Welcome!

ELEC 8560 – Computer Networks

Wide Area Networks

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Outline

- Telephone Networks
- Cable Networks
- Cellular Networks
- Satellite Networks

- Recommended reading: Forouzan – Chapter 5
- Extra reading: Kurose and Ross – Chapter 7

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Outline

- Telephone Networks
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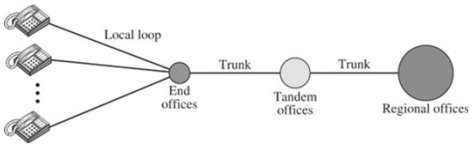
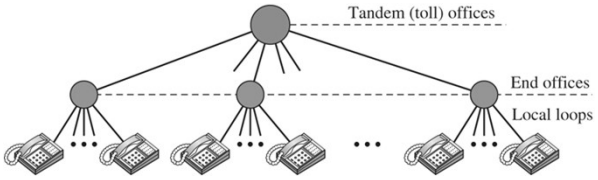
Telephone Networks



- Started analog, now both digital and analog
- Major components:
  - Local loops:
    - twisted-pair cable connects subscriber phone to nearest end office or local central office
    - When used for voice, has a bandwidth of 4 kHz
    - UWindsor phone no.: 519-253-3000 (area code-office number-local loop number)
  - Trunks:
    - transmission media (usually optical fiber) that handle communication between offices
    - handles hundreds or thousands of connections through multiplexing
  - Switching offices: end offices, tandem offices, and regional offices
    - have switches to connect several local loops or trunks
    - allows a connection between different subscribers without needing permanent physical links

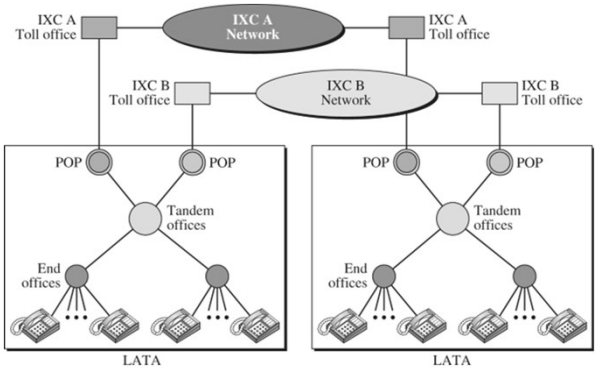
Local-Access Transport Areas (LATAs)

- A country is divided into multiple LATAs
  - For example, USA is divided into more than 245 LATAs
- A LATA can be a small or large metropolitan area
- Services offered by the common carriers (telephone companies) inside a LATA are called intra-LATA services
  - Carrier that handles these services is called a local exchange carrier (LEC)
  - Intra-LATA services can be provided by several LECs



LATAs (cont.)

- Services between LATAs are called inter-LATA services and handled by interexchange carrier (IXC)
- These carriers interact with one another via a switching office called a point of presence (POP)

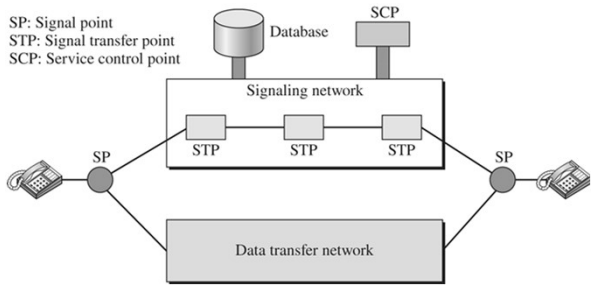


Signaling

- Telephone network, at its beginning, used a circuit-switched network with dedicated links (no multiplexing yet)
  - First, was performed by human operators
  - Later, signaling became automatic
    - Telephones send a digital signal defining telephone number
    - Switches use the digital signals to create a connection between the caller and the called parties
  - Both in-band and out-of-band signaling were used
    - In-band means the same 4 kHz are used for signaling and voice
    - Out-of-band means the 4 kHz is partitioned for voice channel and signaling channel

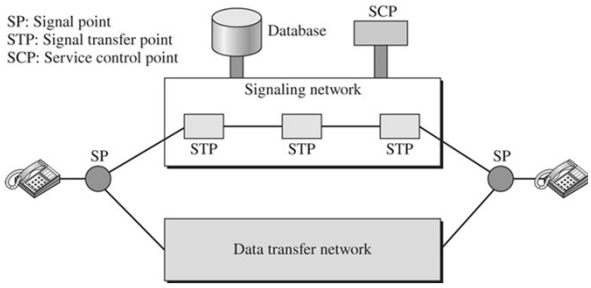
Data Transfer and Signaling Networks

- As telephone networks evolved into a complex network, today's telephone network is split into two networks:
  - Data transfer network:
    - Can carry multimedia information today
    - For the most part, a circuit-switched network, although it can also be a packet-switched
  - Signaling network
    - Packet-switched network involving the layers similar to those in the Internet model



Data Transfer and Signaling Networks (cont.)

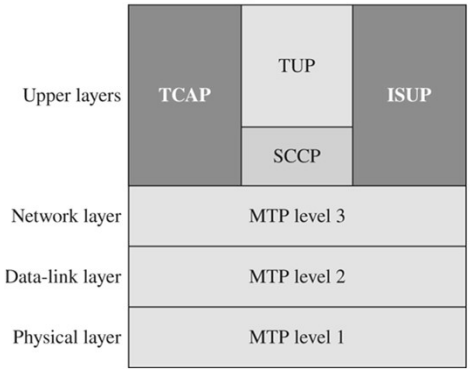
- User phone (or computer) is connected to a signaling point (SP)
  - Link between user and SP is common for both networks
- Signaling network uses nodes called STP that receive and forward signaling messages
- An SCP controls the whole operation



Signaling System Seven (SS7)

- The protocol used in the signaling network
  - Similar to the five-layer Internet model, but layers have different names
- For example,
  - MTP level 1: physical layer specifications
  - MTP level 2: packetization, source and destination addresses in packet header, CRC for error checking, etc.
  - MTP level 3: end-to-end connectivity using datagrams, routers, switches, etc.

MTP: Message transfer part
SCCP: Signaling connection control point
TCAP: Transaction capabilities application port
TUP: Telephone user port
ISUP: ISDN user port

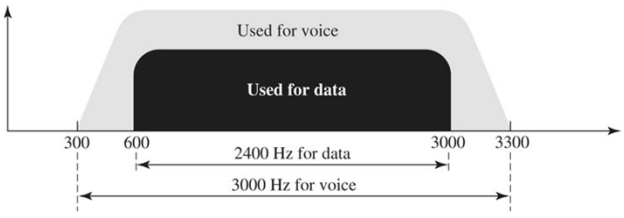


Services Provide by Telephone Networks

- Telephone companies provide two types of services:
  - Analog services:
    - In the beginning, telephone companies provided their subscribers with analog services
    - These services still continue today
    - For example, dial-up calling (called analog switched service)
  - Digital services:
    - Later telephone companies began offering digital services to their subscribers
    - Digital services are less sensitive than analog services to noise and other forms of interference
    - For example, dial-up internet (called switched/56 service)

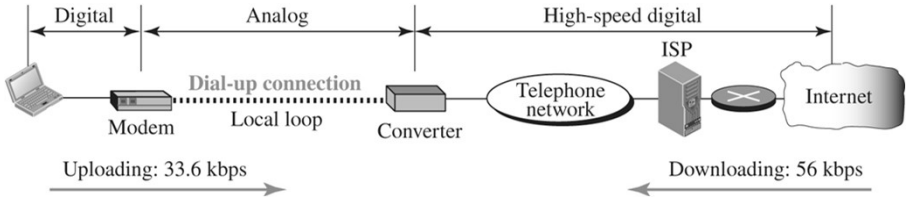
Dial-Up Service

- Traditional telephone lines can carry frequencies between 300 and 3300 Hz, i.e., a bandwidth of 3000 Hz
  - This range is used for transmitting voice
  - Voice signals can handle a great deal of interference and distortion without loss of intelligibility in this range
  - Data signals require a higher degree of accuracy to ensure integrity, hence range is reduced to 600 – 3000 Hz



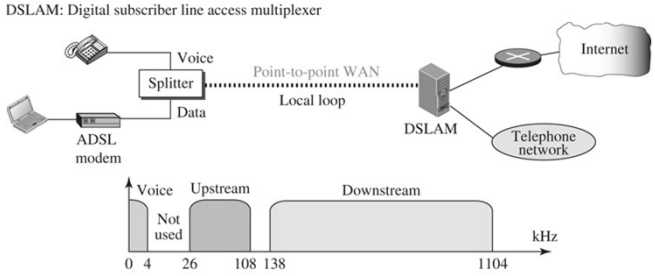
Example: Dial-up Network to Provide Internet Services

- A modem is used to perform analog-to-digital and digital-to-analog conversion at sender and receiver, respectively, e.g., 56K modems



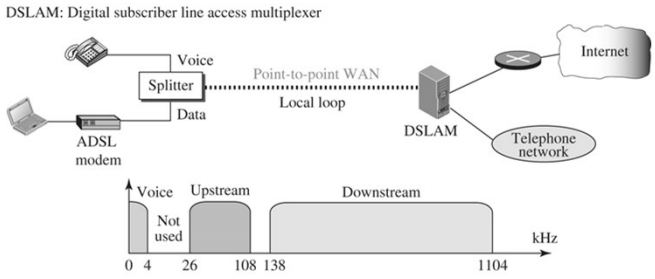
Digital Subscriber Line (DSL)

- Traditional modems reached their peak data rate (e.g., 56 kbps)
- DSL technology is developed to provide higher-speed access to the Internet over existing telephone network
  - Twisted-pair cables in telephone lines can handle bandwidths up to 1.1 MHz
  - Filters installed at end offices limits the bandwidth to 4 kHz
  - DSL removes the filter and use the entire bandwidth up to 1.104 MHz
  - Notice the splitter and modem at the user and DSLAM at the ISP



Example: Asymmetric DSL (ADSL)

- Provides higher data rates in the downstream compared to upstream direction
- Theoretical data rates are up to 13.4 Mbps downstream and 1.44 Mbps upstream
  - Usually below 8 Mbps and 500 kbps due to noise



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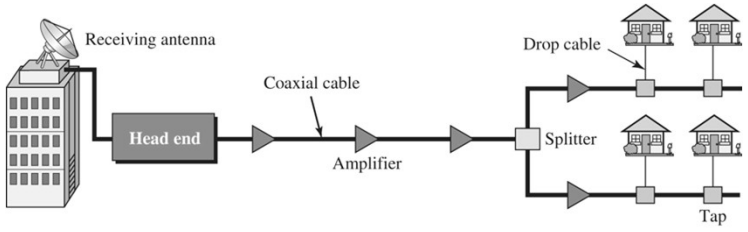
Cable Network

- Cable networks were originally created to provide access to TV for subscribers with no wireless reception
- Later, cable networks became popular with people who just wanted a better signal
- Eventually, cable networks were used to provide internet access

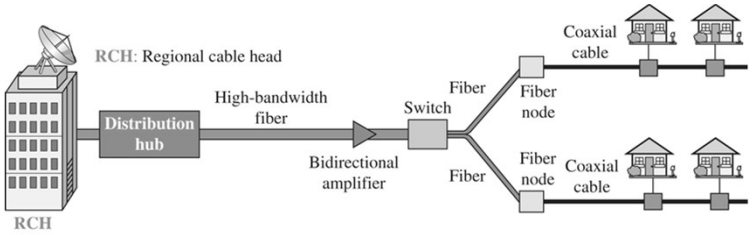
Traditional Cable Network

- Cable TV started to distribute broadcast video signals to locations with poor or no reception in the late 1940s
- It was called community antenna TV (CATV):
  - An antenna at the top of a tall hill or building received the signals from the TV stations and distributed them, via coaxial cables, to the community
  - Amplifiers are installed to renew weak signals
  - Unidirectional



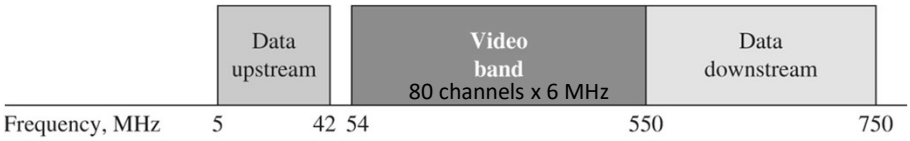
Hybrid Fiber-Coaxial (HFC) Network

- The second generation of cable networks
- Uses a combination of fiber-optic and coaxial cable
  - Transmission medium from the cable TV office to a box, called the fiber node, is optical fiber
  - From the fiber node through the neighborhood and into the house is still coaxial cable
  - Bidirectional



Cable TV for Data Transfer

- Cable companies competing with telephone companies for the residential customer who wants high-speed data transfer
  - DSL technology provides high-data-rate connections for residential subscribers over the local loop
  - However, DSL uses the existing unshielded twisted-pair cable, which is very susceptible to interference
  - Cable TV networks solve this problem by dividing the bandwidth of coaxial cables into three bands

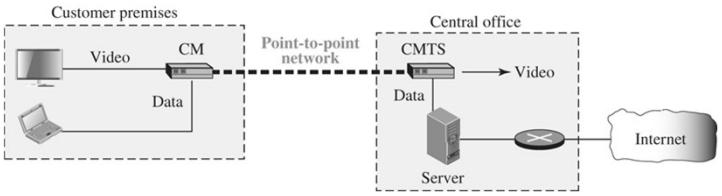


Cable TV for Data Transfer (cont.)

- Both upstream and downstream bands are shared by the subscribers
- The upstream data bandwidth is 37 MHz
  - Only 6 channels of 6 MHz available in the upstream direction (i.e., FDM)
  - Subscribers use time-sharing by dividing the band into channels (i.e., TDM)
  - Channels are shared between subscribers in the same neighborhood
  - Some time slots are assigned, some have contention (i.e., random access)
- The downstream data bandwidth is 200 MHz
  - Only 33 channels of 6MHz available in the downstream direction (i.e., FDM)
  - Multicasting solution is adopted in which each channel is shared by a group of subscribers and data is sent to everyone in the group and modems can keep or discard based on the destination address

CM and CMTS

- To use a cable network for data transmission, we need two key devices:
  - Cable modem (CM):
    - Installed on the subscriber premises
    - Separates video from data
  - Cable modem transmission system (CMTS):
    - Installed inside the cable company
    - Receives data from the Internet and sends them to the subscriber
    - Receives data from the subscriber and passes them to the Internet



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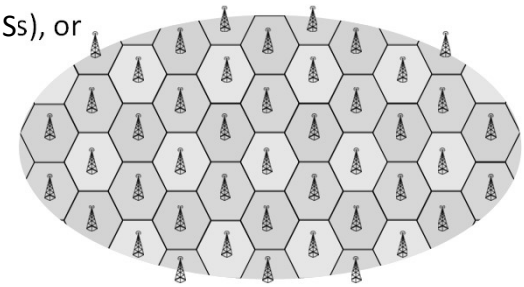
Cellular Networks

- The solution for wide-area mobile Internet
- Widespread use:
  - More mobile-broadband-connected devices than fixed-broadband-connected devices (5-1 in 2019)!
- Provide communications between
  - Two mobile units, called mobile stations (MSs), or
  - One mobile unit and one stationary unit, often called a base station (BS)
- Coverage area of a BS is called a cell
- A service provider must be able to
  - Locate and track a caller
  - Assign a channel to the call
  - Transfer the channel from BS to BS as the caller moves out of range



Cellular Networks (cont.)

Similarities to wired Internet

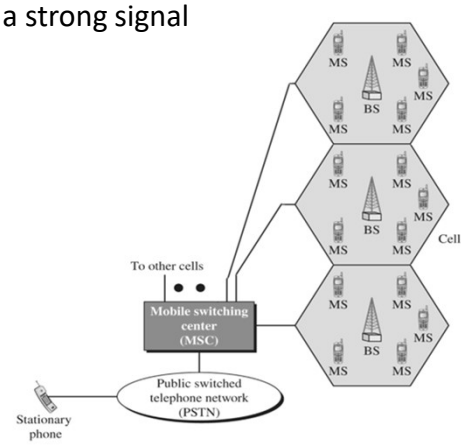
- Edge/Core distinction, but both below to same carrier
- Global cellular network: a network of networks
- Widespread use of protocols we have studied (Ethernet, etc.)
- Interconnected to wired internet

Differences from wired internet

- Different wireless link layer
- Mobility as a 1-st class service
- User identity (via SIM card)
- Business model: users subscribe to a cellular provider
- Strong notion of home network versus roaming on foreign networks
- Global access, with authentication infrastructure, and inter-carrier settlements

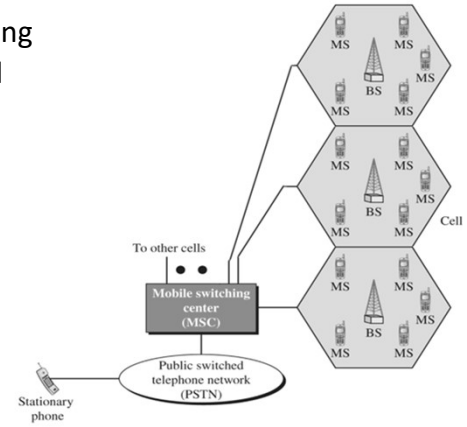
Making a Call

- Transmitting:
  - Caller enters the (7 or 10 digits) phone number and presses call
  - MS scans the band seeking a setup channel with a strong signal
  - MS sends data (phone number) to closest BS
  - BS relays the data to MSC
  - MSC sends the data on to the telephone central office



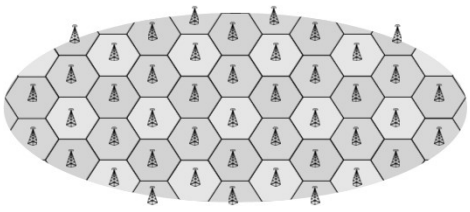
Making a Call (cont.)

- Receiving:
  - Telephone central office sends the number to the MSC
  - MSC searches for the location of MS by sending query signals to each cell in a process called paging
  - Once MS is found, MSC transmits a ringing signal
  - When MS answers, MSC assigns a voice channel to the call and voice communication begins



Frequency Reuse

- In general, neighboring cells cannot use the same set of frequencies for communication → interference
- Issue: set of frequencies available is limited
- Solution:
  - Exploit the fact that power falls off with distance of signal propagation
  - Nearby stations assigned different sets of channels to minimize interference
  - Channel sets can be reused at spatially separated locations
  - Cells with the same channel set are called co-channel cells



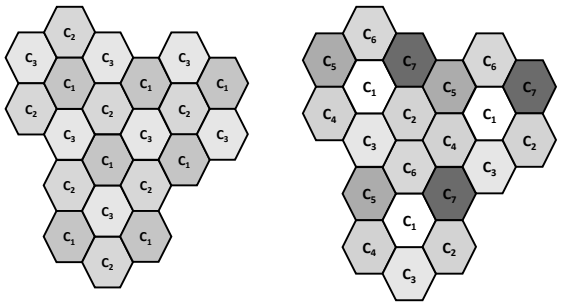
Frequency Reuse (cont.)

- Reuse factor: cluster size of cells the use a unique set of frequencies

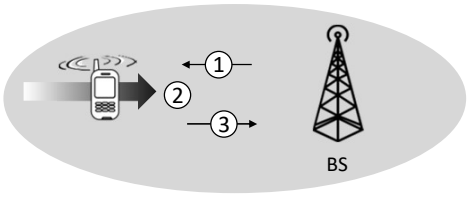
What are the reuse factors in the two cases below?

Solution:

- Reuse factor = 3 (left) and 7 (right)



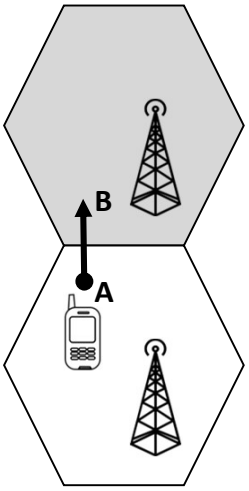
Cell Association



1. BS broadcasts primary synch signal every 5 ms on all frequencies
   - BSs from multiple carriers may be broadcasting synch signals
2. Mobile finds a primary synch signal
   - Mobile then finds info broadcast by BS: channel bandwidth, configurations, BS's cellular carrier info
   - Mobile may get info from multiple BSs, multiple cellular networks
3. Mobile selects which BS to associate with (*e.g.,* preference for home carrier)
4. More steps still needed to authenticate, establish state, set up data plane

Handoff

- In practice, MSs are served by a BS based on signal strength
- Issue: when MS moves from one cell to another, the signal may become weak
- Solution:
  - MSC monitors the level of the signal every few seconds
  - If the strength of the signal falls below a threshold
    - MSC identifies the new base station
    - MSC allocate new voice and control channels associated with the new base station
    - MSC changes the channel carrying the call from current cell to new cell
  - This process of transferring the call is called Handoff



Evolution of Cellular Networks


Wikipedia

- 1G (1970s)
  - Examples: AMPS, NMT, TACS, ETACs
  - Analog circuit switching, FM, FDMA, voice only
  - Poor quality, poor battery life, large mobile phones, not secure, limited number of users
- 2G (1980s-1990s)
  - 64kbps
  - Examples: GSM, CDMA, GPRS
  - Digital circuit switching, voice and data (SMS), encryption
  - Low data rate, limited number of users, low mobility, incompatible standards and bands


Wikipedia

- 3G (2000s)
  - 384 kbps
  - Examples: CDMA2000, UMTS, HSDPA, HSPA+
  - Circuit and packet switching, higher data rate, multimedia, video calling, better security
  - High cost of licenses, infrastructure, and mobile phones

Evolution of Mobile Communication (cont.)

- 4G (2010s)
  - 100 Mbps
  - Examples: LTE-Advanced
  - More bandwidth (broadband internet), packet switching only (All IP), MIMO, low latency (50 ms), reduced cost, high mobility (350 km/h)
- 5G (2020s)
  - 10 Gbps
  - Example: 5G-NR, mmWave
  - Ultra low latency (<1 ms), ultra reliability, mmWave, Massive MIMO, higher mobility (500 km/h), massive connections (1M connections per km^2)

Example: Evolution of Mobile Communication

How long does it take to download a 4.7 GB movie on 3G, 4G, and 5G networks?

Solution:

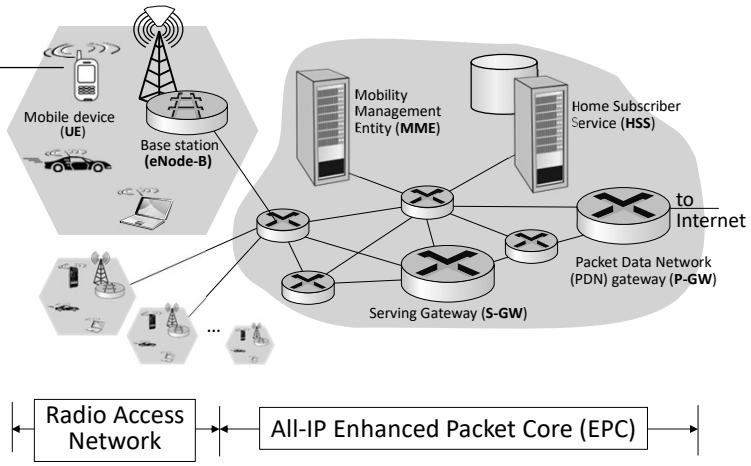
- 3G download time = $4.7 \times 8 \times 10^9$/384 kbps = 27 hr and 12 min
- 4G download time = $4.7 \times 8 \times 10^9$/100 Mbps = 6 min and 16 sec
- 5G download time = $4.7 \times 8 \times 10^9$/10 Gbps = 3.76 sec

Elements of 4G LTE Network Architecture

Mobile device:

- Smartphone, tablet, laptop, IoT, etc. with 4G LTE radio
- 64-bit International Mobile Subscriber Identity (IMSI), stored on SIM (Subscriber Identity Module) card

LTE jargon: User Equipment (UE)

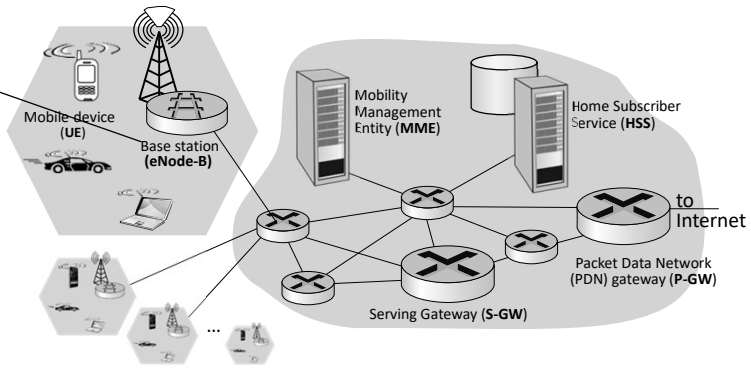


Elements of 4G LTE Network Architecture

Base station:

- At edge of carrier network
- Manages wireless radio resources, mobile devices in its coverage area (i.e., cell)
- Coordinates device authentication with other elements
- Similar to Wi-Fi AP but:
  - Active role in user mobility
  - Coordinates with nearly base stations to optimize radio use

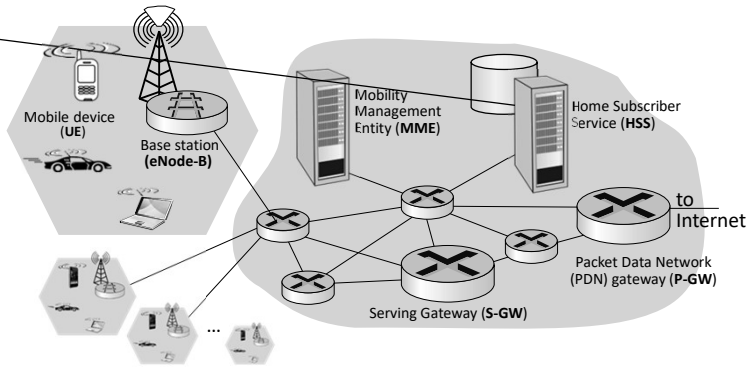
LTE jargon: eNode-B



Elements of 4G LTE Network Architecture

Home Subscriber Service

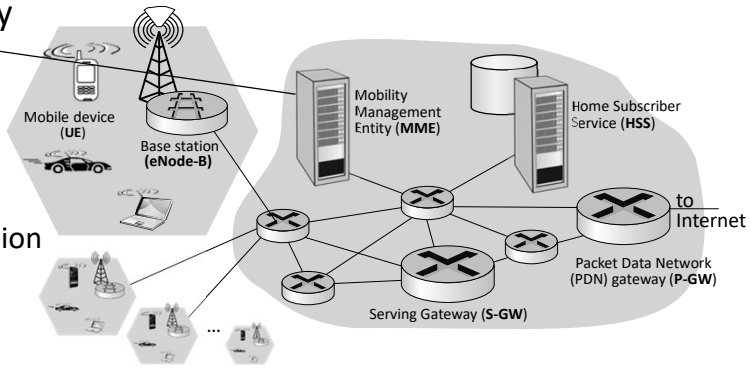
- Acts as database of subscriber information
- Works with MME in device authentication to determine permitted services



Elements of 4G LTE Network Architecture

Mobility Management Entity

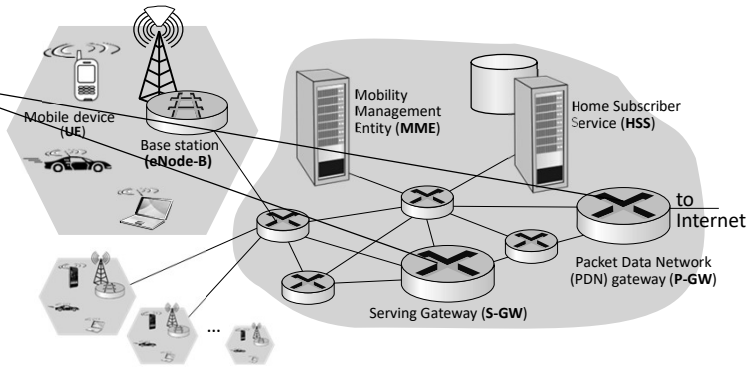
- Device authentication coordinated with HSS
- Mobile device management:
  - Handover between cells
  - Tracking/paging device location
- Path setup from UE to P-GW



Elements of 4G LTE Network Architecture

Serving Gateway (S-GW), PDN Gateway (P-GW)

- Lie on data path from mobile to/from Internet
- P-GW:
  - Provides access to external PDNs (e.g., Internet)
- S-GW:
  - Interface module for signaling between P-GW and MME



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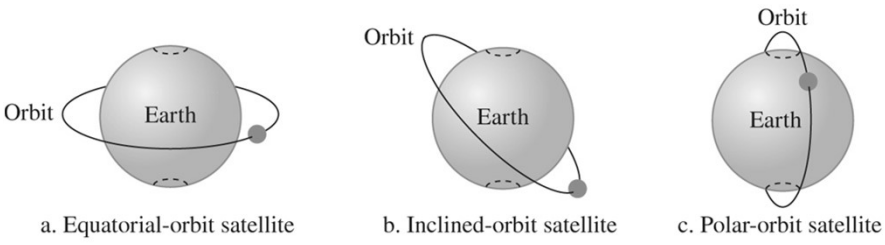
Satellite Networks

- A satellite network is a combination of nodes that provides communication from one point on the Earth to another
- A node in the network can be a satellite, an Earth station, or an end-user terminal or telephone
- Better for broadcast of video (e.g., Satellite TV) and audio (e.g., SiriusXM Radio) over large regions
- Difficult to provide two-way voice and data (power constraints, delay, bulky phones)

Orbits

- Satellites need to have an orbit



a. Equatorial-orbit satellite b. Inclined-orbit satellite c. Polar-orbit satellite

- Kepler's law is used to calculate the time required for a satellite to make a complete trip around the Earth

$$Period = (1/100)\ Altitude^{1.5}$$

Altitude is measured from the center of the Earth in kilometer

Example

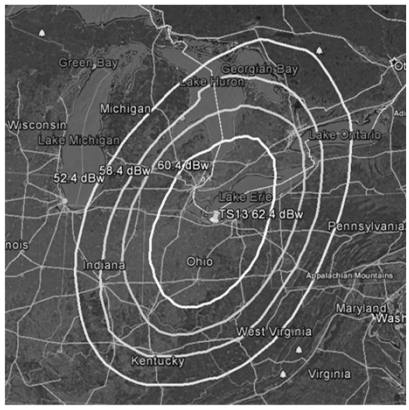
What is the period of a satellite that is located at an orbit approximately 37,865 km above the Earth? Assume radius of Earth is 6,378 km.

Solution:

$$\text{Period} = (1/100) \times (35{,}786+6378)^{1.5} = 86{,}579 \text{ s} = 24 \text{ h}$$

Footprint

- Signal from a satellite is normally aimed at a specific area called the footprint
  - Signal power at the center of the footprint is maximum
  - Power decreases as we move out from the footprint center
  - Boundary of the footprint is the location where the power level is at a predefined threshold



solidsignal.com

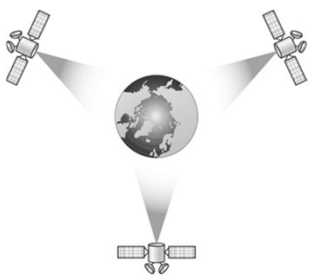
Frequency Band for Satellite Communication

- Satellite microwave communications are in the gigahertz (GHz) range
- Each satellite sends and receives over two different bands
- Transmission from the Earth to the satellite is called the uplink
- Transmission from the satellite to the Earth is called the downlink

Band	*Downlink, GHz*	*Uplink, GHz*	*Bandwidth, MHz*
L	1.5	1.6	15
S	1.9	2.2	70
C	4.0	6.0	500
Ku	11.0	14.0	500
Ka	20.0	30.0	3500

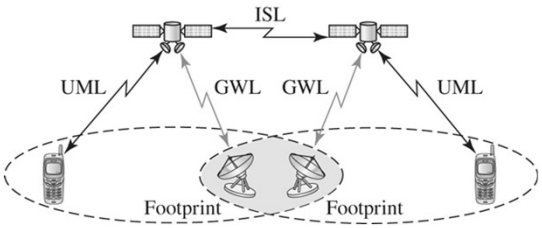
Three Categories of Satellites

- Geostationary Earth Orbit (GEO)
  - Orbiting at higher altitudes (35786 km) – 24 hr to circle Earth
  - Move at the same speed as the Earth → easy to track
  - Larger coverage area (up to 33% of earth surface)
  - High transmit power and high latency (250 ms)
  - Satellite TV and Radio, weather



Three Categories of Satellites (cont.)

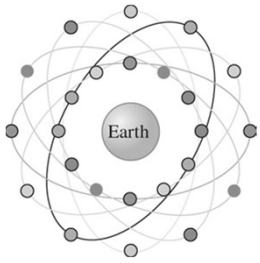
- Low Earth Orbit (LEO)
  - Constellation of satellites orbiting the earth (500-2000 km)
  - Low transmit power and low communication latency (5-10 ms)
  - Small footprint → visible for 10-40 min → frequent handover
  - Telecommunications

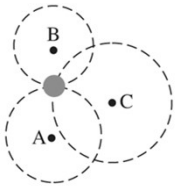


ISL: Inter-Satellite Links
UML: User Mobile Link
GWL: Gateway Link

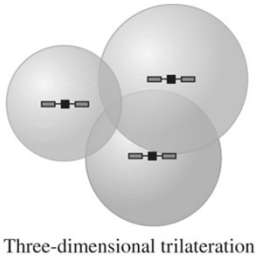
Three Categories of Satellites (cont.)

- Medium Earth Orbit (MEO)
  - Orbiting between the two Van Allen belts (5000-15000 km) – 6-8 hr to circle Earth
  - Global Positioning System (GPS) at an altitude about 18000 km





a. Two-dimensional trilateration



b. Three-dimensional trilateration

Summary

- We covered:
  - Wired WANs: Telephone Networks and Cable Networks
  - Wireless WANs: Cellular Networks and Satellite Networks