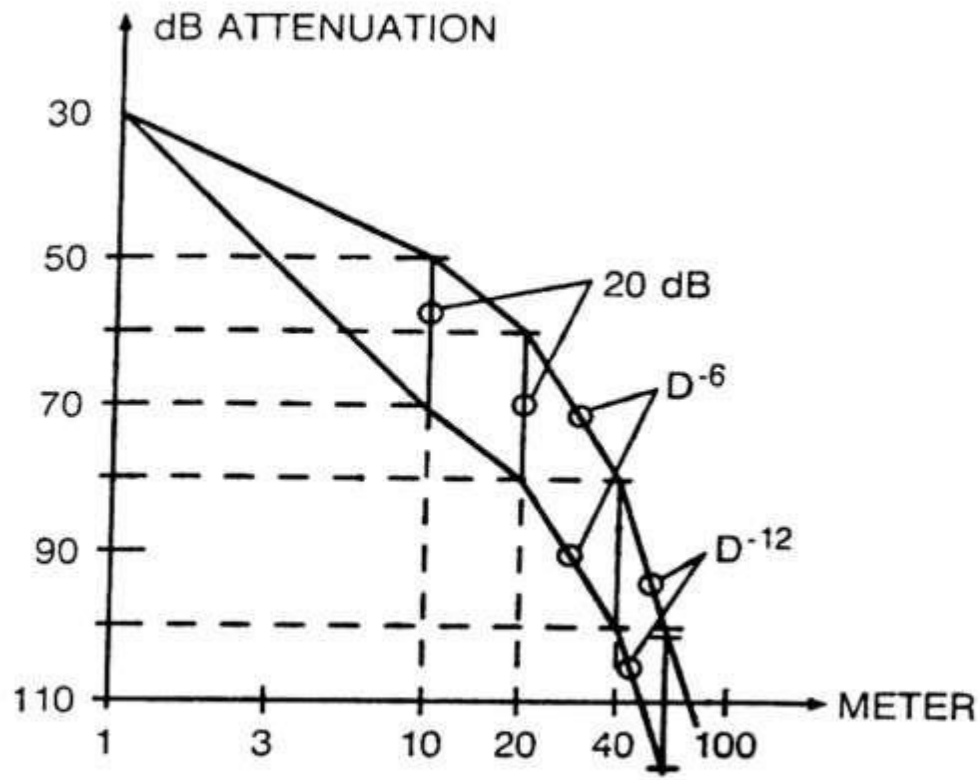


Figure 4.27 Ericsson in-building path loss model [from [Ake88] © IEEE].

Attenuation factor model

- Obtained by measurement in multiple floors building

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

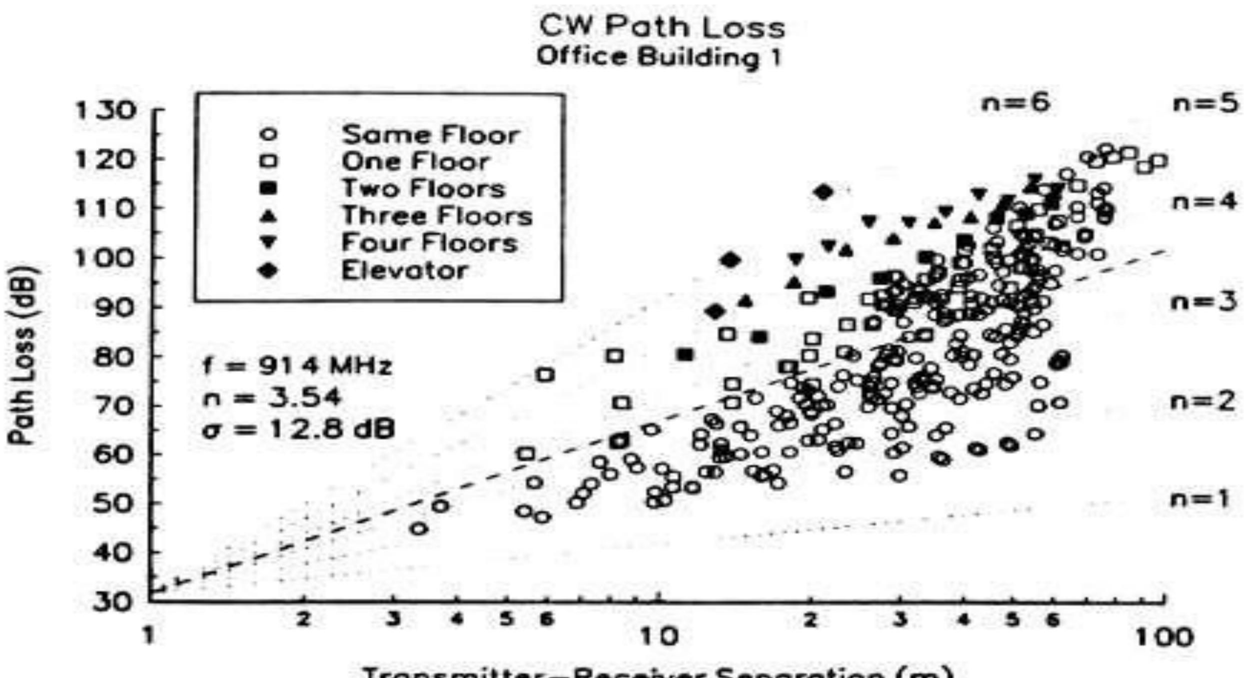


Figure 4.28 Scatter plot of path loss as a function of distance in Office Building 1 [from [Sei92b] © IEEE].

Attenuation factor model

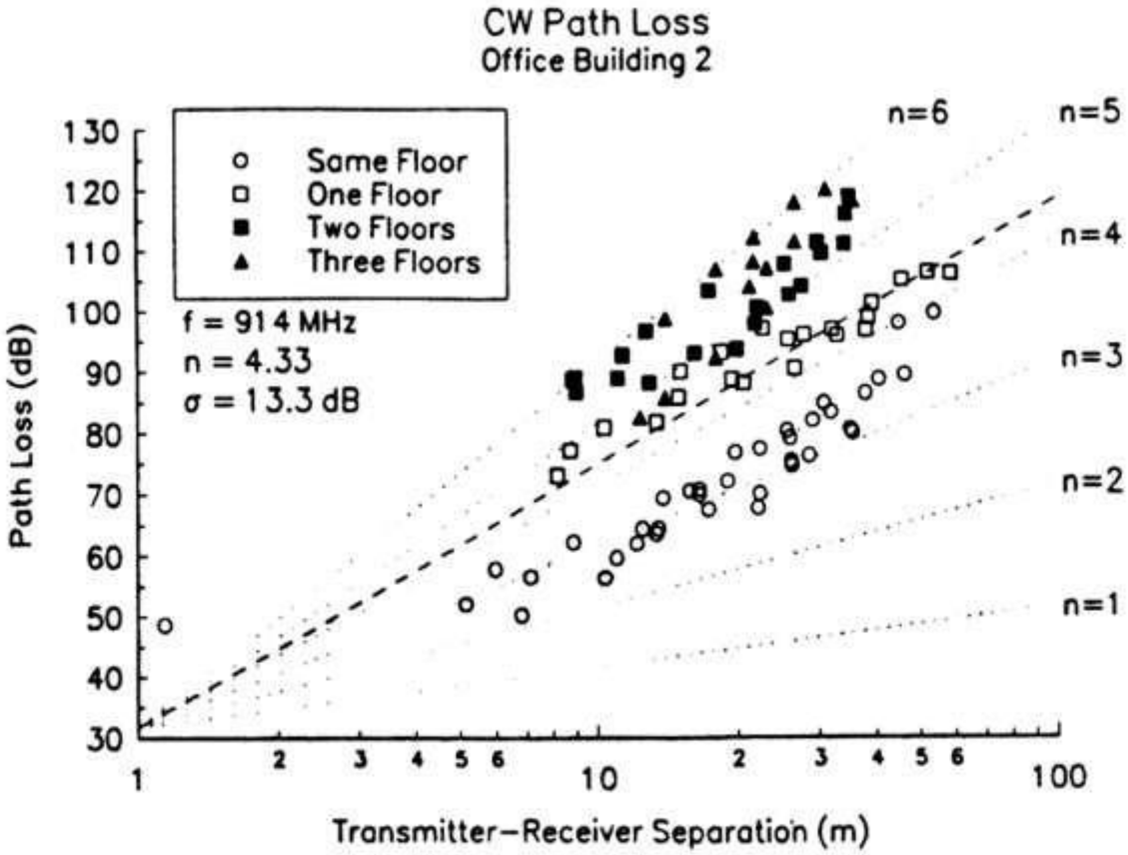


Figure 4.29 Scatter plot of path loss as a function of distance in Office Building 2 [from [Sei92b] © IEEE].

Signal penetration into building

- <u>Effect of frequency</u>

  - Penetration loss decreases with increasing frequency

- <u>Effect of Height</u>

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

  - At lower heights the Urban clutter induces greater attenuation
  - Up to some height attenuation decreases but then again increase after a few floors
  - Increase in attenuation at higher floors is due to the Shadowing effects of adjacent buildings

Mobile Radio Propagation

Small-scale Path loss

Chapter 4

Wireless communication

Small-Scale Fading and Multipath

- The term fading is used to describe rapid fluctuation of the amplitude of a radio signal over a short period of time or travel distance
- Fading is caused by destructive interference between two or more versions of the transmitted signal being slightly out of phase due to the different propagation time
- This is also called multipath propagation
- The different components are due to reflection and scattering form trees buildings and hills etc.

Small-Scale Fading and Multipath

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

  From Different direction

  With Different propagation delays,

  With Different amplitudes

  With Different phases

- Each of the factor given above is random

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

Effects of Fading/Multipath

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

Factors influencing small-scale fading

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

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

Factors influencing small-scale fading

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

The coherence bandwidth of a wireless channel is the range of frequencies that are allowed to pass through the channel without distortion. **This is the bandwidth over which the channel transfer function remains virtually constant.**

Some Terminologies

- Level Crossing Rate

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

- Fading Rate

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

- Depth of Fading

  Ratio of mean square value and minimum value of fading

- Fading Duration

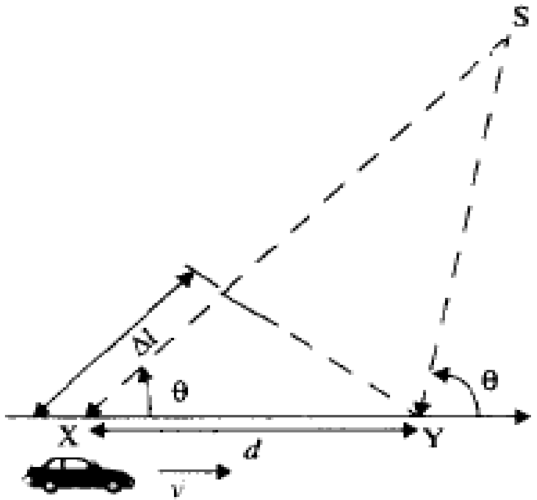
  Time for which signal remain below a certain threshold

Doppler shift **Book sy**

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

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

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



Impulse response of Multipath channel

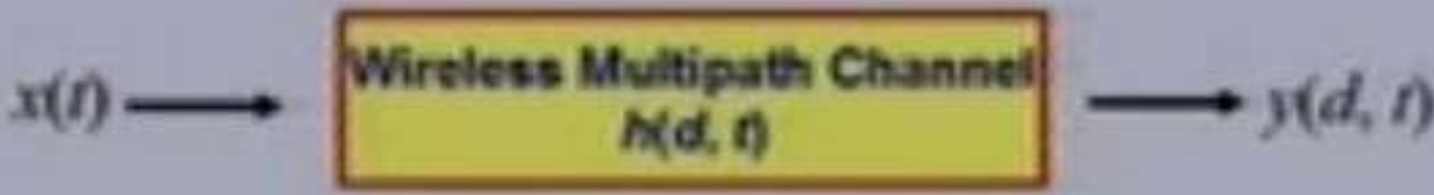
- The small scale variations of a mobile radio signal can be directly related to the impulse response of mobile radio channel.
- Impulse response contains information to Simulate and Analyze the channel
- The mobile radio channel can be modeled as Linear filter with time varying impulse response
- In case of mobile reception, the length and attenuation of various paths will change with time i.e. Channel is time varying.
- The time variation is strictly due to receiver movement (t=d/v).

Impulse response of Multipath channel

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

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

Impulse response Model of Multipath channel



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

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

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

Impulse Response Model of Multipath channel

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

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

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

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

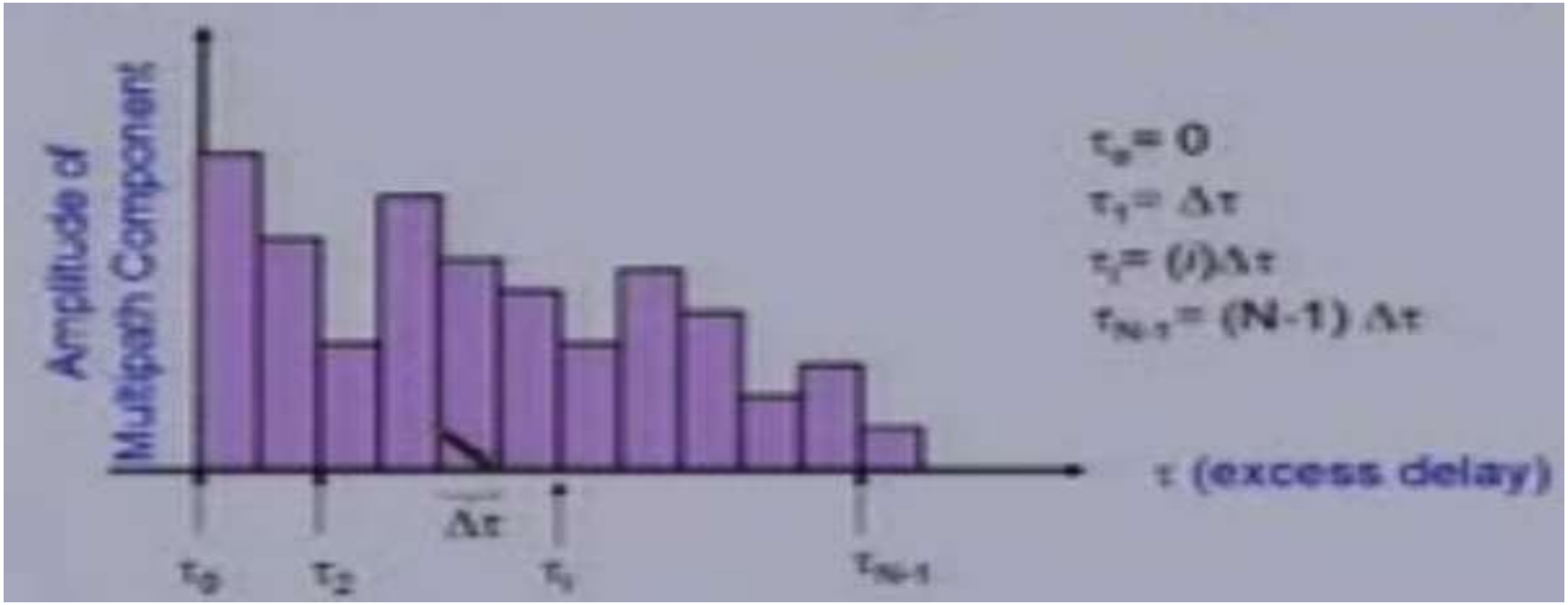
The ***impulse response*** is both a function of t and τ

t represents the variations due to motion

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

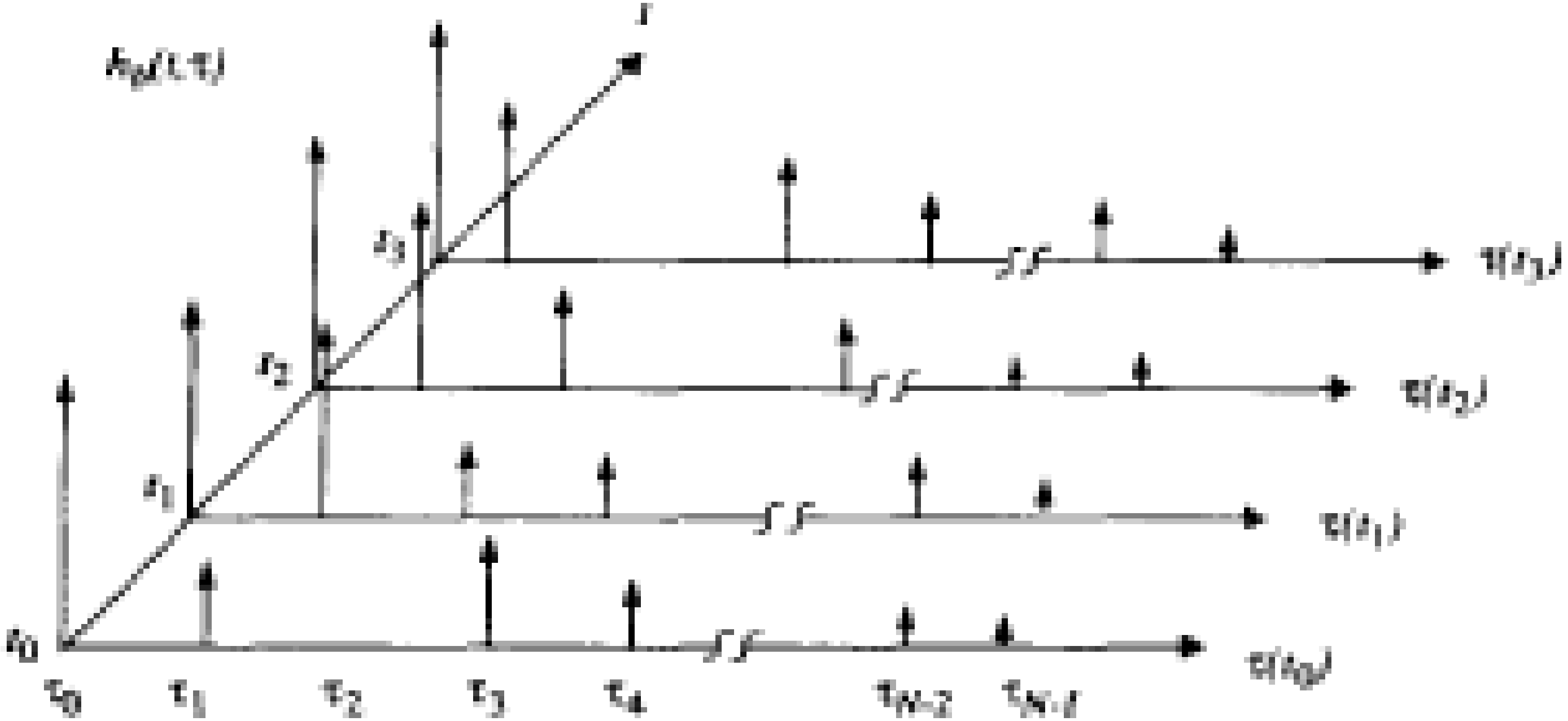
Discrete time Impulse Response Model of Multipath channel

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



Discrete time Impulse Response Model of Multipath channel

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



Discrete time Impulse Response Model of Multipath channel

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

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

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

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

Power Delay Profile

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

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

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

Measuring PDPs

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

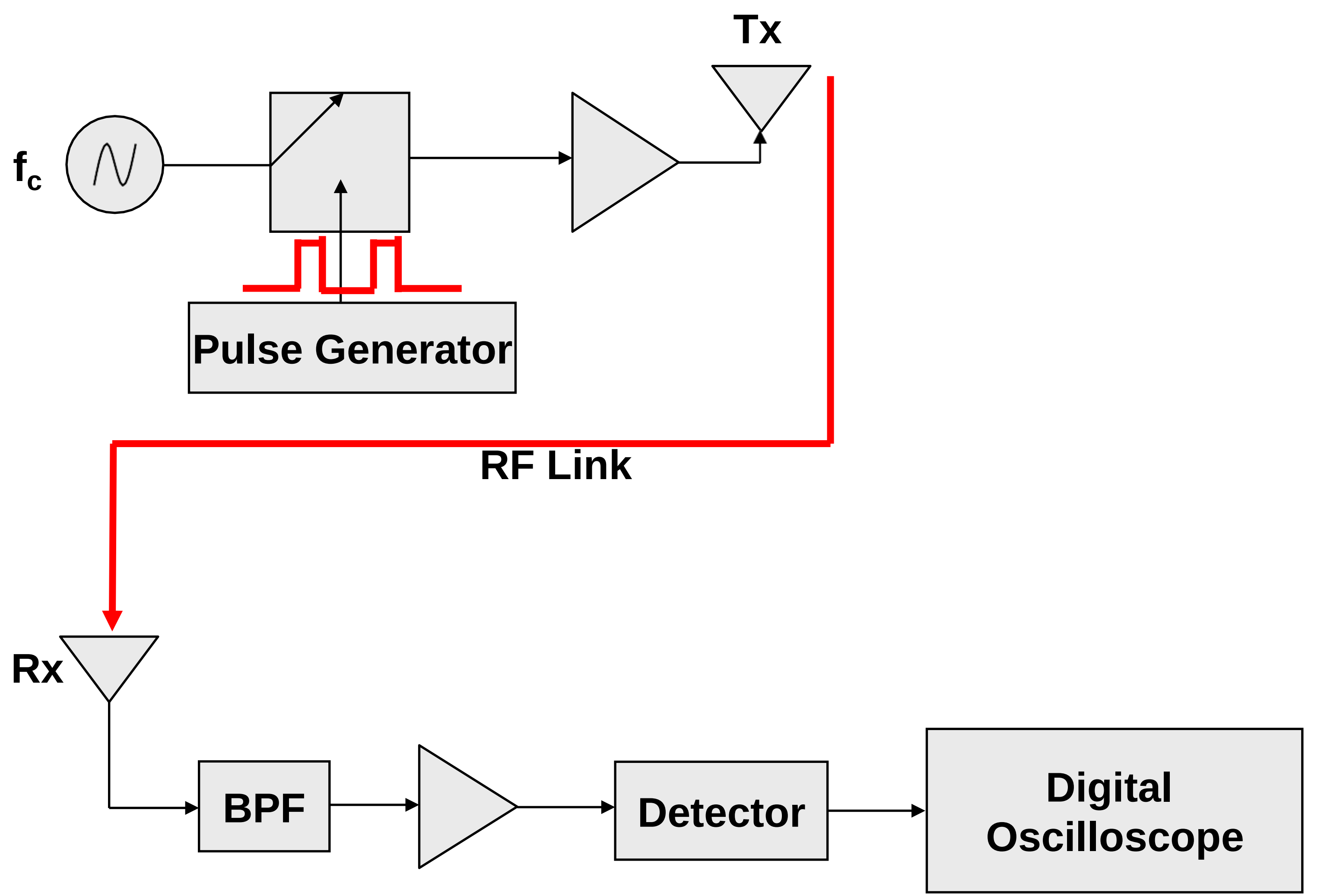
Small-Scale Multipath Measurements

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

Direct RF Pulse System

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

Direct RF Pulse System



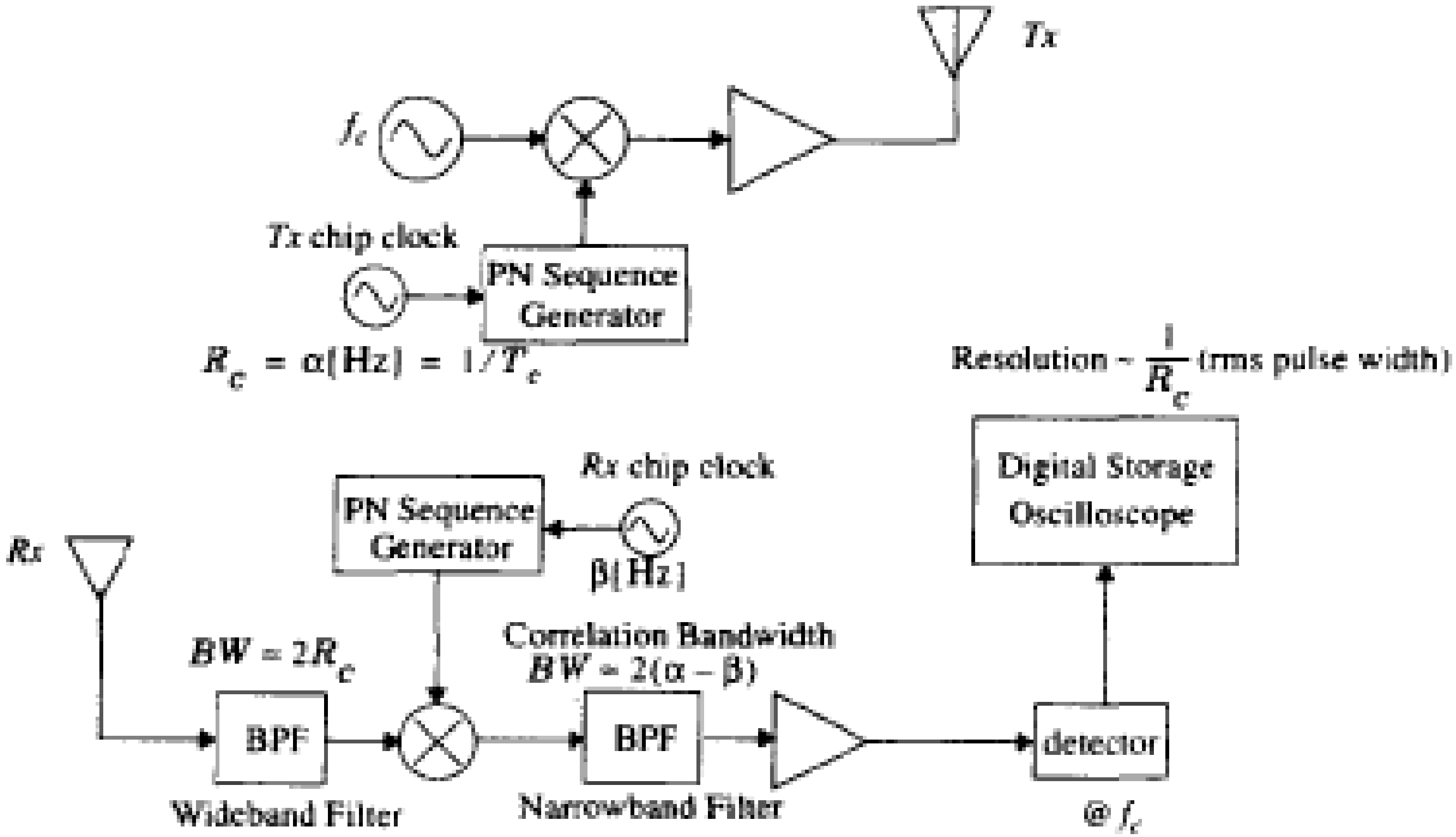
Direct RF Pulse System

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

Spread Spectrum Sliding Correlator Channel Sounding

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

Spread Spectrum Sliding Correlator Channel Sounding



Spread Spectrum Sliding Correlator Channel Sounding

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

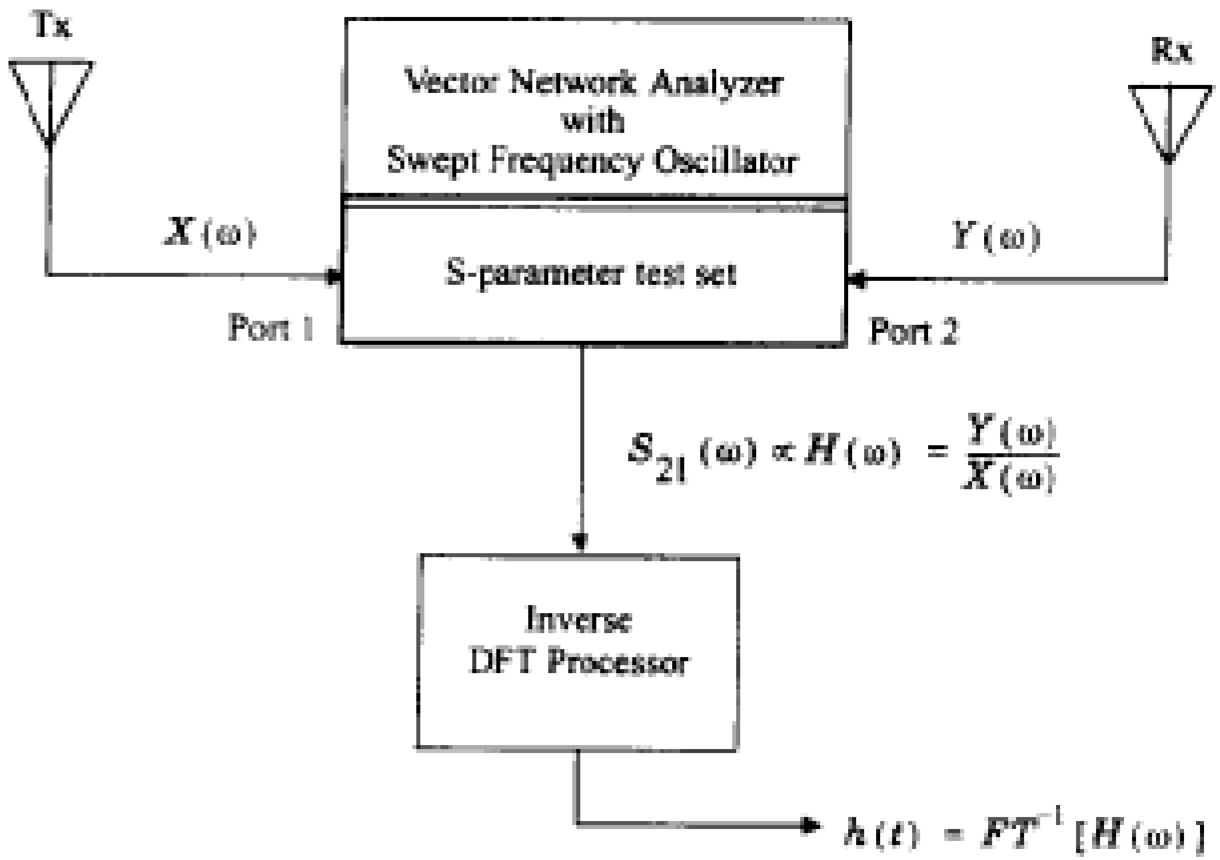
Spread Spectrum Sliding Correlator Channel Sounding

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

Frequency Domain Channel Sounding

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

Frequency Domain Channel Sounding



Frequency Domain Channel Sounding

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

Frequency Domain Channel Sounding

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

Parameters of Mobile Multipath Channels

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

Timer Dispersion Parameters

- Determined from a power delay profile

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

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

Rms delay spread (σ_τ):

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

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

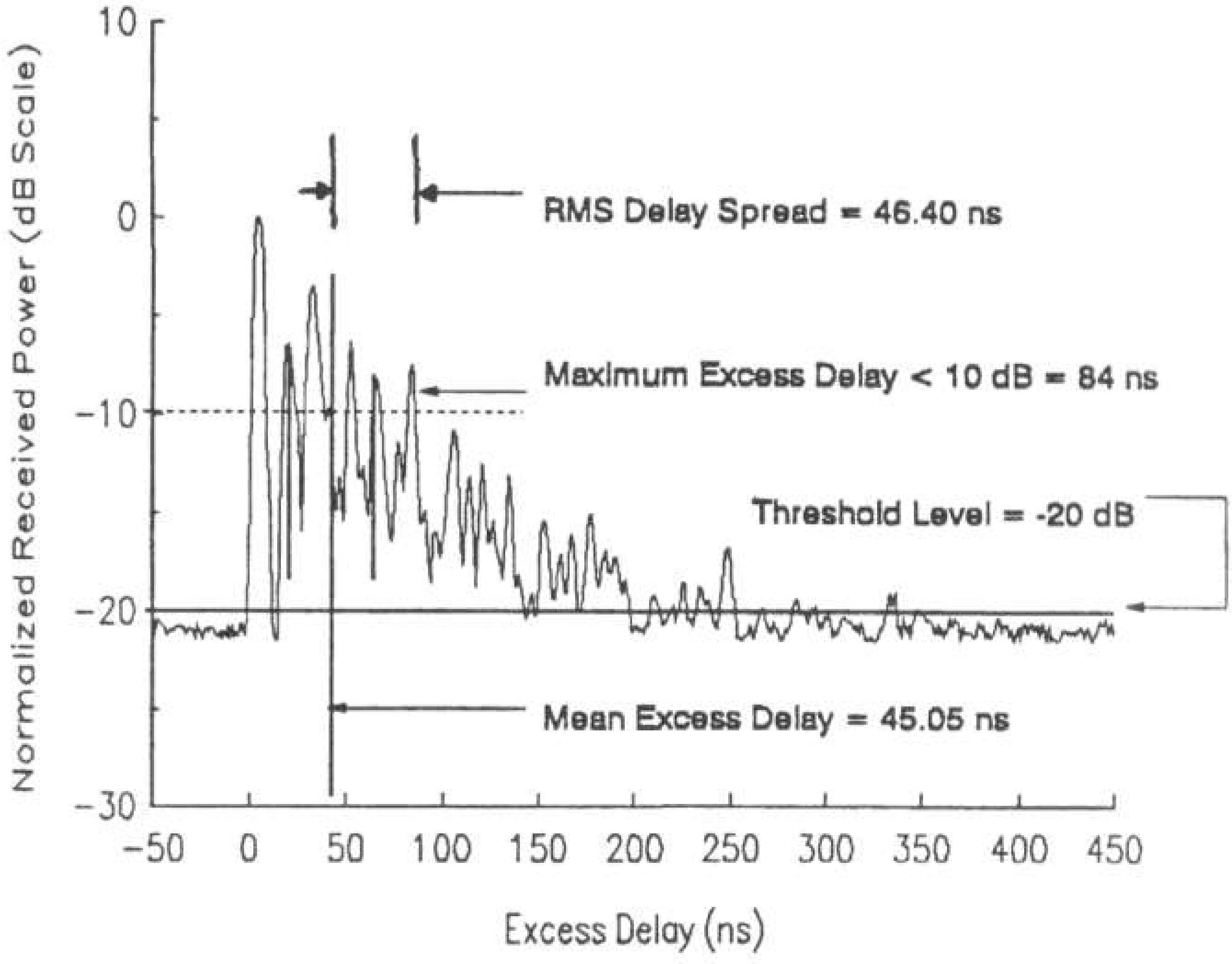
Timer Dispersion Parameters

Maximum Excess Delay (X dB):

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

It is also called *excess delay spread*.

RMS Delay Spread



Noise Threshold

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

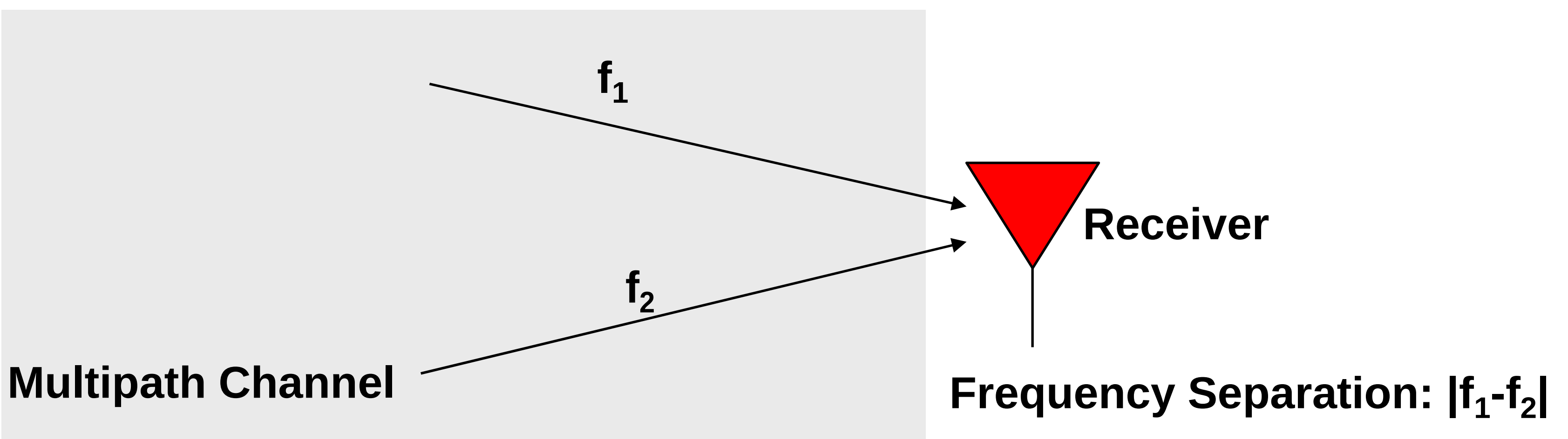
- If noise threshold is set too low, then the noise will be processed as multipath and thus causing the parameters to be higher.

Delay Spread, Coherence BW

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

Coherence Bandwidth (B_C)

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



Coherence Bandwidth

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

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

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

σ is rms delay spread

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

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

This is called 50% coherence bandwidth.

Coherence Bandwidth

- Example:
  - For a multipath channel, s is given as 1.37ms.
  - The 50% coherence bandwidth is given as: 1/5s = 146kHz.
    - This means that, for a good transmission from a transmitter to a receiver, the range of transmission frequency (channel bandwidth) should not exceed 146kHz, so that all frequencies in this band experience the same channel characteristics.
    - Equalizers are needed in order to use transmission frequencies that are separated larger than this value.
    - This coherence bandwidth is enough for an AMPS channel (30kHz band needed for a channel), but is not enough for a GSM channel (200kHz needed per channel).

Doppler Spread and Coherence time

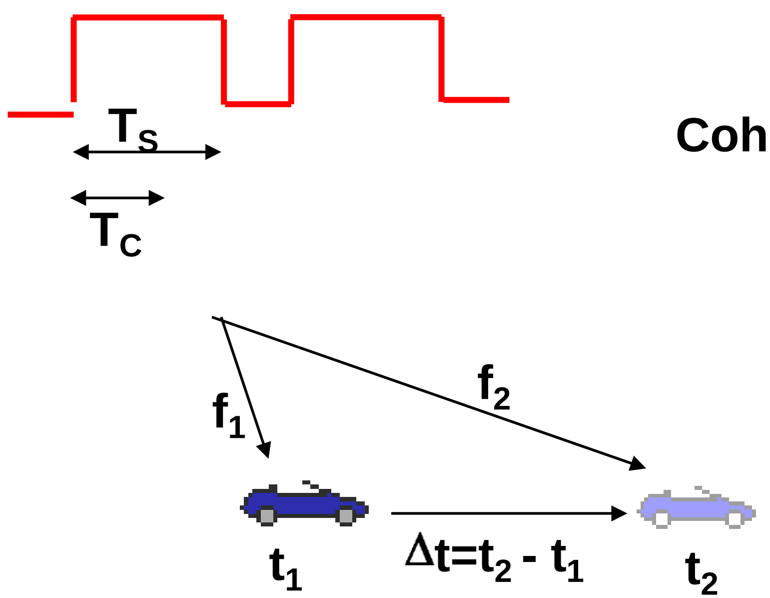
- Delay spread and Coherence bandwidth describe the time dispersive nature of the channel in a local area. They don't offer information about the time varying nature of the channel caused by relative motion of transmitter and receiver.
- Doppler Spread and Coherence time are parameters which describe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

Doppler Spread

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

Coherence Time

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



Coherence time (T_C) is defined as:

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

Coherence Time

- Coherence time is also defined as:

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

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

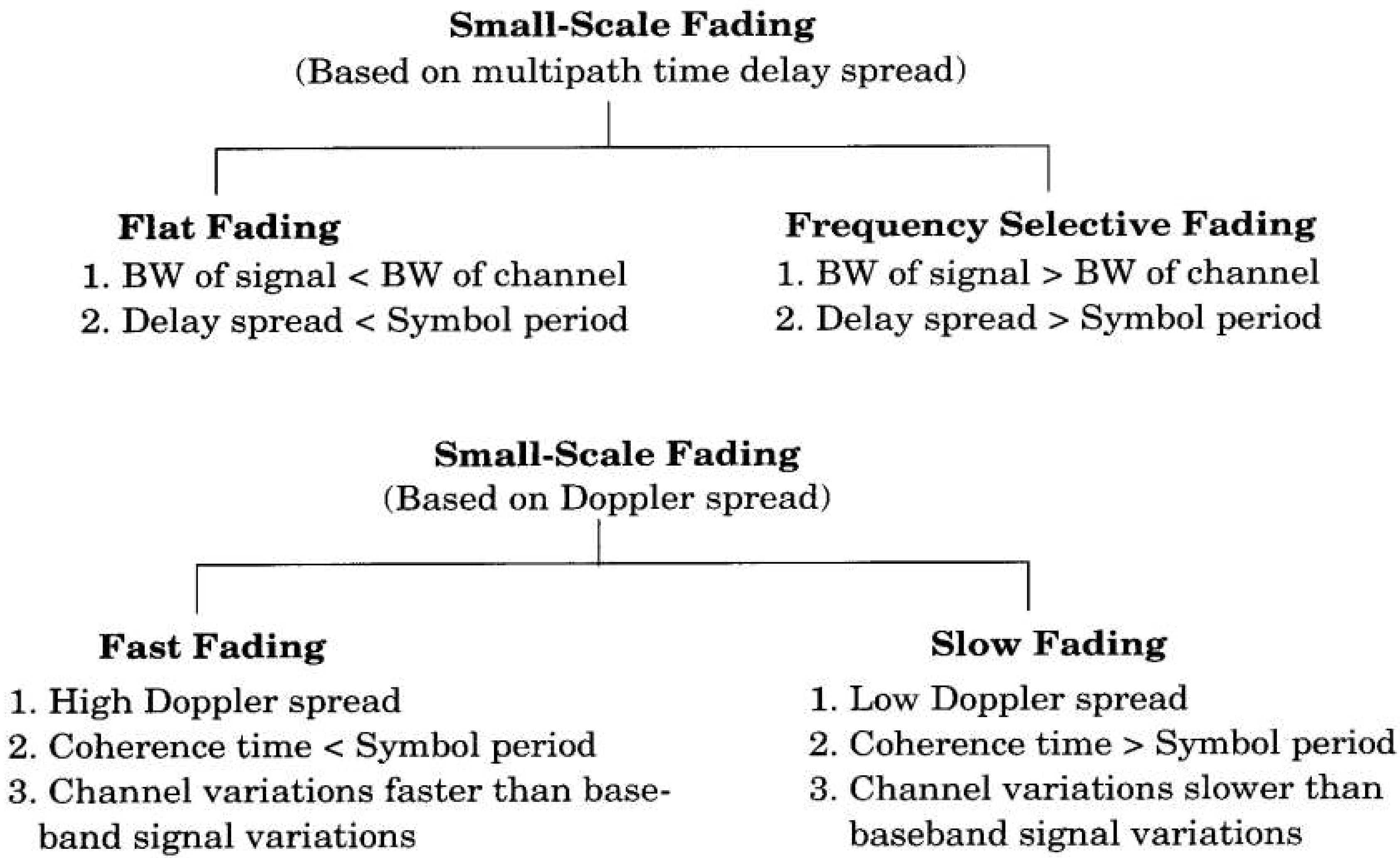


Figure 5.11 Types of small-scale fading.

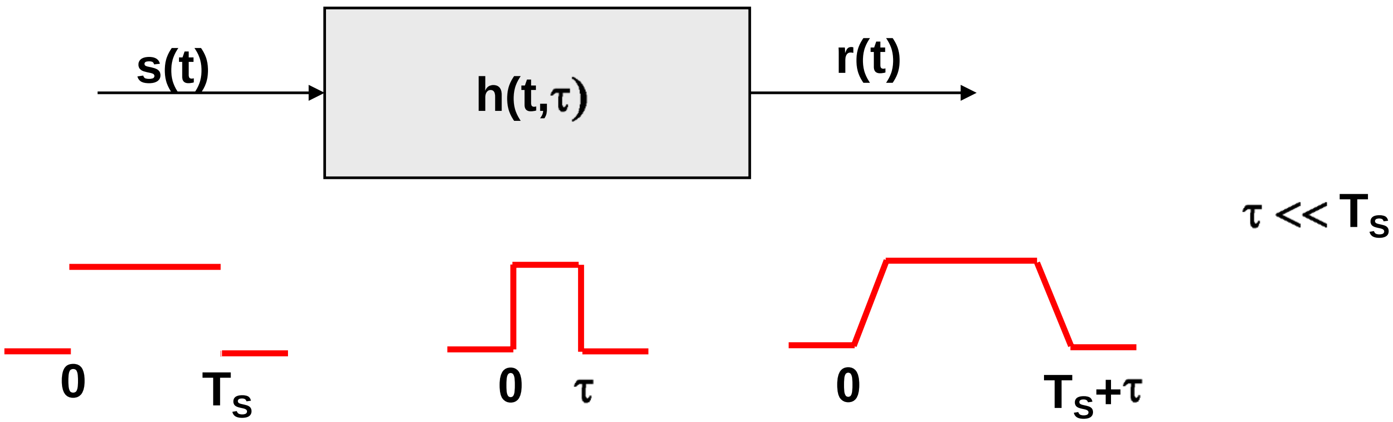
Classification of Multipath Channels

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

Flat fading:

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

Flat Fading



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

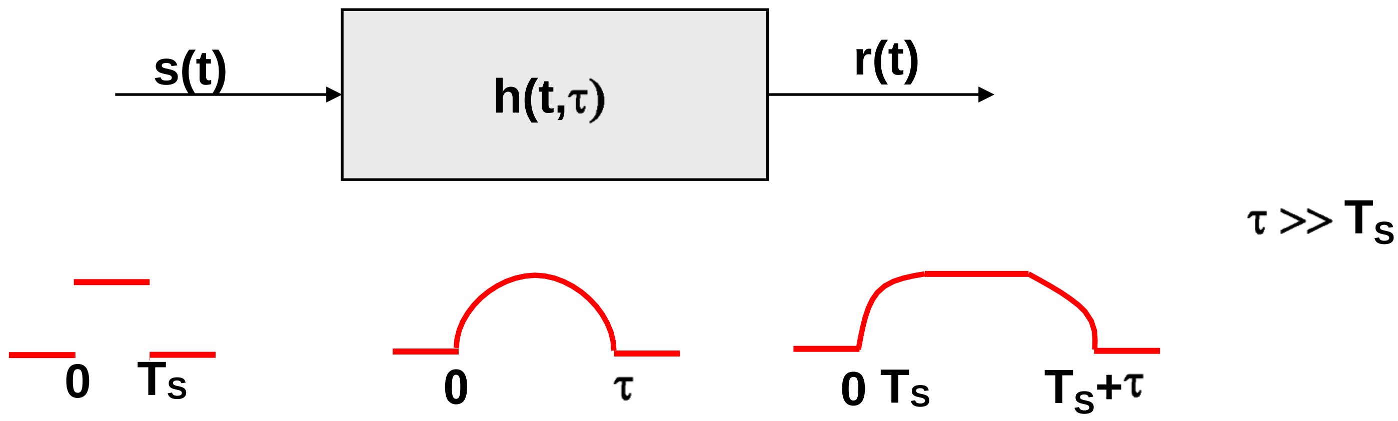
B_C: Coherence bandwidth
B_S: Signal bandwidth
T_S: Symbol period
σ_τ: Delay Spread

Frequency selective fading:

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

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

Frequency Selective Fading



Causes distortion of the received baseband signal

Causes Inter-Symbol Interference (ISI)

Occurs when:

$B_S > B_C$

and

$T_S < \sigma_\tau$

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

Fast Fading

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

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

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

Slow Fading

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

Occurs when:

$B_S >> B_D$
and
$T_S << T_C$

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

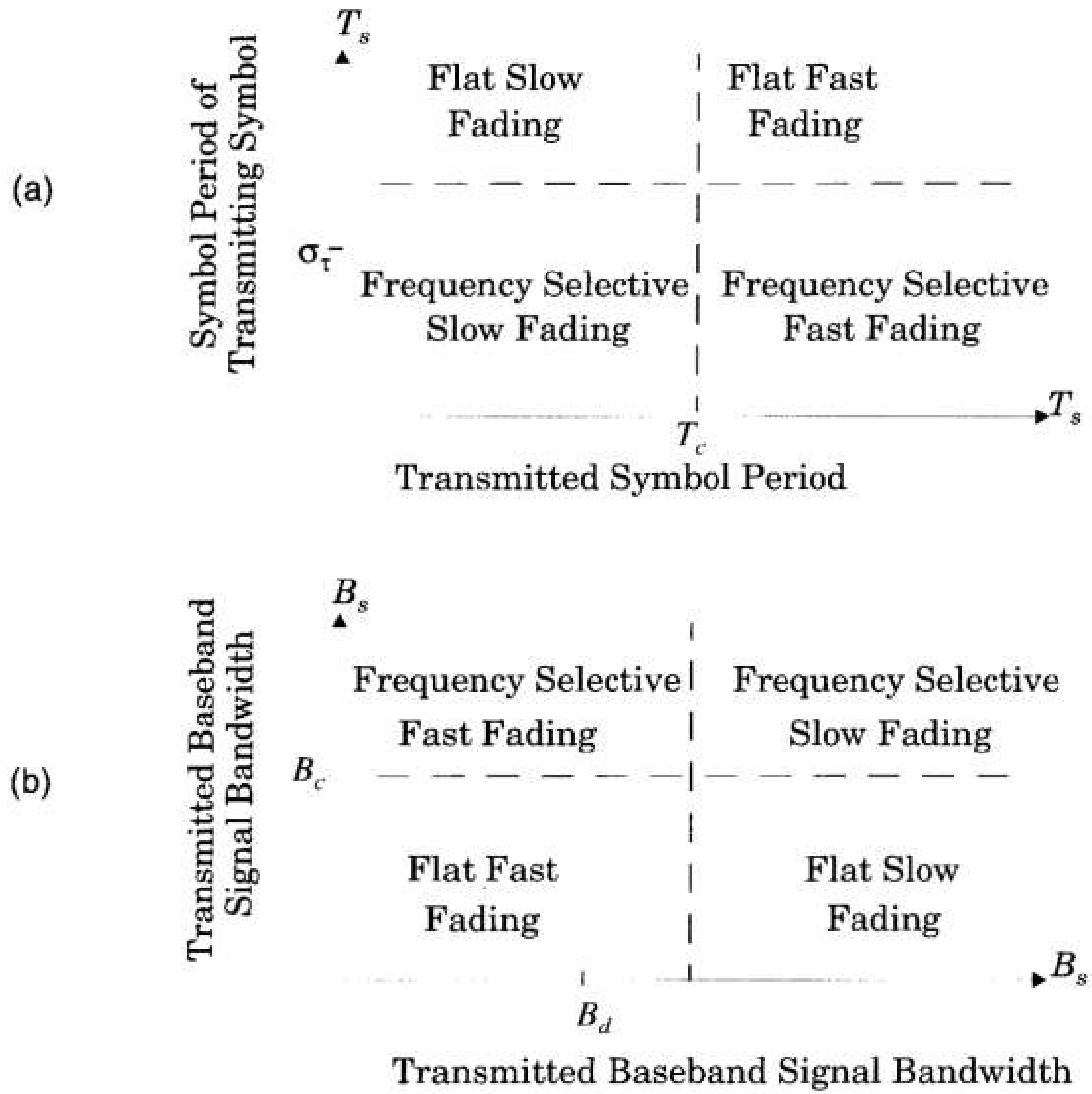


Figure 5.14 Matrix illustrating type of fading experienced by a signal as a function of: (a) symbol period; and (b) baseband signal bandwidth.

Fading Distributions

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

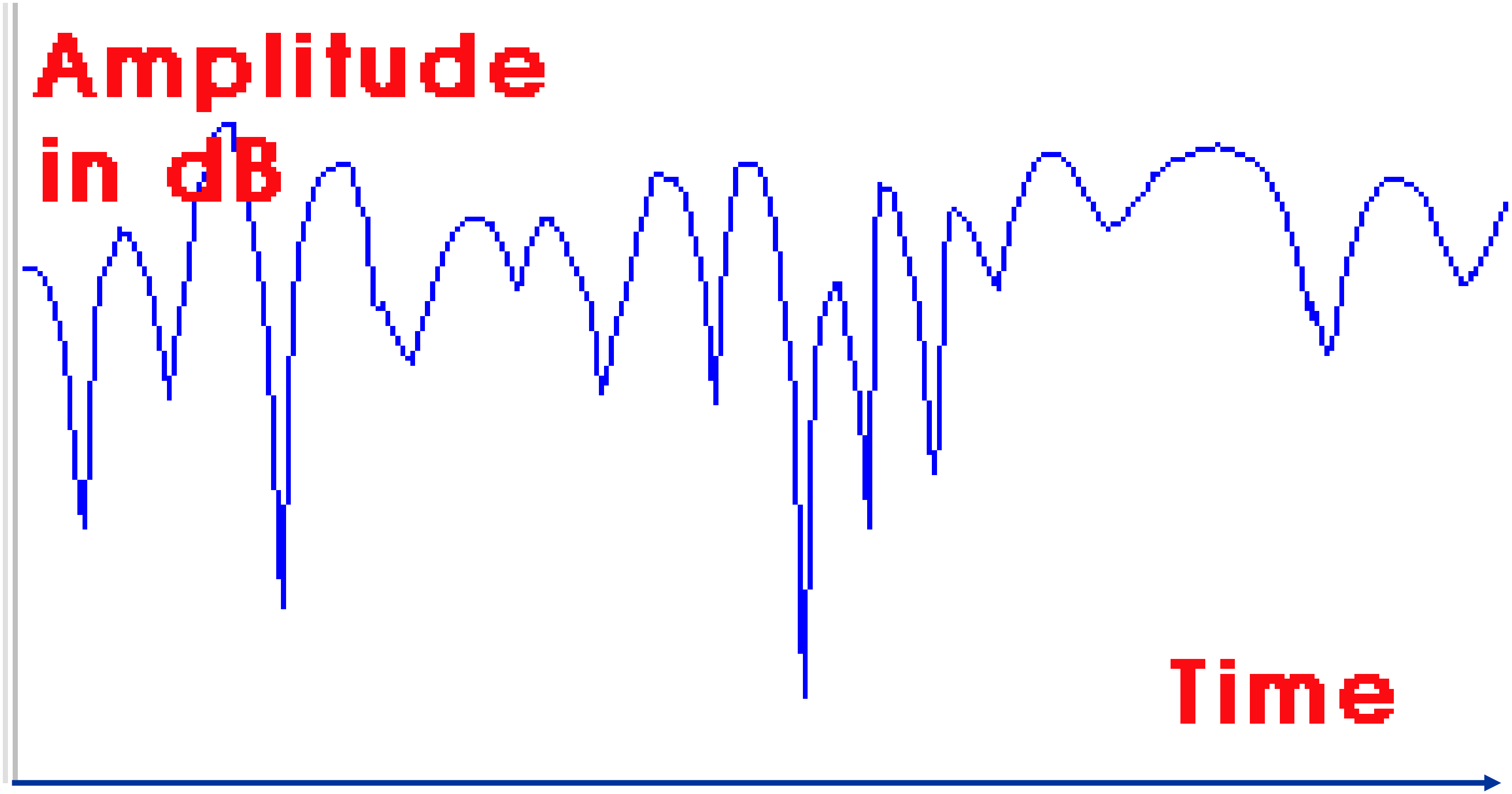
$$r(t) = \sum_{i=0}^{N-1} a_i \exp(j\theta_i(t,\tau))$$

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

Rayleigh and Ricean Distributions

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

Rayleigh Fading



Rayleigh

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

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

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

Rayleigh

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

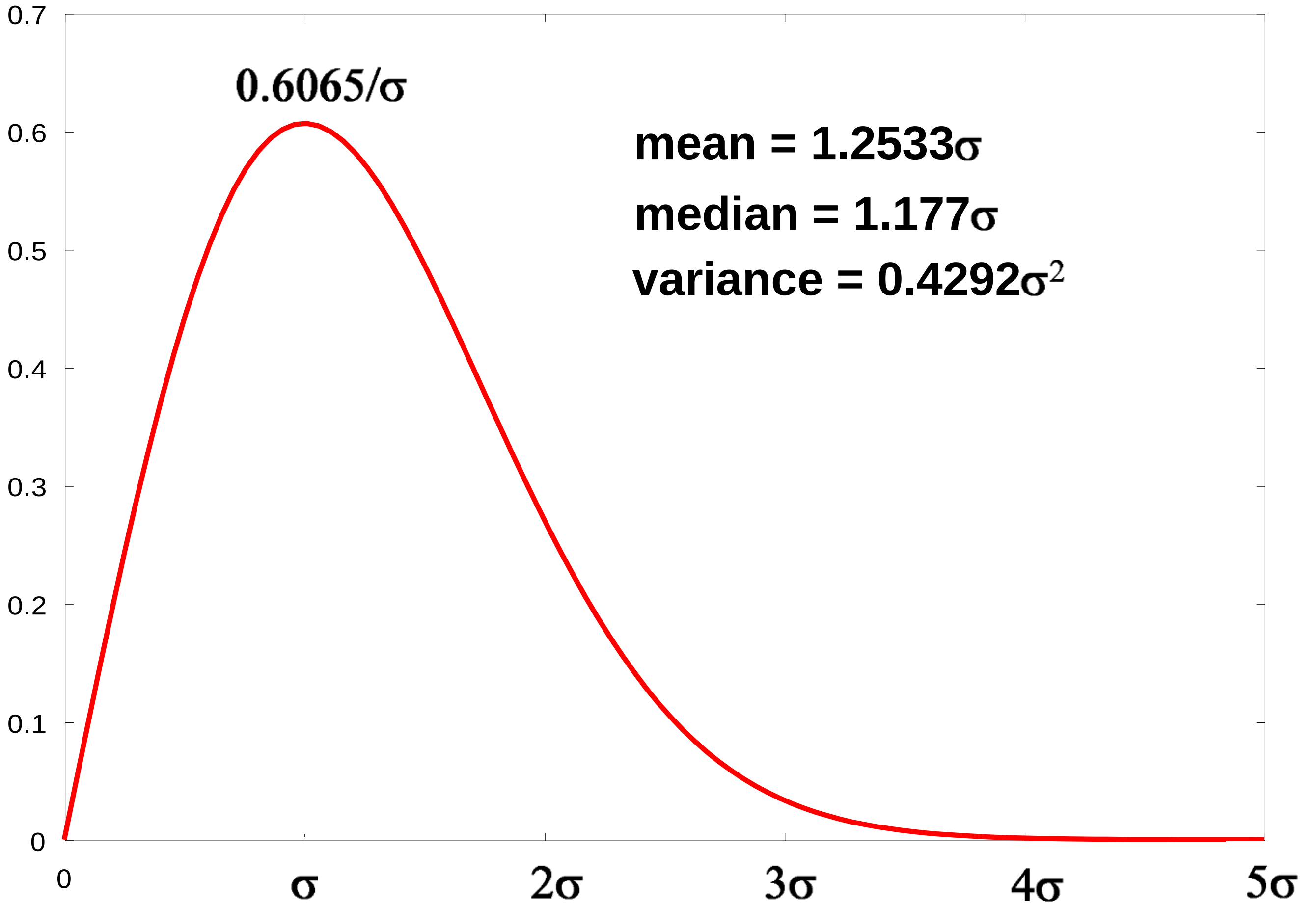
$$P(R) = P_r(r \le R) = \int_0^R p(r)dr = 1 - e^{-\frac{R^2}{2\sigma^2}}$$

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

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

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

Rayleigh PDF

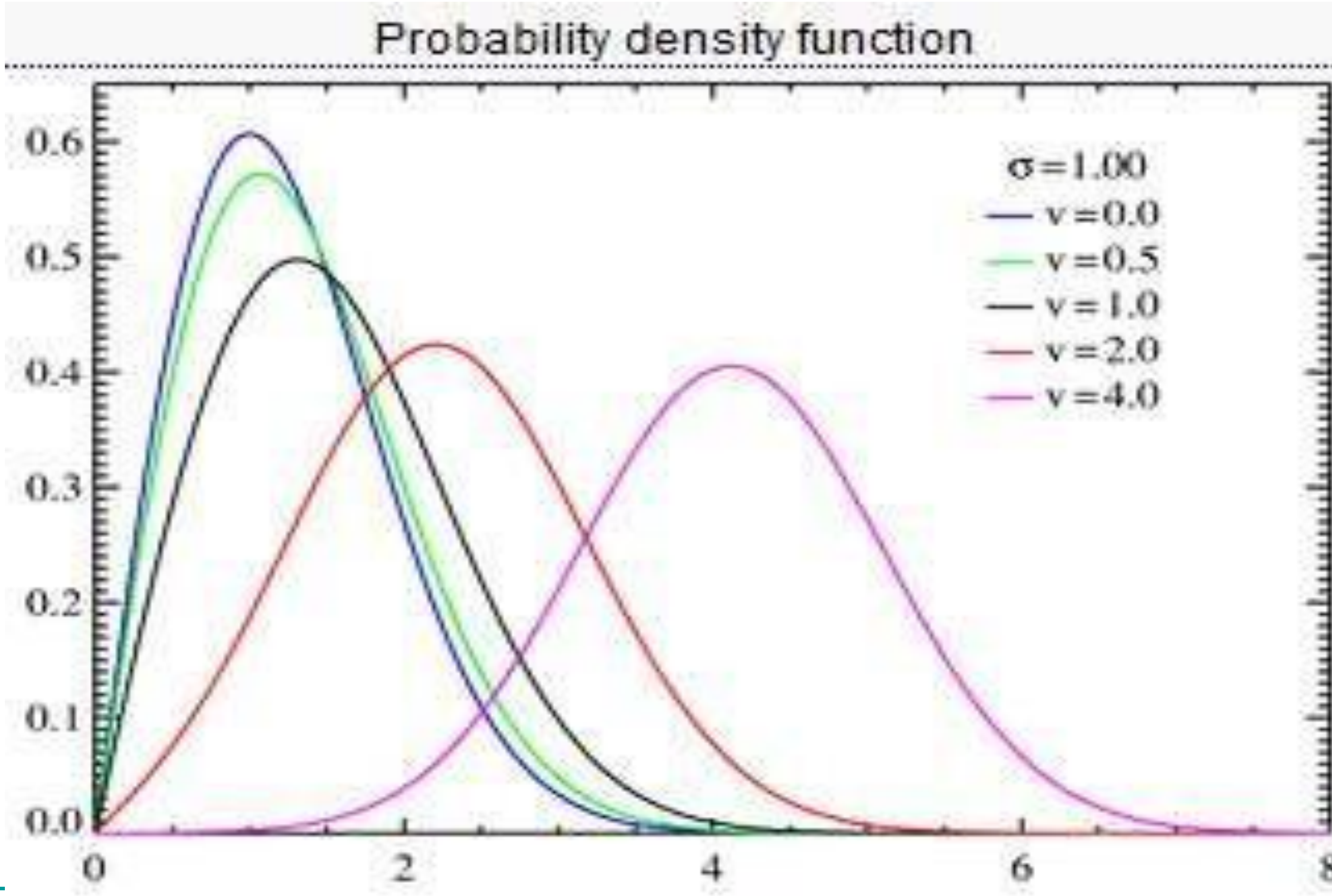


Ricean Distribution

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

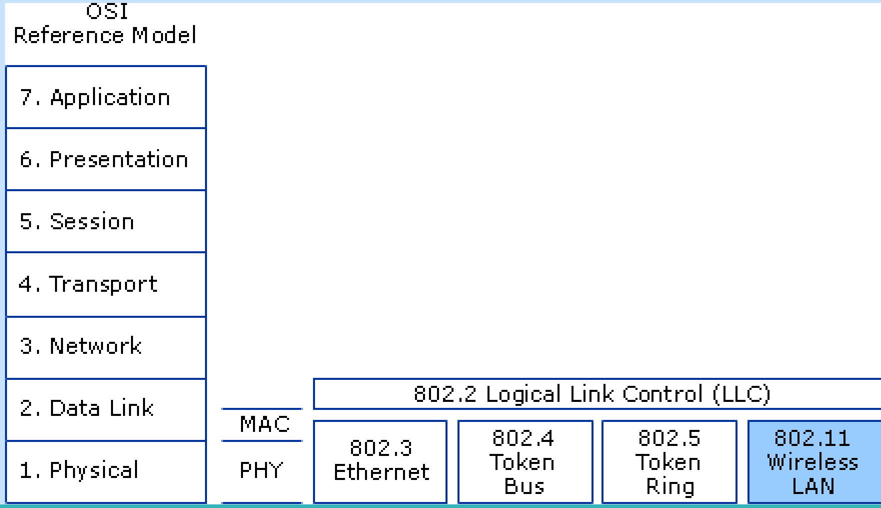
$$f(x \mid \nu, \sigma) = \frac{x}{\sigma^2} \exp\left(\frac{-(x^2 + \nu^2)}{2\sigma^2}\right) I_0\left(\frac{x\nu}{\sigma^2}\right)$$

Ricean Distribution



IEEE 802.11 Architecture and Services

- In 1990, IEEE 802 Committee formed a new working group, IEEE 802.11, specifically devoted to wireless LANs, with a charter to develop a MAC protocol and physical medium specification

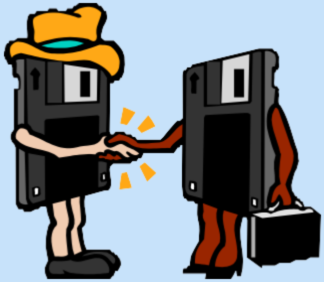


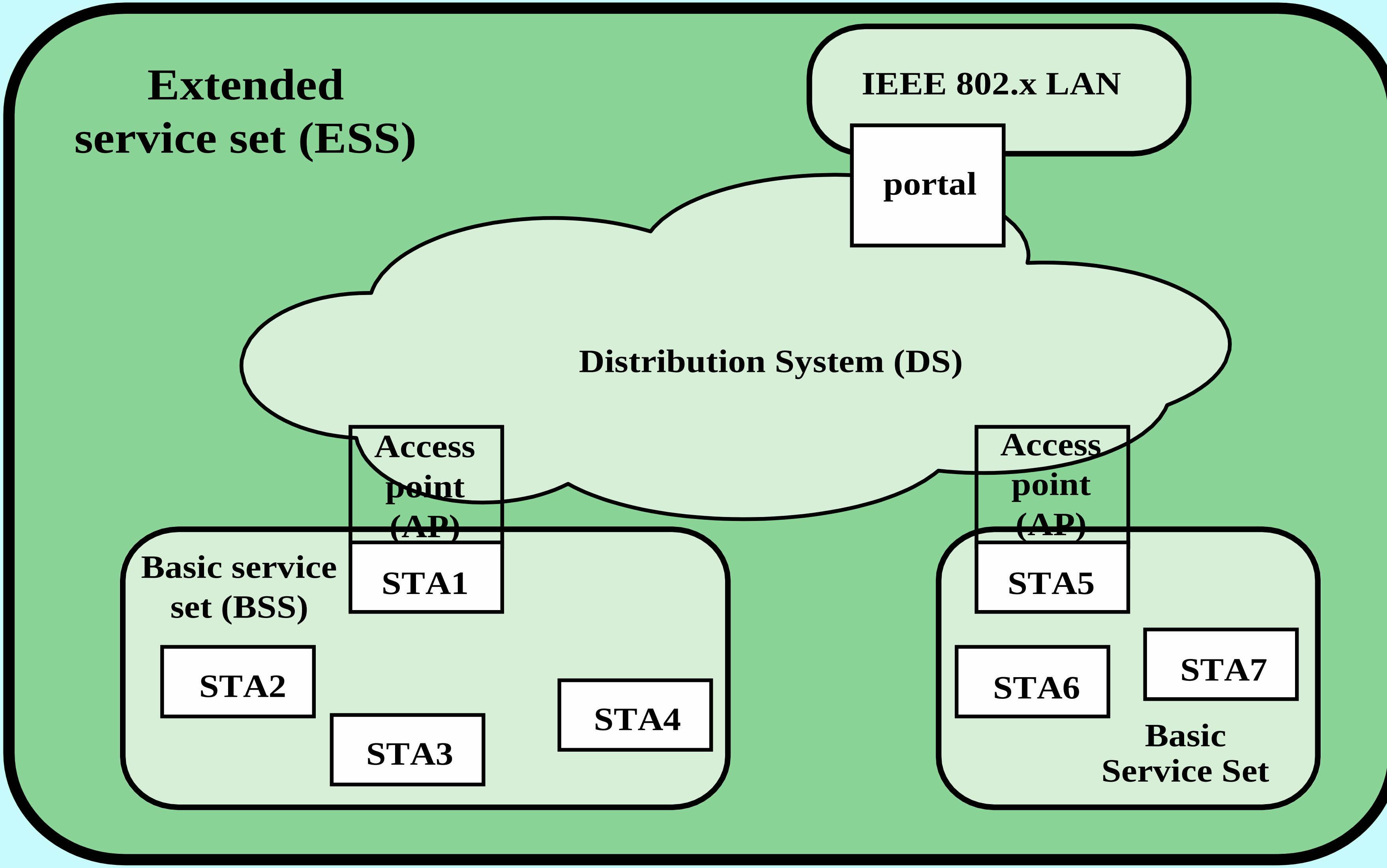
Key IEEE 802.11 Standards

Standard	Scope
IEEE 802.11a	Physical layer: 5-GHz OFDM at rates from 6 to 54 Mbps
IEEE 802.11b	Physical layer: 2.4-GHz DSSS at 5.5 and 11 Mbps
IEEE 802.11c	Bridge operation at 802.11 MAC layer
IEEE 802.11d	Physical layer: Extend operation of 802.11 WLANs to new regulatory domains (countries)
IEEE 802.11e	MAC: Enhance to improve quality of service and enhance security mechanisms
IEEE 802.11g	Physical layer: Extend 802.11b to data rates >20 Mbps
IEEE 802.11i	MAC: Enhance security and authentication mechanisms
IEEE 802.11n	Physical/MAC: Enhancements to enable higher throughput
IEEE 802.11T	Recommended practice for the evaluation of 802.11 wireless performance
IEEE 802.11ac	Physical/MAC: Enhancements to support 0.5–1 Gbps in 5-GHz band
IEEE 802.11ad	Physical/MAC: Enhancements to support ≥ 1 Gbps in the 60-GHz band

Wi-Fi Alliance

- There is always a concern whether products from different vendors will successfully interoperate
- Wireless Ethernet Compatibility Alliance (WECA)
  - Industry consortium formed in 1999
- Renamed the Wi-Fi Alliance
  - Created a test suite to certify interoperability for 802.11 products



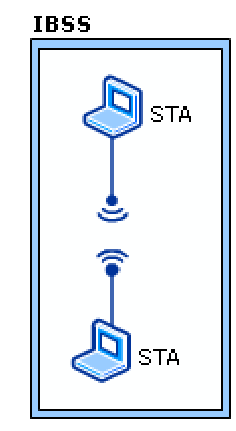


STA = station

Figure 13.4 IEEE 802.11 Architecture

IEEE 802.11 Architecture and Services

- Basic service set (BSS) consists of some number of stations executing the same MAC protocol and competing for access to the same shared wireless medium
- A BSS may be isolated or it may connect to a backbone distribution system (DS) through an access point (AP)
- In a BSS, client stations do not communicate directly with one another
- In an IBSS the stations all communicate directly
  - No AP is involved.
  - An IBSS is typically an ad hoc network.

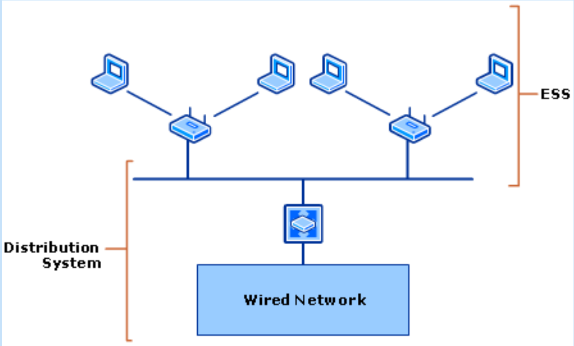


IEEE 802.11 Architecture and Services

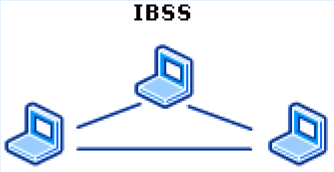
- An extended service set (ESS) consists of two or more basic service sets interconnected by a distribution system
- To integrate the IEEE 802.11 architecture with a traditional wired LAN, a portal is used

IEEE 802.11 Operating Modes

- 802.11 Infrastructure Mode
    - at least one wireless AP and one wireless client.



- 802.11 Ad Hoc Mode
    - wireless clients communicate directly with each other without the use of a wireless AP

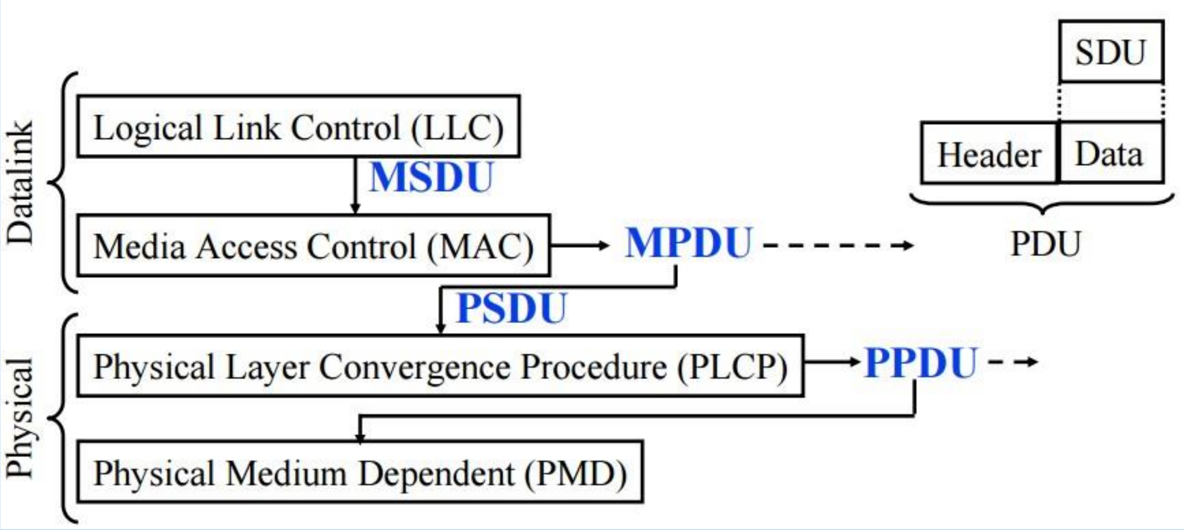


IEEE 802.11 Terminology

Access point (AP)	Any entity that has station functionality and provides access to the distribution system via the wireless medium for associated stations
Basic service set (BSS)	A set of stations controlled by a single coordination function
Coordination function	The logical function that determines when a station operating within a BSS is permitted to transmit and may be able to receive PDUs
Distribution system (DS)	A system used to interconnect a set of BSSs and integrated LANs to create an ESS
Extended service set (ESS)	A set of one or more interconnected BSSs and integrated LANs that appear as a single BSS to the LLC layer at any station associated with one of these BSSs
Frame	Synonym for MAC protocol data unit
MAC protocol data unit (MPDU)	The unit of data exchanged between two peer MAC entities using the services of the physical layer
MAC service data unit (MSDU)	Information that is delivered as a unit between MAC users
Station	Any device that contains an IEEE 802.11 conformant MAC and physical layer

IEEE 802.11 Terminology

- Each layer has Service Data Unit (SDU) as input
- Each layer makes Protocol Data Unit (PDU) as output to communicate with the corresponding layer at the other end
- SDUs may be fragmented or aggregated to form a PDU
- PDUs have a header specific to the layer



IEEE 802.11 Services

IEEE 802.11 defines nine services that need to be provided by WLAN

Service	Provider	Used to support
Association	Distribution system	MSDU delivery
Authentication	Station	LAN access and security
Deauthentication	Station	LAN access and security
Dissassociation	Distribution system	MSDU delivery
Distribution	Distribution system	MSDU delivery
Integration	Distribution system	MSDU delivery
MSDU delivery	Station	MSDU delivery
Privacy	Station	LAN access and security
Reassocation	Distribution system	MSDU delivery

Distribution of Messages Within a DS

Services involved with the distribution of messages within a DS

Distribution service

- Primary service used by stations to exchange MAC frames when frame must traverse the DS to get from a station in one BSS to a station in another BSS
- If stations are in the same BSS, distribution service logically goes through the single AP of that BSS

Integration service

- Enables transfer of data between a station on an IEEE 802.11 LAN and a station on an integrated IEEE 802.x LAN
- Takes care of any address translation and media conversion logic required for the exchange of data

Association-Related Services

- DS requires information about stations within the ESS that is provided by the association-related services
- Station must be associated before DS can deliver data to or accept data from it
- 3 mobility transition types

No transition
stationary or in single BSS

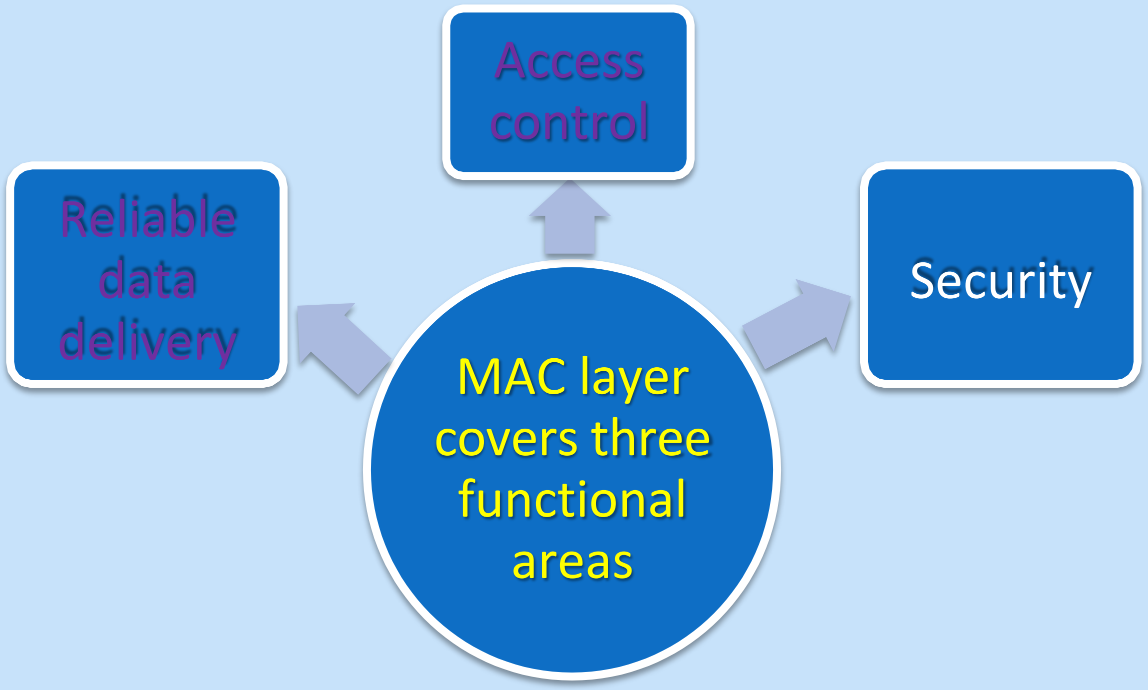
BSS transition
between BSS in same ESS

ESS transition
between BSS in different ESS

Association-Related Services

- Association station must establish an association with an AP within a particular BSS
  - The AP can then communicate this information to other APs within the ESS to facilitate routing and delivery of addressed frames
- **Reassociation** Enables an established association to be transferred from one AP to another, allowing a mobile station to move from one BSS to another
- **Disassociation:** A notification from either a station or an AP that an existing association is terminated

IEEE 802.11 Medium Access Control

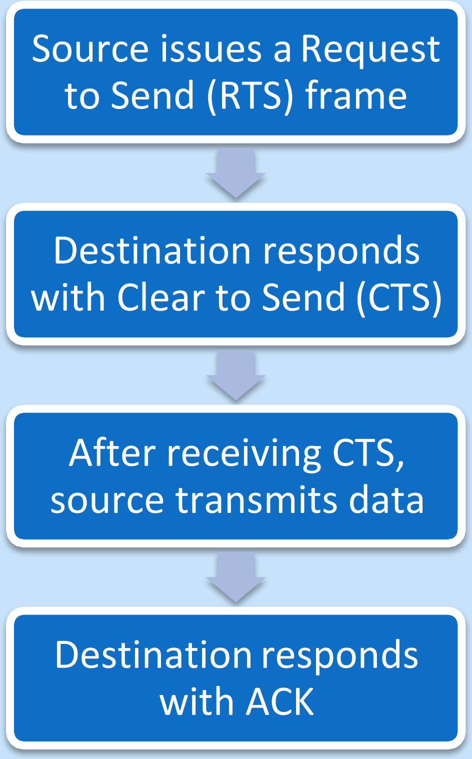


Reliable Data Delivery

- 802.11 physical and MAC layers unreliable
  - Noise, interference, and other propagation effects result in the loss of a significant number of frames
  - The issue can be addressed at a higher layer such as TCP
    - Timers used for retransmission at higher layers are typically on the order of seconds
- More efficient to deal with errors at MAC level
- 802.11 includes frame exchange protocol
  - Station receiving frame returns acknowledgment (ACK) frame
  - Exchange treated as atomic unit
  - If no ACK within short period of time, retransmit

Reliable Data Delivery

- To further enhance reliability, a four frame exchange may be used
  - RTS alerts all stations within range of source that exchange is under way
  - CTS alerts all stations within range of destination
  - Other stations don’t transmit to avoid collision
  - RTS and CTS exchange is a required function of MAC but may be disabled



MAC Algorithm

- Two types of proposals for a MAC algorithm
  - Distributed access protocol which distribute the decision to transmit over all the nodes using a carrier sense mechanism
  - Centralized access protocol which involve regulation of transmission by a centralized decision maker

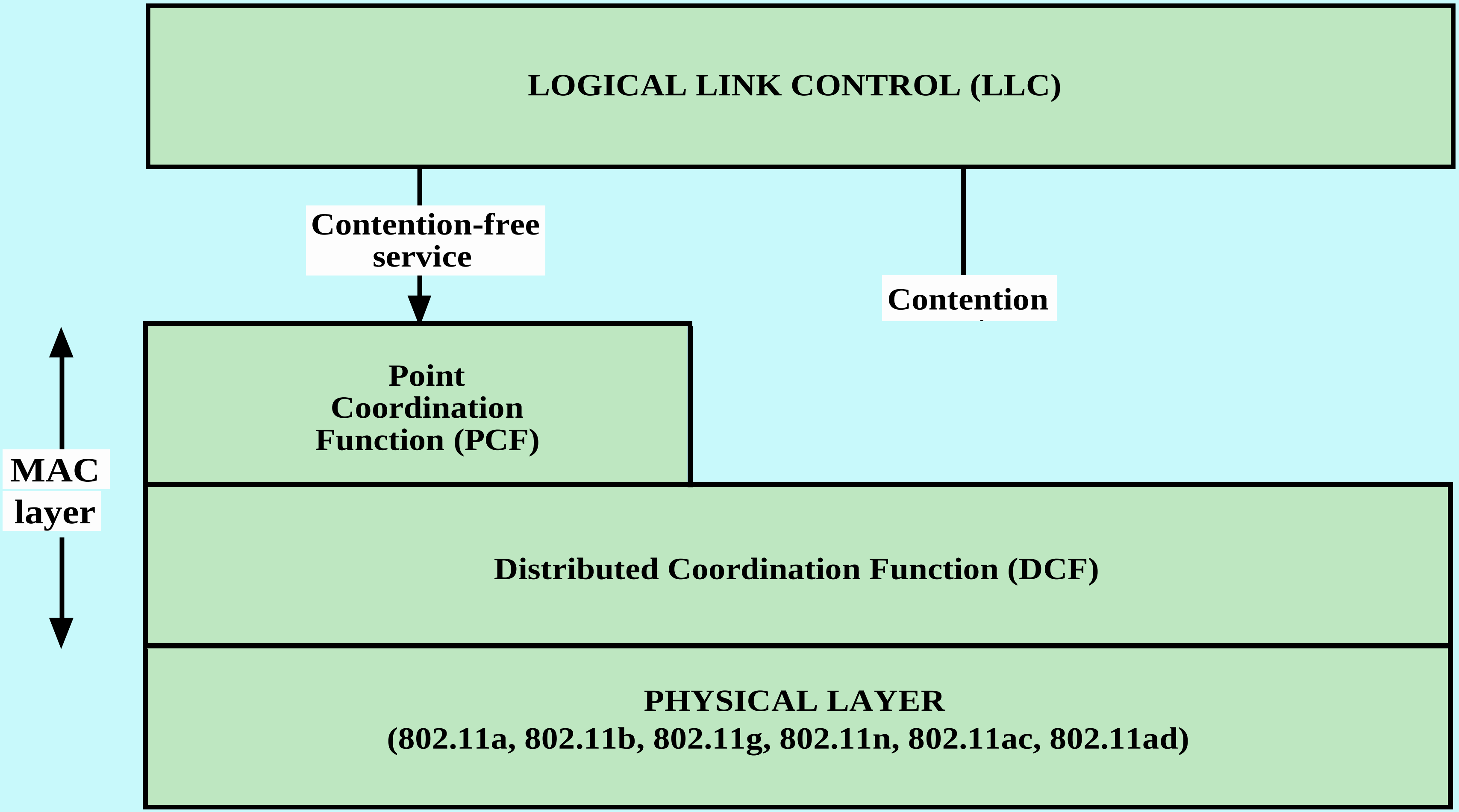
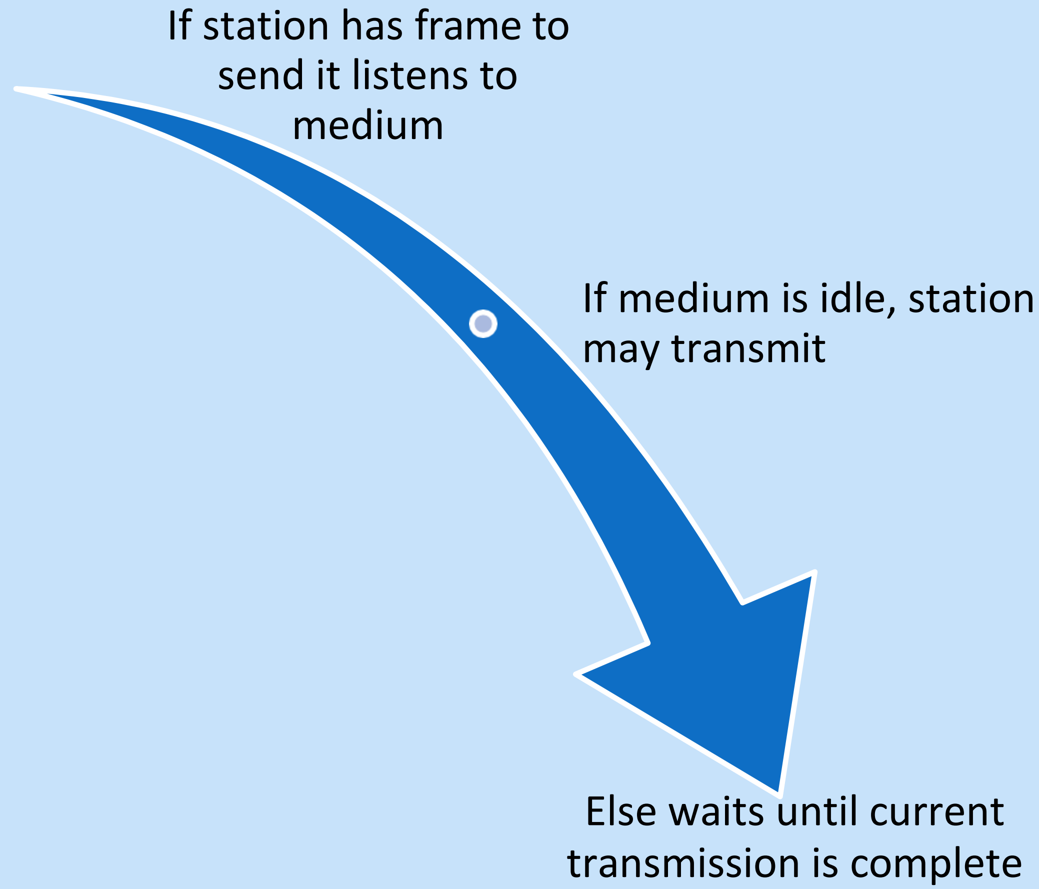


Figure 13.5 IEEE 802.11 Protocol Architecture

Distributed Coordination Function (DCF)

- DCF sublayer uses CSMA algorithm
- Does not include a collision detection function because it is not practical on a wireless network
- Includes a set of delays that amounts as a priority scheme



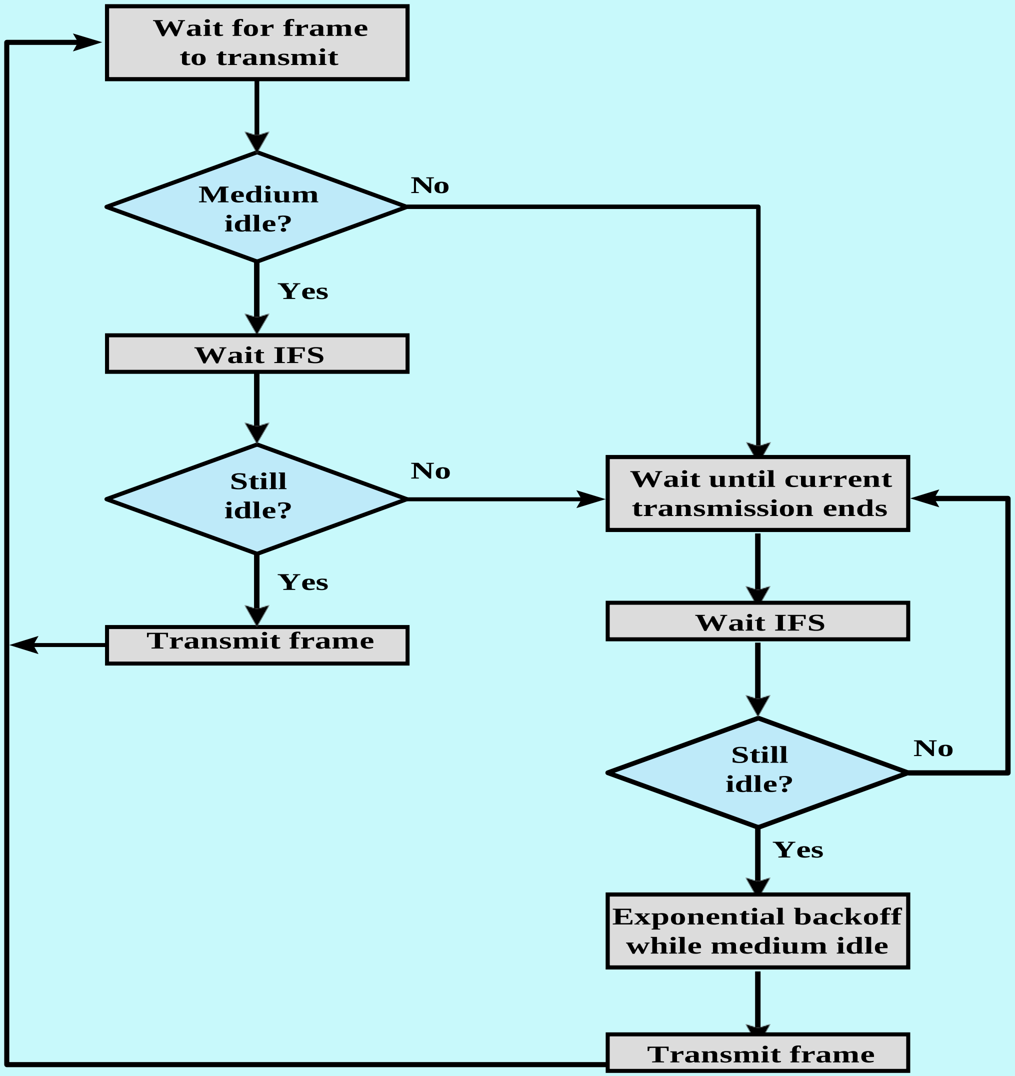


Figure 13.6 IEEE 802.11 Medium Access Control Logic

Priority IFS Values

SIFS

short IFS

For all immediate response actions

PIFS

point coordination function IFS

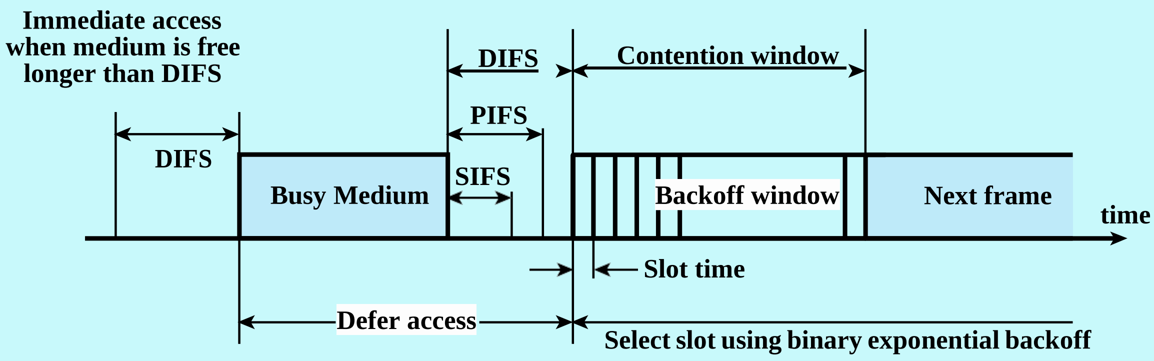
Used by the centralized controller in PCF scheme when issuing polls

DIFS

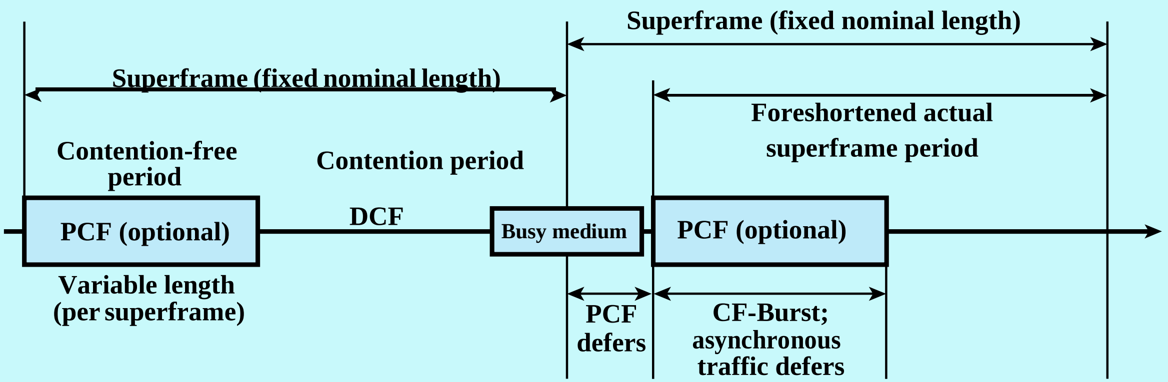
distributed coordination function IFS

Used as minimum delay for asynchronous frames contending for access

During the first part of Superframe interval, the point coordinator issues polls in a round-robin fashion to all stations configured for polling. The point coordinator then idles for the remainder of the superframe, allowing a contention period for asynchronous access



(a) Basic Access Method



PCF Superframe Construction

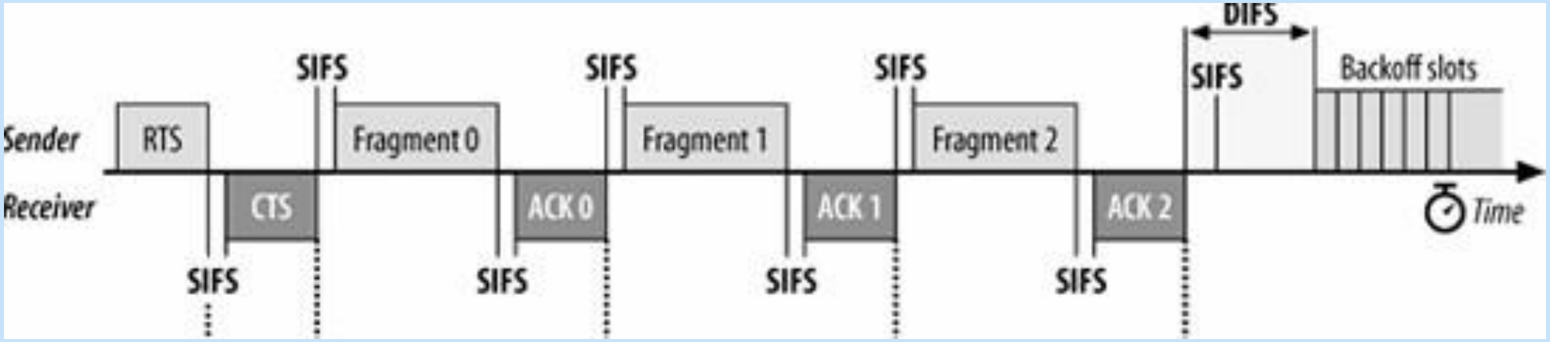
(b)

Figure 13.7 IEEE 802.11 MAC Timing

SIFS

- Any station using SIFS to determine transmission opportunity has the highest priority
- SIFS is used in the following circumstances:
  - Acknowledgment (ACK)
    - Station responds with an ACK frame after waiting only for a SIFS gap
    - Provides for efficient collision recovery
  - Clear to Send (CTS)
    - Station ensures data frame gets through by issuing RTS

SIFS



DIFS
SIFS
Backoff slots
SIFS
SIFS
SIFS
Sender
RTS
Fragment 0
Fragment 1
Fragment 2
Receiver
CTS
ACK 0
ACK 1
ACK 2
Time
SIFS
SIFS
SIFS
SIFS

Point Coordination Function (PCF)

- **Point coordination function** (**PCF**) resides in a point coordinator also known as Access Point , to coordinate the communication within the network
- The AP waits for PIFS duration rather than DIFS duration to grasp the channel
- Channel access in PCF mode is centralized
  - Access to the medium is restricted by the point coordinator
  - Associated stations can transmit data only when they are allowed to do so by the point coordinator
    - Due to the priority of PCF over DCF, stations that only use DCF might not gain access to the medium
    - To prevent this, a repetition interval has been designed to cover both Contention free or PCF & Contention Based or DCF traffic

PCF Operation

- Reserving the medium during the contention-free period
- The polling list
  - Stations get on the polling list when they associate with the AP
  - Polls any associated stations on a polling list for data transmissions
  - Each CF-Poll is a license to transmit one frame
  - Multiple frames can be transmitted only if the access point sends multiple poll requests

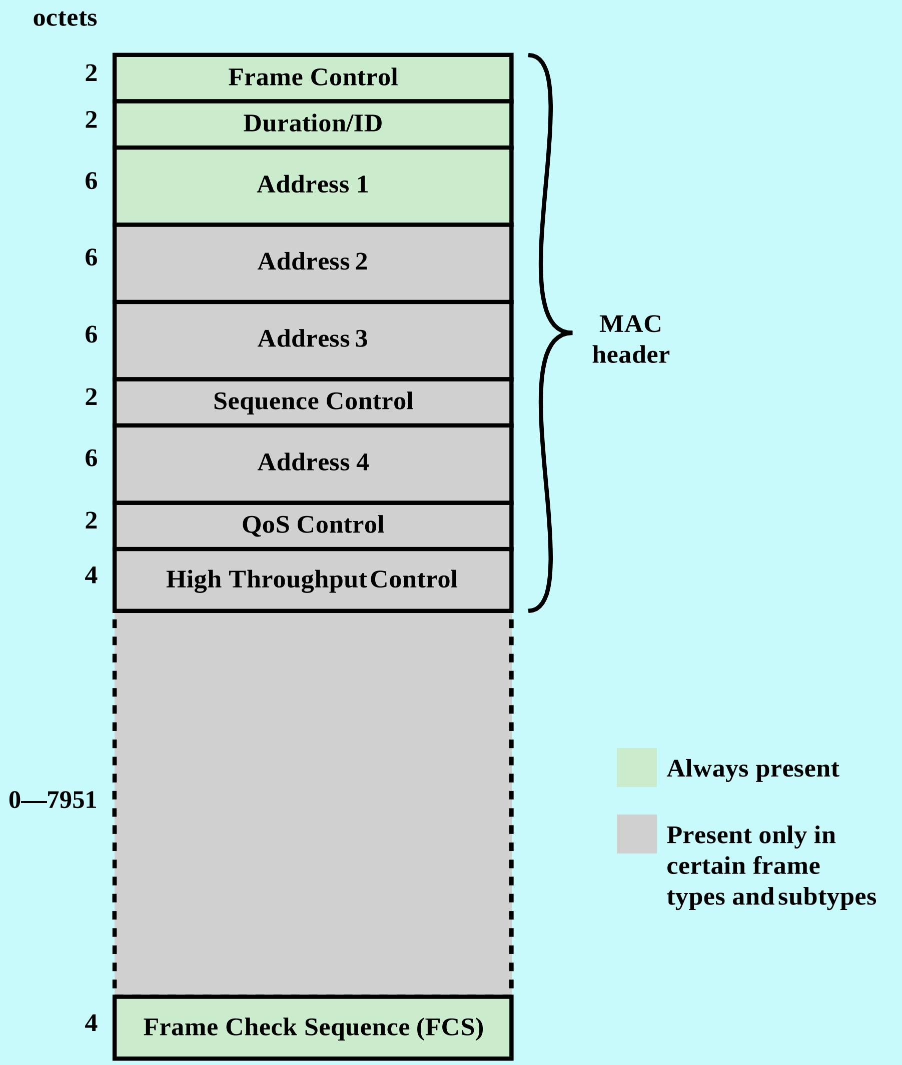


Figure 13.8 IEEE 802.11 MAC Frame Format

Frame Control Field

2 bits	2	4	1	1	1	1	1	1	1	1
Protocol Version	Type	Subtype	To DS	From DS	More Fragments	Retry	Power Mgt.	More data	WEP	Order

A description of each Frame Control field subfield are as follows:

- **Protocol Version** provides the current version of the 802.11 protocol used. Receiving STAs use this value to determine if the version of the protocol of the received frame is supported.
- **Type and Subtype** determines the function of the frame. There are three different frame type fields: control, data, and management. There are multiple subtype fields for each frame type . Each subtype determines the specific function to perform for its associated frame type.

Subtype value	Subtype name
Management frames (type=00)[a]	
0000	Association request
0001	Association response
0010	Reassociation request
0011	Reassociation response
0100	Probe request
0101	Probe response
1000	Beacon
1001	Announcement traffic indication message (ATIM)
1010	Disassociation
1011	Authentication
1100	Deauthentication
Control frames (type=01)[b]	
1010	Power Save (PS)-Poll
1011	RTS
1100	CTS
1101	Acknowledgment (ACK)
1110	Contention-Free (CF)-End
1111	CF-End+CF-Ack
Data frames (type=10)[c]	
0000	Data
0001	Data+CF-Ack
0010	Data+CF-Poll
0011	Data+CF-Ack+CF-Poll
0100	Null data (no data transmitted)
0101	CF-Ack (no data transmitted)
0110	CF-Poll (no data transmitted)
0111	Data+CF-Ack+CF-Poll

Frame Control Field

2 bits	2	4	1	1	1	1	1	1	1	1
Protocol Version	Type	Subtype	To DS	From DS	More Fragments	Retry	Power Mgt.	More data	WEP	Order

A description of each Frame Control field subfield are as follows:

- **Protocol Version** provides the current version of the 802.11 protocol used. Receiving STAs use this value to determine if the version of the protocol of the received frame is supported.
- **Type and Subtype** determines the function of the frame. There are three different frame type fields: control, data, and management. There are multiple subtype fields for each frame type . Each subtype determines the specific function to perform for its associated frame type.
- **To DS and From DS** indicates whether the frame is going to or exiting from the DS (distributed system), and is only used in data type frames of STAs associated with an AP.
- **More Fragments** indicates whether more fragments of the frame, either data or management type, are to follow.
- **Retry** indicates whether or not the frame, for either data or management frame types, is being retransmitted.
- **Power Management** indicates whether the sending STA is in active mode or power-save mode.
- **More Data** indicates to a STA in power-save mode that the AP has more frames to send. It is also used for APs to indicate that additional broadcast/multicast frames are to follow.
- **WEP** indicates whether or not encryption and authentication are used in the frame. It can be set for all data frames and management frames, which have the subtype set to authentication.
- **Order** indicates that all received data frames must be processed in order.

Control Frames

Assist in the reliable delivery of data frames

Power Save-Poll (PS-Poll)

- The purpose is to request that the AP transmit a frame that has been buffered for this station while the station was in power saving mode

Request to Send (RTS)

- First frame in four-way frame exchange

Clear to Send (CTS)

- Second frame in four-way exchange

Acknowledgment (ACK)

- Acknowledges correct receipt

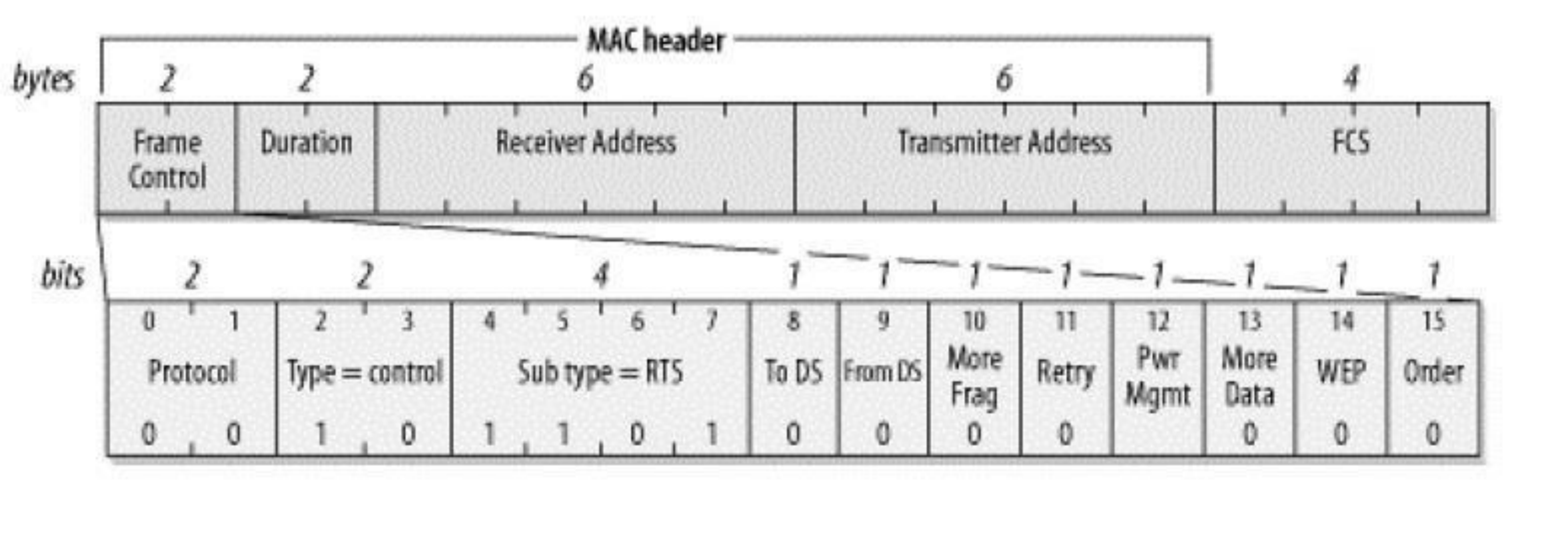
Contention-Free (CF)-end

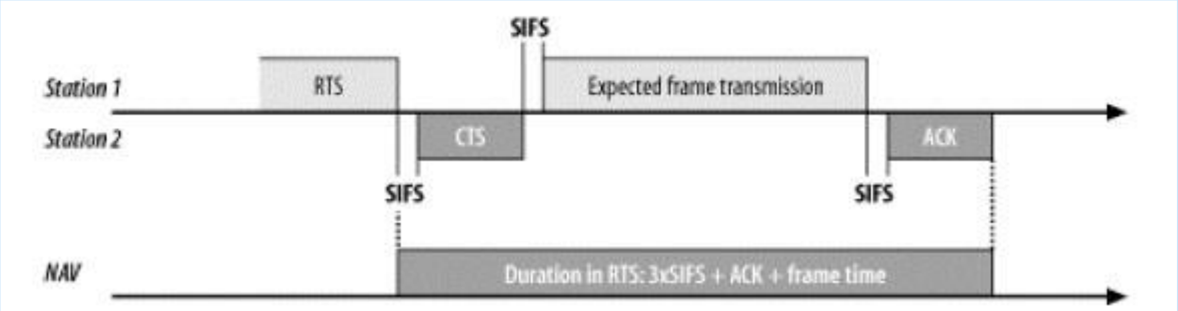
- Announces end of contention-free period that is part of PCF

CF-End + CF-Ack:

- Acknowledges CF-end to end contention-free period and release stations from associated restrictions

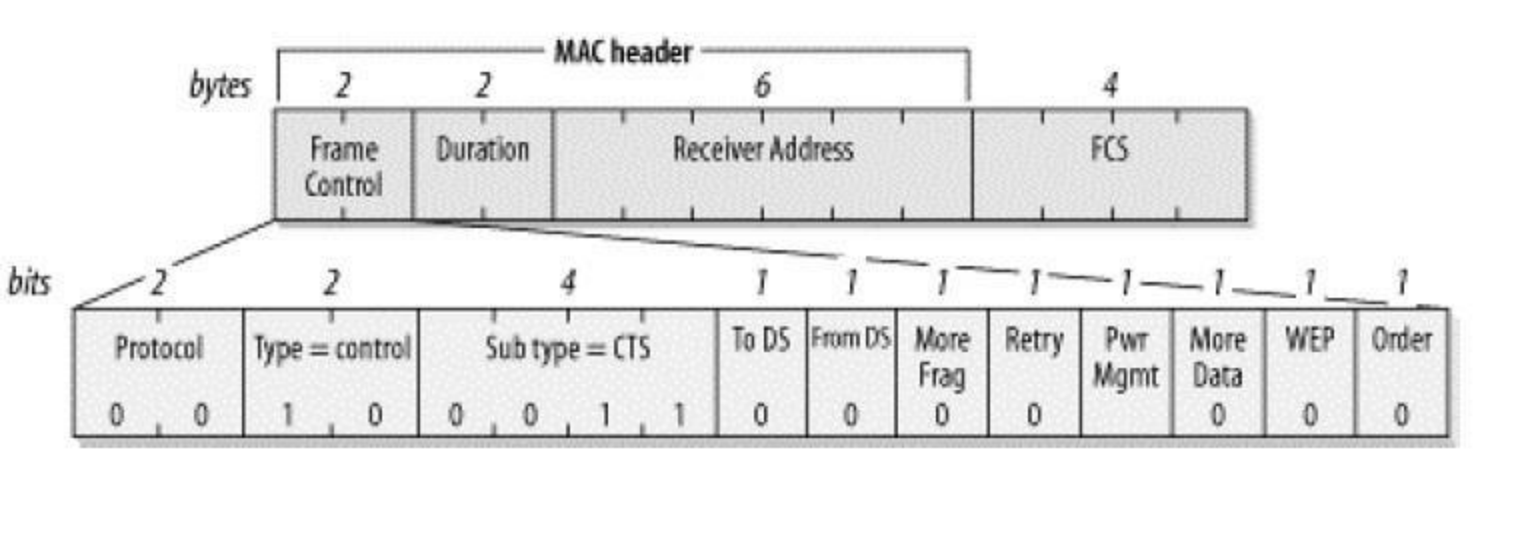
Control Frames

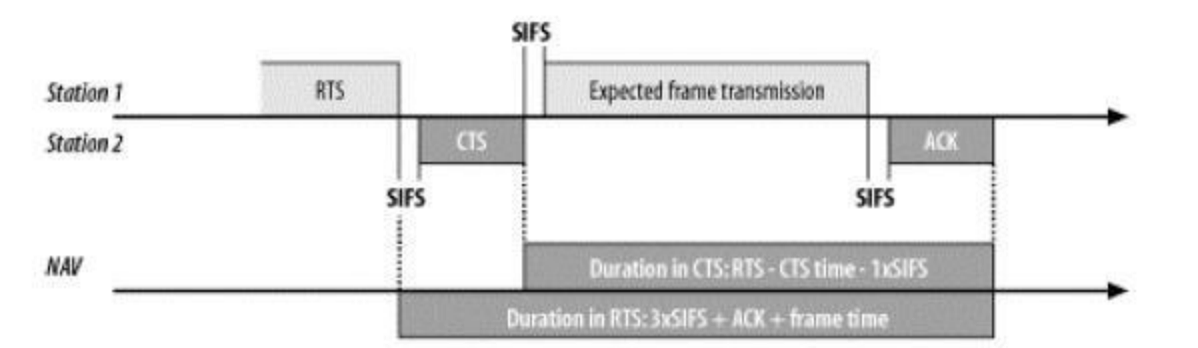




Duration field in RTS frame

Control Frames





The receiver of a CTS frame is the transmitter of the previous RTS frame, so the MAC copies the transmitter address of the RTS frame into the receiver address of the CTS frame

Data Frames

- Data frames carry higher-level protocol data in the frame body
- Eight data frame subtypes
  - Organized in two groups
    - First four carry upper-level data
    - Remaining do not carry any user data
  - Data
    - Simplest data frame, it may be used in both a contention or contention-free period
  - Data + CF-Ack
    - Carries data and acknowledges previously received data during contention-free period
  - Data + CF-Poll
    - Used by point coordinator to deliver data and also to request that the mobile station send a data frame that it may have buffered
  - Data + CF-Ack + CF-Poll
    - Combines Data + CF-Ack and Data + CF-Poll

Data Frames

Frame type	Contention-based service	Contention-free service	Carries data	Does not carry data
Data	✓		✓	
Data+CF-Ack		✓	✓	
Data+CF-Poll		AP only	✓	
Data+CF-Ack+CF-Poll		AP only	✓	
Null	✓	✓		✓
CF-Ack		✓		✓
CF-Poll		AP only		✓
CF-Ack+CF-Poll		AP only		✓

Management Frames

Used to manage communications between stations and APs

Management of associations

- Request, response, reassociation, dissociation, and authentication

Management Frames

- **Beacon**
  - announce the existence of a network
  - transmitted at regular intervals to allow mobile stations to find and identify a network, as well as match parameters for joining the network
- **Probe Request**
  - Mobile stations use Probe Request frames to scan an area for existing 802.11 networks
  - Include SSID and the rates supported by the mobile station
  - Stations that receive Probe Requests use the information to determine whether the mobile station can join the network
- **Probe Response**

Management Frames

- Disassociation and Deauthentication
- Association Request
- Authentication