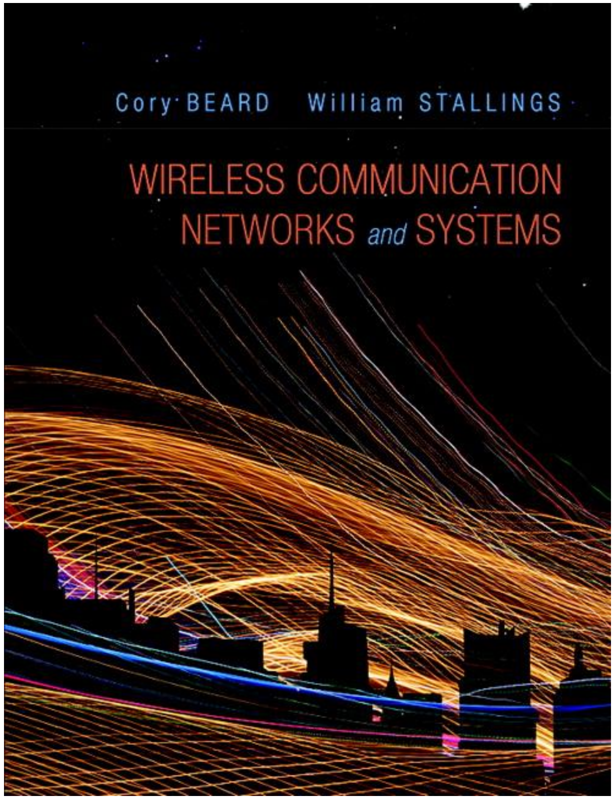
PART 4



Wireless Communication Networks and Systems
1st edition
Cory Beard, William Stallings

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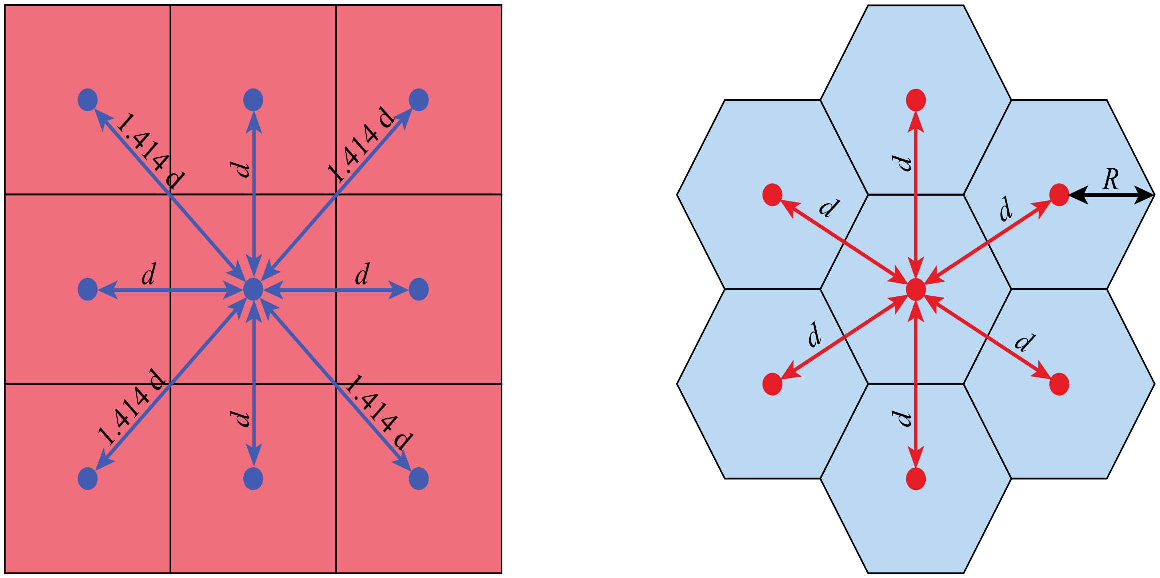
Cellular Networks

- Revolutionary development in data communications and telecommunications
- Foundation of mobile wireless
  - Telephones, smartphones, tablets, wireless Internet, wireless applications
- Supports locations not easily served by wireless networks or WLANs
- Four generations of standards
  - 1G: Analog
  - 2G: Still used to carry voice
  - 3G: First with sufficient speeds for data networking, packets only
  - 4G: Truly broadband mobile data up to 1 Gbps

Cellular Network Organization

- Use multiple low-power transmitters (100 W or less)
- Areas divided into cells
  - Each served by its own antenna
  - Served by base station consisting of transmitter, receiver, and control unit
  - Band of frequencies allocated
  - Cells set up such that antennas of all neighbors are equidistant (hexagonal pattern)

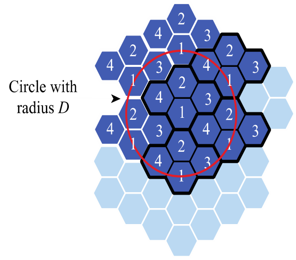


(a) Square pattern (b) Hexagonal pattern

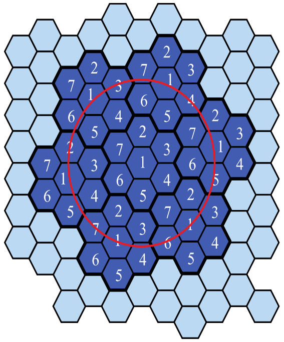
13.1 CELLULAR GEOMETRIES

Frequency Reuse

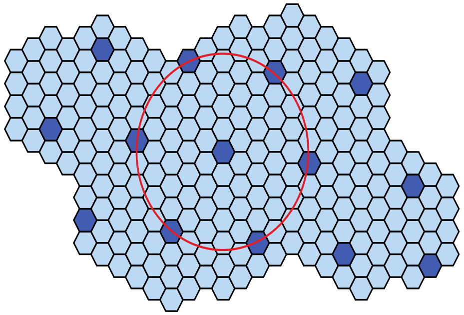
- Adjacent cells assigned different frequencies to avoid interference or crosstalk
- Objective is to reuse frequency in nearby cells
  - 10 to 50 frequencies assigned to each cell
  - Transmission power controlled to limit power at that frequency escaping to adjacent cells
  - The issue is to determine how many cells must intervene between two cells using the same frequency



(a) Frequency reuse pattern for $N = 4$



(b) Frequency reuse pattern for $N = 7$

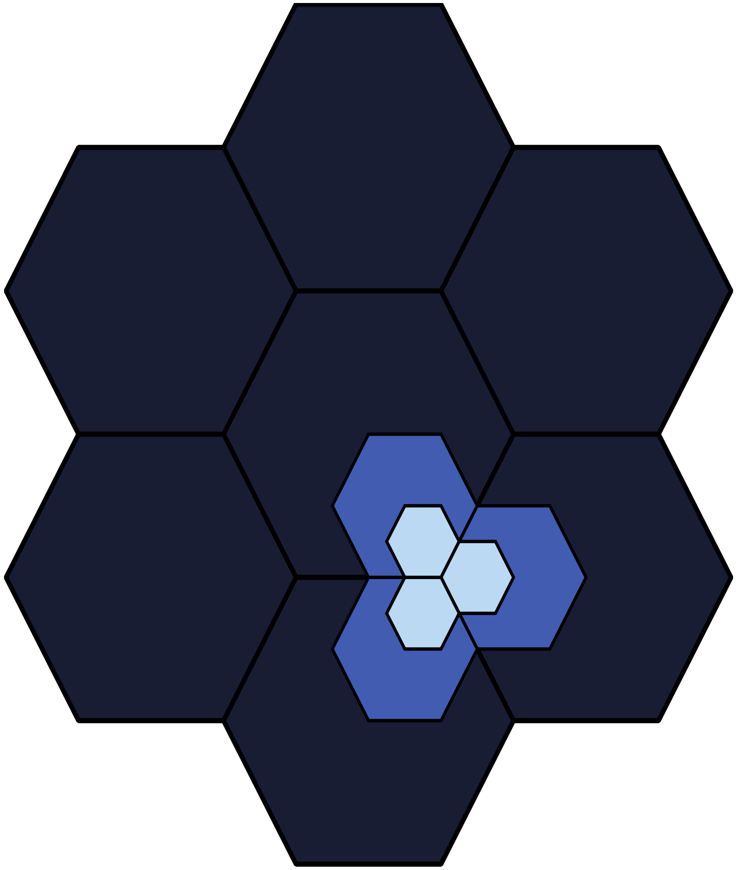


(c) Black cells indicate a frequency reuse for $N = 19$

13.2 FREQUENCY REUSE PATTERNS

Approaches to Cope with Increasing Capacity

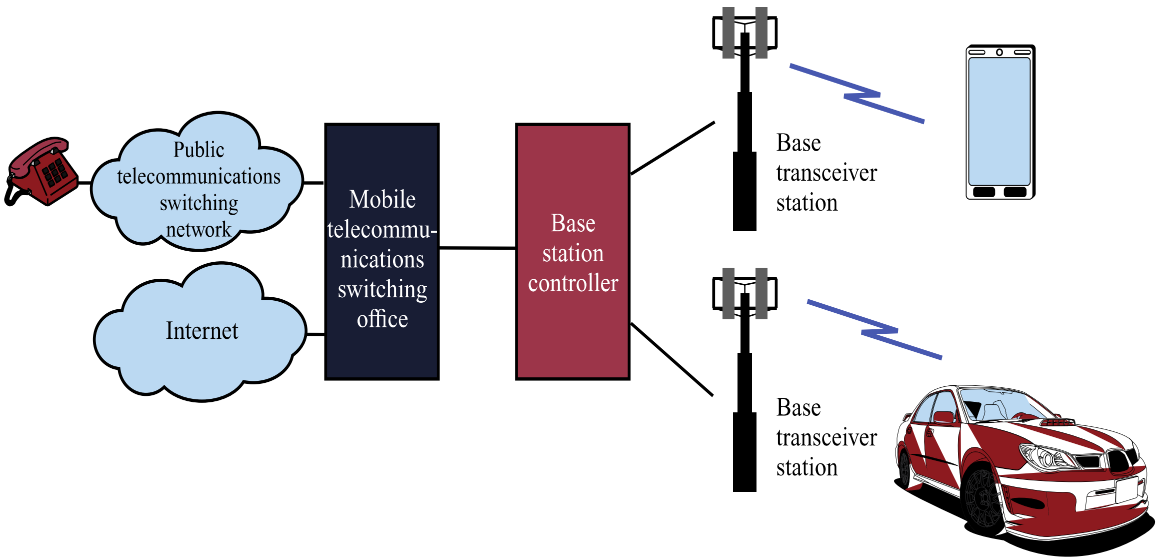
- Adding new channels
- Frequency borrowing – frequencies are taken from adjacent cells by congested cells
- Cell splitting – cells in areas of high usage can be split into smaller cells
- Cell sectoring – cells are divided into a number of wedge-shaped sectors, each with their own set of channels
- Network densification – more cells and frequency reuse
  - Microcells – antennas move to buildings, hills, and lamp posts
  - Femtocells – antennas to create small cells in buildings
- Interference coordination – tighter control of interference so frequencies can be reused closer to other base stations
  - Inter-cell interference coordination (ICIC)
  - Coordinated multipoint transmission (CoMP)



13.3 CELL SPLITTING

Cellular Systems Terms

- Base Station (BS) – includes an antenna, a controller, and a number of receivers
- Mobile telecommunications switching office (MTSO) – connects calls between mobile units
- Two types of channels available between mobile unit and BS
  - Control channels – used to exchange information having to do with setting up and maintaining calls
  - Traffic channels – carry voice or data connection between users



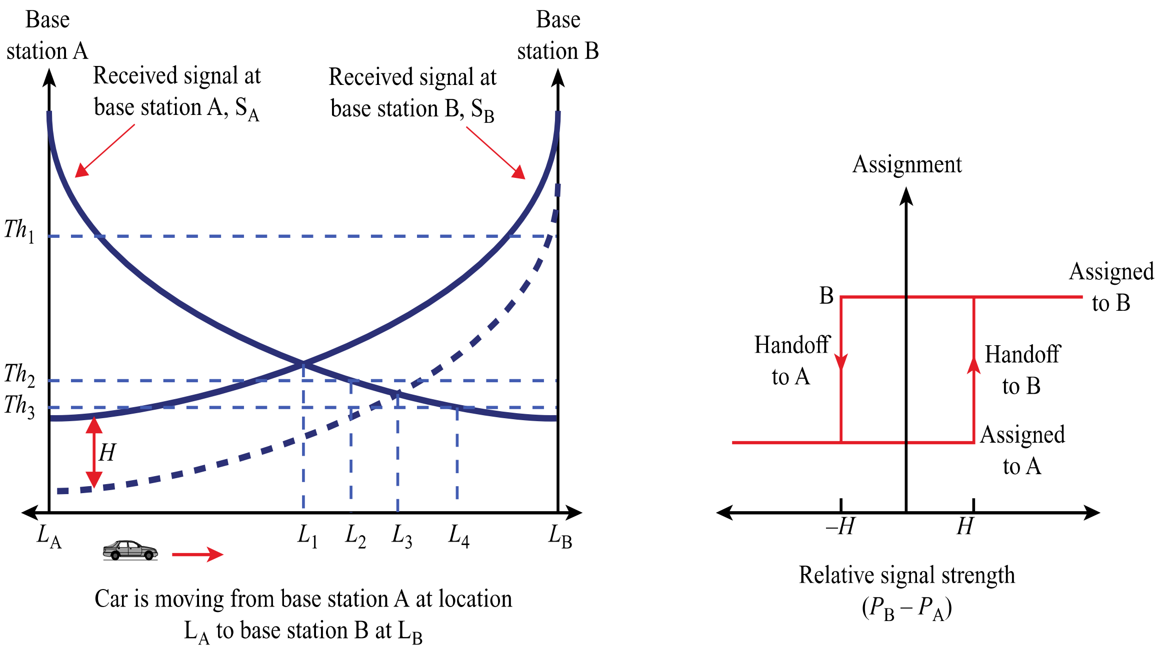
13.5 OVERVIEW OF CELLULAR SYSTEM

Mobile Radio Propagation Effects

- Signal strength
  - Must be strong enough between base station and mobile unit to maintain signal quality at the receiver
  - Must not be so strong as to create too much co-channel interference with channels in another cell using the same frequency band
- Fading
  - Signal propagation effects may disrupt the signal and cause errors

Handoff Strategies Used to Determine Instant of Handoff

- Relative signal strength
- Relative signal strength with threshold
- Relative signal strength with hysteresis
- Relative signal strength with hysteresis and threshold
- Prediction techniques



(a) Handoff decision as a function of handoff scheme

(b) Hysteresis mechanism

13.7 HANDOFF BETWEEN TWO CELLS

First-Generation Analog

- Advanced Mobile Phone Service (AMPS)
  - In North America, two 25-MHz bands allocated to AMPS
    - One for transmission from base to mobile unit
    - One for transmission from mobile unit to base
  - Each band split in two to encourage competition
  - Frequency reuse exploited

Differences Between First and Second Generation Systems

- Digital traffic channels – first-generation systems are almost purely analog; second-generation systems are digital
  - Using FDMA/TDMA or CDMA
- Encryption – all second generation systems provide encryption to prevent eavesdropping
- Error detection and correction – second-generation digital traffic allows for detection and correction, giving clear voice reception
- Channel access – second-generation systems allow channels to be dynamically shared by a number of users

Global System for Mobile Communications (GSM)

- FDMA/TDMA approach
- Developed to provide a common second-generation technology for Europe
  - Over 6.9 billion subscriber units by the end of 2013
- Mobile station communicates across the Um interface (air interface) with base station transceiver in the same cell as mobile unit
- Mobile equipment (ME) – physical terminal, such as a telephone or PCS
  - ME includes radio transceiver, digital signal processors and subscriber identity module (SIM)
- GSM subscriber units are generic until SIM is inserted
  - SIMs roam, not necessarily the subscriber devices

GSM Radio Link

- Combination of FDMA and TDMA
- 200 kHz carriers
- Each with a data rate of 270.833 kbps
- 8 users share each carrier

Generalized Packet Radio Service (GPRS)

- Phase 2 of GSM
- Provides a datagram switching capability to GSM
  - Instead of sending data traffic over a voice connection which requires setup, sending data, and teardown
  - GPRS allows users to open a persistent data connection
  - Also has a new system architecture for data traffic
  - 21.4 kbps from a 22.8 kbps gross data rate
  - Can combine up to 8 GSM connections
    - Overall throughputs up to 171.2 kbps

Enhanced Data Rates for GSM Evolution (EDGE)

- The next generation of GSM
  - Not yet 3G, so called “2.G” by some
- Three-fold increase in data rate
  - Up to 3 bits/symbol for 8-PSK from 1 bit/symbol for GMSK for GSM.
  - Max data rates per channel up to $22.8 \times 3 = 68.4$ kbps per channel
  - Using all eight channels in a 200 kHz carrier, gross data transmission rates up to 547.2 kbps became possible
    - Actual throughput up to 513.6 kbps.
- A later release of EDGE (3GPP Release 7) increased downlink data rates over 750 kbps and uplink data rates over 600 kbps

IS-95 Forward Link

- Most widely used CDMA cellular standard is IS-95, used mainly in North America
- Forward link channels
  - Pilot (channel 0) - allows the mobile unit to acquire timing information, provides phase reference and provides means for signal strength comparison
  - Synchronization (channel 32) - used by mobile station to obtain identification information about cellular system
  - Paging (channels 1 to 7) - contain messages for one or more mobile stations
  - Traffic (channels 8 to 31 and 33 to 63) – the forward channel supports 55 traffic channels
    - 9600 or 14,400 bps

ITU’s initial View of Third-Generation Capabilities

- The ITU’s International Mobile Telecommunications for the year 2000 (IMT-2000) initiative
- Voice quality comparable to the public switched telephone network
- 144 kbps data rate available to users in high-speed motor vehicles over large areas
- 384 kbps available to pedestrians standing or moving slowly over small areas
- Support for 2.048 Mbps for office use
  - Much higher rates were developed

ITU's initial View of Third-Generation Capabilities

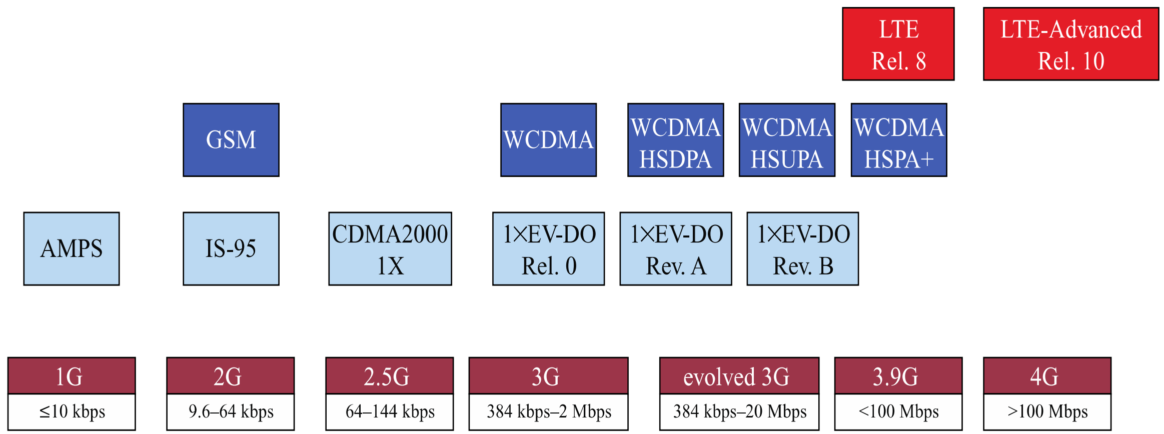
- Symmetrical / asymmetrical data transmission rates
- Support for both packet switched and circuit switched data services
- An adaptive interface to the Internet to reflect efficiently the common asymmetry between inbound and outbound traffic
- More efficient use of the available spectrum in general
- Support for a wide variety of mobile equipment
- Flexibility to allow the introduction of new services and technologies

WCDMA and UMTS

- WCDMA is part of a group of standards from
  - IMT-2000
  - Universal Mobile Telephone System (UMTS)
  - Third-Generation Partnership Project (3GPP) industry organization
- 3GPP originally released GSM
  - Issued Release 99 in 1999 for WCDMA and UMTS
  - Subsequent releases were “Release 4” and onwards
  - Many higher layer network functions of GSM were carried over to WCDMA

WCDMA and UMTS

- 144 kbps to 2 Mbps, depending on mobility
- High Speed Downlink Packet Access (HSDPA)
  - Release 5
  - 1.8 to 14.4 Mbps downlink
  - Adaptive modulation and coding, hybrid ARQ, and fast scheduling
- High Speed Uplink Packet Access (HSUPA)
  - Release 6
  - Uplink rates up to 5.76 Mbps
- High Speed Packet Access Plus (HSPA+)
  - Release 7 and successively improved in releases through Release 11
  - Maximum data rates increased from 21 Mbps up to 336 Mbps
  - 64 QAM, 2×2 and 4×4 MIMO, and dual or multi-carrier combinations
- 3GPP Release 8 onwards introduced Long Term Evolution (LTE)
  - Pathway to 4G, Chapter 14



13.13 EVOLUTION OF CELLULAR WIRELESS SYSTEMS

CDMA2000 and EV-DO

- CDMA2000 first introduced 1xRTT (Radio Transmission Technology)
  - 1 times the 1.2288 Mcps spreading rate of a 1.25 MHz IS-95 CDMA channel
  - Not 3G, so considered by some as “2.5G”
- Evolution-Data Only (1×EV-DO)
  - Also 1×EV-DV (data/voice) which never succeeded
  - 1×EV-DO Release 0
    - 2.4 Mbps uplink, 153 kbps downlink
    - Only using 1.25 MHz of 5 MHz required of CDMA
  - 1×EV-DO Release A
    - 3.1 Mbps downlink, 1.8 Mbps uplink, QoS
  - 1×EV-DO Release B
    - 5 MHz bandwidth, 14.7 Mpbs uplink, 5.4 Mbps downlink
- EV-DO uses only IP, but VoIP can be used for voice

4G Technology

- High-speed, universally accessible wireless service capability
- Creating a revolution
  - Networking at all locations for tablets, smartphones, computers, and devices.
  - Similar to the revolution caused by Wi-Fi
- LTE and LTE-Advanced will be studied here
  - Goals and requirements, complete system architecture, core network (Evolved Packet System), LTE channel and physical layer
  - Will first study LTE Release 8, then enhancements from Releases 9-12

Purpose, motivation, and approach to 4G

- Ultra-mobile broadband access
  - For a variety of mobile devices
- International Telecommunication Union (ITU) 4G directives for IMT-Advanced
  - All-IP packet switched network.
  - Peak data rates
    - Up to 100 Mbps for high-mobility mobile access
    - Up to 1 Gbps for low-mobility access
  - Dynamically share and use network resources
  - Smooth handovers across heterogeneous networks, including 2G and 3G networks, small cells such as picocells, femtocells, and relays, and WLANs
  - High quality of service for multimedia applications

Purpose, motivation, and approach to 4G

- No support for circuit-switched voice
  - Instead providing Voice over LTE (VoLTE)
- Replace spread spectrum with OFDM

Table 14.1 Wireless Network Generations

Technology	1G	2G	2.5G	3G	4G
Design began	1970	1980	1985	1990	2000
Implementation	1984	1991	1999	2002	2012
Services	Analog voice	Digital voice	Higher capacity packetized data	Higher capacity, broadband	Completely IP based
Data rate	1.9. kbps	14.4 kbps	384 kbps	2 Mbps	200 Mbps
Multiplexing	FDMA	TDMA, CDMA	TDMA, CDMA	CDMA	OFDMA, SC-FDMA
Core network	PSTN	PSTN	PSTN, packet network	Packet network	IP backbone

LTE Architecture

- Two candidates for 4G
  - IEEE 802.16 WiMax (described in Chapter 16)
    - Enhancement of previous fixed wireless standard for mobility
  - Long Term Evolution
    - Third Generation Partnership Project (3GPP)
    - Consortium of Asian, European, and North American telecommunications standards organizations
- Both are similar in use of OFDM and OFDMA
- LTE has become the universal standard for 4G
  - All major carriers in the United States

LTE Architecture

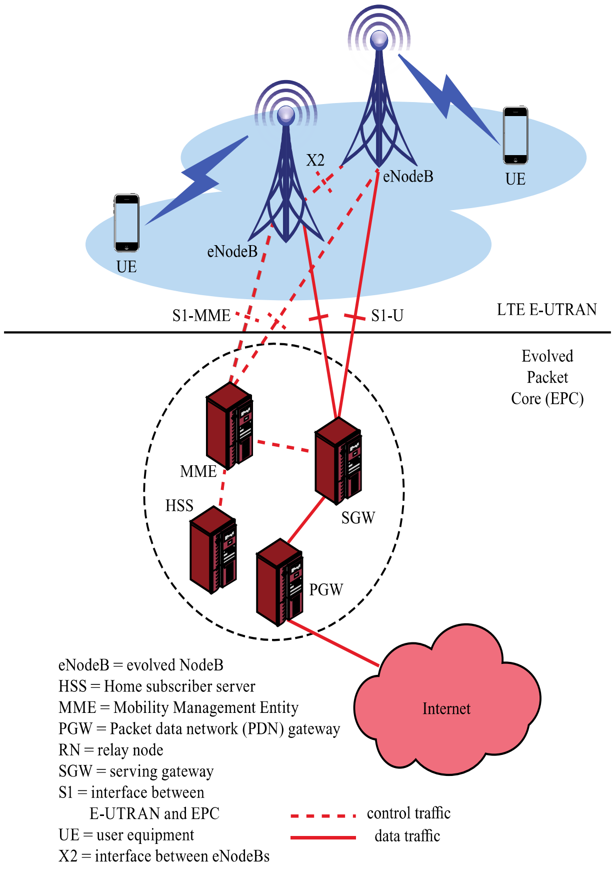
- Some features started in the 3G era for 3GPP
- Initial LTE data rates were similar to 3G
- 3GPP Release 8
  - *Clean slate* approach
  - Completely new air interface
    - OFDM, OFDMA, MIMO
- 3GPP Release 10
  - Known as *LTE-Advanced*
  - Further enhanced by Releases 11 and 12

Table 14.2 Comparison of Performance Requirements for LTE and LTE-Advanced

System Performance		LTE	LTE-Advanced
Peak rate	Downlink	100 Mbps @20 MHz	1 Gbps @100 MHz
	Uplink	50 Mbps @20 MHz	500 Mbps @100 MHz
Control plane delay	Idle to connected	<100 ms	< 50 ms
	Dormant to active	<50 ms	< 10 ms
User plane delay		< 5ms	Lower than LTE
Spectral efficiency (peak)	Downlink	5 bps/Hz @2×2	30 bps/Hz @8×8
	Uplink	2.5 bps/Hz @1×2	15 bps/Hz @4×4
Mobility		Up to 350 km/h	Up to 350—500 km/h

LTE Architecture

- evolved NodeB (eNodeB)
  - Most devices connect into the network through the eNodeB
- Evolution of the previous 3GPP NodeB
  - Now based on OFDMA instead of CDMA
  - Has its own control functionality, rather than using the Radio Network Controller (RNC)
    - eNodeB supports radio resource control, admission control, and mobility management
    - Originally the responsibility of the RNC



14.2 Overview of the EPC/LTE Architecture

Evolved Packet System

- Evolved Packet Core (EPC)
  - Operator or carrier core network
  - It is important to understand the EPC to know the full functionality of the architecture
- Some of the design principles of the EPS
  - Clean slate design
  - Packet-switched transport for traffic belonging to all QoS classes including conversational, streaming, real-time, non-real-time, and background
  - Radio resource management for the following: end-to-end QoS, transport for higher layers, load sharing/balancing, policy management/enforcement across different radio access technologies
  - Integration with existing 3GPP 2G and 3G networks
  - Scalable bandwidth from 1.4 MHz to 20 MHz
  - Carrier aggregation for overall bandwidths up to 100 MHz

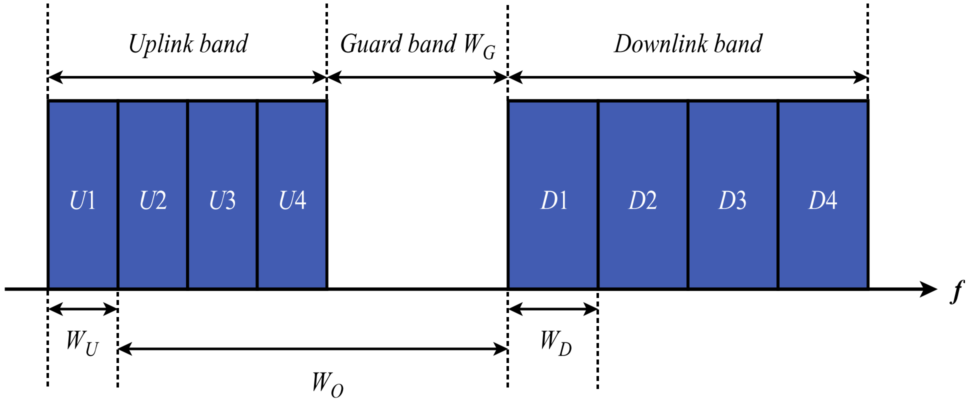
LTE Radio Access Network

- LTE uses MIMO and OFDM
  - OFDMA on the downlink
  - SC-OFDM on the uplink, which provides better energy and cost efficiency for battery-operated mobiles
- LTE uses subcarriers 15 kHz apart
  - Maximum FFT size is 2048
  - Basic time unit is

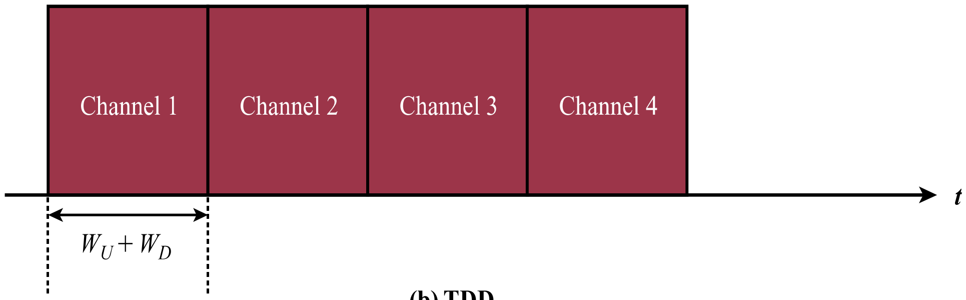
    $T_s = 1/(15000 \times 2048) = 1/30{,}720{,}000$ seconds.
  - Downlink and uplink are organized into *radio frames*
    - Duration 10 ms., which corresponds to $307200T_s$.

LTE Radio Access Network

- LTE uses both TDD and FDD
  - Both have been widely deployed
  - Time Division Duplexing (TDD)
    - Uplink and downlink transmit in the same frequency band, but alternating in the time domain
  - Frequency Division Duplexing (FDD)
    - Different frequency bands for uplink and downlink
- LTE uses two cyclic prefixes (CPs)
  - Normal CP = $144 \times T_s = 4.7$ µs.
  - Extended CP = $512 \times T_s = 16.7$ µs.
    - For worse environments



(a) FDD



(b) TDD

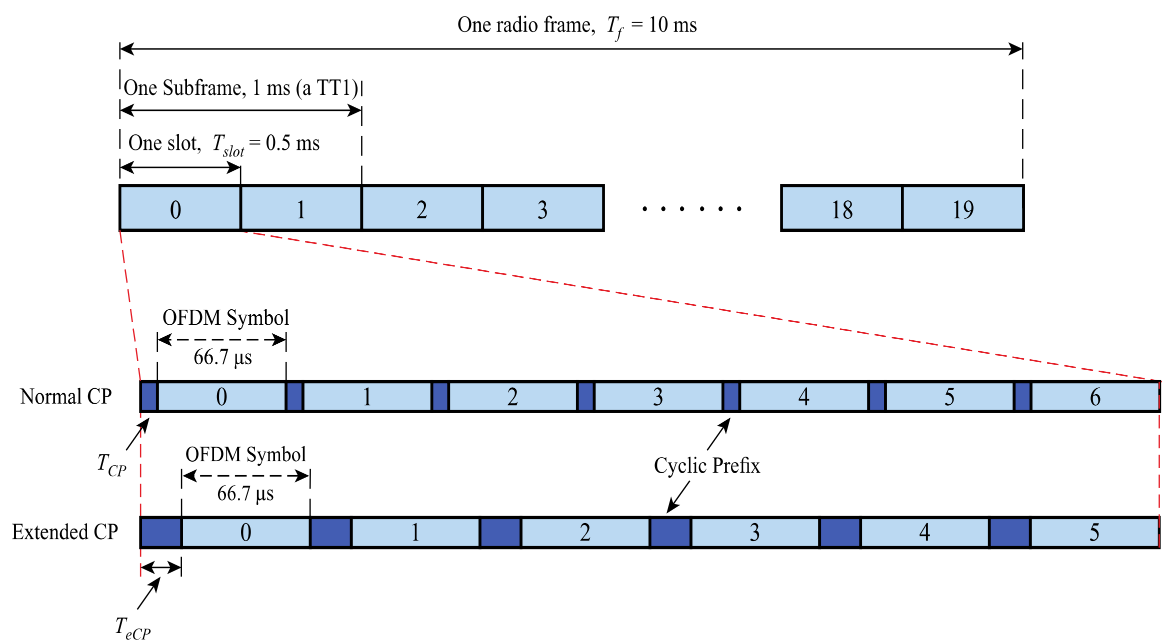
14.10 Spectrum Allocation for FDD and TDD

FDD Frame Structure type 1

- Three different time units
  - The *slot* equals T_{slot} = 15360 × T_s = 0.5 ms
  - Two consecutive slots comprise a *subframe* of length 1 ms.
    - Channel dependent scheduling and link adaptation (otherwise known as adaptive modulation and coding) occur on the time scale of a subframe (1000 times/sec.).
  - 20 slots (10 subframes) equal a *radio frame* of 10 ms.
    - Radio frames schedule distribution of more slowly changing information, such as system information and reference signals.

FDD Frame Structure type 1

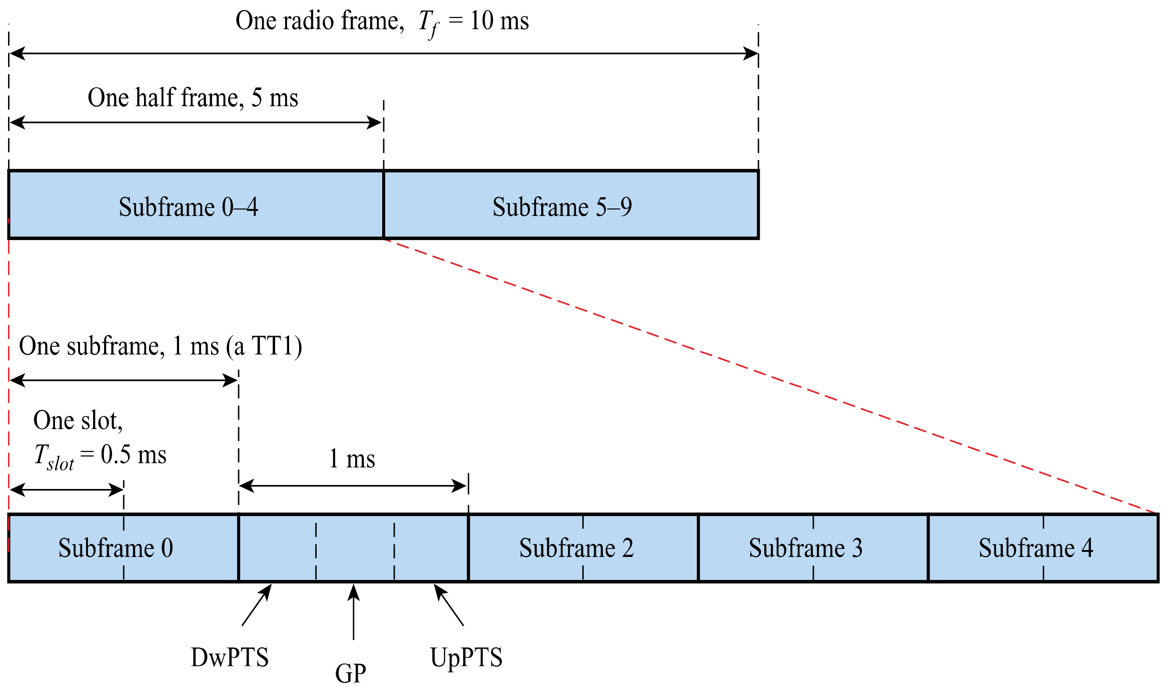
- Normal CP allows 7 OFDM symbols per slot
- Extended CP only allows time for 6 OFDM symbols
  - Use of extended CP results in a 1/7 = 14.3% reduction in throughput
  - But provides better compensation for multipath



14.11 FDD Frame Structure, Type 1

TDD Frame Structure Type 2

- Radio frame is again 10 ms.
- Includes special subframes for switching downlink-to-uplink
  - Downlink Pilot TimeSlot (DwPTS): Ordinary but shorter downlink subframe of 3 to 12 OFDM symbols
  - Uplink Pilot TimeSlot (UpPTS): Short duration of one or two OFDM symbols for sounding reference signals or random access preambles
  - Guard Period (GP): Remaining symbols in the special subframe in between to provide time to switch between downlink and uplink



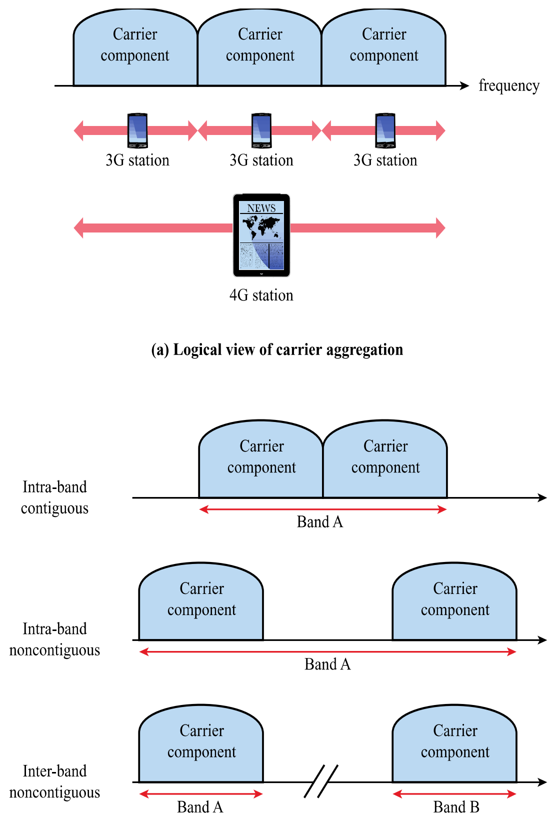
14.12 TDD Frame Structure, Type 2

LTE-Advanced

- So far we have studied 3GPP Release 8
  - Releases 9-12 have been issued
- Release 10 meets the ITU 4G guidelines
  - Took on the name LTE-Advanced
- Key improvements
  - Carrier aggregation
  - MIMO enhancements to support higher dimensional MIMO
  - Relay nodes
  - Heterogeneous networks involving small cells such as femtocells, picocells, and relays
  - Cooperative multipoint transmission and enhanced intercell interference coordination
  - Voice over LTE

Carrier Aggregation

- Ultimate goal of LTE-Advanced is 100 MHz bandwidth
  - Combine up to 5 component carriers (CCs)
  - Each CC can be 1.4, 3, 5, 10, 15, or 20 MHz
  - Up to 100 MHz
- Three approaches to combine CCs
  - Intra-band Contiguous: carriers adjacent to each other
  - Intra-band noncontiguous: Multiple CCs belonging to the same band are used in a noncontiguous manner
  - Inter-band noncontiguous: Use different bands



(a) Logical view of carrier aggregation

(b) Types of carrier aggregation

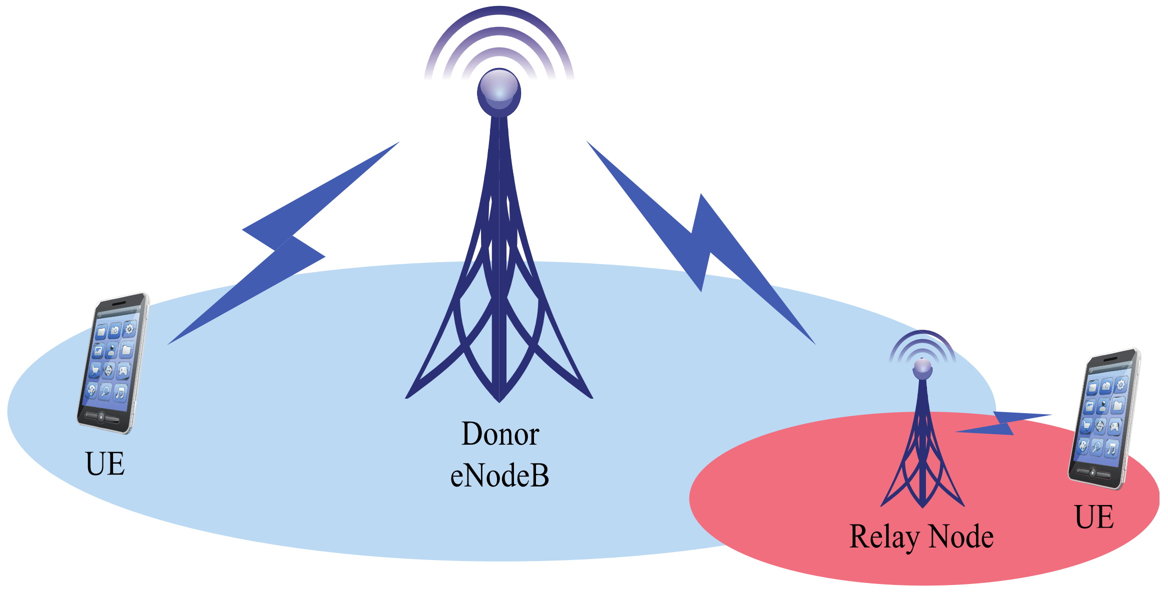
14.14 Carrier Aggregation

Enhanced MIMO

- Expanded to 8 × 8 for 8 parallel layers
- Or multi-user MIMO can allow up to 4 mobiles to receive signals simultaneously
  - eNodeB can switch between single user and multi-user every subframe
- Downlink reference signals to measure channels are key to MIMO functionality
  - UEs recommend MIMO, precoding, modulation, and coding schemes
  - Reference signals sent on dynamically assigned subframes and resource blocks

Relaying

- Relay nodes (RNs) extend the coverage area of an eNodeB
  - Receive, demodulate and decode the data from a UE
  - Apply error correction as needed
  - Then transmit a new signal to the base station
- An RN functions as a new base station with smaller cell radius
- RNs can use out-of-band or inband frequencies



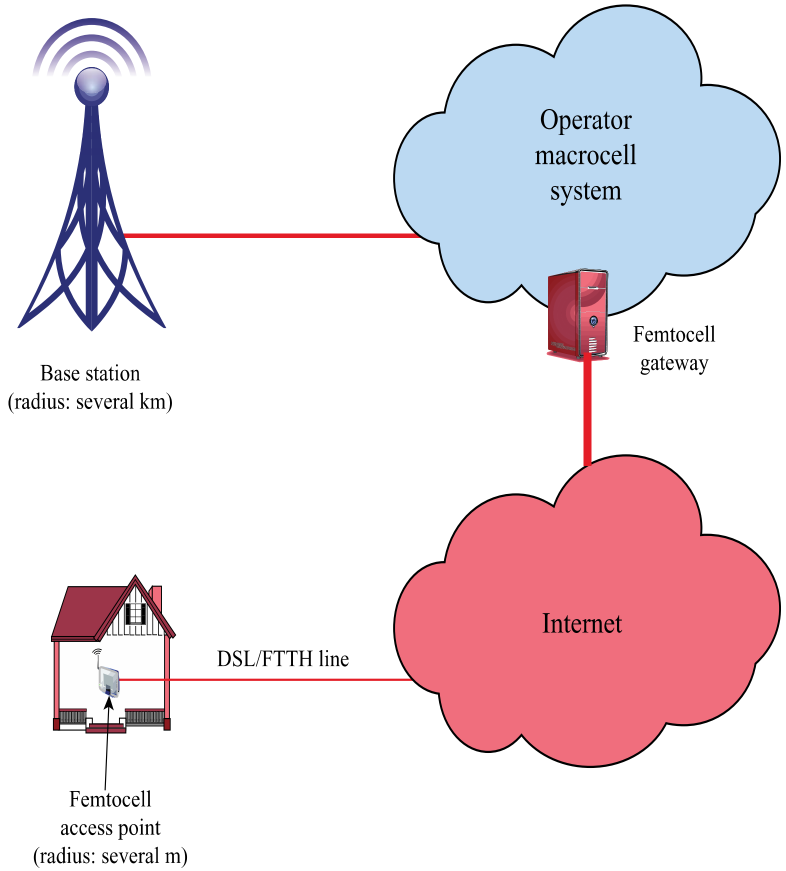
14.15 Relay Nodes

Heterogeneous networks

- It is increasingly difficult to meet data transmission demands in densely populated areas
- *Small cells* provide low-powered access nodes
  - Operate in licensed or unlicensed spectrum
  - Range of 10 m to several hundred meters indoors or outdoors
  - Best for low speed or stationary users
- *Macro cells* provide typical cellular coverage
  - Range of several kilometers
  - Best for highly mobile users

Heterogeneous networks

- Femtocell
  - Low-power, short-range self-contained base station
  - In residential homes, easily deployed and use the home's broadband for backhaul
  - Also in enterprise or metropolitan locations
- *Network densification* is the process of using small cells
  - Issues: Handovers, frequency reuse, QoS, security
- A network of large and small cells is called a *heterogeneous network* (*HetNet*)



14.16 The Role of Femtocells

Coordinated Multipoint Transmission and Reception

- Release 8 provides intercell interference coordination (ICIC)
  - Small cells create new interference problems
  - Release 10 provides enhanced ICIC to manage this interference
- Release 11 implemented Coordinated Multipoint Transmission and Reception (CoMP)
  - To control scheduling across distributed antennas and cells
  - *Coordinated scheduling/coordinated beamforming* (CS/CB) steers antenna beam nulls and mainlobes
  - *Joint processing* (JT) transmits data simultaneously from multiple transmission points to the same UE
  - *Dynamic point selection* (DPS) transmits from multiple transmission points but only one at a time

Voice over LTE

- The GSM Association is the cellular industry's main trade association
  - GSM Association documents provide additional specifications for issues that 3GPP specifications left as implementation options.
- Defined profiles and services for Voice over LTE (VoLTE)
- Uses the IP Multimedia Subsystem (IMS) to control delivery of voice over IP streams
  - IMS is not part of LTE, but a separate network
  - IMS is mainly concerned with signaling.
- The GSM Association also specifies services beyond voice, such as video calls, instant messaging, chat, and file transfer in what is known as the Rich Communication Services (RCS).

5G

- **5G** is the fifth generation cellular network technology. The industry association 3GPP defines any system using "5G NR" (5G New Radio) software as "5G", a definition that came into general use by late 2018. Others may reserve the term for systems that meet the requirements of the ITU IMT-2020. 3GPP will submit their 5G NR to the ITU. It follows 2G, 3G and 4G and their respective associated technologies (such as GSM, UMTS, LTE, LTE Advanced Pro and others).

5G cont.

- 5G networks are digital cellular networks, in which the service area covered by providers is divided into small geographical areas called *cells*. Analog signals representing sounds and images are digitized in the phone, converted by an analog to digital converter and transmitted as a stream of bits. All the 5G wireless devices in a cell communicate by radio waves with a local antenna array and low power automated transceiver (transmitter and receiver) in the cell, over frequency channels assigned by the transceiver from a pool of frequencies which are reused in other cells. The local antennas are connected with the telephone network and the Internet by a high bandwidth optical fiber or wireless backhaul connection. As in other cell networks, a mobile device crossing from one cell to another is automatically "handed off" seamlessly to the new cell.

5G cont.

- There are plans to use millimeter waves for 5G. Millimeter waves have shorter range than microwaves, therefore the cells are limited to smaller size; The waves also have trouble passing through building walls. Millimeter wave antennas are smaller than the large antennas used in previous cellular networks. They are only a few inches (several centimeters) long. Another technique used for increasing the data rate is massive MIMO (multiple-input multiple-output). Each cell will have multiple antennas communicating with the wireless device, received by multiple antennas in the device, thus multiple bit streams of data will be transmitted simultaneously, in parallel. In a technique called *beam forming* the base station computer will continuously calculate the best route for radio waves to reach each wireless device, and will organize multiple antennas to work together as phased arrays to create beams of millimeter waves to reach the device.

5G cont.

- The new 5G wireless devices also have 4G LTE capability, as the new networks use 4G for initially establishing the connection with the cell, as well as in locations where 5G access is not available.
- 5G can support up to a million devices per square kilometer, while 4G supports only up to 100,000 devices per square kilometer

Speed

- 5G NR speed in sub-6 GHz bands can be slightly higher than the 4G with a similar amount of spectrum and antennas, though some 3GPP 5G networks will be slower than some advanced 4G networks, such as T-Mobile's LTE/LAA network, which achieves 500+ Mbit/s in Manhattan and Chicago. The 5G specification allows LAA (License Assisted Access) as well but LAA in 5G has not yet been demonstrated. Adding LAA to an existing 4G configuration can add hundreds of megabits per second to the speed, but this is an extension of 4G, not a new part of the 5G standard

Latency

- In 5G, the "air latency" target is 1–4 milliseconds, although the equipment shipping in 2019 has tested air latency of 8–12 milliseconds. The latency to the server must be added to the "air latency." Verizon reports the latency on its 5G early deployment is 30 ms

- Initially, the term was associated with the International Telecommunication Union's IMT-2020 standard, which required a theoretical peak download speed of 20 gigabits per second and 10 gigabits per second upload speed, along with other requirements. Then, the industry standards group 3GPP chose the 5G NR (New Radio) standard together with LTE as their proposal for submission to the IMT-2020 standard

- The first phase of 3GPP 5G specifications in Release-15 is scheduled to complete in 2019. The second phase in Release-16 is due to be completed in 2020.
- 5G NR can include lower frequencies (FR1), below 6 GHz, and higher frequencies (FR2), above 24 GHz. However, the speed and latency in early FR1 deployments, using 5G NR software on 4G hardware (non-standalone), are only slightly better than new 4G systems, estimated at 15 to 50% better

New radio frequencies

- The air interface defined by 3GPP for 5G is known as New Radio (NR), and the specification is subdivided into two frequency bands, FR1 (below 6 GHz) and FR2 (mmWave), each with different capabilities

Frequency range 1 (< 6 GHz)

- The maximum channel bandwidth defined for FR1 is 100 MHz, due to the scarcity of continuous spectrum in this crowded frequency range. The band most widely being used for 5G in this range is around 3.5 GHz. The Korean carriers are using 3.5 GHz although some millimeter wave spectrum has also been allocated.

Frequency range 2 (> 24 GHz)

- The minimum channel bandwidth defined for FR2 is 50 MHz and the maximum is 400 MHz, with two-channel aggregation supported in 3GPP Release 15. In the U.S., Verizon is using 28 GHz and AT&T is using 39 GHz. 5G can use frequencies of up to 300 GHz. The higher the frequency, the greater the ability to support high data transfer speeds without interfering with other wireless signals or becoming overly cluttered. Due to this, 5G can support approximately 1,000 more devices per meter than 4G

FR2 coverage

- 5G in the 24 GHz range or above use higher frequencies than 4G, and as a result, some 5G signals are not capable of traveling large distances (over a few hundred meters), unlike 4G or lower frequency 5G signals (sub 6 GHz). This requires placing 5G base stations every few hundred meters in order to utilize higher frequency bands. Also, these higher frequency 5G signals cannot easily penetrate solid objects, like cars, trees and walls, because of the nature of these higher frequency electromagnetic waves

Massive MIMO

- Massive MIMO (multiple input and multiple output) antennas increases sector throughput and capacity density using large numbers of antennas and Multi-user MIMO (MU-MIMO). Each antenna is individually-controlled and may embed radio transceiver components. Nokia claimed a five-fold increase in the capacity increase for a 64-Tx/64-Rx antenna system. The term "massive MIMO" was coined by Nokia Bell Labs researcher Dr. Thomas L. Marzetta in 2010, and has been launched in 4G networks, such as Softbank in Japan

Small cell

- Small cells are low-powered cellular radio access nodes that operate in licensed and unlicensed spectrum that have a range of 10 meters to a few kilometers. Small cells are critical to 5G networks, as 5G's radio waves can't travel long distances, because of 5G's higher frequencies.

Beamforming

- Beamforming, as the name suggests, is used to direct radio waves to a target. This is achieved by combining elements in an antenna array in such a way that signals at particular angles experience constructive interference while others experience destructive interference. This improves signal quality and data transfer speeds. 5G uses beamforming due to the improved signal quality it provides. Beamforming can be accomplished using Phased array antennas.

Wifi-cellular convergence

- One expected benefit of the transition to 5G is the convergence of multiple networking functions to achieve cost, power and complexity reductions. LTE has targeted convergence with Wi-Fi band/technology via various efforts, such as License Assisted Access (LAA; 5G signal in unlicensed frequency bands that are also used by Wi-Fi) and LTE-WLAN Aggregation (LWA; convergence with Wi-Fi Radio), but the differing capabilities of cellular and Wi-Fi have limited the scope of convergence. However, significant improvement in cellular performance specifications in 5G, combined with migration from Distributed Radio Access Network (D-RAN) to Cloud- or Centralized-RAN (C-RAN) and rollout of cellular small cells can potentially narrow the gap between Wi-Fi and cellular networks in dense and indoor deployments. Radio convergence could result in sharing ranging from the aggregation of cellular and Wi-Fi channels to the use of a single silicon device for multiple radio access technologies

- On 3 April 2019, South Korea became the first country to adopt 5G. Just hours later, Verizon launched its 5G services in the United States, and disputed South Korea's claim of becoming the world's first country with a 5G network, because allegedly, South Korea's 5G service was initially launched for just 6 South Korean celebrities so that South Korea could claim the title of having the world's first 5G network.In fact, the three main South Korean telecommunication companies (SK Telecom, KT and LG Uplus) added more than 40,000 users to their 5G network on the launch day

Mobile applications and mobile IP

Importance of apps

- Apps have driven major developments in networking
  - Not just wireless communication and networks
- Variety of platforms
- Free or low cost applications
  - Mobile computing on small devices made easy
- Make use of the many sensors on mobile devices
  - Location, light, acceleration, magnetic field, etc.

Mobile application platforms

- Mobile operating systems are quite similar to desktop counterparts
  - Memory management, process scheduling, device drivers, security
- Many derive source and systems principles from previous systems
  - For example, Android from Linux

Mobile application platforms

- Environments dictate very different needs
  - Limited computing power and battery life
  - Different interaction styles – touch or voice commands
  - Most mobile platforms pair a traditional OS with additional abstractions to tailor to the special needs
- Platforms can be extended by third parties with apps
  - Provide ease of programming
  - Ensure a unified user interface across apps
  - Maintain security

Resource constraints

- Limited RAM, processing, and storage
  - So they can interface with remote cloud services
- Examples
  - Social networking, banking, chat platforms
  - Use location sensors to determine a user's location
    - Remote computation determines restaurants that are nearby and displays results in appealing ways

Interaction Layer

- Much different user interface than traditional computers
  - Instead of using a mouse and keyboard
  - Use touch or voice input
  - Gestures
  - Special features for users who are visually or otherwise impaired

Two example hardware stacks

- Apple's iOS (iPhone/iPad) and Google's Android
  - Same principles apply to other platforms
- iOS runs on a limited set of devices
  - Developers can be certain about device characteristics
  - Applications are written in Objective C and Swift
    - Compiled using Apple's compiler
    - Use libraries

Two example hardware stacks

- Google's Android may be installed on a wide range of devices
  - Range of hardware configurations is much larger
  - Google Play does enforce some restrictions, but ultimately the set of configurations is large
  - Device manufacturers compile a unique version of Android called a ROM
    - "ROM" here means firmware/OS and system apps
- Android and iOS have similar programming design
  - Based on a core operating system which handles apps, coordinates resources, and manages core concerns such as security.

Mobile App Development

- Typically happens in the same languages as desktops
  - Java for Android, Objective C for iOS
  - Mobile specific features use application programming interfaces (APIs) for access to:
    - GUI interaction
    - Sensor data
    - Authentication and account access
    - Interaction with remote servers

Mobile App Development

- Apps can be highly context aware
  - Much more than a mobile web site
- Mobile platforms provide custom toolchains to run code on a device
  - For example, Android takes Java bytecode and translates it to Dalvik virtual machine code
    - Dalvik is a virtual machine for Android
  - iOS uses the LLVM cross compiler

A look inside Android

- Started by Android, Inc., acquired by Google in 2005
- Open Handset Alliance (OHA)
  - Consortium of over 80 firms to develop open standards for mobile devices
  - OHA is responsible for Android OS releases
- Open-source nature of Android has been key to its success

Mobile IP Uses

- Enable computers to maintain Internet connectivity while moving from one Internet attachment point to another
- Mobile – user's point of attachment changes dynamically and all connections are automatically maintained despite the change
- Nomadic - user's Internet connection is terminated each time the user moves and a new connection is initiated when the user dials back in
  - New, temporary IP address is assigned

Long range communications

- Rich History
- Satellite
  - Communications
  - GPS
  - Television
- Fixed broadband wireless
  - Point-to-point communication
  - Over long distances
  - Recent example: Smart grid

Satellite-Related Terms

- Earth Stations – antenna systems on or near earth
- Uplink – transmission from an earth station to a satellite
- Downlink – transmission from a satellite to an earth station
- Transponder – electronics in the satellite that convert uplink signals to downlink signals

Ways to Categorize Communications Satellites

- Coverage area
  - Global, regional, national
- Service type
  - Fixed service satellite (FSS)
  - Broadcast service satellite (BSS)
  - Mobile service satellite (MSS)
- General usage
  - Commercial, military, amateur, experimental

Classification of Satellite Orbits

- Circular or elliptical orbit
  - Circular with center at earth's center
  - Elliptical with one foci at earth's center
- Orbit around earth in different planes
  - Equatorial orbit above earth's equator
  - Polar orbit passes over both poles
  - Other orbits referred to as inclined orbits
- Altitude of satellites
  - Geostationary orbit (GEO)
  - Medium earth orbit (MEO)
  - Low earth orbit (LEO)

Geometry Terms

- Elevation angle - the angle from the horizontal to the point on the center of the main beam of the antenna when the antenna is pointed directly at the satellite
- Minimum elevation angle
- Coverage angle - the measure of the portion of the earth's surface visible to the satellite

Minimum Elevation Angle

- Reasons affecting minimum elevation angle of earth station's antenna (>0^o)
  - Buildings, trees, and other terrestrial objects block the line of sight
  - Atmospheric attenuation is greater at low elevation angles
  - Electrical noise generated by the earth's heat near its surface adversely affects reception

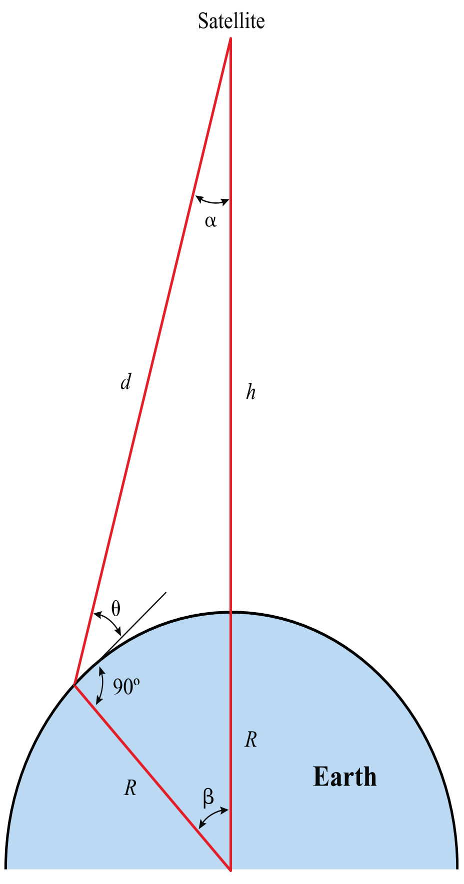


Figure 16.1 Coverage and Elevation Angles

GEO Orbit

- Advantages of the the GEO orbit
  - No problem with frequency changes
  - Tracking of the satellite is simplified
  - High coverage area
- Disadvantages of the GEO orbit
  - Weak signal after traveling over 35,000 km
  - Polar regions are poorly served
  - Signal sending delay is substantial

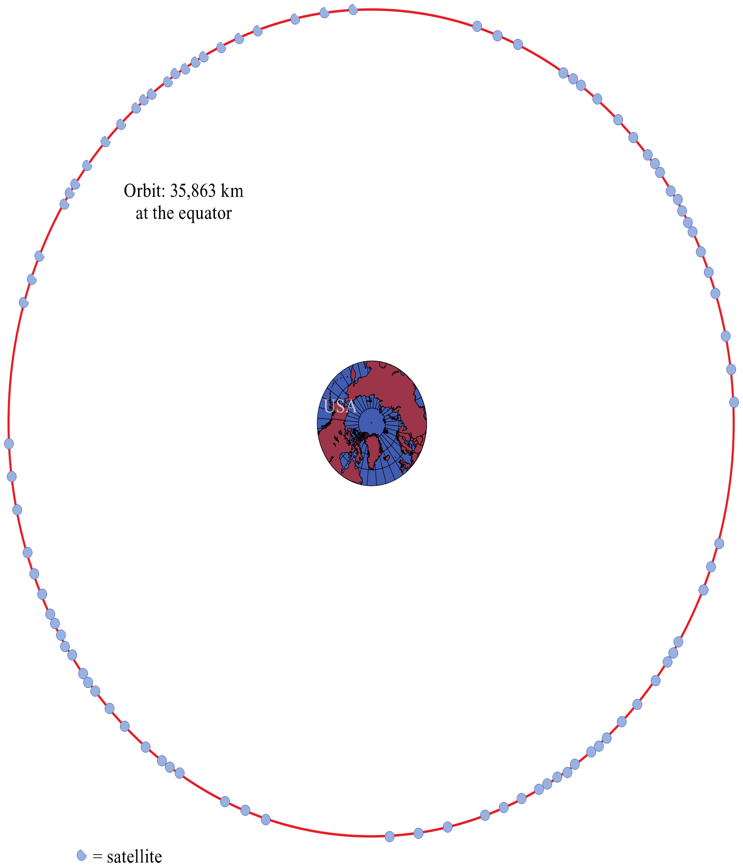


Figure 16.3 Geostationary Earth Orbit (GEO)

LEO Satellite Characteristics

- Circular/slightly elliptical orbit under 2000 km
- Orbit period ranges from 1.5 to 2 hours
- Diameter of coverage is about 8000 km
- Round-trip signal propagation delay less than 20 ms
- Maximum satellite visible time up to 20 min
- System must cope with large Doppler shifts
- Atmospheric drag results in orbital deterioration

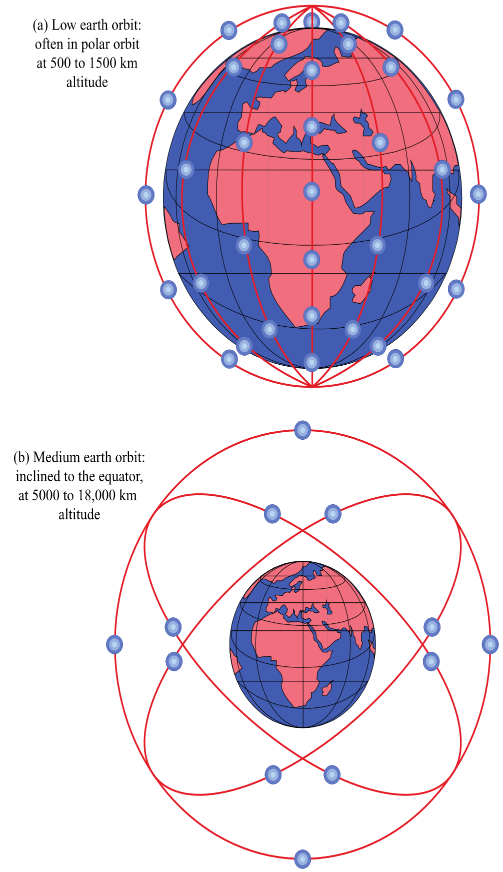


Figure 16.4 LEO and MEO Orbits

LEO Categories

- Little LEOs
  - Frequencies below 1 GHz
  - 5MHz of bandwidth
  - Data rates up to 10 kbps
  - Aimed at paging, tracking, and low-rate messaging
- Big LEOs
  - Frequencies above 1 GHz
  - Support data rates up to a few megabits per sec
  - Offer same services as little LEOs in addition to voice and positioning services

MEO Satellite Characteristics

- Circular orbit at an altitude in the range of 5000 to 12,000 km
- Orbit period of 6 hours
- Diameter of coverage is 10,000 to 15,000 km
- Round trip signal propagation delay less than 50 ms
- Maximum satellite visible time is a few hours

Satellite Link Performance Factors

- Distance between earth station antenna and satellite antenna
- For downlink, terrestrial distance between earth station antenna and “aim point” of satellite
  - Displayed as a satellite footprint
- Atmospheric attenuation
  - Affected by oxygen, water, angle of elevation, and higher frequencies

Capacity Allocation Strategies

- Frequency division multiple access (FDMA)
- Time division multiple access (TDMA)
- Code division multiple access (CDMA)

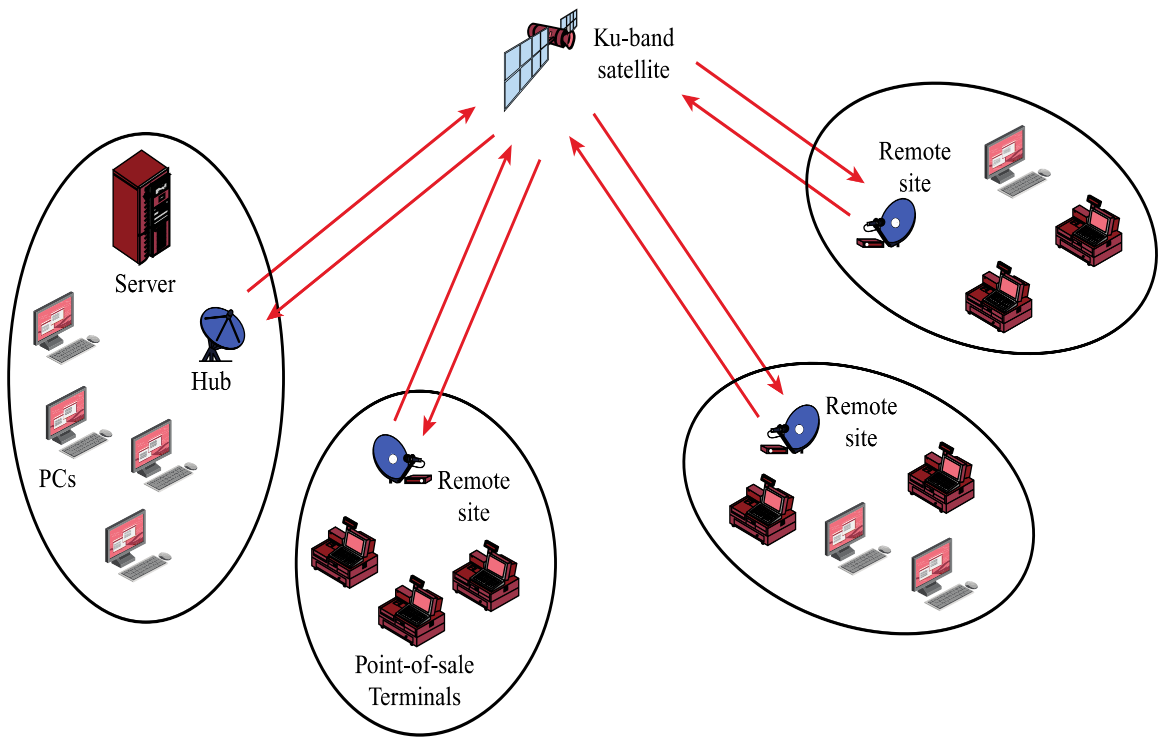


Figure 16.9 Typical VSAT Configuration

Frequency-Division Multiplexing

- Alternative uses of channels in point-to-point configuration
  - 1200 voice-frequency (VF) voice channels
  - One 50-Mbps data stream
  - 16 channels of 1.544 Mbps each
  - 400 channels of 64 kbps each
  - 600 channels of 40 kbps each
  - One analog video signal
  - Six to nine digital video signals

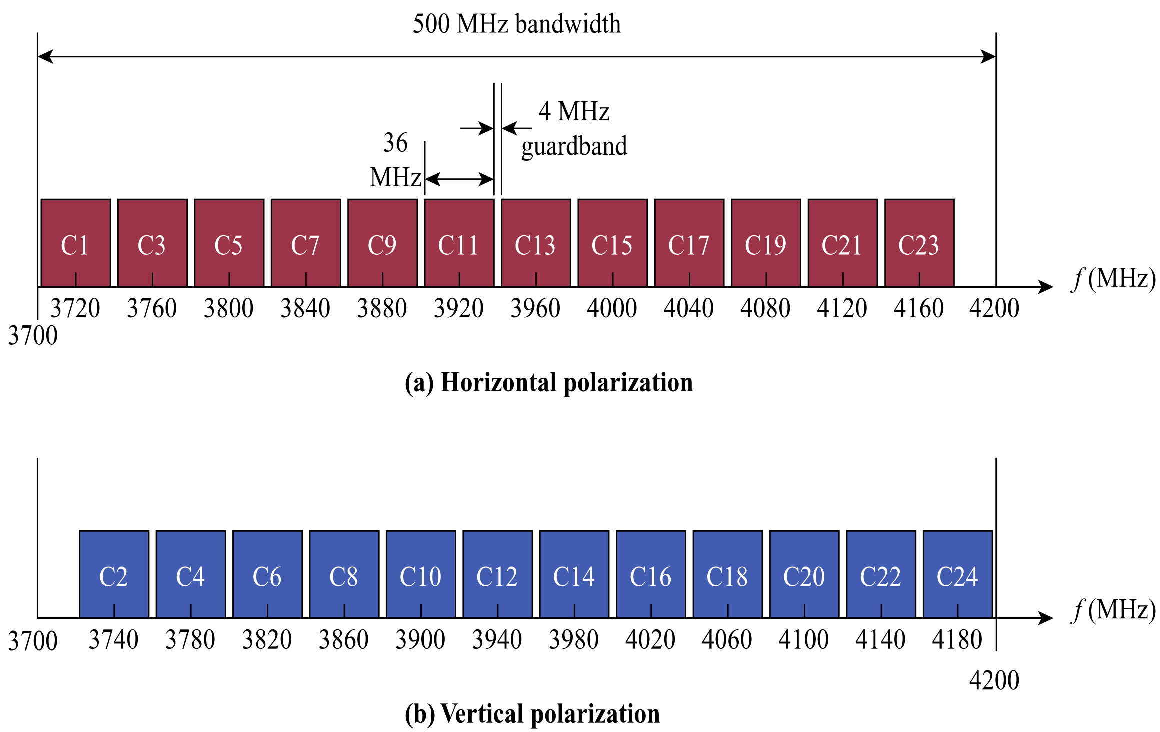


Figure 16.10 Typical Satellite Transponder Frequency Plan for the Downlink Channels

Frequency-Division Multiple Access

- Factors which limit the number of subchannels provided within a satellite channel via FDMA
  - Thermal noise
  - Intermodulation noise
  - Crosstalk

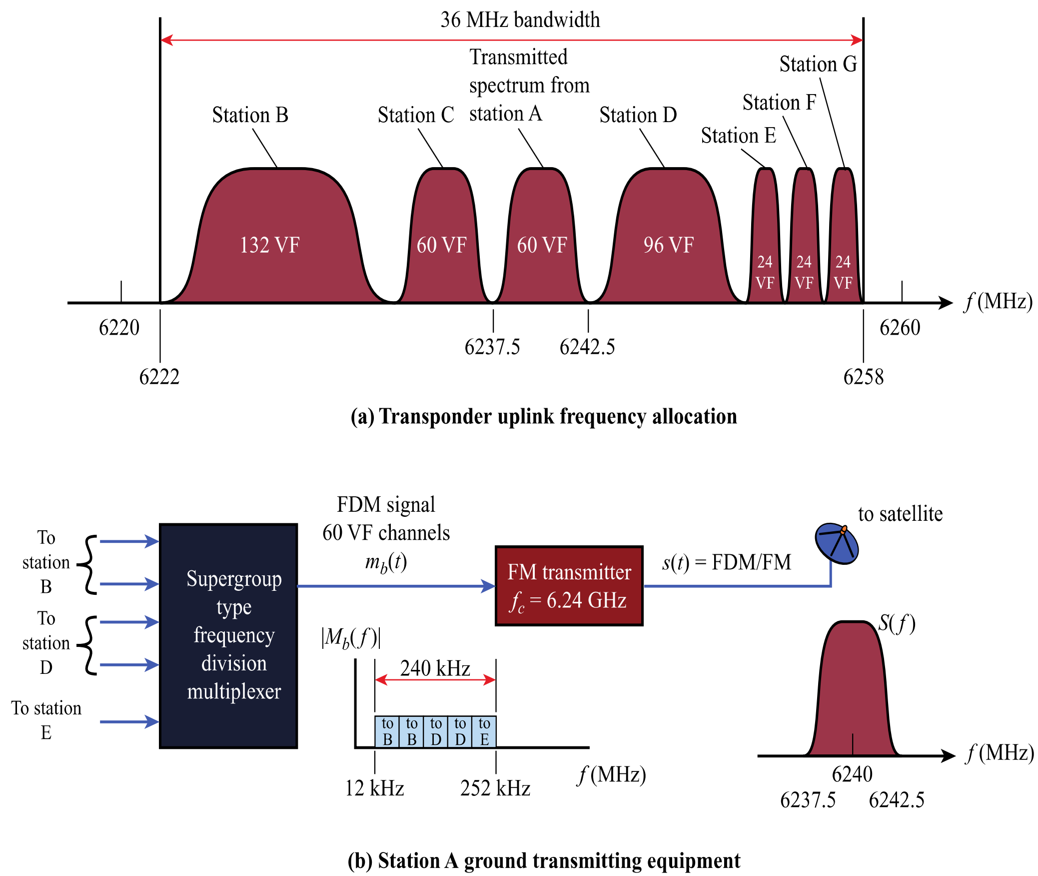


Figure 16.11 Fixed-Assignment FDMA Format for Satellite Communication

Forms of FDMA

- Fixed-assignment multiple access (FAMA)
  - The assignment of capacity is distributed in a fixed manner among multiple stations
  - Demand may fluctuate
  - Results in the significant underuse of capacity
- Demand-assignment multiple access (DAMA)
  - Capacity assignment is changed as needed to respond optimally to demand changes among the multiple stations

Reasons for Increasing Use of TDM Techniques

- Cost of digital components continues to drop
- Advantages of digital components
  - Use of error correction
- Increased efficiency of TDM
  - Lack of intermodulation noise

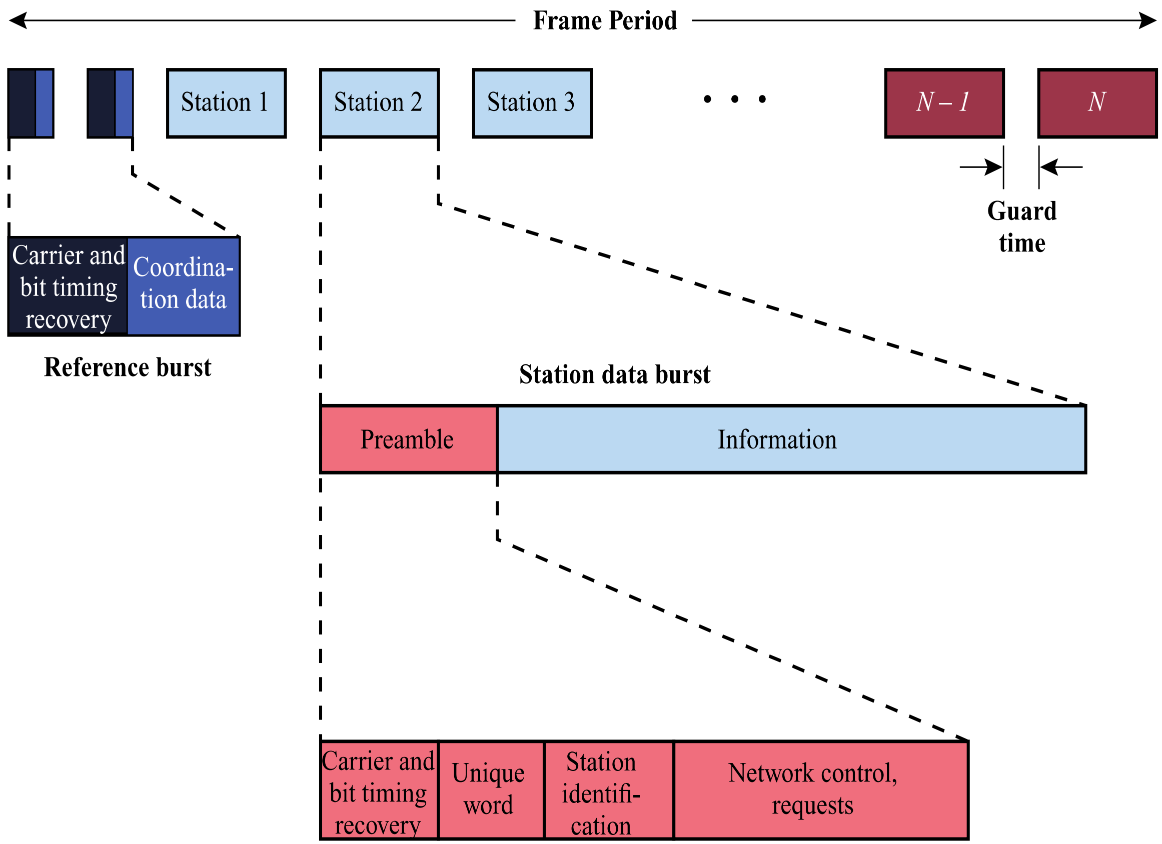


Figure 16.12 Example of TDMA Frame Format

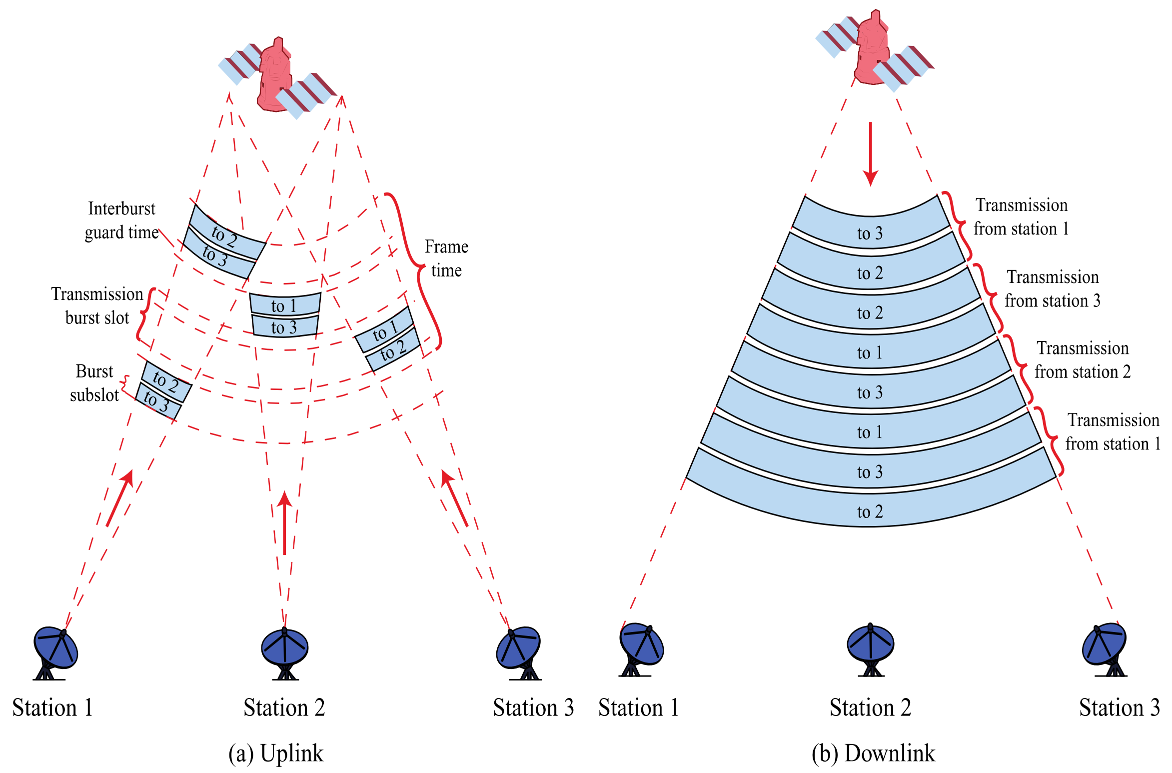


Figure 16.13 TDMA Operation

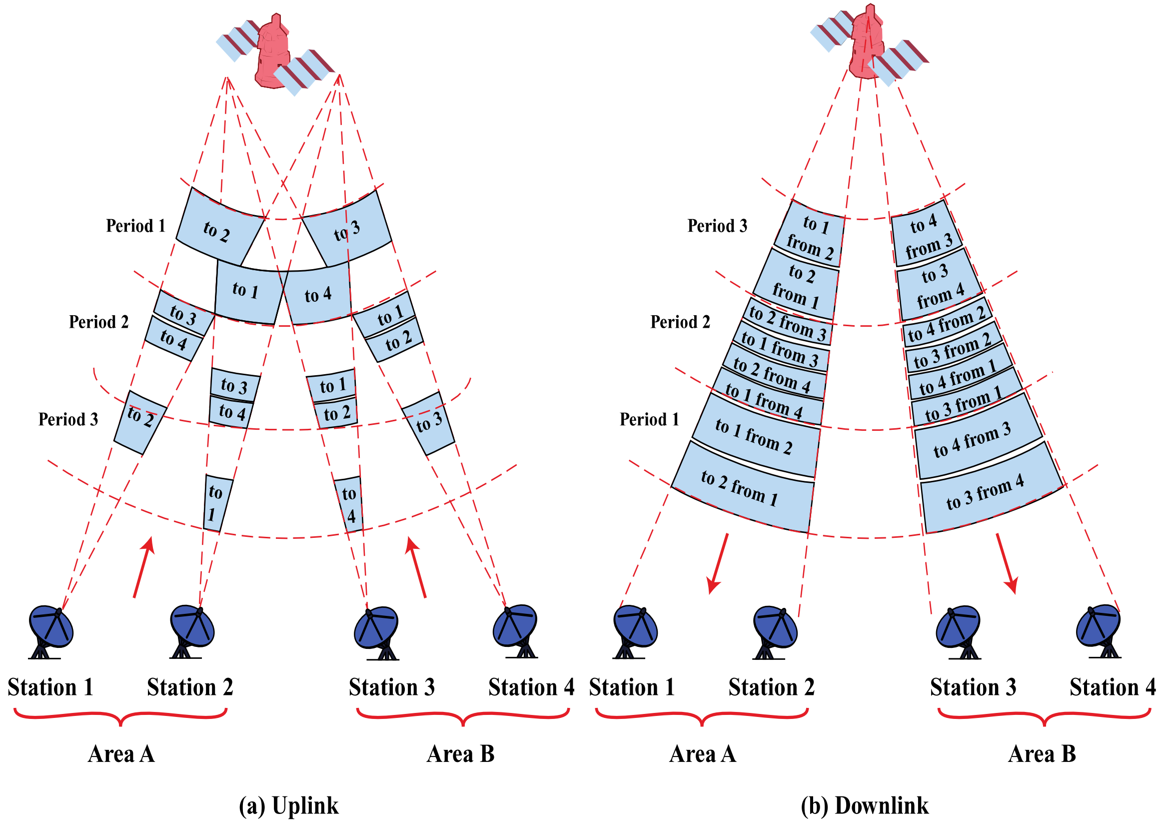


Figure 16.15 SS/TDMA Operation

Global positioning system

- GPS was developed by U.S. Department of Defense
- 24 MEO satellites
  - Six orbital planes at 20,350 km altitude
  - Orbit every 12 hours
- GPS receiver must observe at least 4 satellites
  - Three provide distance measurement
  - Intersection of three spheres provides two points of intersection, one of which is unrealistic
  - Fourth satellite is used to adjust timing offsets

Global positioning system

- Uses Direct Sequence Spread Spectrum
  - Can keep from unauthorized use
    - Until 2000, GPS signals were intentionally degraded
  - Low received signal energy is required
  - All satellites can use the same frequency band
- Complexities of operation
  - Knowing satellite locations
  - Atmospheric effects
  - Differential GPS can provide more accuracy if a terrestrial reference point is also known

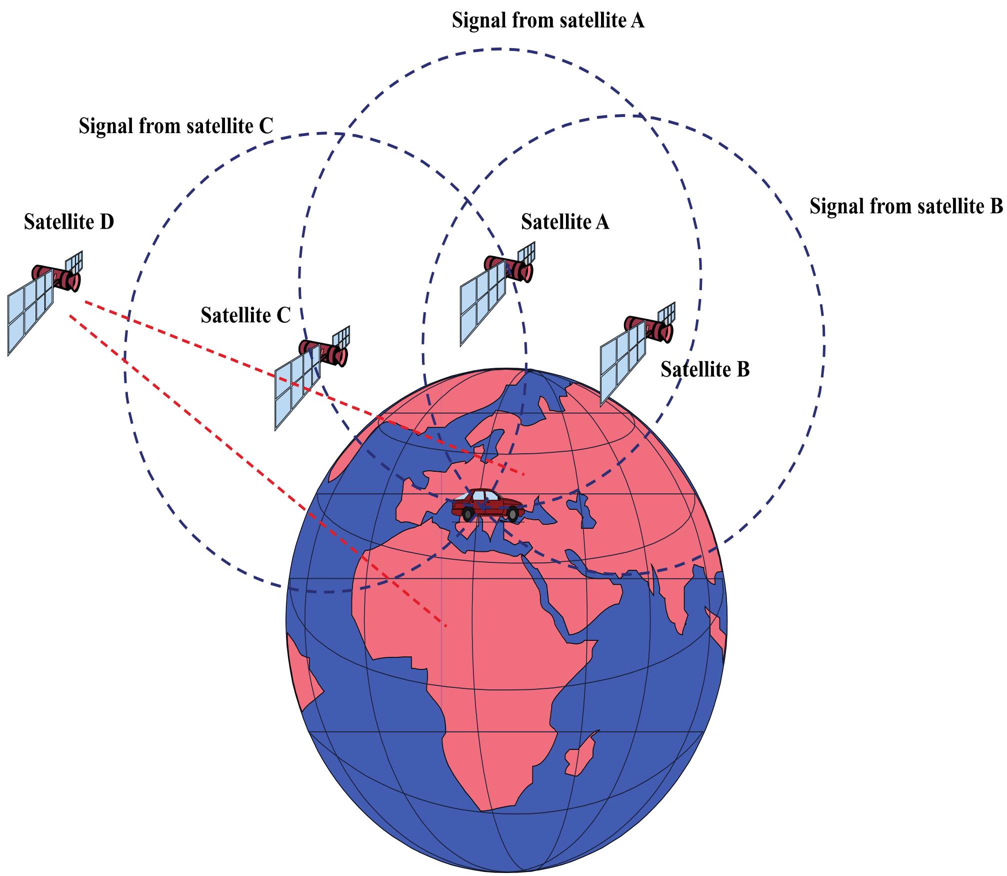


Figure 16.16 Global Positioning System

IEEE 802.16/WiMAX Standards Development

- Started in 1999
- Use wireless links with microwave or millimeter wave radios
- Use licensed spectrum
- Create wireless metropolitan area networks (WMANs)
- Provide public network service to fee-paying customers
- Use point-to-multipoint architecture with stationary rooftop or tower-mounted antennas

IEEE 802.16/WiMAX Standards Development

- Provide efficient transport of heterogeneous traffic supporting quality of service (QoS)
- Use wireless links with microwave or millimeter wave radios

- The WiMAX (Worldwide Interoperability for Microwave Access) Forum
  - Industry consortium
  - Formed to promote the 802.16 standards and to develop interoperability specifications

802.16 Physical Layer

- Wireless MAN-SC
  - 10-66 GHz bands
  - Line of sight required
  - TDMA and demand-assignment multiple access
- Wireless MAN-OFDM
  - Below 11 GHz
  - LOS is not necessary
- Wireless MAN-OFDMA
  - Enhanced version of Wireless MAN-OFDM for OFDMA