Wireless and Mobile Networks

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Audio/Video recordings of this lecture are available on-line at:

http://www.cse.wustl.edu/~jain/cse473-23/

Student Questions

Overview

1. Wireless Link Characteristics
2. Wireless LANs and PANs
3. Cellular Networks
4. Mobility Management
5. Impact on Higher Layers

Note: This class lecture is based on Chapter 7 of the textbook (Kurose and Ross) and the figures provided by the authors.

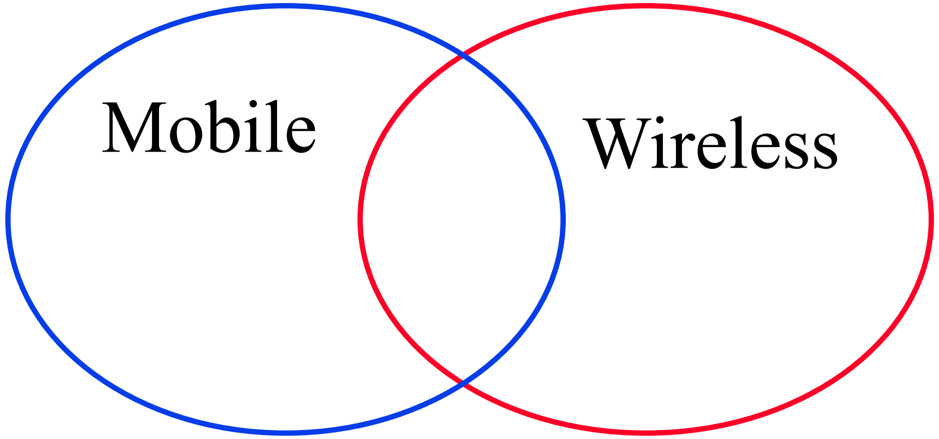
Student Questions

Wireless Link Characteristics

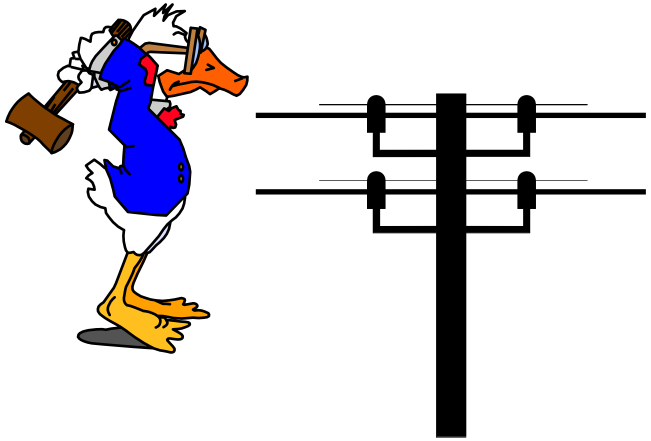
- Mobile vs. Wireless
- Wireless Networking Challenges
- Peer-to-Peer or Base Stations?
- Code Division Multiple Access (CDMA)
  - Direct-Sequence Spread Spectrum
  - Frequency Hopping Spread Spectrum

Student Questions

Mobile vs Wireless



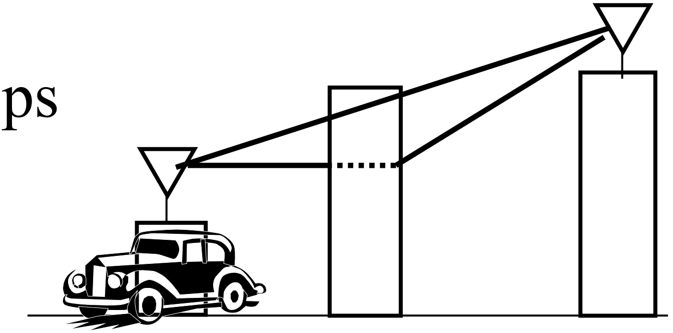
- ❑ Mobile vs. Stationary
- ❑ Wireless vs. Wired
- ❑ Wireless ⇒ media sharing issues
- ❑ Mobile ⇒ routing, addressing issues



Student Questions

Wireless Networking Challenges

1. Propagation Issues: Shadows, Multipath
2. Interference ⇒ High loss rate, Variable Channel
   ⇒ Retransmissions and Cross-layer optimizations
3. Transmitters and receivers moving at high speed
   ⇒ Doppler Shift
4. Low power transmission ⇒ Limited reach
   100mW in WiFi base station vs. 100 kW TV tower
5. License-Exempt spectrum ⇒ Media Access Control
6. Limited spectrum ⇒ Limited data rate
   Original WiFi (1997) was 2 Mbps.
   New standards allow up to 200 Mbps
7. No physical boundary ⇒ Security
8. Mobility ⇒ Seamless handover



Student Questions

□ When new buildings are constructed, do the builders take into account that it may obstruct wireless signals?

No. No such study has been done. Carriers and enterprises have to structure their wireless afterward.

□ Is the multipath meaning in each signal transmission? It will split into multi-subparts and follow different paths.

Each bit is split into multiple paths.

□ How is the Doppler effect taken into account when receiving or transmitting signals?

The physical layer design takes care of the maximum speed allowed. Networks designed for cars will not work for airplanes.

□ Why does radio not suffer from the same propagation issues as wireless?

It also suffers from the same issues. Analog and digital have different timescales. Bits are in microseconds or nanoseconds. Analog words are in seconds.

□ Could you explain how the data rate physically works for wireless? What allows us to achieve faster data rates?

It will be covered in this chapter.

Wireless Networking Challenges

1. Propagation Issues: Shadows, Multipath
2. Interference ⇒ High loss rate, Variable Channel
   ⇒ Retransmissions and Cross-layer optimizations
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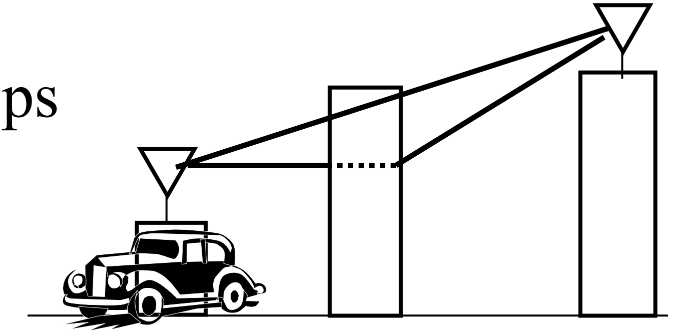


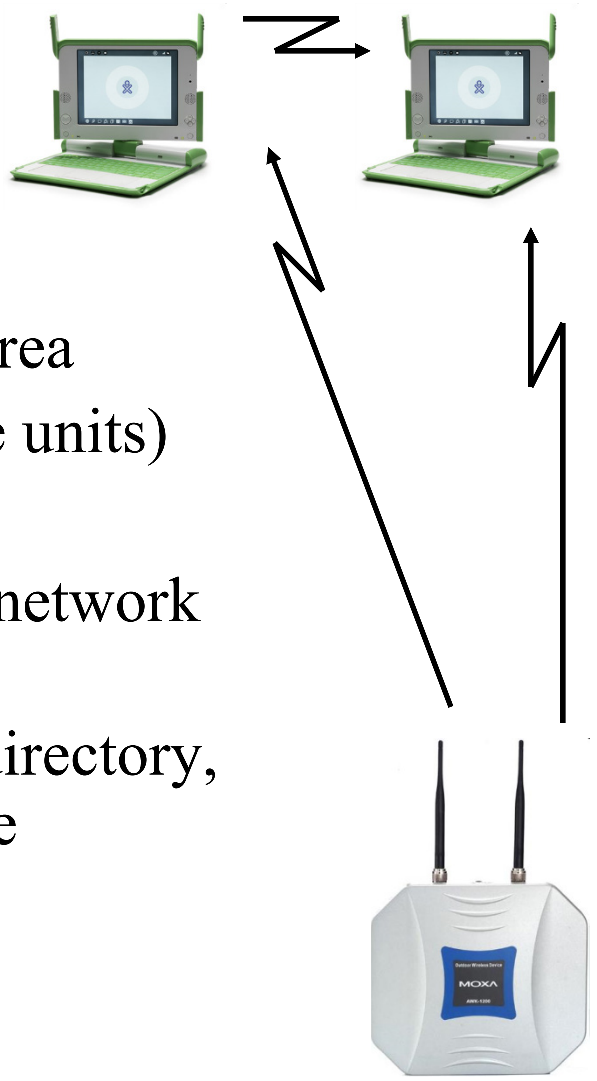
Student Questions

❑ Are there any traffic issues in wireless transmission?

Yes. Multiple transmissions interfere with each other like sounds in a room.

Peer-to-Peer or Base Stations?

- Ad-hoc (Autonomous) Group:
  - Two stations can communicate
  - All stations have the same logic
  - No infrastructure, Suitable for small area
- Infrastructure-Based: Access points (base units)
  - Stations can be simpler than bases.
  - The base provides connection for off-network traffic
  - The base provides location tracking, directory, and authentication ⇒ Scalable to large networks
- IEEE 802.11 provides both.



Student Questions

- ❑ If there are three computers in a small area but no base stations, is it also called an Ad-hoc Group?

Yes. Any number of stations can form an ad=hoc group for communication.

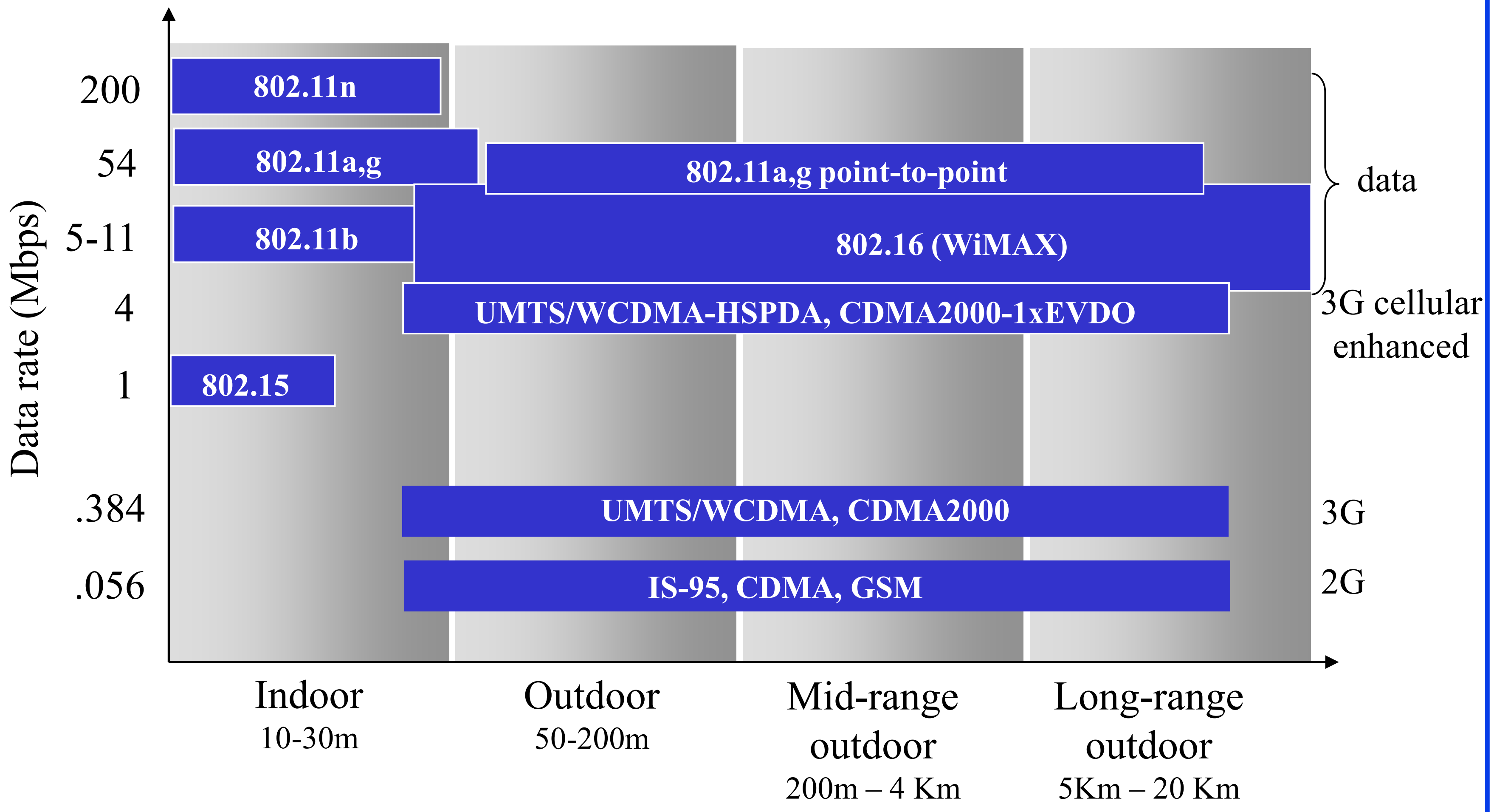
- ❑ Does Ad-hoc have anything to do with P2P we discussed before, like BitTorrent?

No. Bit torrent is between computers far away in different countries. Here, we are talking about computers in the same room.

- ❑ Is using base station more common than peer-to-peer?

Yes, base stations are common.

Characteristics of Selected Wireless Link Standards

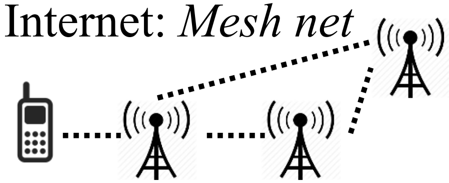
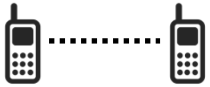
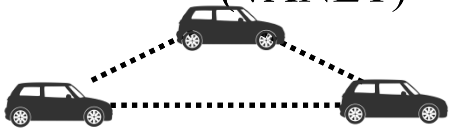


Student Questions

❑ For the same power provided, does a lower data rate (longer wavelength) means a longer distance?

Longer wavelength => Lower frequency => Lower Hz. Coding determines Bits/Hz. So data rate depends on Coding and wavelength. For the same power and coding, longer wavelengths will have a lower data rate and longer distances.

Wireless Network Taxonomy

	Single hop	Multiple hops
Infrastructure (Access Points, Towers)	Host connects to base station (WiFi, WiMAX, cellular) which connects to larger Internet 	Host may have to relay through several wireless nodes to connect to larger Internet: *Mesh net* 
No Infrastructure	No base station (Bluetooth, ad hoc nets) 	Relay to reach other a given wireless node. Mobile Ad-hoc Network (MANET), Vehicular Ad-hoc Network (VANET) 

Student Questions

- ❑ The hop here is a link over wireless transmission, right? Then will those stations eventually be wired into the Internet?

Sometimes, wireless is used over multiple hops without wires. That is multi-hop wireless.

- ❑ What is the difference between Mobile Ad-hoc and hoc nets? Is it just the difference in the number of devices?

Mobile means moving. Two computers communicating in Ad-hoc mode may are may not be mobile. A mobile ad-hoc network means at least one of the nodes is moving.

- ❑ So VANETs do not yet exist?

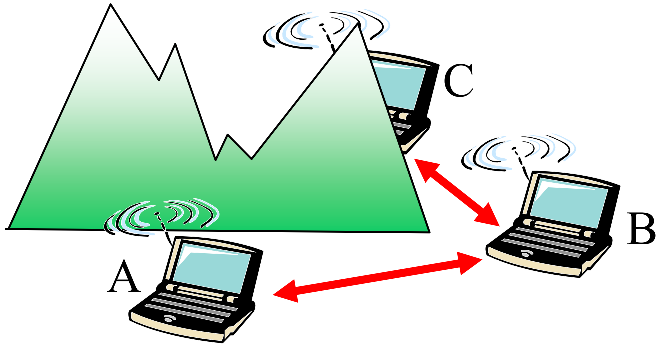
Not common. Emergency vehicles (fire brigades and military) use it.

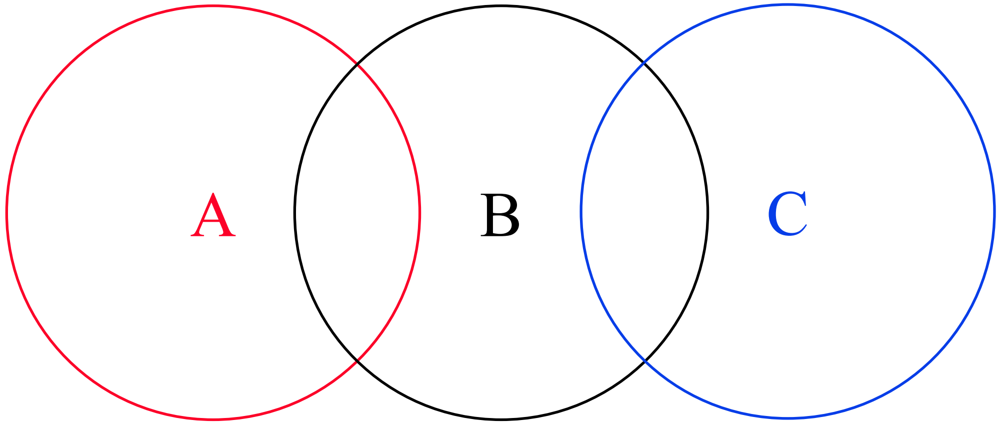
- ❑ What is the difference between MANET and VANET again? Is VANET the next generation of MANET?

M=Mobile. It could be between a walking person and the tower.

V=Vehicle-to-vehicle without a tower.

Hidden Node Problem

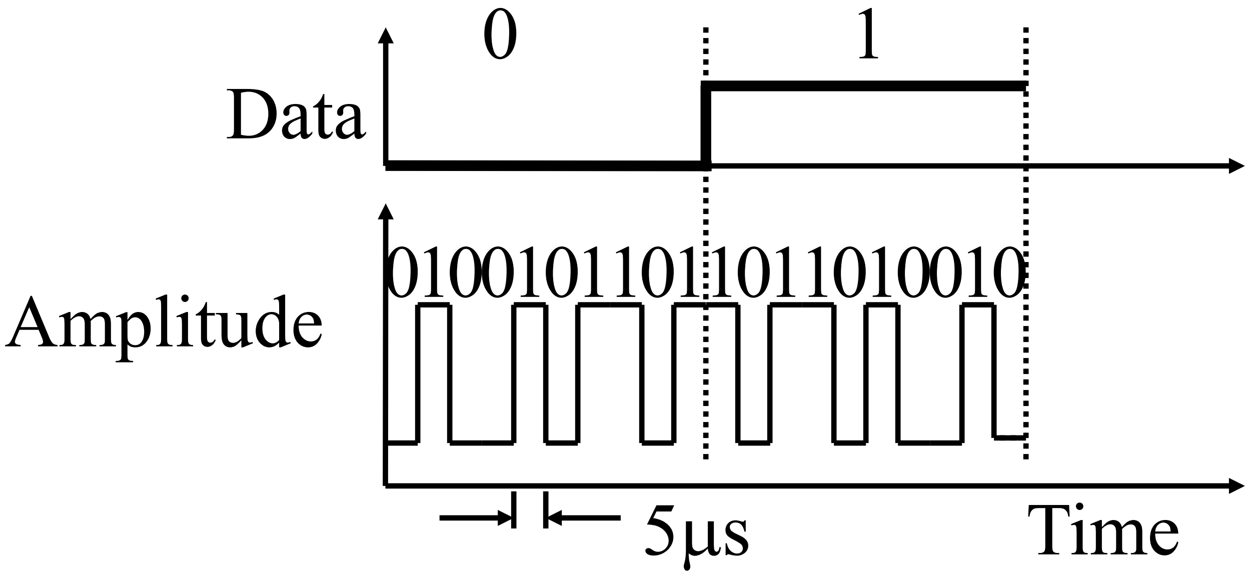




- B and A can hear each other.
  B and C can hear each other.
  A and C cannot hear each other.
  ⇒ C is hidden for A and vice versa.
- C may start transmitting while A is also transmitting.
  A and C can't detect collisions.
- Only the receiver can help avoid collisions.

Student Questions

Direct-Sequence Spread Spectrum CDMA



- Spreading factor = Code bits/data bit, 10-100 commercial (Min 10 by FCC), 10,000 for military
- Signal bandwidth >10 × data bandwidth
- Code sequence synchronization
- Correlation between codes ⇒ Interference ⇒ Orthogonal

Student Questions

Would you clarify the meaning of “bandwidth” here?

Band = Frequency Band
Bandwidth=Width of the Frequency Band
(See next slide)

What’s an example of an orthogonal code?

See the example on slide 7.12

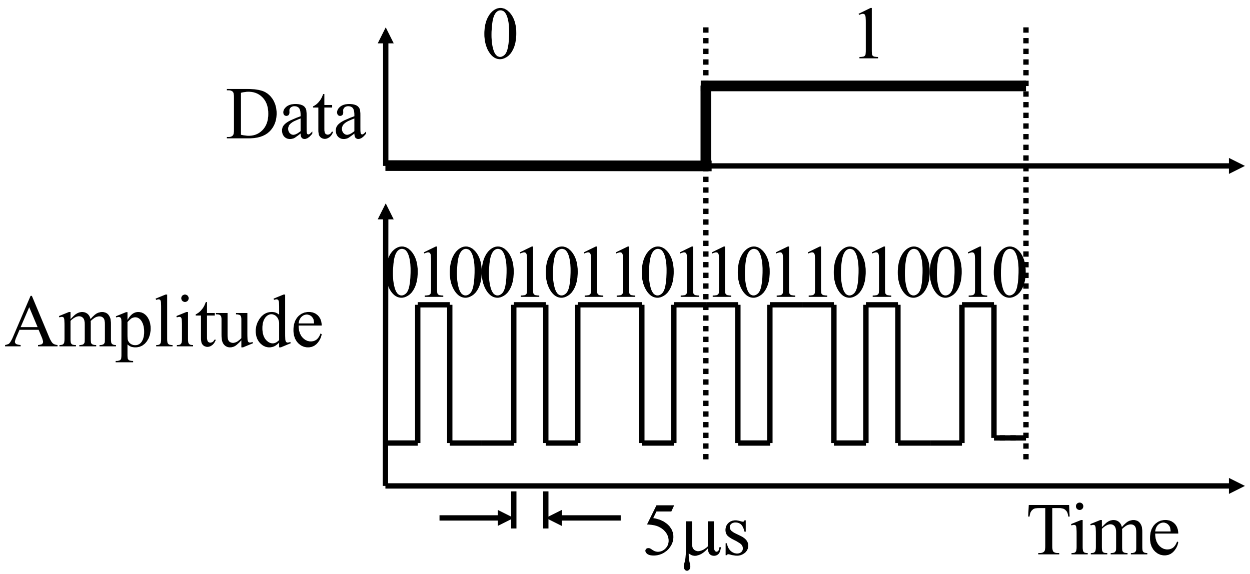
- For best orthogonality, can we just use 1's comp negated 0's code bit sequence for 1's code bit sequence? *Orthogonality requires using only some of the bit combinations. 1-Bit transmission requires at least two code bits for orthogonality.*
- Once set, will the code of a transmitter be changed?

Yes. It is changed frequently in “code division multiple access (CDMA).”

- When the bits sent by multiple senders are mixed, how does the CDMA receiver recover the original bits sent？ *See the example in the next few slides.*
- What is meant by "Interference -> Orthogonal"?

Interference leads to a need for orthogonal coding.

Direct-Sequence Spread Spectrum CDMA



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Student Questions

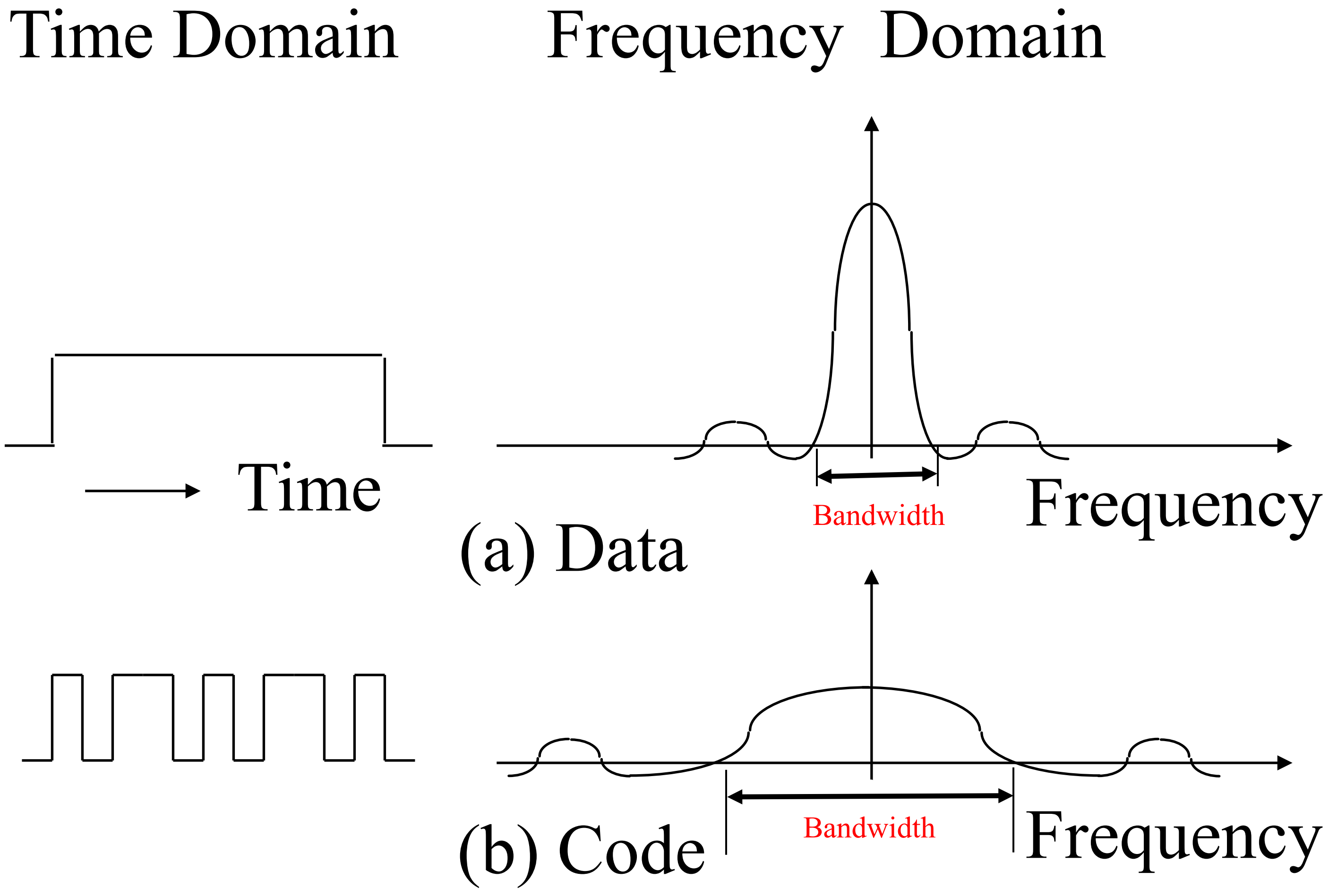
- ❑ Why did the FCC decide on 10 bits to be the minimum? *So that a small number of users can share the space.*
- ❑ If CDMA is sending different codes to a different host, what's the difference between CDMA and TDMA?

In CDMA, all users transmit simultaneously. Time is not divided.
In TDMA, they take a turn. Time is divided into time slots.

- ❑ Are the codes representing 0 and 1 opposite each other on every code bit?

Yes. In n-dimensional space, 0 and 1 should be as far from each other as possible. This is achieved by making the code for 0 a complement of the code for 1 and vice versa.

DS Spectrum



Time Domain

Frequency Domain

Time

(a) Data

Bandwidth

Frequency

(b) Code

Bandwidth

Frequency

Student Questions

❑ Why is the second graph horizontally stretched?

It has higher frequency bandwidth.

❑ Could you re-explain this slide? Is the benefit of this transmission method to allow two signals to be transmitted at once? Unsure how this improves things.

Allows user multiplexing.

FDMA = Frequency Division (1G)
TDMA = Time Division (2G)

CDMA = Code Division (3G)

❑ Can you explain these line graphs again? *Sure.*

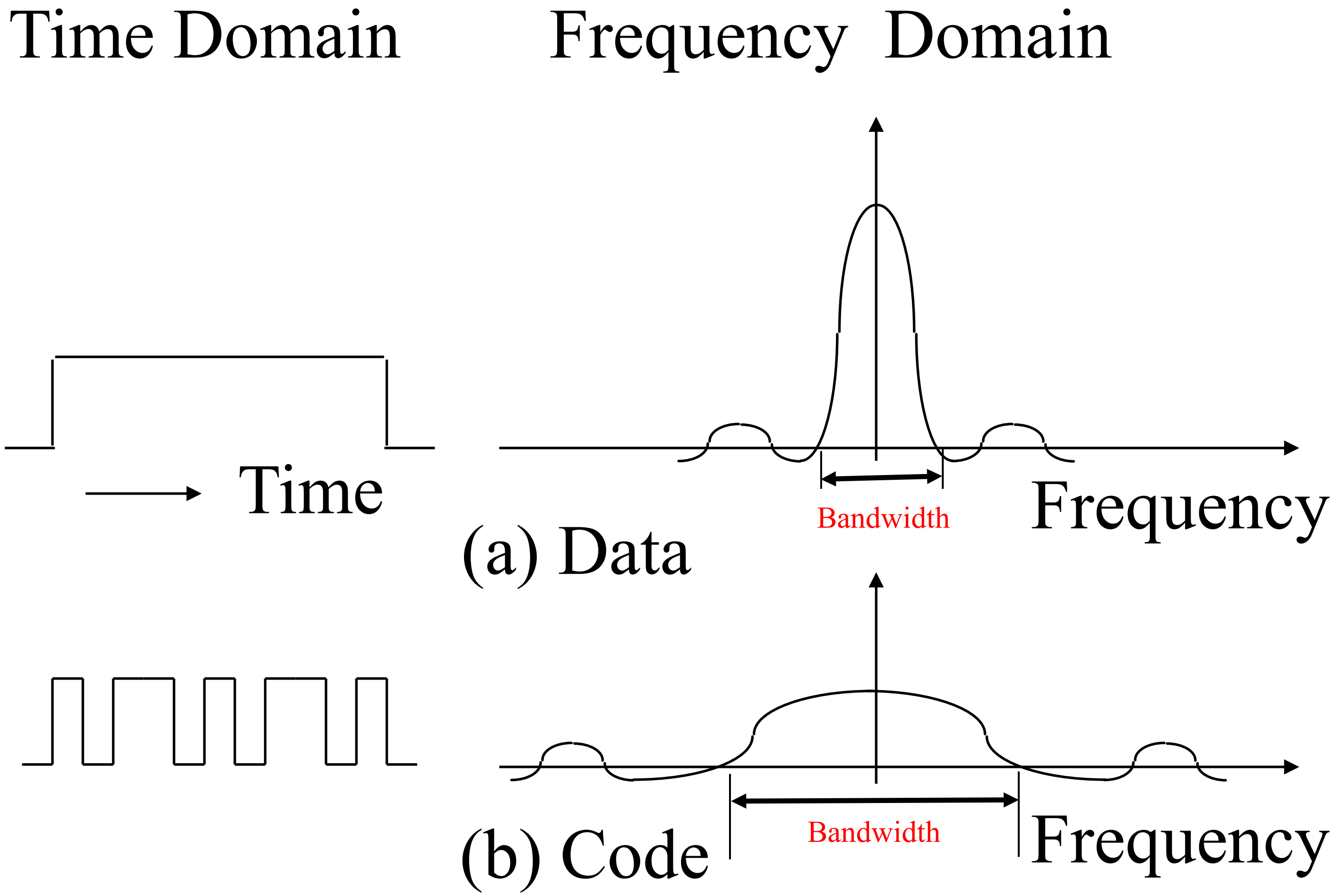
❑ In FHSS, when should we tell the receiver the random generator seed we use? What is the range of the random number generated?

Random number generator and seeds are exchanged at the beginning of communication and periodically. The range is up to the users and standard bodies.

❑ What are the advantages of spreading the spectrum? Is it just to increase the range of frequencies where the peak is at the highest?

Allows code division multiplexing

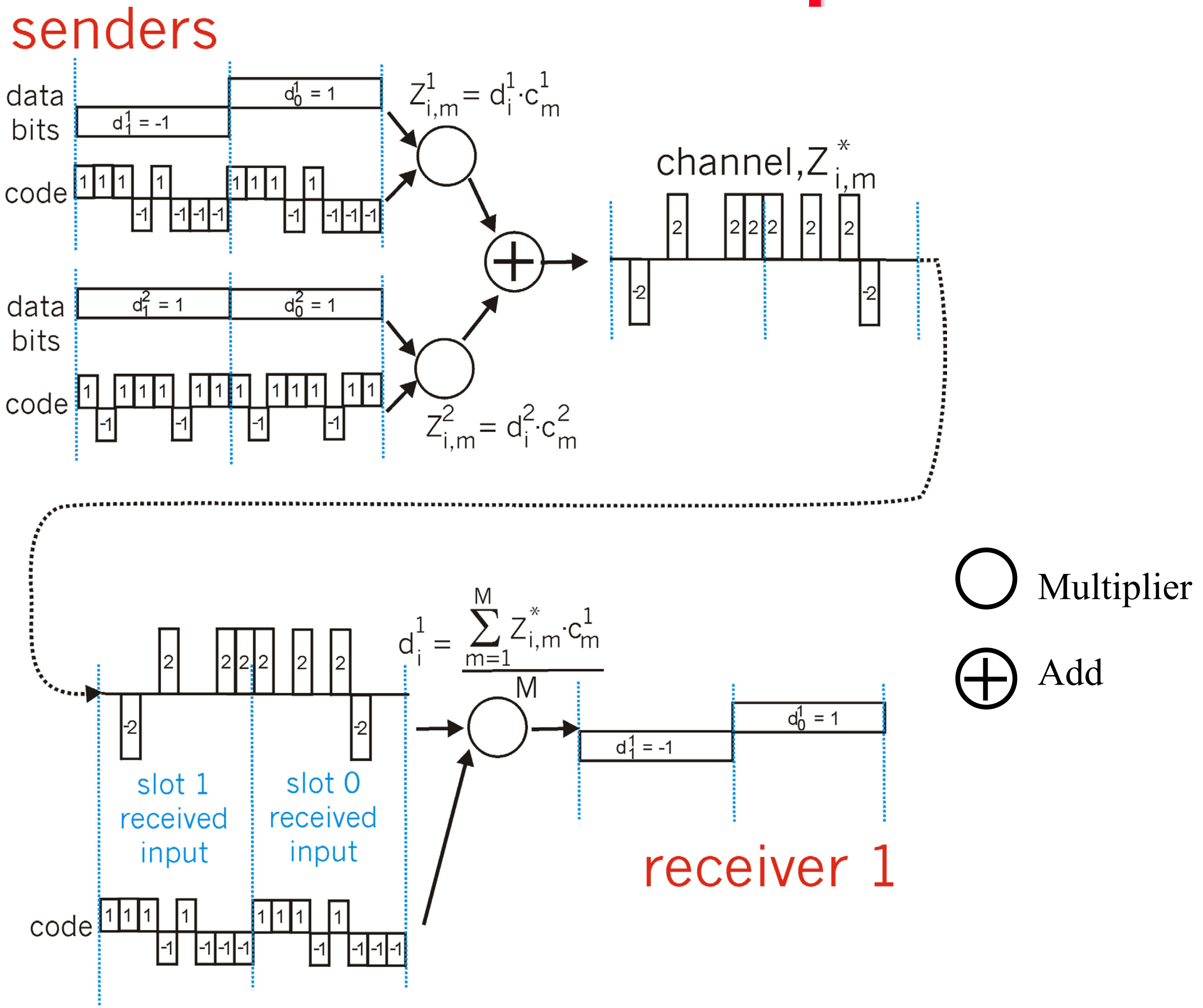
DS Spectrum



Student Questions

- ❑ What is the meaning of the vertical axis?
  Signal power

Two Sender CDMA Example



Student Questions

❑ What are the codes for 0 and 1, respectively, in this depiction?

0 is -1. 1 is +1

User 1: 1 data = 11101000 code

User 2: 1 data = 10111011 code

❑ Can you go over this diagram again? *Sure.*

❑ What is the M in the equation at the bottom? *Number of code bits/data bit. M=8 in the example as shown.*

❑ Page 541 in the book says that "if the senders' codes are chosen carefully, each receiver can recover the data sent by a given sender." Is there a simple example to illustrate that if you don't choose carefully, you can't complete the case where the receiver accepts the corresponding sender? *The correct statement is that if the sender codes are not orthogonal, the data cannot be recovered correctly. Orthogonality is defined as* $\sum_{m=1}^{M} Z_{1,m}Z_{2,m} = 0$

Homework 7A: CDMA Coding

- [6 points] Two CDMA senders use the codes (1, -1, 1, -1) and (1, -1, -1, 1). The first sender transmits data bit 1 while the 2nd transmits –1 at the same time. What is the combined signal waveform seen by a receiver? Draw the waveform.

Student Questions

- Which of those codes corresponds to 0 and 1?

1 data = code seq

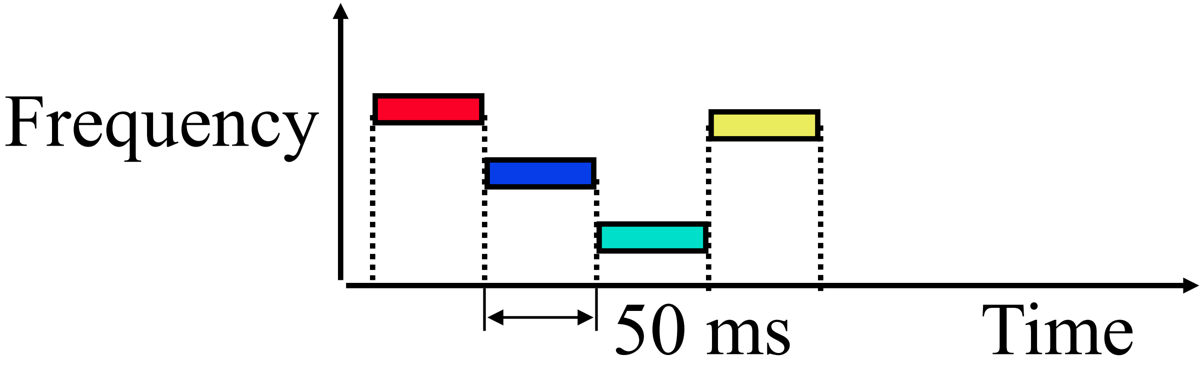
0 data = -code seq

User 1:

1 ={1, -1, 1, -1}

0 = {-1, 1, -1, 1}

Frequency Hopping Spread Spectrum



- Pseudo-random frequency hopping
- Spreads the power over a wide spectrum ⇒ Spread Spectrum
- Developed initially for military
- Patented by actress Hedy Lamarr (1942)
- Narrowband interference can't jam

Student Questions

- When you said, “just keep hopping”, does the receiver knows how the sender will change the frequency all the time?

The sender changes the frequency all the time. The receiver knows what frequency will be when.

- Does Frequency Hopping Spread Spectrum work better than Direct-Sequence Spread Spectrum since it's more common?

Both are used.

- How do the two devices agree on the first number to send through the number generators?

The number is exchanged at the connection initiation.

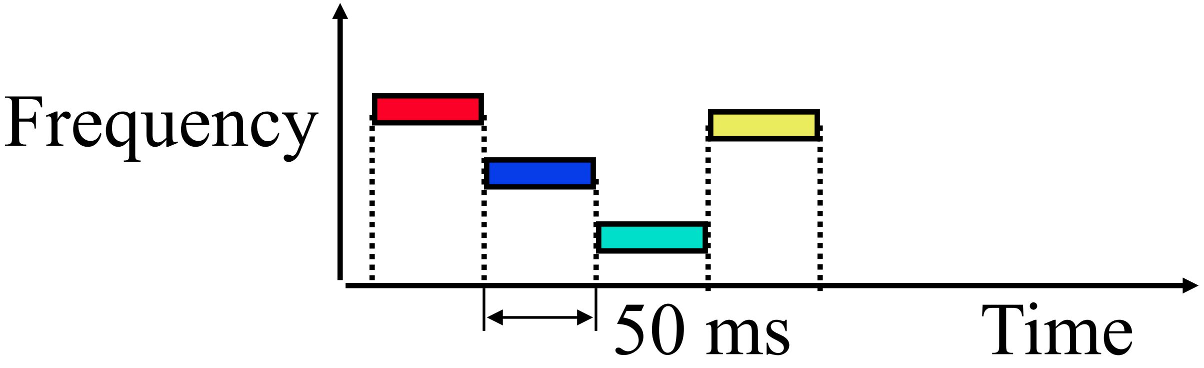
- How does the receiver keep track of the frequency changes from the transmitter?

Both sender and transmitter use the same random number generator with the same seed.

- What is the purpose of using a random-generation formula? Is it for security purposes?

To avoid interference.

Frequency Hopping Spread Spectrum



- Pseudo-random frequency hopping
- Spreads the power over a wide spectrum ⇒ Spread Spectrum
- Developed initially for military
- Patented by actress Hedy Lamarr (1942)
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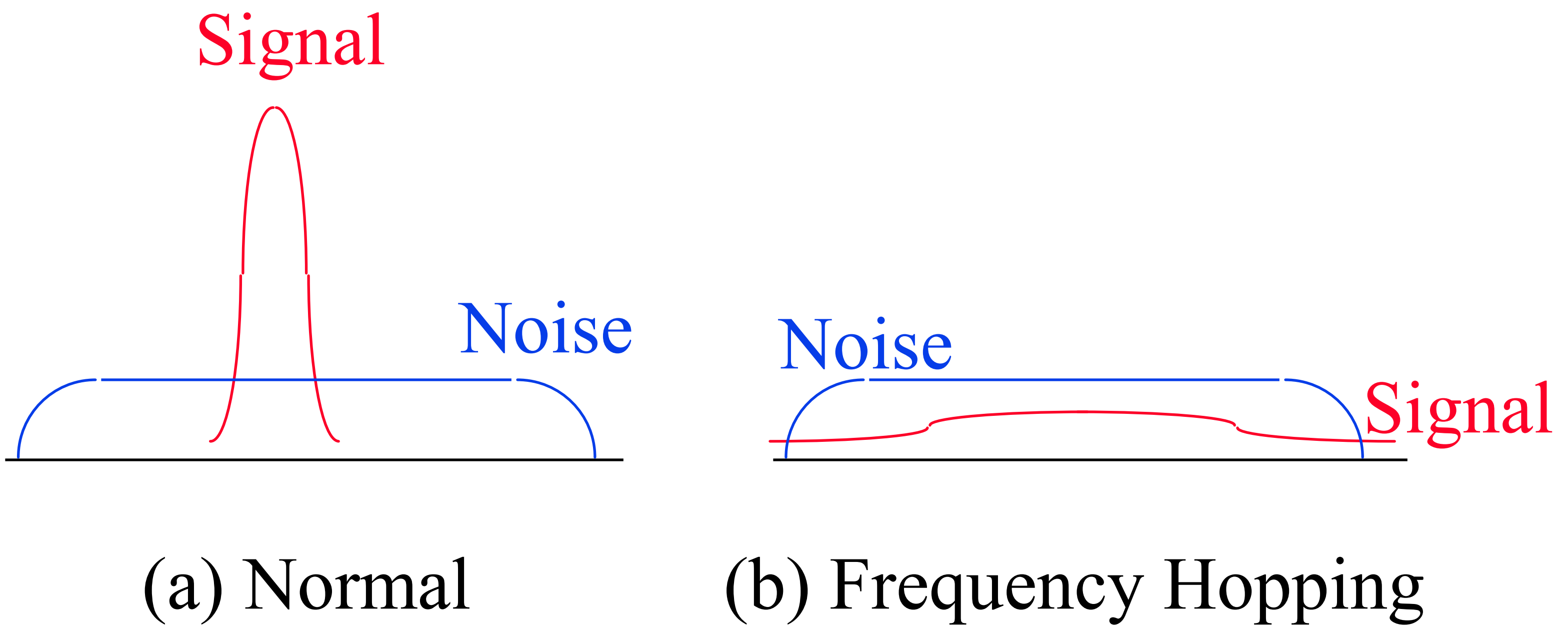
Student Questions

- Is this called "pseudo-random" because it is not "truly random"? If 2 people start with the same seed, will they have the same sequence of numbers? *Yes.*

Spectrum



(a) Normal

(b) Frequency Hopping

Student Questions

- ❑ How do adversaries jam a non-frequency hopping signal?

Transmitting at the same frequency at the same time

Review: Wireless Link Characteristics

1. Wireless is not the same as mobile. However, most mobile nodes are wireless.
2. A wireless signal is affected by shadows, multipath, interference, and Doppler shift.
3. A wireless network can be ad-hoc or infrastructure based.
4. Multi-hop ad-hoc networks are called MANET.
5. It is not possible to do collision detection in wireless
6. Code division multiple access is commonly used in wireless

Ref: Section 7.2, Review Exercises R3-R4

Student Questions

- ❑ Is it possible to do collision detection in ad-hoc mode?

No. Ad-hoc is almost similar to Infrastructure based. The nodes perform the functions performed by the base station.

- ❑ *Can you clarify in the slide, you mention, "It is not possible to do collision detection in wireless," but in the Q&A, your answer to the question "Is it possible to do collision detection in ad-hoc?" is "Yes." Which is correct?*

I was wrong in Q&A. I have corrected the answer above.

Wireless LANs and PANs

- IEEE 802.11 Wireless LAN PHYs
- 4-Way Handshake
- IEEE 802.11 MAC
- 802.11 Frame Format
- 802.11 Frame Addressing
- 802.11 Rate Adaptation
- Power Management
- IEEE 802.15.4
- IEEE 802.15.4 MAC
- ZigBee Overview

Student Questions

IEEE 802.11 Wireless LAN PHYs

- ❑ **802.11**: 2.4 GHz, 1-2 Mbps
- ❑ **802.11b**: 2.4 GHz, 11 Mbps nominal
  - ➢ Direct sequence spread spectrum (DSSS) in the physical layer
  - ➢ All hosts use the same chipping code
- ❑ **802.11a**: 5.8 GHz band, 54 Mbps nominal
- ❑ **802.11g**: 2.4 GHz band, 54 Mbps nominal
- ❑ **802.11n**: 2.4 or 5.8 GHz, Multiple antennae, up to 200 Mbps
- ❑ These are different PHY layers. All have the same MAC layer.
- ❑ All use CSMA/CA for multiple access
- ❑ All have base station and ad-hoc network versions
- ❑ Supports multiple priorities
- ❑ Supports time-critical and data traffic
- ❑ Power management allows a node to doze off

Student Questions

❑ Can you explain the benefits of raising the frequency from 2.4GHz to 5.8GHz

More available spectrum

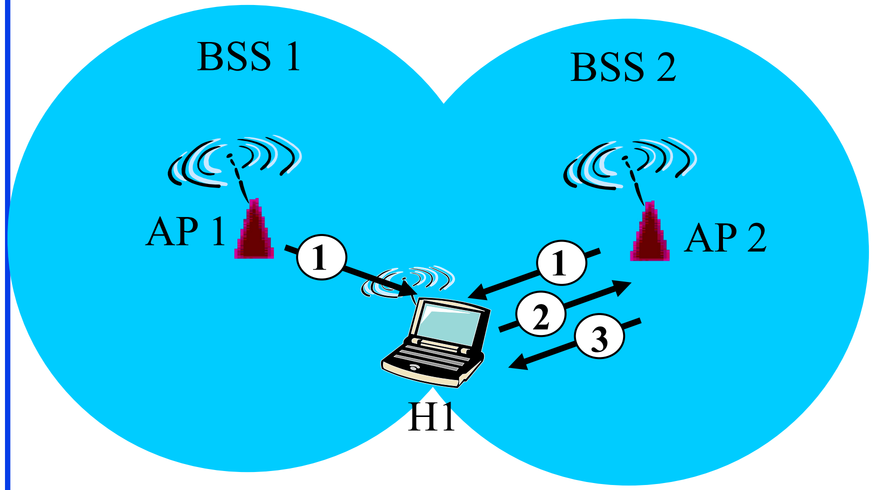
❑ Why 2.4/5.8GHz, not other frequencies?

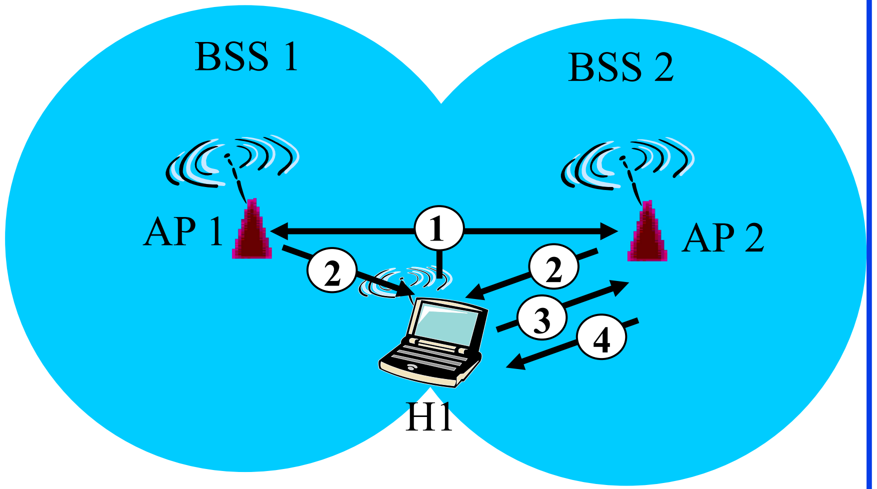
All frequencies are allocated.

❑ Can you please explain the purpose of DSSS in the physical layer?

Code division multiplexing

802.11: Passive/Active Scanning





Passive Scanning:

(1) Beacon frames sent from APs

(2) Association Request frame sent: H1 to selected AP

(3) Association Response frame sent: selected AP to H1

Active Scanning:

(1) **Probe Request** frame broadcast from H1

(2) Probes response frame sent from APs

(3) Association Request frame sent: H1 to selected AP

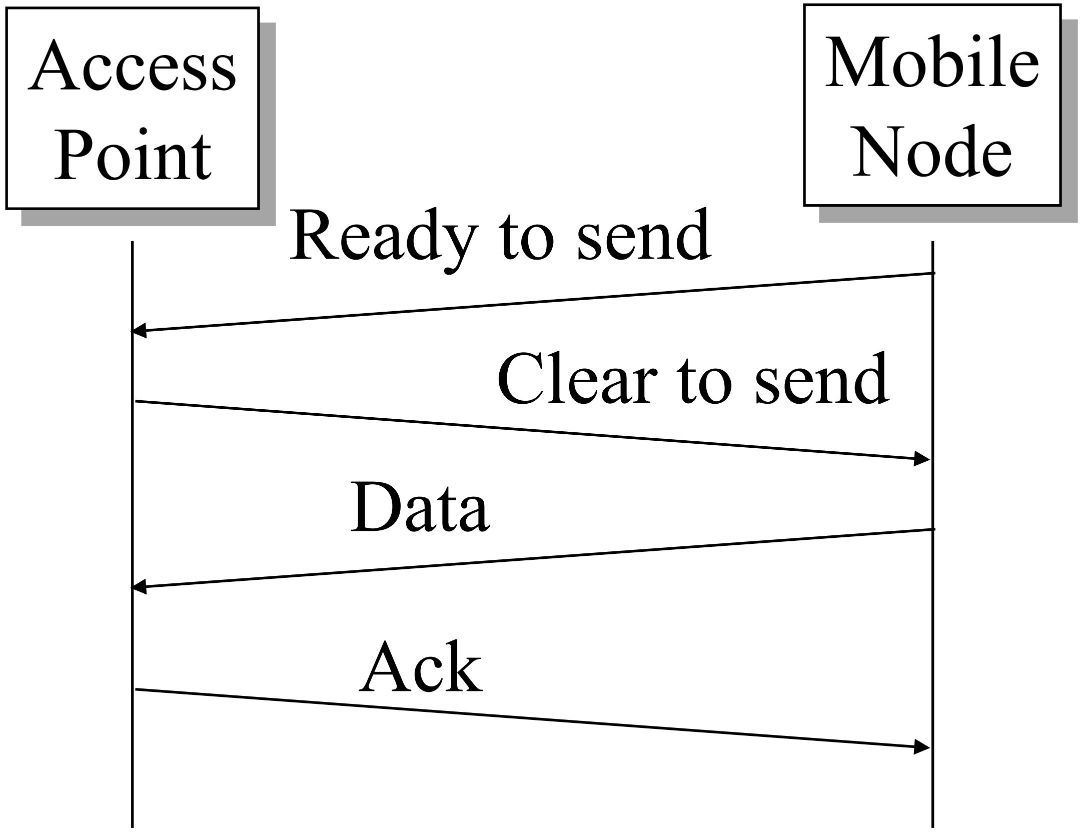
(4) Association Response frame sent: selected AP to H1

Student Questions

❑ When we search for **Wi-Fi** on our device, we can see some "hidden networks," which require the name of that network (SSID) to connect. Do these hidden networks have anything to do with passive/active scanning (just guessing)?

When setting up your network, you can choose to announce or not announce your SSID. These hidden networks respond to their names but do not announce their names. This increases security.

4-Way Handshake



Student Questions

- ❑ Why don't we do a 3-way handshake like TCP?

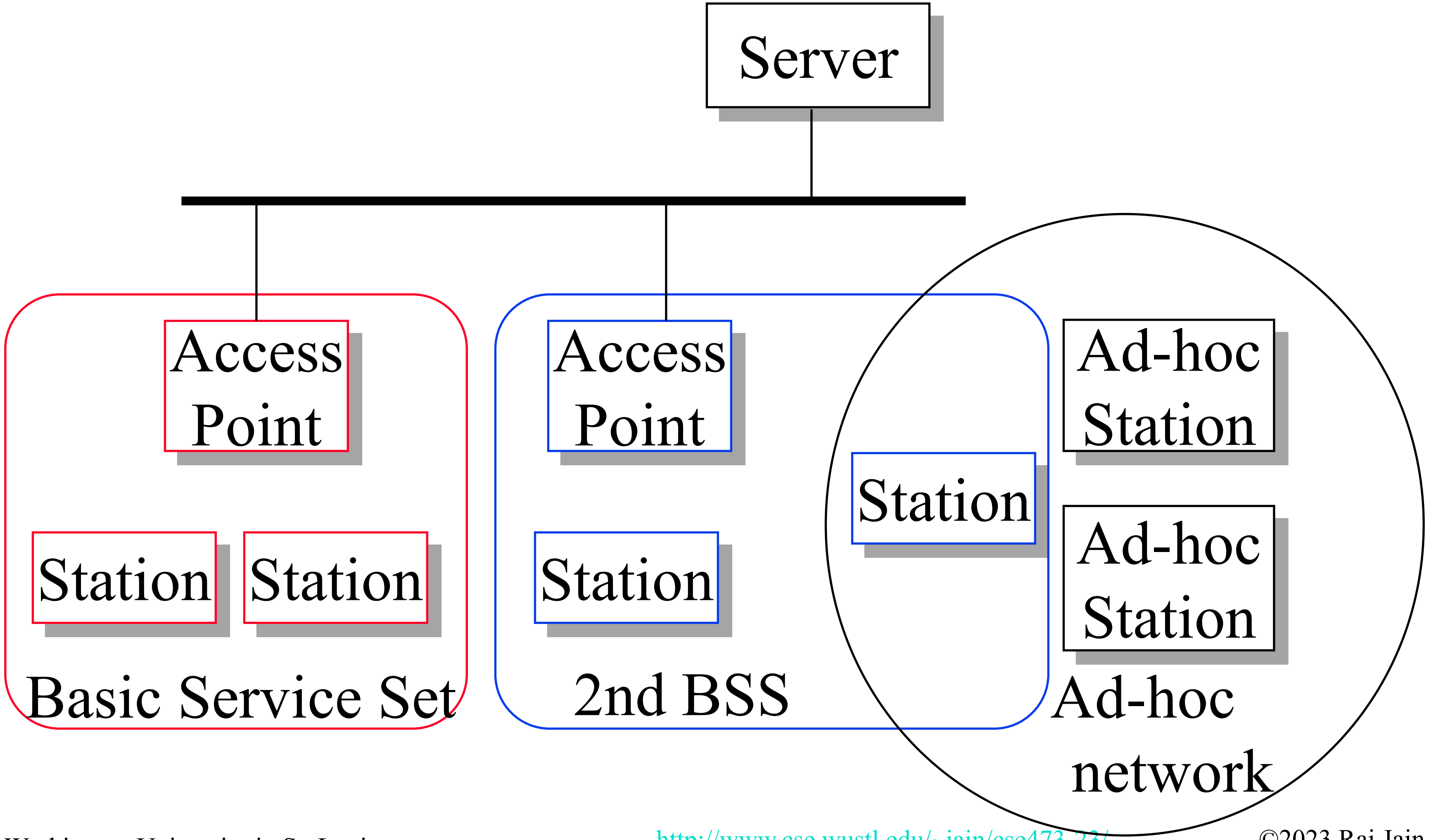
In TCP, multiple users do not interfere with each other.

IEEE 802.11 MAC

- Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA)
- Listen before you talk. If the medium is busy, the transmitter backs off for a random period.
- Avoids collision by sending a short message:
  Ready to send (RTS)
  RTS contains dest. address and duration of the message.
  Tells everyone to backoff for the duration.
- The destination sends: Clear to send (CTS)
- Can not detect collision ⇒ Each packet is acked.
- MAC level retransmission if not acked.

Student Questions

IEEE 802.11 Architecture



Student Questions

Architecture (Cont.)

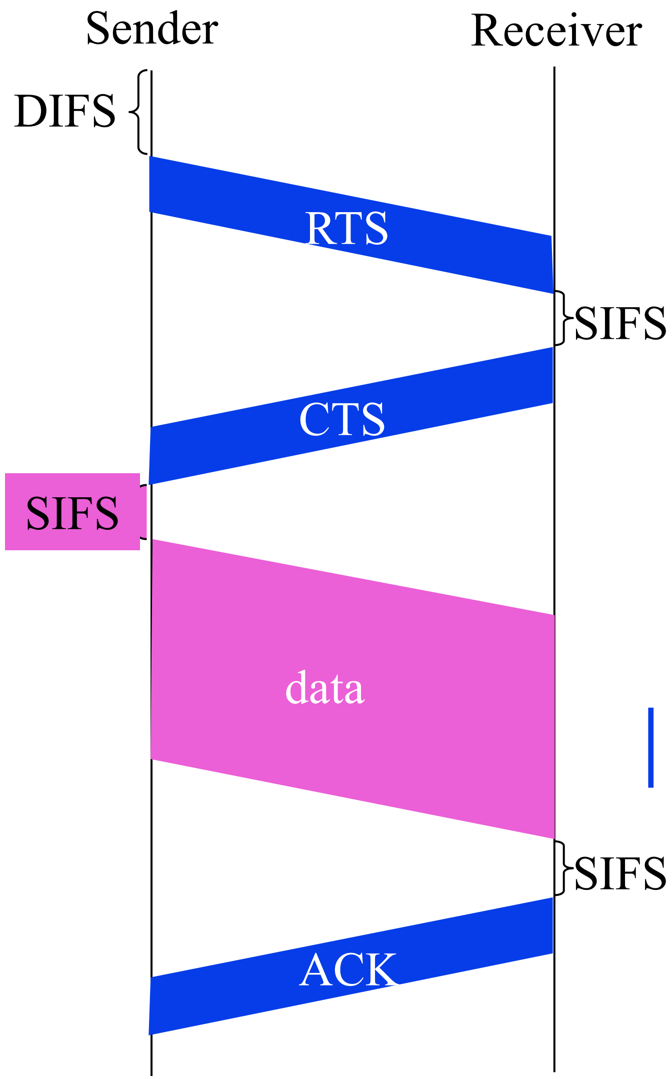
- Basic Service Area (BSA) = Cell
  Area: Geographical area = a room or a building
- Each BSA may have several wireless LANs
- Extended Service Area (ESA) = Multiple BSAs interconnected via Access Points (AP) = multiple rooms in your home with different extenders advertising the same SSID
- Basic Service Set (BSS)
  = Set of stations associated with an AP =$\{MAC_1,\ldots,MAC_n\}$.
  Each BSS has a Service Set ID (SSID), e. g., WUSTL-Guest
- Extended Service Set (ESS)
  = Set of stations in an ESA
- Ad-hoc networks coexist and interoperate with infrastructure-based networks.

Student Questions

- What is the difference between SSID and BSSID?

BSSID is the SSID of the BSS.

Transmission Example



SIFS, DIFS are intervals set by the standards. 11b and 11ac have different values.

RTS, CST, ACK are each one slot time long.

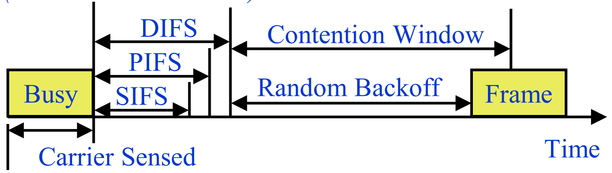
Each frame has a duration field.

Every frame is heard by every one.

Student Questions

- What is DIFS, and what are 11b and 11ac?

DIFS = Distributed Inter-Frame Spacing (See new slide 7.63)



- Initial inter-frame space (IFS)
- Highest priority frames, e.g., Acks, use short IFS (SIFS)
- Medium priority time-critical frames use “Point Coordination Function IFS” (PIFS)
- Asynchronous data frames use “Distributed coordination function IFS” (DIFS)
- How long is one slot time here?

Each standard defines the slot time.

Homework 7B: WiFi Transmission

- [6 points] Suppose an 802.11b station is configured to always reserve the channel with the RTS/CTS sequence. Suppose this station suddenly wants to transmit 2,000 bytes of data, and all other stations are idle at this time. Assume a frame without data is 32 bytes long, and the transmission rate is **10** Mbps. Using SIFS of 30us and DIFS of 60us, ignoring propagation delay and assuming no bit errors, calculate the time required to transmit the frame and receive the acknowledgment.

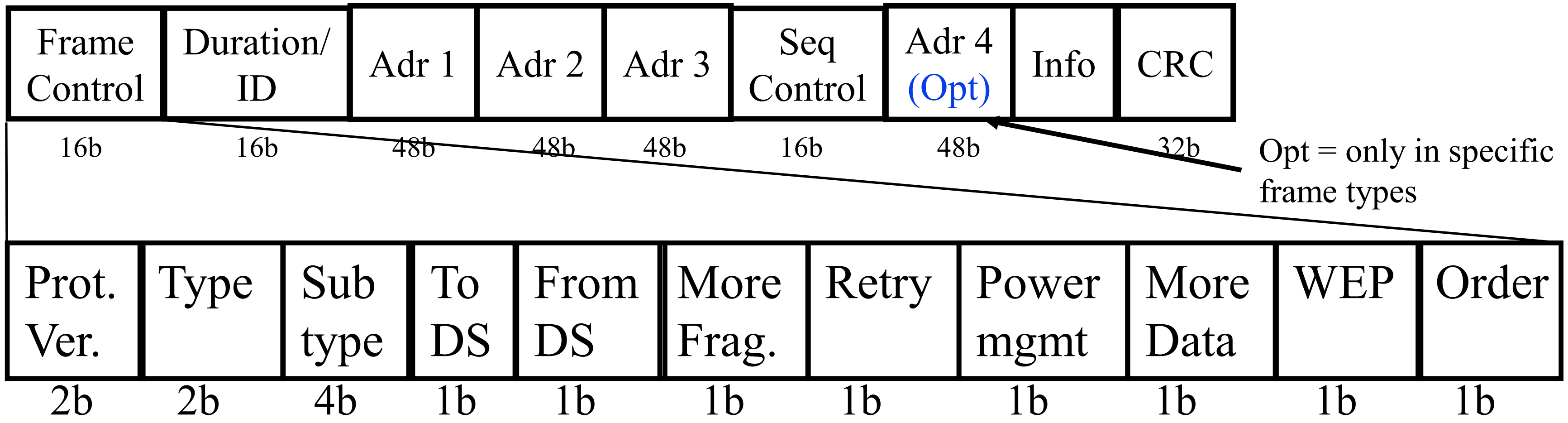
Ref: Problem P7

Student Questions

- Could you go over HW 7B? Is there a specific formula we use to calculate time?

You need to know the bit rate of 802.11b. It is 11 Mbps.

Wi-Fi Frame Format



Frame Control	Duration/ ID	Adr 1	Adr 2	Adr 3	Seq Control	Adr 4 (Opt)	Info	CRC
16b	16b	48b	48b	48b	16b	48b		32b

Opt = only in specific frame types

Prot. Ver.	Type	Sub type	To DS	From DS	More Frag.	Retry	Power mgmt	More Data	WEP	Order
2b	2b	4b	1b	1b	1b	1b	1b	1b	1b	1b

- Type: Control, management, or data
- Sub-Type: Association, disassociation, re-association, probe, authentication, de-authentication, CTS, RTS, Ack, …
- Retry/retransmission
- Going to Power Save mode
- More buffered data at AP for a station in power save mode
- Wireless Equivalent Privacy (Security) info in this frame
- Strict ordering

Student Questions

- Why is there no offset?

Header size is known.

- Given the more frags field, how does fragmentation work with Wi-Fi? Is there still the interframe space between fragments?

Seq. Control = Sequence number + Fragment #
More data => Do not go to sleep. You have more coming (nothing to do with fragmentation.

- What are the subtypes here?

Different types of control and management frames.

MAC Frame Fields

- **Duration/Connection ID**:
  - If used as a duration field, it indicates time (in μs) channel will be allocated for successful transmission of the MAC frame. Includes time until the end of Ack
  - In some control frames, it contains an association or connection identifier
- **Sequence Control**:
  - 4-bit fragment number subfield
    - For fragmentation and reassembly
  - 12-bit sequence number
  - Number frames between given transmitter and receiver

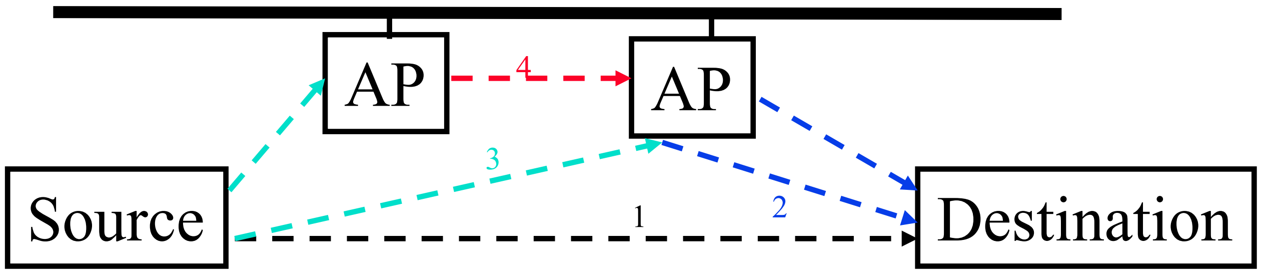
Student Questions

- What is the function of MAC frame in Internet?

Mac Frame = Wi-Fi Frame

802.11 Frame Address Fields

- All stations filter on "Address 1"



	To Distribution System	From Distribution System	Address 1	Address 2	Address 3	Address 4
1	0	0	Destination Address	Source Address	BSS ID	-
2	0	1	Destination Address	BSS ID	Source Address	-
3	1	0	BSS ID	Source Address	Destination Address	-
4	1	1	Receiver AP Address	Transmitter AP Address	Destination Address	Source Address

Student Questions

- Why doesn't the last row need a BSS ID?

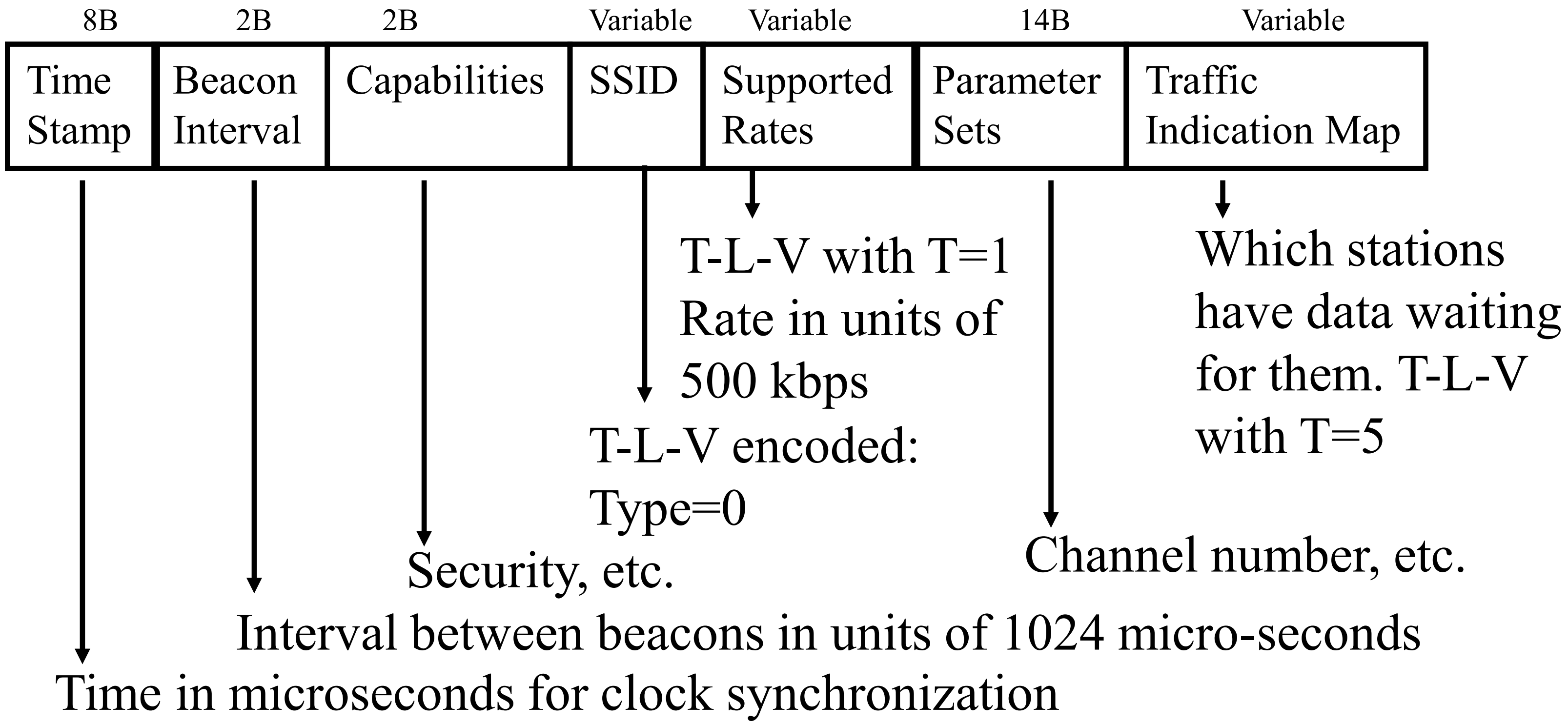
BSS ID is basically a multicast to all base stations on this SSID. Any AP can receive and forward. In the last row, the packet is addressed to a specific AP identified by the receiver address.

- Is the BSS ID the Access Point address? Why does the first row need a BSS ID?

In General:
Adr1 = This hop Wi-Fi Receiver
Adr2 = This hop Wi-Fi Transmitter
Adr3 = BSSID/Source*/Destination* (in order)*
*Adr4 = Source**
**if not specified in the earlier fields*
A Wi-Fi node can be on multiple BSS. In other cases, we know the BSS from other addresses. In case 1, It needs to be explicitly identified.
Analogy: Destination: New York City
BSS ID: Airport (LaGuardia or JFK)
AP Address: Airline
Case 1 is private plane.

Beacon Frame Format

- Info field in the 802.11 frame (after Address 4)



8B	2B	2B	Variable	Variable	14B	Variable
Time Stamp	Beacon Interval	Capabilities	SSID	Supported Rates	Parameter Sets	Traffic Indication Map

T-L-V with T=1 Rate in units of 500 kbps

Which stations have data waiting for them. T-L-V with T=5

T-L-V encoded: Type=0

Channel number, etc.

Security, etc.

Interval between beacons in units of 1024 micro-seconds

Time in microseconds for clock synchronization

Ref: Nayarasi, "802.11 Mgmt: Beacon Frame," https://mrncciew.com/2014/10/08/802-11-mgmt-beacon-frame/

Student Questions

- Why do SNR ratios use deciBels over another unit of measurement?

Ratios are divisions. It is easy to deal with ratios on a log scale. dB is a log scale unit.

- Is there a tradeoff between SNR and BER? Is there an extent that an SNR that is too high starts to cause problems (like in machine learning with bias-variance tradeoff)?

SNR = Cause

BER = Effect

Coding and retransmission decide acceptable BER ⇒ SNR

- What kinds of values are stored in SSID's `V`?

Sample SSID values are WUSTL 2.0, WUSTL Guest, Public Free Wi-Fi, etc.

- Can multiple networks have the same SSID? If yes, how would a host be able to tell?

Multiple AP can serve the same SSID, but multiple owners cannot have the same SSID in the same location. Like two different Raj Jains living in my house address.

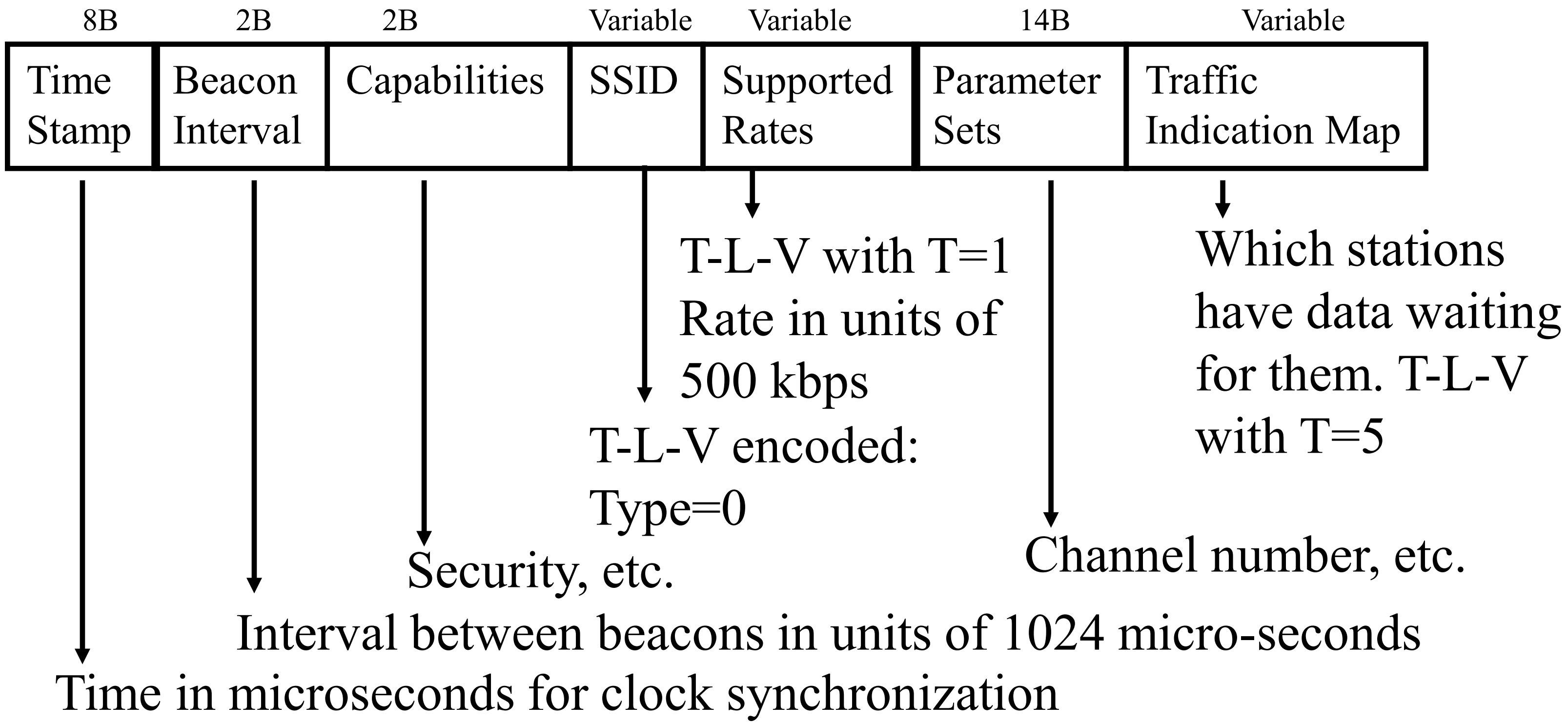
- Could you explain TLV again?

Type-Length-Value.

Example: Type=0, Length=9, Value=WUSTL 2.0

Beacon Frame Format

- Info field in the 802.11 frame (after Address 4)



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Student Questions

- How do you separate T, L, and V from each other in the SSID and Supported Rates fields? If the V has a variable length, how do you know how many bits are required for L?

Type: SSID, Rate, or Map
Length: How many bytes are in the value
Value: Actual value of the field
Example: Student Names
Type: First, Last, Middle, Suffix
Length: 3
Value: Raj

- Can you explain more about capabilities in terms of security?

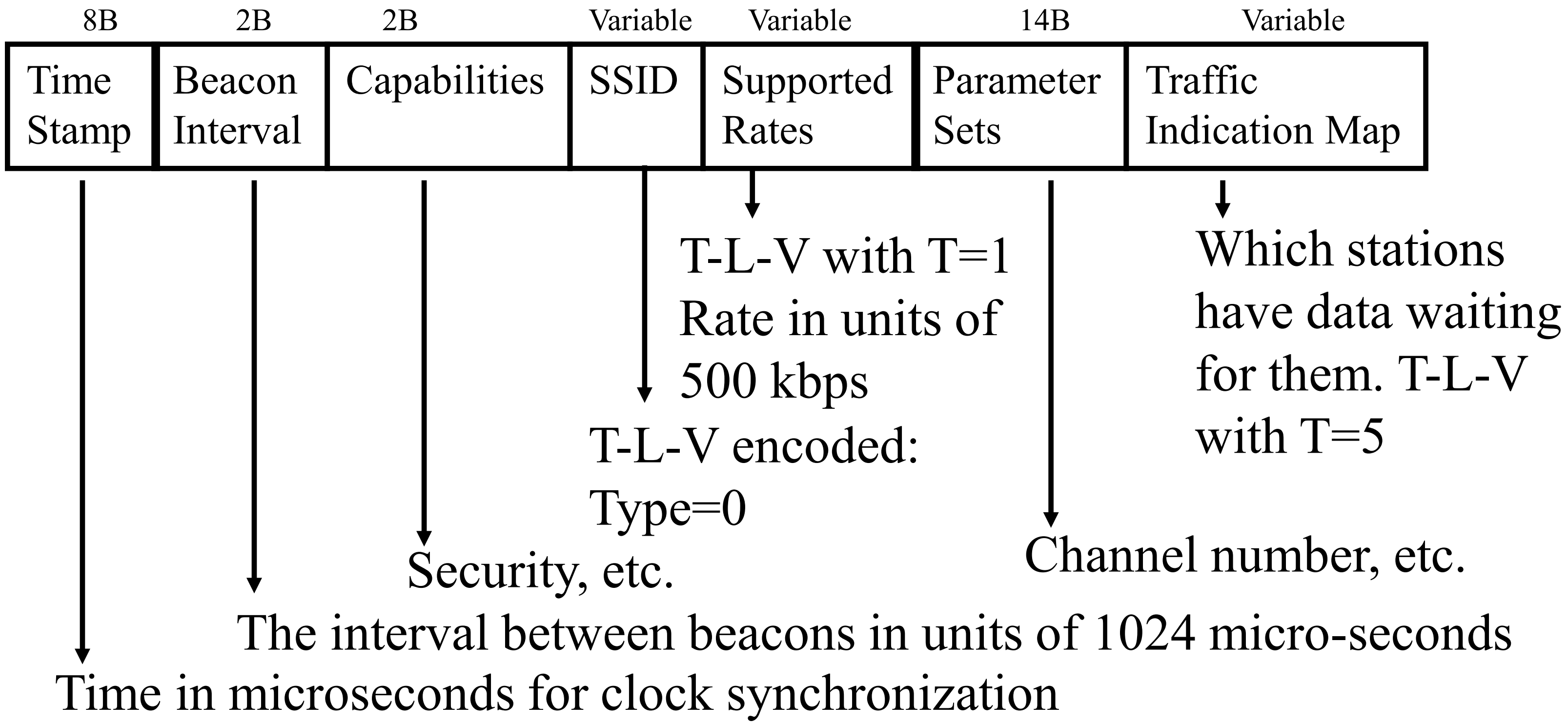
Capabilities: WEP, WPA, WPA2, …

- Can you comment on the tradeoff between SNR and BER?

SNR=Signal to Noise Ratio
BER= Bit Error Rate
Higher noise => Lower Signal to Noise
=> More bit errors
There is no trade-off here. SNR causes BER.

Beacon Frame Format

- ❑ Info field in the 802.11 frame (after Address 4)



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Student Questions

- ❑ Can you go over T-L-V encoding again?

T=L-V={Type, Length, Value}

A vector of 3 elements. The first element is the type, 2nd element is the length, and 3rd element is the value of the field. It is commonly used for variable-length fields. In this slide:

Type:

0=SSID
1=Rate
…
5=Map

Lab 7:WiFi

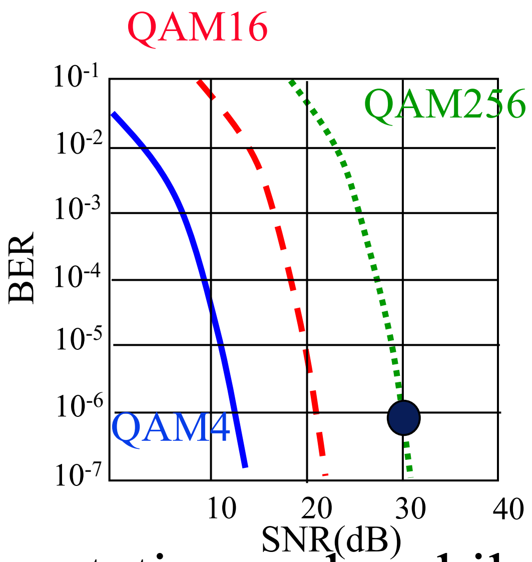
[14 Points] Download the Wireshark traces from http://gaia.cs.umass.edu/wireshark-labs/wireshark-traces.zip

Open *Wireshark_802_11.pcap* in Wireshark. Select **View → Expand All**. Answer the following questions. There is no need to attach screen captures.

1. Frame 1 is a beacon frame. Ignore the first 24 bytes. (The frame control field is 80:00.) What is the SSID of the access point that is issuing this beacon frame?
2. What (in hexadecimal notation) is the source MAC address on Frame 1?
3. What (in hexadecimal notation) is the destination MAC address on Frame 1?
4. What (in hexadecimal notation) is the MAC BSS ID in Frame 1?
5. Frame 50 is a Probe Request, and Frame 51 is a Probe response. What are the sender, receiver, and BSS ID MAC addresses in these frames? What is the purpose of these two types of frames?

Student Questions

802.11 Rate Adaptation



QAM=Quadrature Amplitude Modulation

QAM2^n = n bits/Hz

dB = Deci-Bel

$$= 10 \log_{10} \frac{\text{Power Out}}{\text{Power In}}$$

- The base station and mobile dynamically change transmission rate (physical layer modulation technique) as mobile moves, and SNR varies.
- SNR decreases ⇒BER increases as the node moves away from the base station
- When BER becomes too high, switch to a lower transmission rate but with lower BER

Student Questions

- Why does wireless network coding change due to the BER change?

Use fewer bits per second if BER is high.

- Does the station have to keep track of all mobiles it connects to? Wouldn't that require heavy computation power and storage?

Yes. If you are talking to 5 people at once on a conference call, you need to keep track of who said what.

- Does 20 megahertz a standard? If we want to send things faster in a short time, can we temporarily raise this to 200 or more?

20 MHz is a standard channel width. Some may use more than one channel. Like fitting multiple nodes in a single box.

- Does the "dB" in the slide relate to acoustic units "db"?

dB = deci-Bel

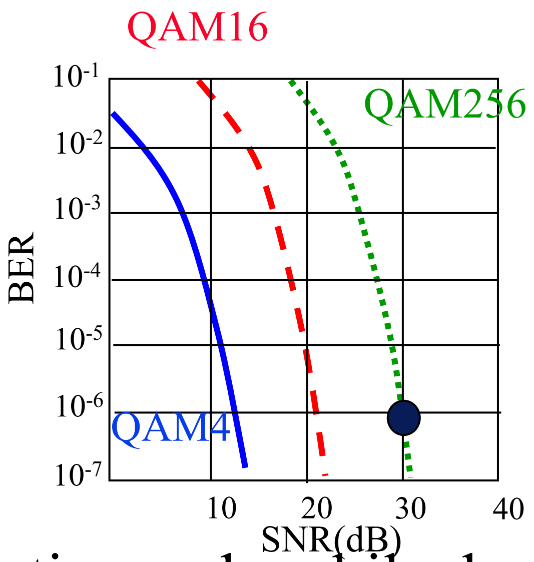
DB = Deca-Bel

B is the name and so always capital.

- How do we maximize SNR?

By increasing the signal power. But that may increase your battery consumption.

802.11 Rate Adaptation



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- ❑ Base station and mobile dynamically change transmission rate (physical layer modulation technique) as mobile moves, SNR varies
- ❑ SNR decreases ⇒BER increase as node moves away from base station
- ❑ When BER becomes too high, switch to lower transmission rate but with lower BER

Student Questions

❑ Is it similar to TCP congestion control?

Not at all.

❑ What causes SNR/BER to change?

If more devices come into the same area, noise increases => SNR decreases.
=> BER increases.

❑ Is there a benefit to measuring the power in log units?

Yes. Everything here multiplies. In log units, they add.

❑ Chapter 7.2: Why does higher SNR result in lower BER?

SNR=Signal/Noise ratio
Higher SNR = Higher Signal or Lower Noise or both
Higher signal results in lower bit errors

Power Management

- ❑ A station can be in one of three states:
  - ➢ Transmitter on
  - ➢ Receiver only on
  - ➢ Dozing: Both transmitter and receivers are off.
- ❑ Access point (AP) buffers traffic for dozing stations.
- ❑ AP announces which stations have frames buffered.
  A traffic indication map is included in each beacon.
  All multicasts/broadcasts are buffered.
- ❑ Dozing stations wake up to listen to the beacon.
  If there is data waiting for it, the station sends a poll frame to get the data.

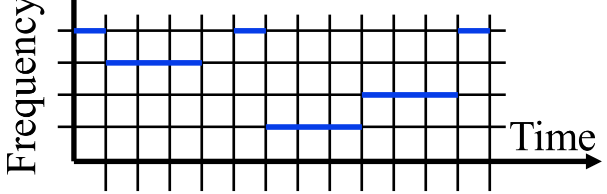
Student Questions

- ❑ How large is the buffer size in AP? Will it be too much data when the station becomes dozing for a long time?

If you doze, you lose. AP will save only a few frames.

Bluetooth

- ❑ Started with Ericsson's Bluetooth Project in 1994
- ❑ Named after Danish king Herald Blatand (AD 940-981) who was fond of blueberries
- ❑ Radio-frequency communication between cell phones over short distances
- ❑ IEEE 802.15.1, approved in early 2002, is based on Bluetooth
- ❑ Key Features:
  - ➢ Lower Power: 10 µA on standby, 50 mA while transmitting
  - ➢ Cheap: $5 per device
- ❑ A piconet consists of a master and several slaves. Master determines the timing and polls slaves for transmission.
- ❑ Frequency hopping spread spectrum



Student Questions

- ❑ Does being the primary node on a piconet have advantages? Since it is coordinating, it will need to spend more energy as far as I can think of, which is bad for that device.

You are right. Only bigger devices can become the primary node. For example, Phone vs. headset. Computer vs. Phone.

- ❑ Is piconet an example of ad-hoc?

No. In ad-hoc, there is no master.

- ❑ Do Bluetooth transmitters use MAC addresses or IP addresses to distinguish each other?

Yes, they use 48-bit IEEE 802 addresses (similar to Ethernet and Wi-Fi).

- ❑ Can the number of participating hosts in a Bluetooth network be more than two?

Yes. You can connect two headsets to some phones at the same time.

- ❑ How does Bluetooth Low Energy (BLE) use even less energy than regular Bluetooth?

Sleep more.

Bluetooth

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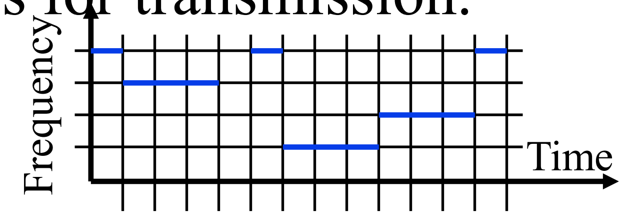


Student Questions

❑ Bluetooth assigns different frequencies to multiple devices.

No. Everyone uses the entire 2.4 GHz band

❑ How wide is the band?

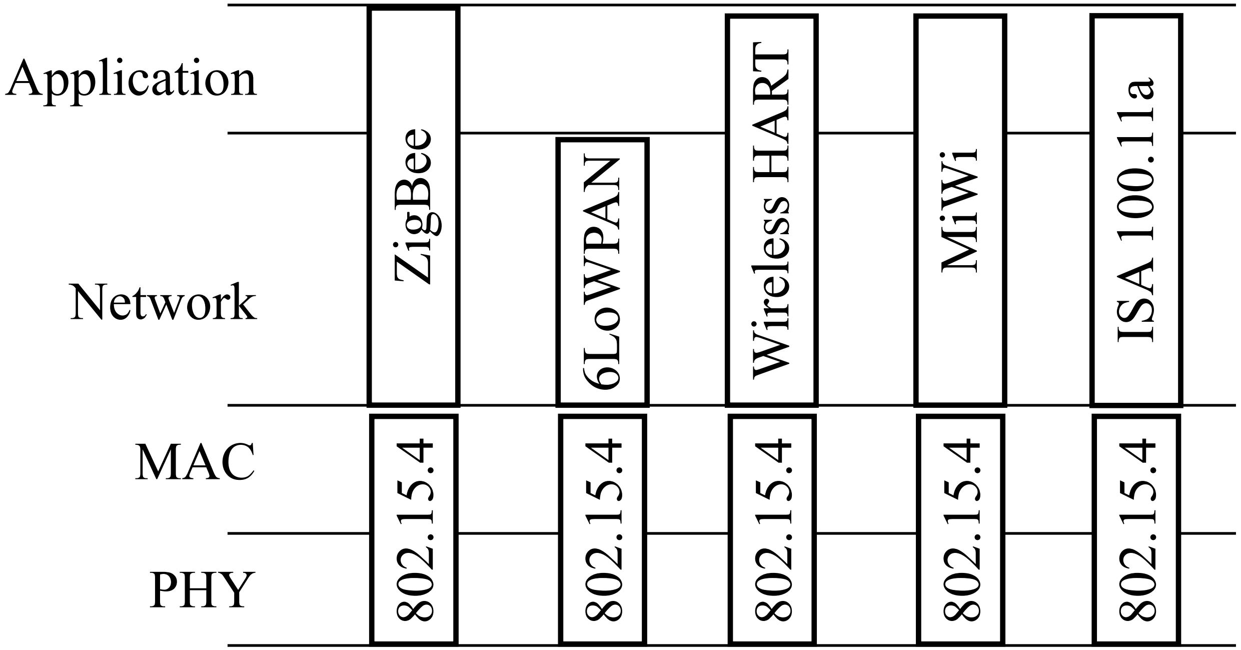
2400-2483.5 MHz

❑ Bluetooth is an example of ad-hoc. However, piconet, based on Bluetooth, is no longer an example of ad-hoc. Is this right?

Ad-hoc = Peer-to-peer with no primary node
Bluetooth nodes dynamically select a primary node.

IEEE 802.15.4

- ❑ Low Rate Wireless Personal Area Network (LR-WPAN)
- ❑ Used by several "Internet of Things" protocols: ZigBee, 6LowPAN, Wireless HART, MiWi, and ISA 100.11a
- ❑ Lower rate, short distance ⇒ Lower power ⇒ Low energy



Application

Network

MAC

PHY

ZigBee | 6LoWPAN | Wireless HART | MiWi | ISA 100.11a

802.15.4 | 802.15.4 | 802.15.4 | 802.15.4 | 802.15.4

Student Questions

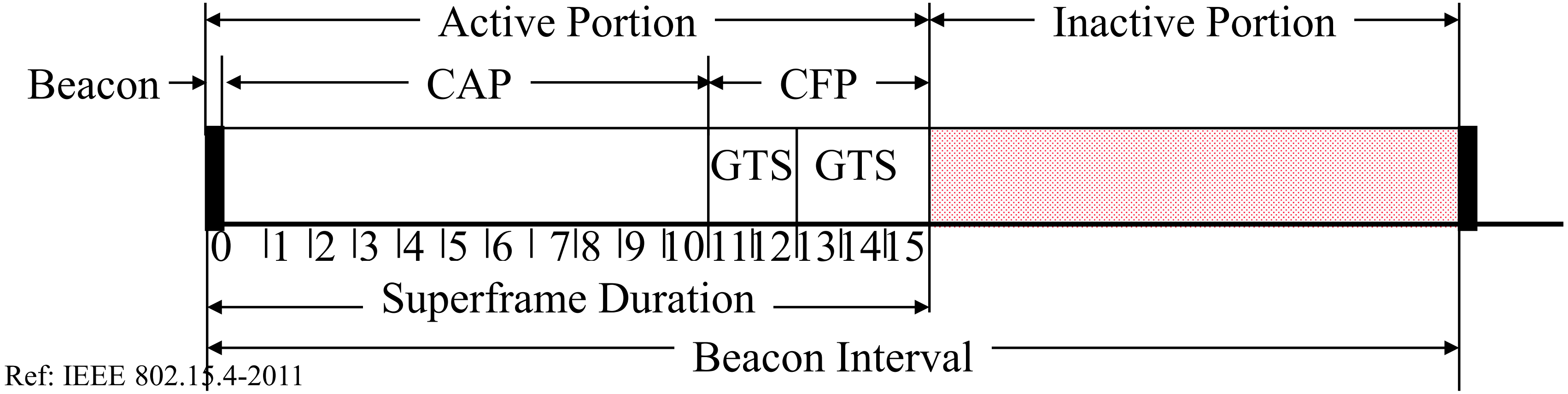
❑ What's the distinction between power and energy?

Power is the rate of Energy usage.
Power is measured in Watts.
Energy is measured in Joules.
Analogy: If you spend $100 per day. You will exhaust your $1000 bank balance in 10 days. The bank balance is the Energy. $100 is your power.

IEEE 802.15.4 MAC

Beacon-Enabled CSMA/CA

- Coordinator sends out beacons periodically
- Part of the beacon interval is inactive ⇒ Everyone sleeps
- Active interval consists of 16 slots
- Contention Access Period (CAP). Slotted CSMA.
- Contention Free Period (CFP)
  - Guaranteed Transmission Services (GTS): For real-time services. Periodic reserved slots.



Ref: IEEE 802.15.4-2011

Student Questions

- What is "superframe duration"?

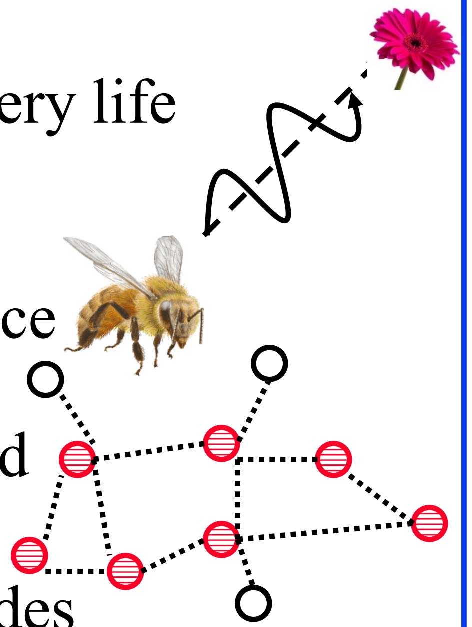
16 slots, as shown.

- Does the coordinator here mean access point?

They call it Hub.

ZigBee Overview

- ❑ Industrial monitoring and control applications requiring small amounts of data, turned off most of the time (<1% duty cycle), e.g., wireless light switches, meter reading
- ❑ Ultra-low power, low-data rate, multi-year battery life
- ❑ **Range**: 1 to 100 m, up to 65000 nodes.
- ❑ IEEE 802.15.4 MAC and PHY.
  Higher layer, interoperability by ZigBee Alliance
- ❑ Named after the zigzag dance of the honeybees
  Direction of the dance indicates location of food
- ❑ Multi-hop ad-hoc mesh network



Multi-Hop Routing: message to non-adjacent nodes

Ad-hoc Topology: No fixed topology. Nodes discover each other

Mesh Routing: End-nodes help route messages for others

Mesh Topology: Loops possible

Ref: ZigBee Alliance, http://www.ZigBee.org

Student Questions

❑ Can you explain more about the difference between Mesh Routing and Mesh Topology?

Routing = Method.
End nodes route other end nodes' packets.

Topology: The nodes are connected not in a star or bus but as a mesh.

It is possible to have all 4 combinations of routing and topologies.

❑ Is the increased distance of ZigBee because of multi-hops? What happens if there are only two nodes 100m apart?

They will each will need enough power to reach 100 m. However, if there are hundreds of nodes, they will each need power to go, say, 1 m and still be able to talk to someone 100m away.

❑ Does this mean that ad-hoc topology can't have a loop?

Dictionary meaning of "ad-hoc" is "created or done as necessary." or not set in advance. They can have loops.

❑ What distinguishes ad-hoc from mesh topology?

Mesh: There is a fixed topology. It may be a linear bus or star, triangle, etc.

ZigBee Overview

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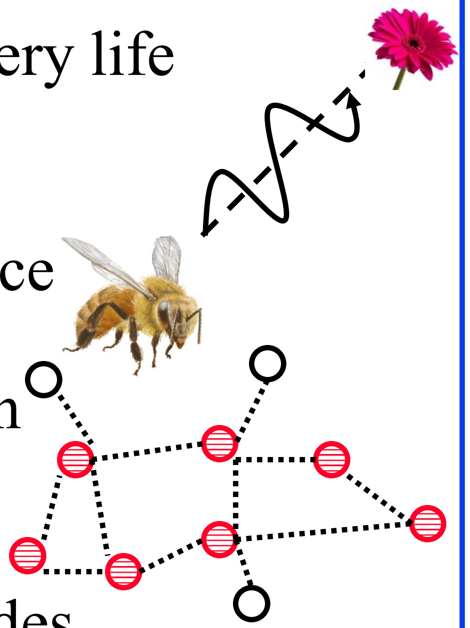

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Ref: ZigBee Alliance, http://www.ZigBee.org

Student Questions

- ❑ How do devices that are turned off most of the time know when to turn themselves back on?

One part of the receiver comes on frequently to listen to beacons. Beacons contain the list of nodes that have frames waiting. That part then wakes up the node, telling the primary to send those frames. After receiving the frame, most of the node goes back to sleep.

Review: Wireless LANs and PANs

1. IEEE 802.11 PHYs: 11, 11b, 11g, 11a, 11n, …
2. IEEE 802.11 MAC uses CSMA/CA with a 4-way handshake: RTS, CTS, data, and ack
3. IEEE 802.11 network consists of ESS consisting of multiple BSSs, each with an AP.
4. 802.11 Frame Format may have up to 4 addresses and includes the final destination's MAC which may not be wireless
5. Power management allows stations to sleep.
6. Bluetooth uses frequency hopping spread spectrum.
7. IEEE 802.15.4 PHY layer allows coordinators to schedule transmissions of other nodes
8. ZigBee uses IEEE 802.15.4

Ref: Section 7.3, Review Exercises R5-R12

Student Questions

❑ If APs buffer traffic for dozing stations, do the APs also send TCP acks on behalf of the dozing stations? If not, then it seems like there will be a lot of timeouts and redundant TCP segments.

No APs are MAC-layer devices. They do not understand L3 or L4 and do not send any TCP acks. They may send L2 MAC Acks. Stations should wake up frequently enough to avoid TCP timeouts if they have a TCP connection.

❑ Does Zigbee also use frequency hopping?

Yes.

Cellular Networks

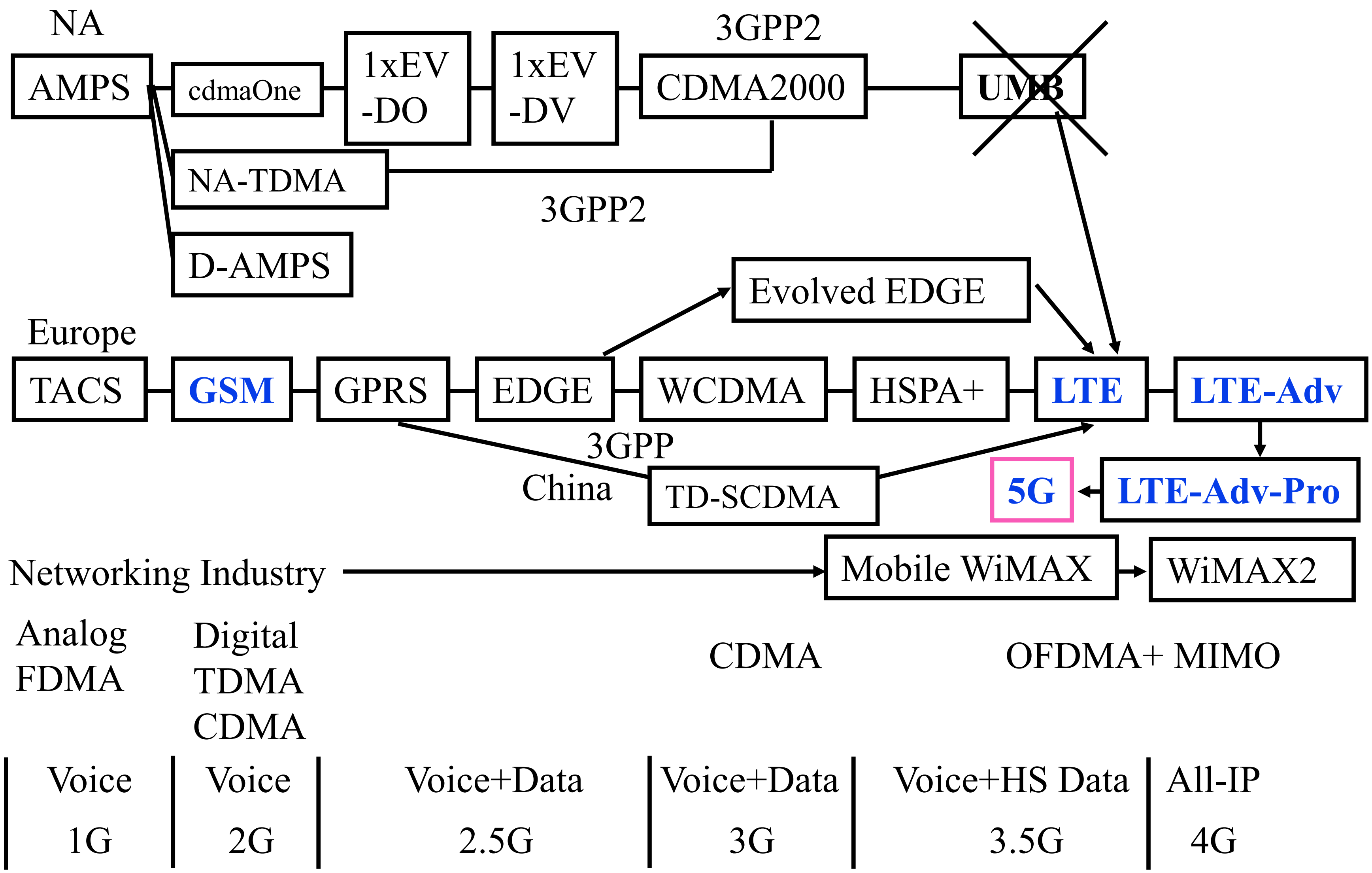
- ❑ Evolution of Cellular Technologies
- ❑ GSM Cellular Architecture
- ❑ Evolved Packet System (EPS)

Student Questions

- ❑ Why is it called "cellular"? from the topology?

Yes. They divide the area into cells.

Cellular Telephony Generations



NA

AMPS

cdmaOne

1xEV -DO

1xEV -DV

3GPP2

CDMA2000

~~UMB~~

NA-TDMA

3GPP2

D-AMPS

Evolved EDGE

Europe

TACS

GSM

GPRS

EDGE

WCDMA

HSPA+

LTE

LTE-Adv

3GPP

China

TD-SCDMA

5G

LTE-Adv-Pro

Networking Industry

Mobile WiMAX

WiMAX2

Analog
FDMA

Digital
TDMA
CDMA

CDMA

OFDMA+ MIMO

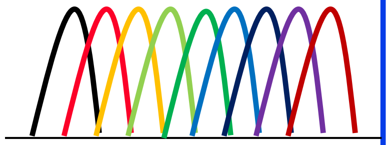
Voice	Voice	Voice+Data	Voice+Data	Voice+HS Data	All-IP
1G	2G	2.5G	3G	3.5G	4G

Student Questions

- ❑ Could you briefly explain what OFDMA is?

Orthogonal Frequency Division Multiplexing

A large number of subcarriers are orthogonal (all others are zero when one peak). A user is assigned several subcarriers.



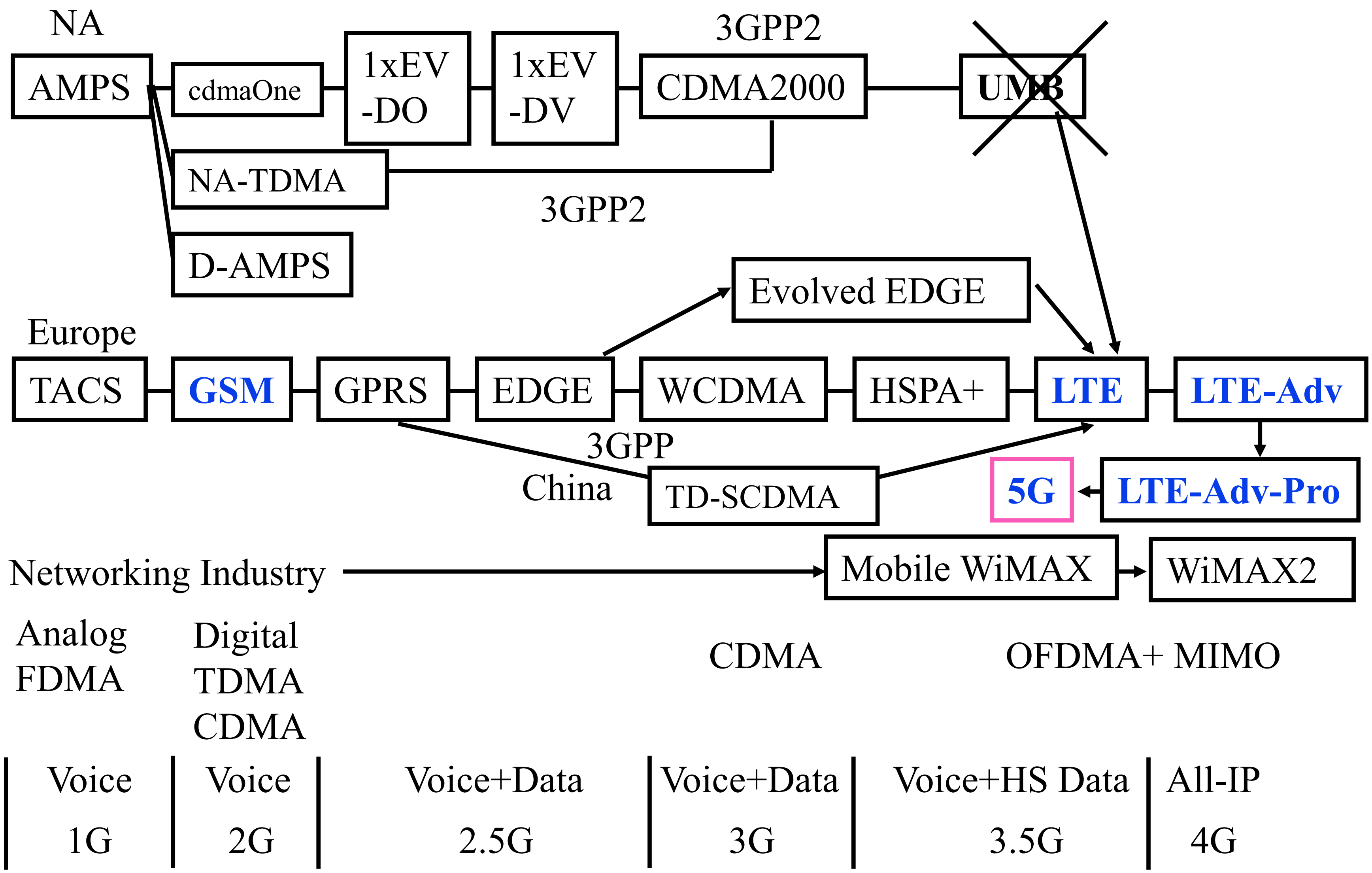
- ❑ Regardless of the correction, is analog faster than digital? Since it doesn't need to convert the waveform to 0 or 1, then translate them back to the waveform signal.

The signal travels at the same speed regardless of analog or digital. If you mean analog is "less complex," then yes, analog is less complex, but it loses a lot more information a lot faster.

- ❑ What is TD-SCDMA? Is it only used by China?

Yes.

Cellular Telephony Generations



NA

AMPS

cdmaOne

1xEV -DO

1xEV -DV

3GPP2

CDMA2000

~~UMB~~

NA-TDMA

3GPP2

D-AMPS

Evolved EDGE

Europe

TACS

GSM

GPRS

EDGE

WCDMA

HSPA+

LTE

LTE-Adv

3GPP

China

TD-SCDMA

5G

LTE-Adv-Pro

Networking Industry

Mobile WiMAX

WiMAX2

Analog
FDMA

Digital
TDMA
CDMA

CDMA

OFDMA+ MIMO

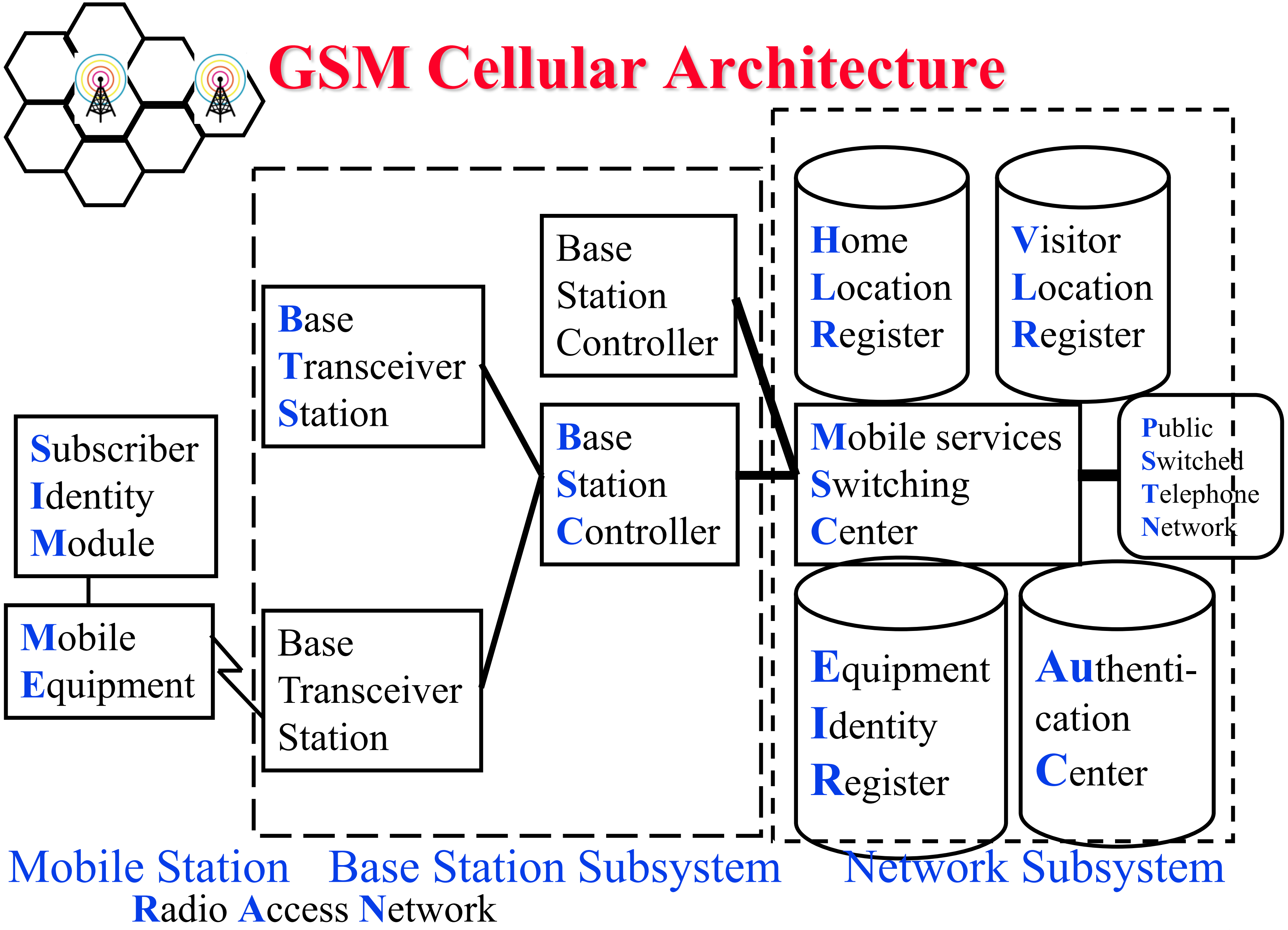
Voice	Voice	Voice+Data	Voice+Data	Voice+HS Data	All-IP
1G	2G	2.5G	3G	3.5G	4G

Student Questions

❑ In general, does 5G still use OFDMA+MIMO?

Yes. The main change is in the use of IP and smaller cells.

GSM Cellular Architecture



Student Questions

- ❑ Does each carrier have its PSTN, or do all share a common PSTN?

Each carrier is supposed to have its PSTN. However, increasingly they have started sharing using SDN or other virtualization techniques.

- ❑ So whatever device has my SIM card gains access to that provider's network, or do you need to configure it somehow?

Any device should be able to use any SIM cards. However, many carriers restrict phone SIMs to phones and do not allow them to be used on iPad. This is against the original intent of SIM.

Cellular Architecture (Cont.)

- Base station controller (BSC) and Base transceiver station (BTS)
- One BTS per cell.
- One BSC can control multiple BTS.
  - Allocates radio channels among BTSs.
  - Manages call handoffs between BTSs.
  - Controls handset power levels
- Mobile Switching Center (MSC) connects to PSTN and switches calls between BSCs. Provides mobile registration, location, and authentication. Contains Equipment Identity Register.

Student Questions

- What is the unit of BER?

BER is dimensionless. It is the ratio of bits in error to the total bits sent.

Cellular Architecture (Cont.)

- Home Location Register (HLR) and Visitor Location Register (VLR) provide calls routing and roaming
- VLR+HLR+MSC functions are generally in one equipment
- Equipment Identity Register (EIR) contains a list of all valid mobiles.
- Authentication Center (AuC) stores the secret keys of all SIM cards.
- Each handset has an International Mobile Equipment Identity (IMEI) number.

Student Questions

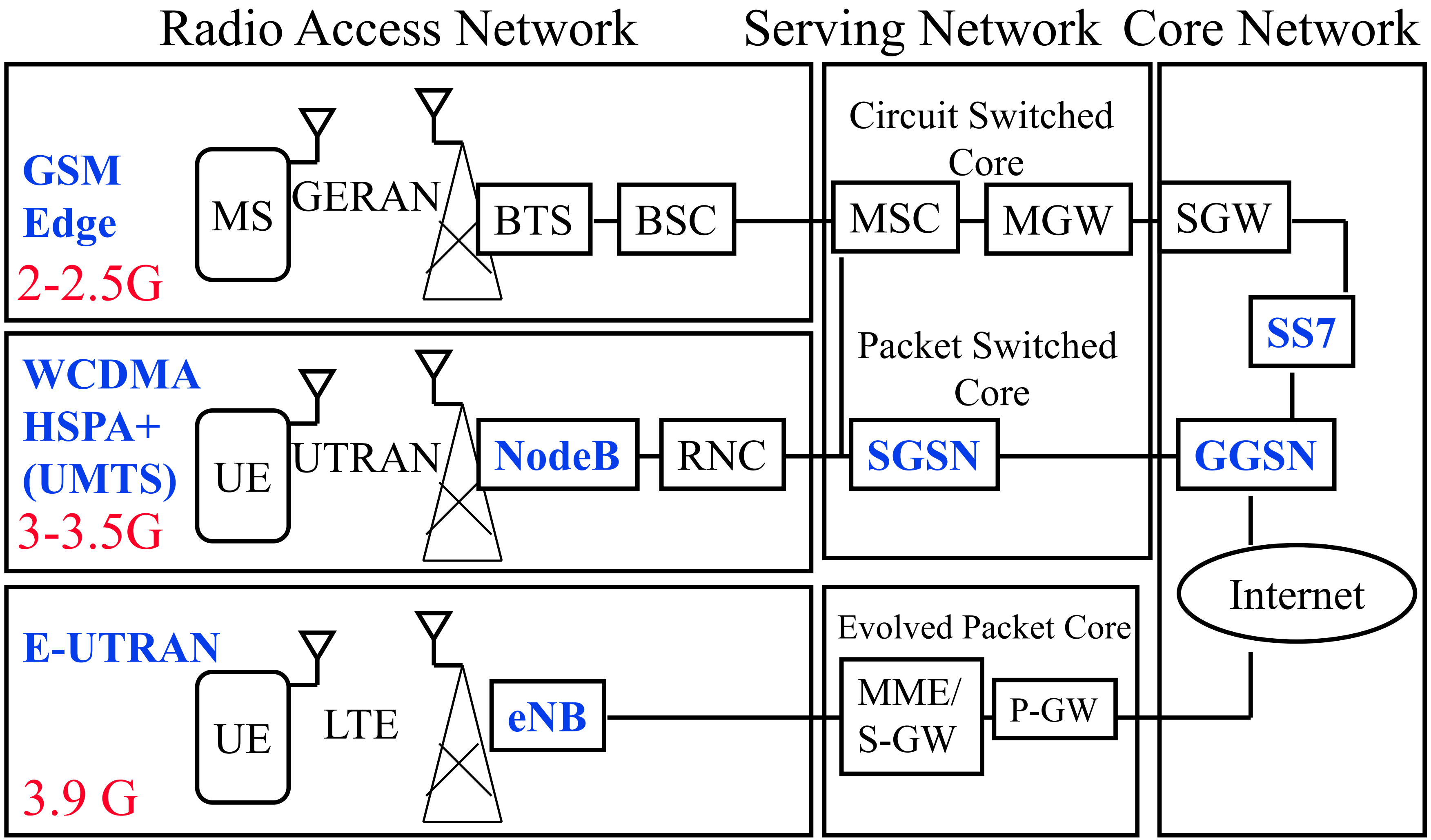
- So LTE is not like 3G, or 3.5G, but it is more like a Radio access network, like UTRAN *or GERAN?*

LTE is 3.9G. Each Generation uses a different technique in its "Radio Access Networks" (RAN). UTRAN and GERAN are examples of RAN.

- How can my host get IP in a cellular network?

The cellular network now provides IP services (e.g., DHCP, routing using IP addresses) and traditional phone services that do not use the IP address.

Evolved Packet System (EPS)



Student Questions

- ❑ As LTE is 3.5G, why did you put it in positions like GERAN and UTRAN?

LTE is 3.9G. I have corrected the previous slide.

- ❑ Is the final connection to the Internet typically via Ethernet?

PPP=Point-to-point protocol

Review: Cellular Networks

1. 1G was Analog voice, 2G was Digital voice, 3G was CDMA with voice and high-speed data, 4G is high-speed data
2. A cellular system has a RAN with BTS, BSC and a network subsystem with HLR, VLR, MSC, EIR, and AuC
3. 3G replaced RAN with UTRAN and BTS with NodeB. 4G uses eNB.

Ref: Section 7.4, Review Exercises R14-R17

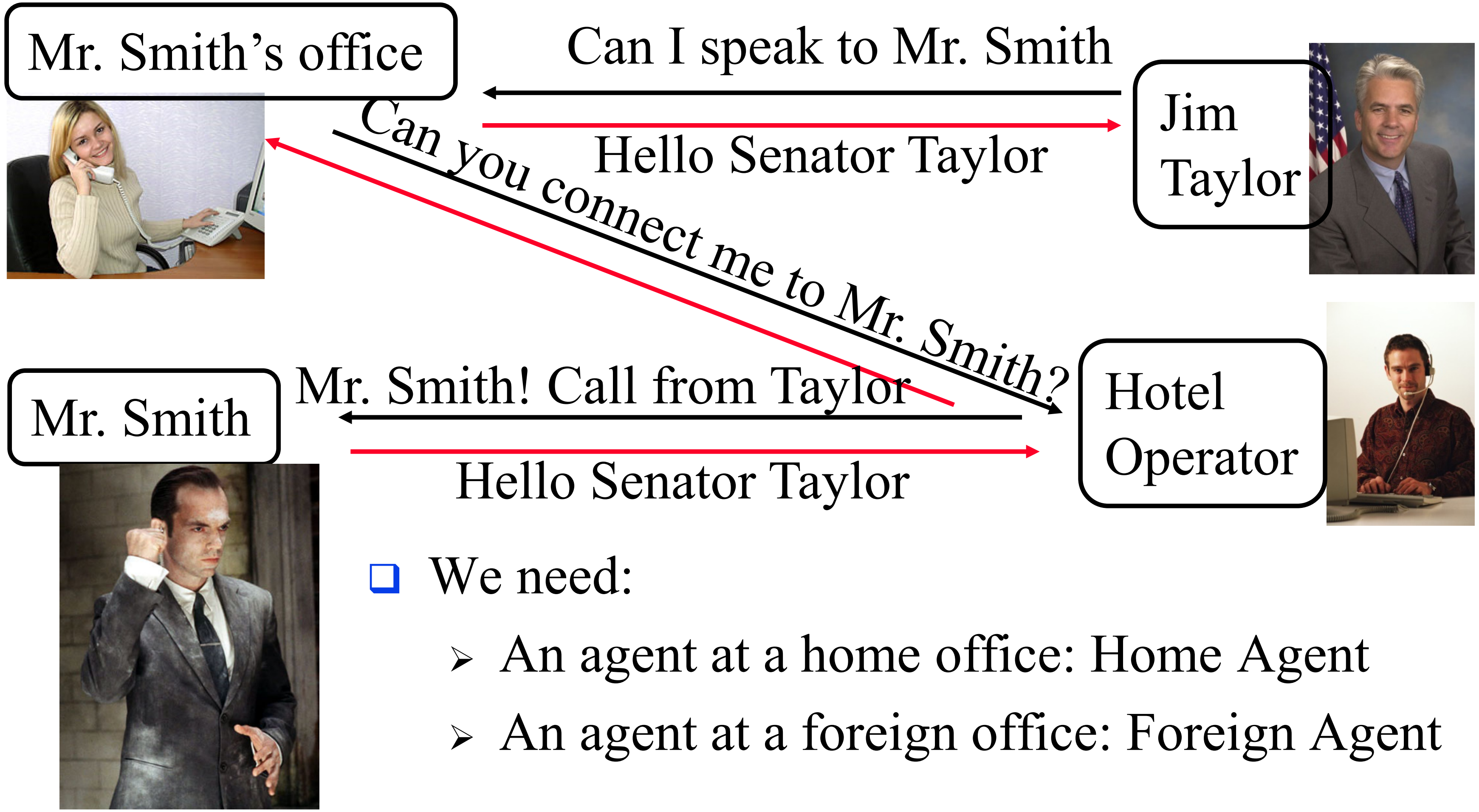
Student Questions

Mobility Management

- Mobile IP
- GSM: Routing to Mobile
- GSM Handoff
- Mobility: GSM versus Mobile IP

Student Questions

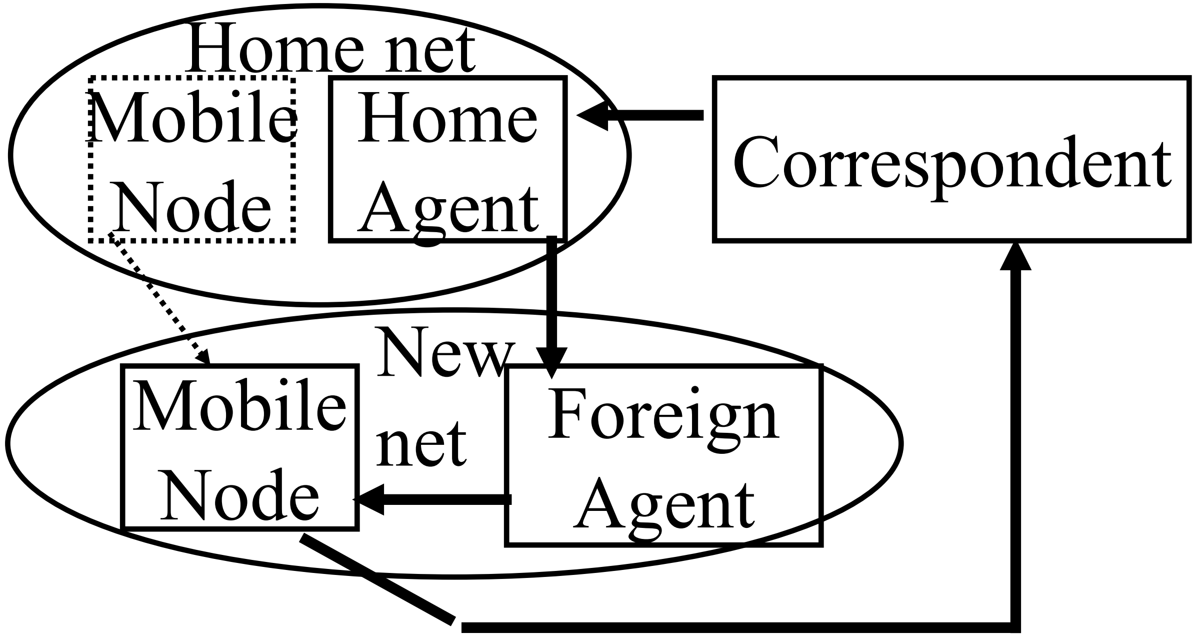
Mobility: Mr. Smith Goes to Washington

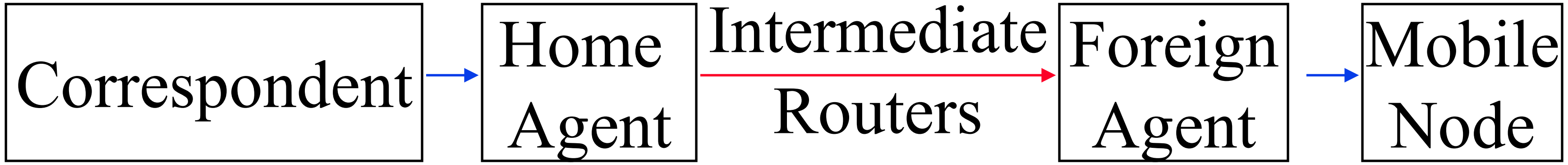


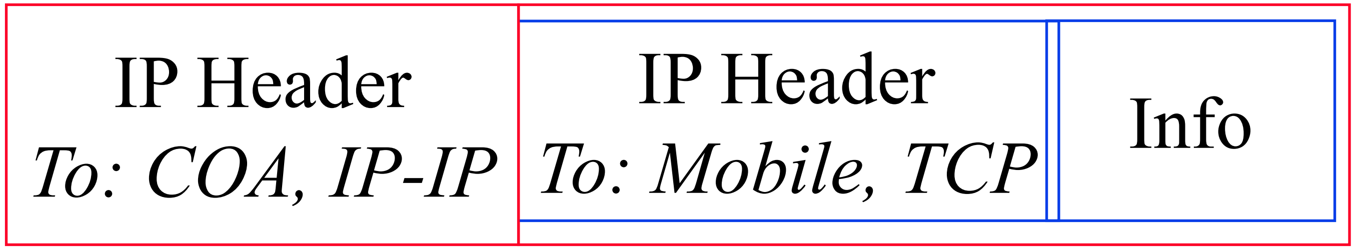
- We need:
  - An agent at a home office: Home Agent
  - An agent at a foreign office: Foreign Agent

Student Questions

Mobile IP: Mechanisms







Student Questions

- ❑ What is the difference between GSM and GPRS?

Original GSM was designed for digital voice. GPRS is an improvement to GSM for digital data transmission.

Mechanism (Cont.)

- ❑ Mobile node finds foreign agents via solicitation or advertising
- ❑ Mobile registers with the foreign agents and informs the home agent
- ❑ The home agent intercepts the mobile node's datagrams and forwards them to the care-of-address
- ❑ Care-of-address (COA): Address of the end-of-tunnel towards the mobile node. It may or may not be a foreign agent.
- ❑ At COA, the datagram is extracted and sent to mobile.

Student Questions

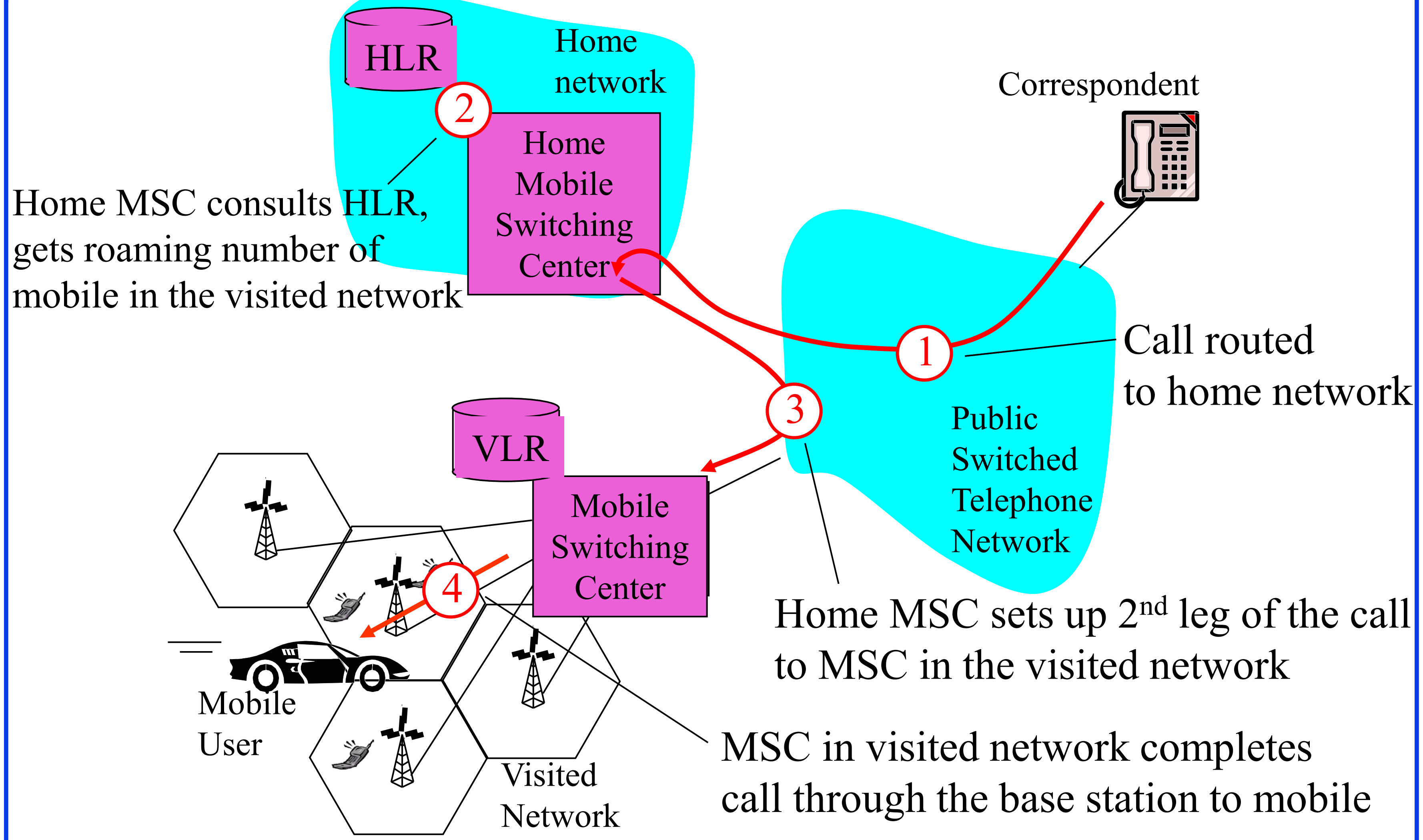
❑ Where does the home agent forward the message if the mobile device is not "home"?

The home agent's job is to keep track of the mobile. (It is like your secretary, girl/boyfriend, wife/husband.)

❑ How does my home agent know I am on vacation?

See above.

GSM: Routing to Mobile



Home MSC consults HLR, gets roaming number of mobile in the visited network

Call routed to home network

Home MSC sets up 2nd leg of the call to MSC in the visited network

MSC in visited network completes call through the base station to mobile

Student Questions

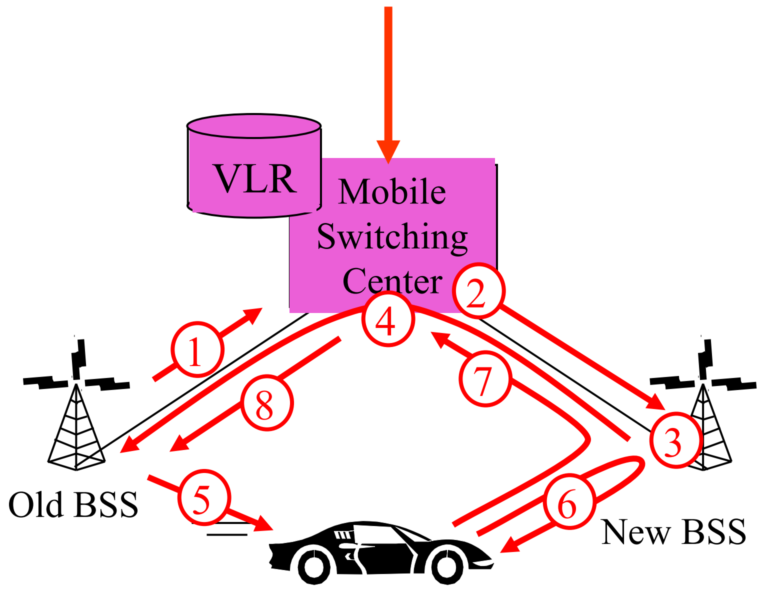
- ❑ Could you go over the example again?

Sure.

- ❑ What is the second leg of the call?

It happens all in the home area. It consists of Home MSC consulting HLR.

GSM: Handoff with Common MSC

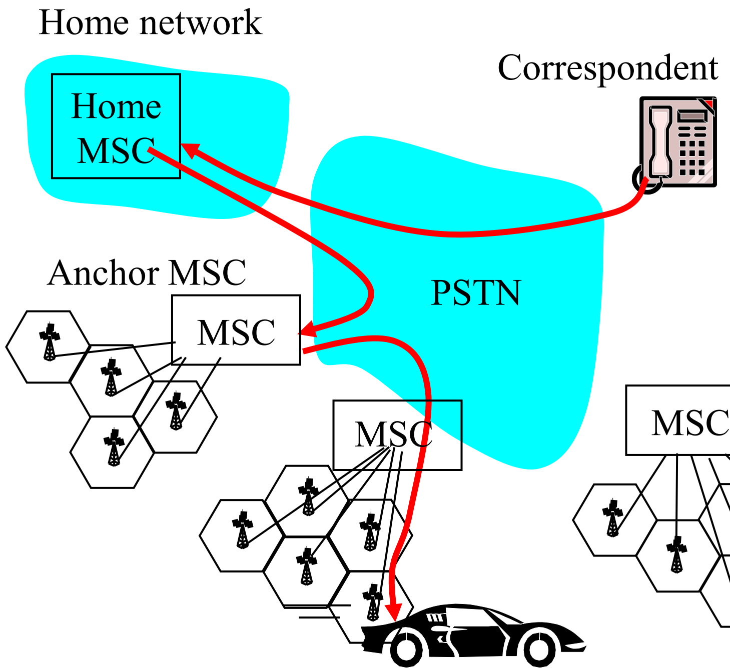


1. Old BSS informs MSC of impending handoff, provides a list of 1$^+$ new BSSs
2. MSC sets up a path (allocates resources) to new BSS
3. New BSS allocates radio channel for use by mobile
4. New BSS signals MSC, old BSS: ready
5. Old BSS tells mobile: perform handoff to new BSS
6. Mobile, new BSS signal to activate the new channel
7. Mobile signals via new BSS to MSC: handoff complete. MSC reroutes call

8 MSC-old-BSS resources released

Student Questions

GSM: Handoff between MSCs



- ❑ *Anchor MSC:* first MSC visited during call
  - ➢ Call remains routed through anchor MSC
- ❑ New MSCs add on to end of MSC chain as mobile moves to new MSC
- ❑ IS-41 allows optional path minimization step to shorten multi-MSC chain

Student Questions

- ❑ What is the minimization step that the IS-41 provides to shorten the Multi MSC chain?

You can bypass many intermediate hops and go straight to the mobile. In the original method, the call went through each tower that you visited during that call.

Review: Mobility Management

- Mobile IP uses Home Agent as an Anchor.
  Packets are tunneled from Home Agent to Care-of-Address
- GSM uses HLR and VLR for mobility. All packets are routed through the home network.
- Handoff between towers in a single network is done through MSC.

Ref: Sections 7.6 and 7.7, Review Exercises R18-R20

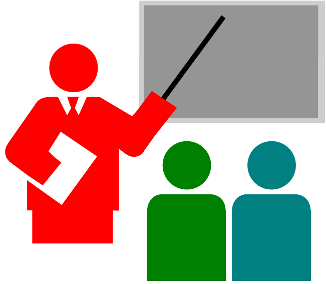
Student Questions

Impact on Higher Layer Protocols

- Layered Architecture ⇒ Upper layers are independent of lower layers
- Wireless ⇒ High error rate ⇒ Frequent packet losses
  ⇒ Triggers TCP congestion control even if there is no overload
- TCP modifications:
  - Local Recovery: Link-level retransmissions and error correction
  - Wireless-aware TCP Sender:
    Distinguish overload (sustained) and random errors
  - Split-Connection: Host1-to-AP + AP-to-Host2

Student Questions

Summary



1. Code division multiple access "was" commonly used in wireless networks
2. IEEE 802.11 uses CSMA/CA with RTS, CTS, data, and ack. A frame may have up to 4 addresses.
3. Bluetooth and ZigBee are PANs that use very little energy
4. Cellular networks have evolved from analog voice to digital voice and finally to high-speed data.
5. Mobile IP uses home agents as anchors.
6. Cellular networks use MSCs to manage mobility.
7. Frequent packet losses due to errors may confuse TCP as network congestion.

Student Questions

□ Is the FHSS not popular as OFDMA?

OFDMA is the latest.

□ What is the range of frequency hopping? Will it be within microwave bandwidth of around 2.4GHz?

Yes, the entire 2.4 GHz band is used for frequency hopping.

□ If I were to trace a route from my PC to Google, is there a way to determine where connections were wireless and wired?

You can do a traceroute. But it does not tell you the speed or technology on any hop.

□ Could you explain the significance of spreading the spectrum using code?

Code-division multiple access (CDMA) allows multiple senders to speak simultaneously without interfering.

CSE 574S: Wireless and Mobile Networking

1. How is wireless different from wired communication?
2. What are the protocols that are used in **IoT**?
3. Why do we need new protocols for IoT?
4. How does **WiFi** work? How 10 Mbps to 10 Gbps?
5. How is **Bluetooth** different from WiFi?
6. How is **ZigBee** different from WiFi?
7. What are other newer wireless protocols for IoT? LORAWAN
8. What is the basic difference between 1G/2G/3G/4G/5G
9. What new features came in with **4G**?
10. What new techniques enabled **5G**?
11. What about 6G? When and how?

Student Questions

Acronyms

1xEV-DO	1 times Evolution to Data Only
1xEV-DV	1 times Evolution to Data and Voice
3GPP1	3rd Generation Partnership Project
6LowPAN	IPv6 over Low Power Personal Area Networks
ACK	Acknowledgement
AMPS	Advanced Mobile Phone System
AP	Access Point
BER	Bit Error Rate
BSA	Basic Service Area
BSC	Base station controller
BSS	ID Basic Service Set Identifier
BTS	Base transceiver station
CA	Collision Avoidance
CAP	Contention Access Period
CDMA	Code Division Multiple Access
CEPT	Committee of European Posts and Telecom

Student Questions

Acronyms (Cont)

CFP	Contention Free Period
COA	Care-Of-Address
CRC	Cyclic Redundancy Check
CSMA	Carrier Sense Multiple Access
CTS	Clear to Transmit
D-AMPS	Digital Advanced Mobile Phone System
dB	Deci-Bel
DCN	Data Communication Network
DHCP	Dynamic Host Control Protocol
DIFS	Distributed Inter-Frame Spacing
DSSS	Direct Sequence Spread Spectrum
E-UTRAN	Evolved UTRAN
EDGE	Enhanced Data rate for GSM evolution
EGPRS	Enhanced GPRS
EIA	Electronic Industry Association
EIR	Equipment Identity Register

Student Questions

Acronyms (Cont)

eNB	evolved Node B
ESA	Extended Service Area
ESS	Extended Service Set
FCC	Federal Communications Commission
FDMA	Frequency Division Multiple Access
GERAN	GSM Enhanced Radio Access Network
GGSN	Gateway GPRS Support Node
GHz	Giga-Hertz
GPRS	General Packet Radio Service
GSM	Global System for Mobile Communications
GTS	Guaranteed Transmission Service
GW	Gateway
HART	Highway Addressable Remote Transducer Protocol
HLR	Home Location Register
HSPA	High Speed Packet Access
HSPDA	High Speed Packet Download Access

Student Questions

Acronyms (Cont)

ID	Identifier
IEEE	Institution of Electrical and Electronics Engineers
IFS	Inter-frame space
IMEI	International Mobile Equipment Identity
IP	Internet Protocol
IS	International Standard
ISA	International Society of Automation
ISDN	Integrated Switched Digital Network
kW	Kilo-Watt
LAN	Local Area Network
LR	Long-Range
LTE	Long-Term Evolution
mA	Milli-Ampere
MAC	Media Access Control
MANET	Mobile Ad-hoc Network
MGW	Media Gateway

Student Questions

Acronyms (Cont)

MHz	Mega Hertz
MIMO	Multiple Input Multiple Output
MME	Mobility Management Entity
MS	Mobile Subscriber
MSC	Mobile Switching Center
mW	Milli-Watt
NA	North America
NAT	Network Address Translator
NodeB	Node B (Base Station)
PAN	Personal Area Network
PC	Personal Computer
PHY	Physical Layer
PIFS	Point-Coordination Inter-Frame Spacing
PSTN	Public Switched Telephone Network
QAM	Quadrature Amplitude Modulation

Student Questions

Acronyms (Cont)

RAN	Radio Access Network
RNC	Radio Network Controller
RTS	Ready to send
SCDMA	Synchronous CDMA
SGSN	Service GPRS Support Node
SGW	Serving Gateway
SIFS	Short Inter-Frame Spacing
SIM	Subscriber Identification Module
SNR	Signal to Noise Ratio
SS7	Signaling System 7
SSID	Service Set Identifier
SYN	Synchronizing Frame
TACS	Total Access Communications System
TCP	Transmission Control Protocol
TD-SCDMA	Time Duplexed Synchronous Code Division Multiple Access
TDMA	Time Division Multiple Access

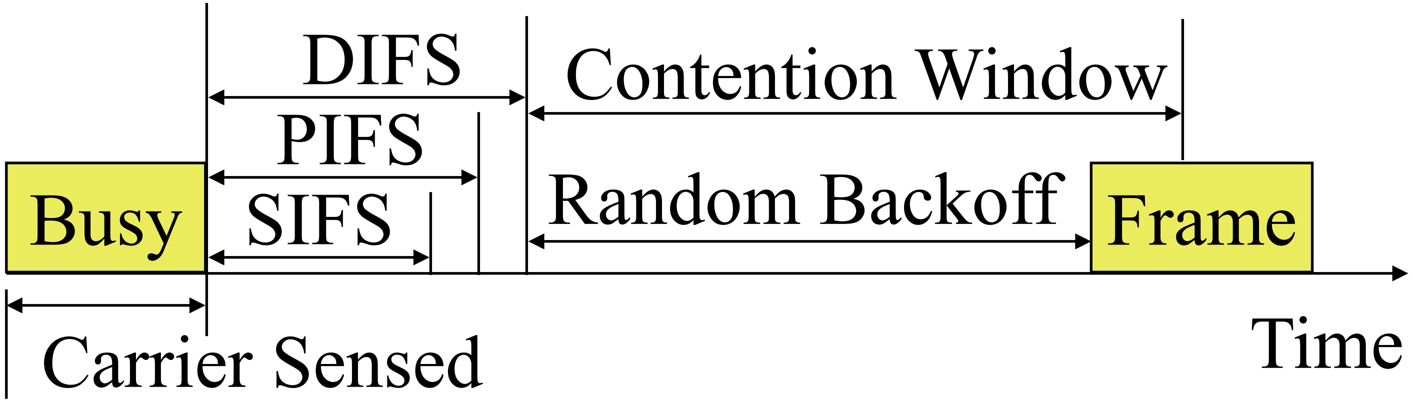
Student Questions

Acronyms (Cont)

TIA	Telecom Industry Association
TV	Television
UE	User Element
UK	United Kingdom
UMB	Ultra Mobile Broadband
UMTS	Universal Mobile Telecommunications System
UTRAN	UMTS Terrestrial Radio Access Network
VANET	Vehicular Ad-hoc Network
VLR	Visitor Location Register
WCDMA	Wide-band CDMA
WEP	Wired Equivalend Privacy
WiFi	Wireless Fidelity
WPAN	Wireless Personal Area Network

Student Questions

IEEE 802.11 Priorities



- Initial inter-frame space (IFS)
- Highest priority frames, e.g., Acks, use short IFS (SIFS)
- Medium priority time-critical frames use "Point Coordination Function IFS" (PIFS)
- Asynchronous data frames use "Distributed coordination function IFS" (DIFS)

Student Questions

- Chapter 7.3.2: How is the value for DIFS and SIFS decided? I know they are determined in the standards, but how are the values computed?

They are based on the distances to be covered by the networks and the precision of timers.

4G/5G

1. LTE architecture and protocol stack
2. Media Access Method used in 4G/5G
3. Mobile-Base station communications and handover
4. 5G performance requirements

Student Questions

LTE vs. 4G

Long-**T**erm **E**volution. 3GPP Release 8, 2009.

1. **LTE is 3.9G** (Pre-4G) cellular technology
   Sold as 4G by some providers (and by our textbook authors)

- ❑ **4G** = International Mobile Telecommunication (IMT) Advanced. Requirements in ITU M.2134-2008
- ❑ IP-based packet switch network
- ❑ 1.0 Gbps peak rate for fixed services with 100 MHz
- ❑ 100 Mbps for mobile services. High mobility to 500 km/hr

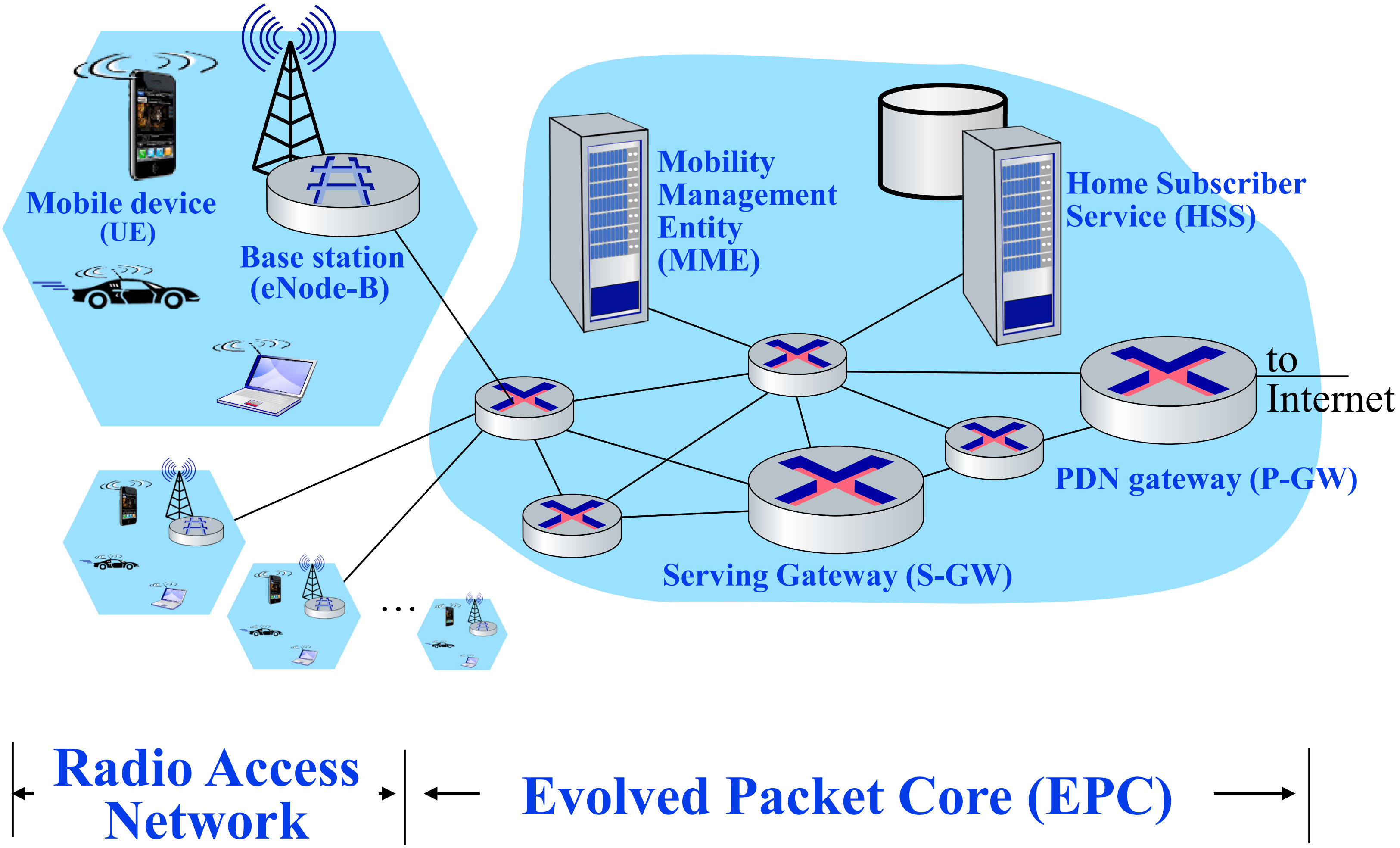
Feature	**Cell**	**Cell Edge**	**Peak**
DL Spectral Efficiency (bps/Hz)	2.2	0.06	15
UL Spectral Efficiency (bps/Hz)	1.4	0.03	6.75

- ❑ Seamless connectivity and global roaming with smooth handovers
- ❑ ITU has approved **LTE-Advanced** as 4G (Oct 2010)

Student Questions

LTE Architecture:

- Evolved Packet Systems (EPS)



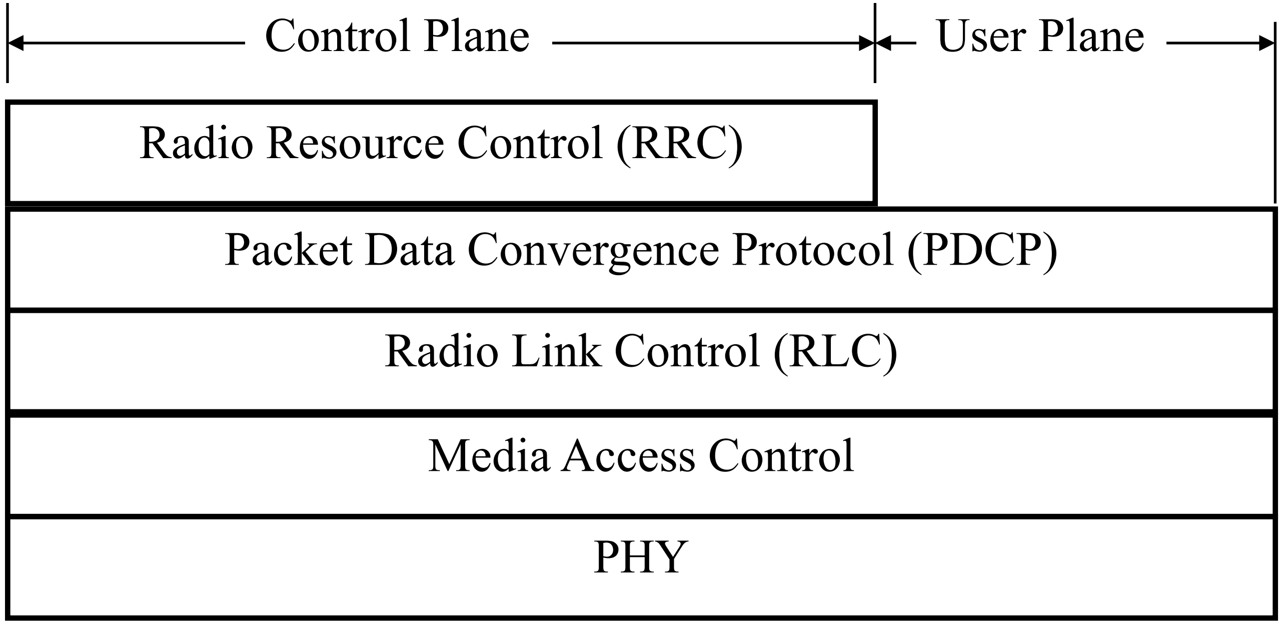
Student Questions

Evolved Packet System

- **User Equipment (UE):** Mobile device, phone, sensors, …
- **Enhanced Node B (eNodeB):** Base Station. Similar to Wi-Fi AP. Coordinates with nearby base stations to optimize radio
- **Serving Gateway**: Demarcation point between RAN and Core. Serves as mobility anchor when terminals move
- **Packet Data Network Gateway (PGW)**: Termination of EPC towards Internet or IMS network. IP services, address allocation, deep packet inspection, policy enforcement
- **Mobility Management Entity (MME)**: Location tracking, paging, roaming, and handovers. All control plane functions related to subscriber and session management.
- **Policy and Charging Rules Function (PCRF)**: Manages QoS (not shown)

Student Questions

LTE Protocol Stack



- **Radio Resource Control (RRC):** Control plane functions of Paging, Connection, Disconnection, Mobility Management, QoS Management

Student Questions

Packet Data Convergence Protocol (PDCP)

1. **Header compression** using IETF Robust Header Compression (ROHC)
2. **Integrity** Protection of control plane data using Message Authentication Code (MAC)
3. **Ciphering** (Encryption)
4. **In-sequence delivery** and duplicated elimination

Student Questions

Radio Link Control Layer

1. Segmentation and Reassembly
2. Aggregation (Concatenation)
3. Re-order out-of-order PDUs, ARQ.

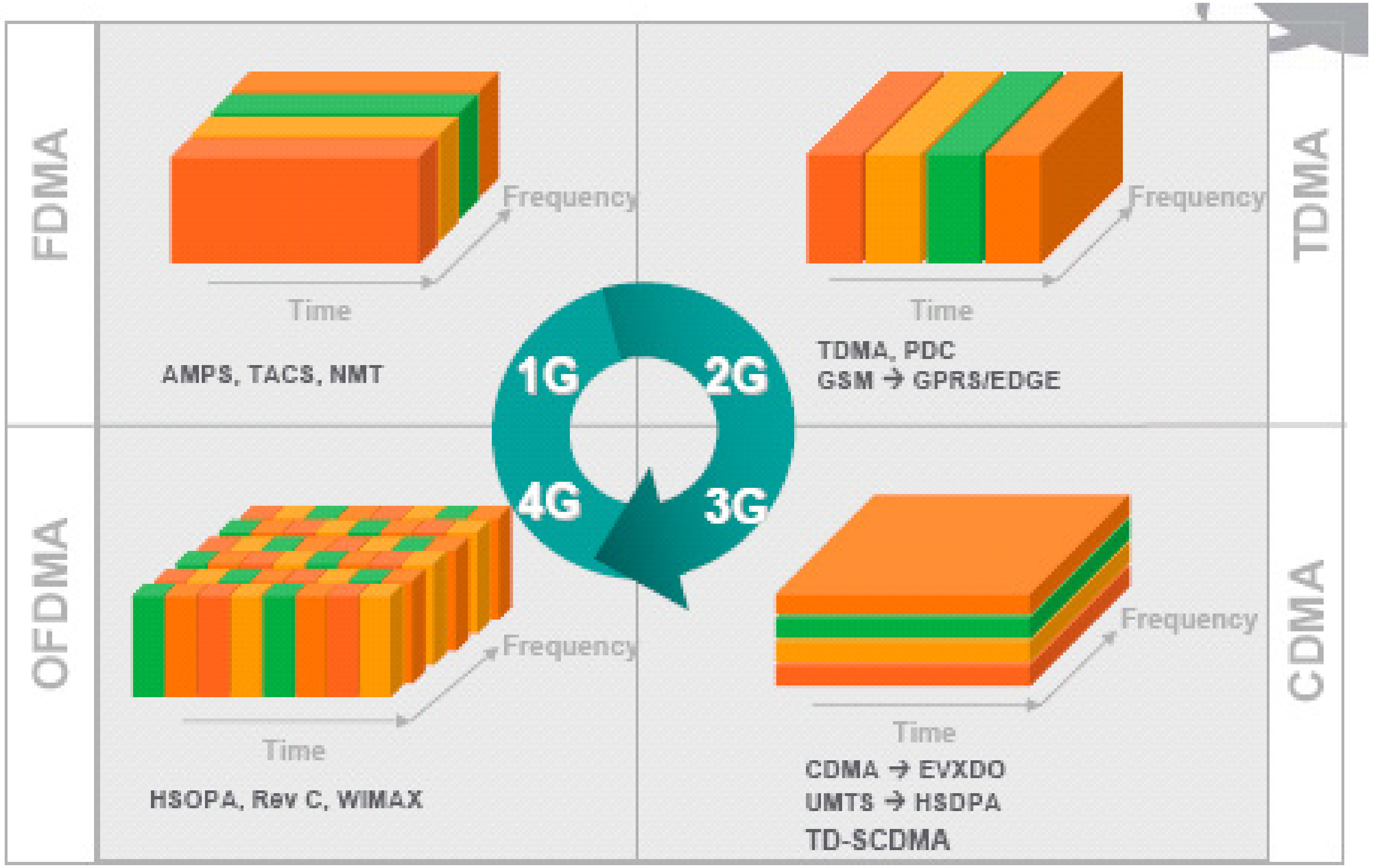
Student Questions

Media Access Control (MAC)

1. Multiplexing of various control and transport channels
2. Transmission scheduling
3. Error control (retransmissions)

Student Questions

Multiple Access Methods



Source: Nortel

Student Questions

- ❑ What's the speed difference among these generations?

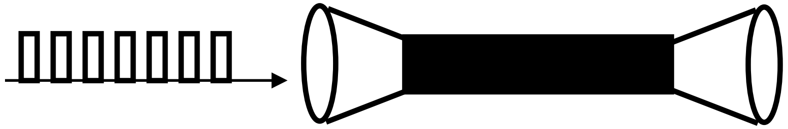
Generally, a factor of 10.

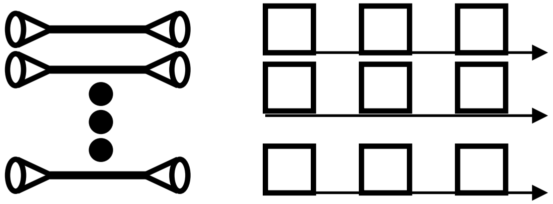
- ❑ Does 5G also do OFDMA?

Yes.

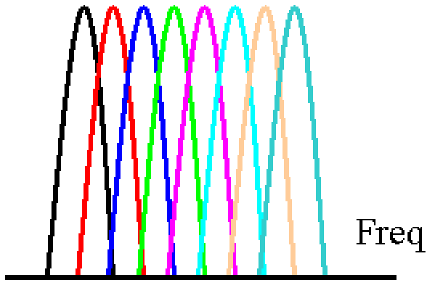
OFDM

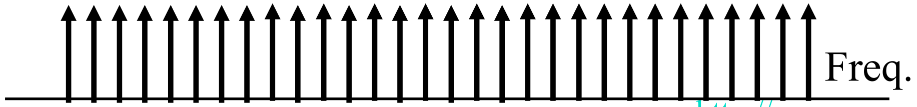
- ❑ Orthogonal Frequency Division Multiplexing
- ❑ Ten 100 kHz channels are better than one 1 MHz Channel ⇒ Multi-carrier modulation





- ❑ Frequency band is divided into 256 or more sub-bands. Orthogonal ⇒ Peak of one at the null of others
- ❑ Each carrier is modulated with a BPSK, QPSK, 16-QAM, 64-QAM, etc., depending on the noise (Frequency selective fading)
- ❑ Used in 802.11a/g, 802.16, Digital Video Broadcast handheld (DVB-H)
- ❑ Easy to implement using FFT/IFFT





Student Questions

❑ What is multi-carrier modulation?

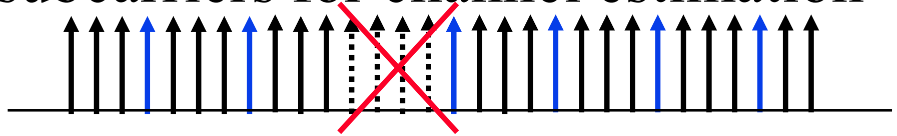
Multicarrier = multiple frequency signals.

❑ What is the input to FFT, and what is the output of it?

FFT: Time domain to Frequency domain
IFFT: Frequency domain to time domain

Advantages of OFDM

- ❑ Easy to implement using FFT/IFFT.
  FFT/IFFT are implemented only as powers of 2 (256, 1024, …)
- ❑ Computational complexity = O(B log BT) compared to previous $O(B^2T)$ for Equalization. Here B is the bandwidth, and T is the delay spread.
- ❑ Graceful degradation if an excess delay
- ❑ Robustness against frequency selective burst errors
- ❑ Allows adaptive modulation and coding of subcarriers
- ❑ Robust against narrowband interference (affecting only some subcarriers)
- ❑ Allows pilot subcarriers for channel estimation

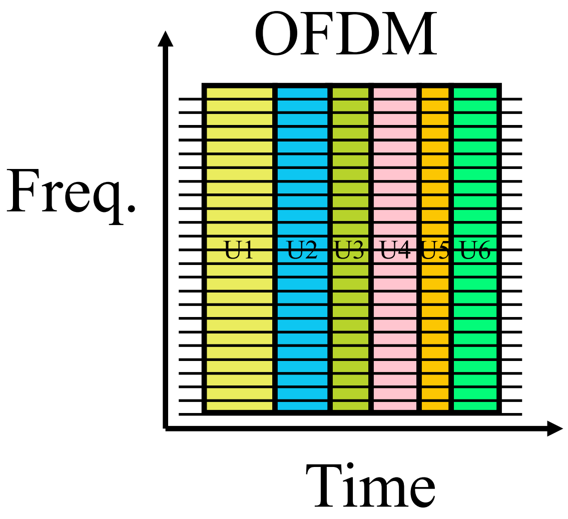


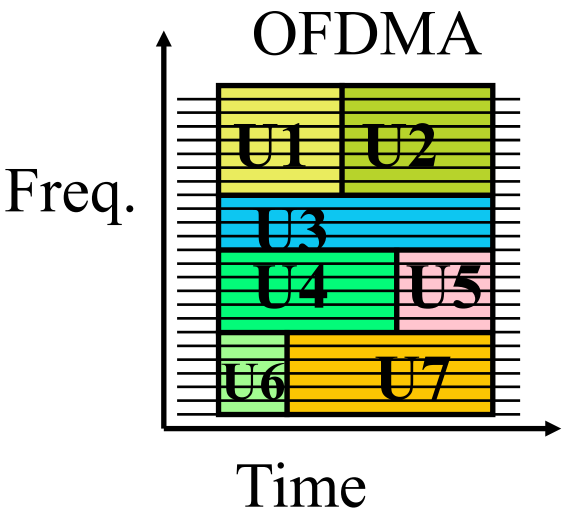
Student Questions

- ❑ Why does OFDM have graceful degradation?
  Because there are multiple carriers. Not all carrier get damaged or equally damaged.
- ❑ What is Equalization?
  Frequency-specific amplification

OFDMA

- Orthogonal Frequency Division Multiple Access
- Each user has a subset of subcarriers for a few slots
- OFDM systems use TDMA
- OFDMA allows Time + Freq DMA ⇒ 2D Scheduling





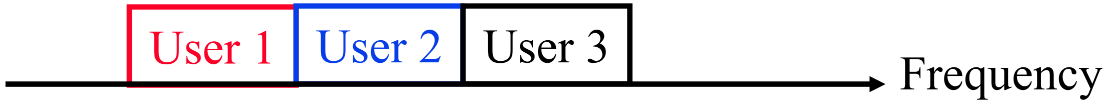
Student Questions

- ❑ What do you mean by 'Each user has a subset of subcarriers for a few slots"?

As shown by colored rectangles in the right diagram.

SC-FDMA

- Single-Carrier Frequency Division Multiple Access
- Each user gets a contiguous part of the channel



User 1 User 2 User 3

Frequency

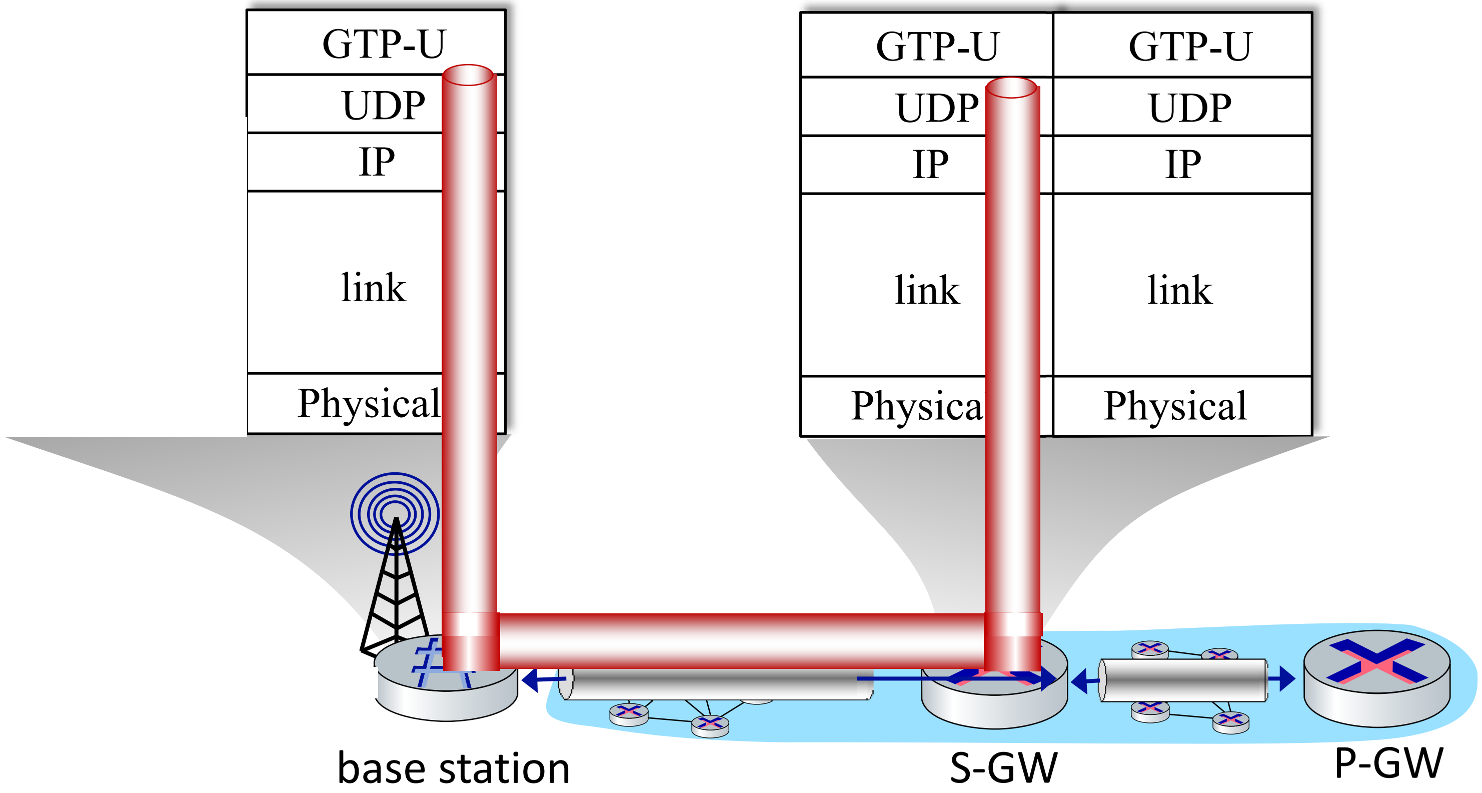
- Uses single carrier modulation and adds a cyclic prefix
- Single carrier ⇒ Not much variation in amplitude
  ⇒ Lower Peak-to-Average Power Ratio (PAPR)
  ⇒ Lower-cost Amplifiers
- Better for uplink because slight mis-synchronization among users does not affect the decoding significantly
- With OFDMA, each user's subcarriers are spread all over the band and may affect other users' subcarriers all over the band

Ref: A. Ghosh, J. Zhang, J. G. Andrews, R. Muhamed, "Fundamentals of LTE," Prentice Hall, 2010, ISBN: 0137033117, 464 pp.

Student Questions

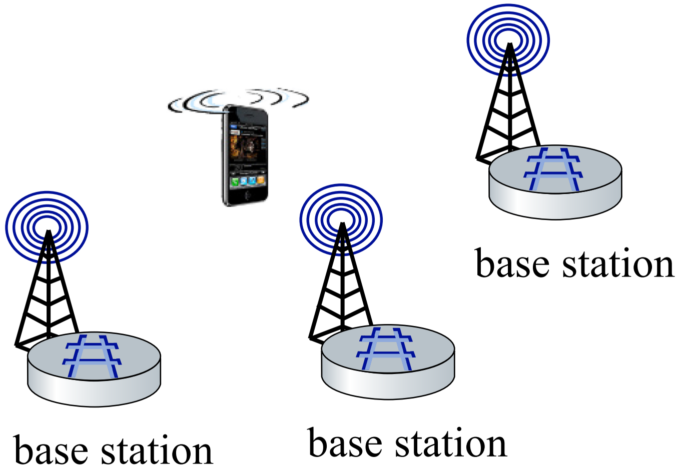
GPRS Tunneling Protocol (GPT)

- **General Packet Radio Service (GPRS)** transfers data in 2G/3G/4G networks. GPT uses UDP tunneling to transfer data over IP.



Student Questions

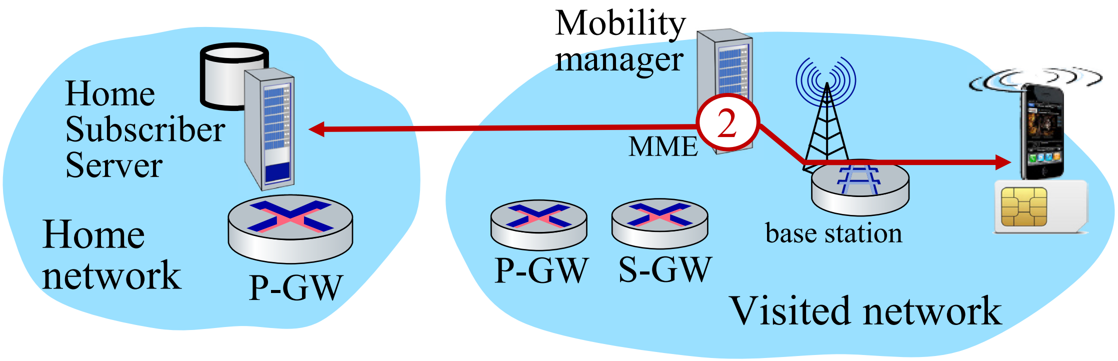
UE Association with a BS



- Each BS broadcasts a primary synch signal every 5ms
- Mobile listens to multiple such broadcasts
  Finds channel bandwidth, configuration, carrier info
- Mobile finds a BS from its compatible carrier and associates with it
- BS authenticates the mobile, sets up all components of the control plane and data plane

Student Questions

Configuring LTE Control-Plane Elements

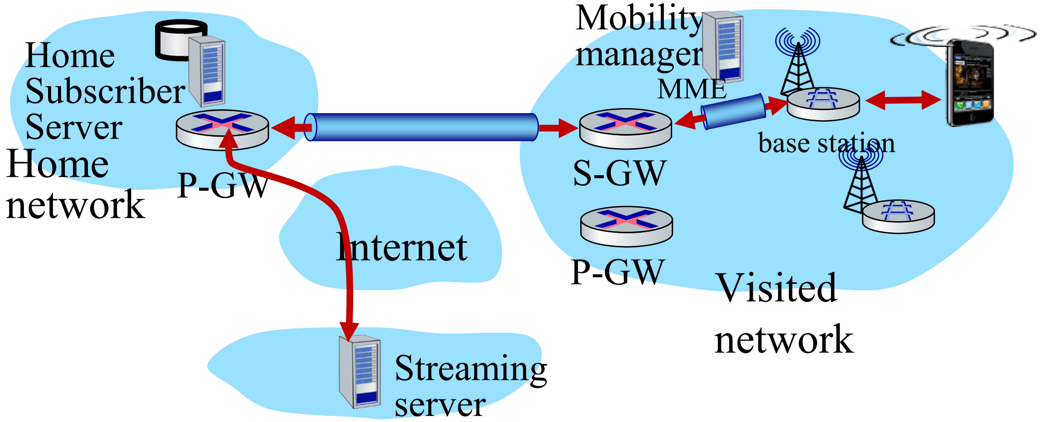


- Mobile communicates with local MME via BS control-plane channel
- MME uses mobile's IMSI info to contact mobile's home HSS
  - Retrieve authentication, encryption, network service information
  - Home HHS knows mobile now resident in visited network
- BS, mobile select parameters for BS-mobile data-plane radio channel

Student Questions

Configuring Data-Plane Tunnels for Mobile

- S-GW to BS Tunnel: when mobile changes base stations, change the endpoint IP address of the tunnel
- S-GW to Home P-GW Tunnel: implementation of indirect routing
- Tunneling via GTP (GPRS tunneling protocol): mobile’s datagram to streaming server encapsulated using GTP inside UDP, inside a datagram



Student Questions

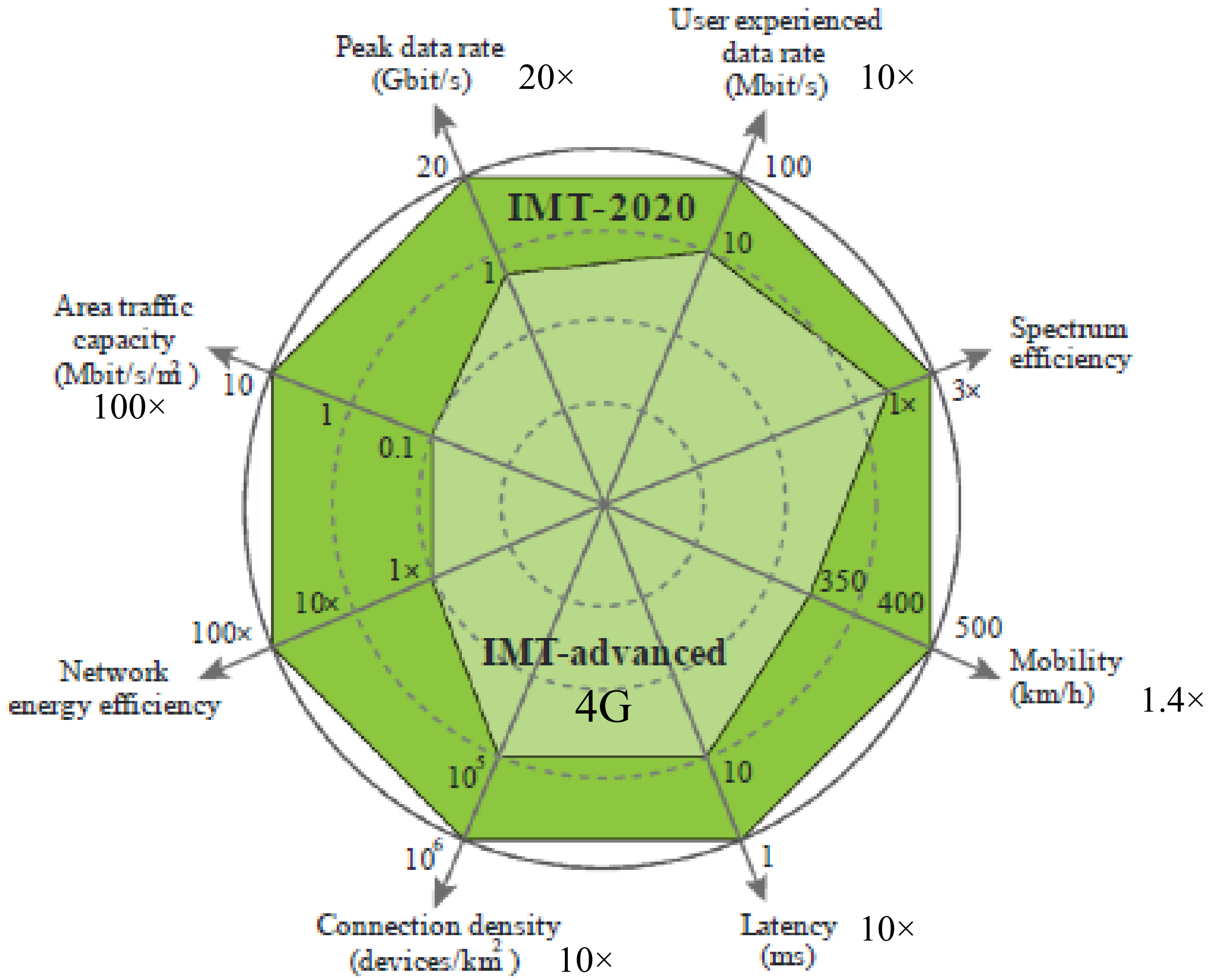
LTE Mobile Sleep Modes

data plane

- LTE mobiles put radio to sleep to conserve battery
- Light Sleep: Wake up periodically (100 ms). Check downstream transmissions to see if there are any calls.
- Deep Sleep: 5-10s of inactivity. May find that the BS has changed. Will re-establish association with a new BS.

Student Questions

5G Definition



Ref: ITU-R Recommendation M.2083-0, "IMT Vision – Framework and overall objectives of the future development of IMT for 2020 and beyond," Sep. 2015, 21 pp., https://www.itu.int/dms_pubrec/itu-r/rec/m/R-REC-M.2083-0-201509-I!!PDF-E.pdf

Student Questions

- ❑ How do we decide the area traffic capacity? How is it related to connection density?

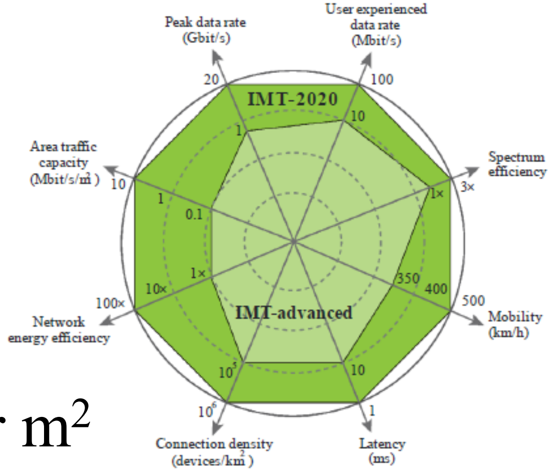
Area Traffic=Total traffic at the tower = # of connections × traffic per connection

- ❑ Is it always 20x faster for every generation?

No. Set based on available options.

5G Definition (Cont)

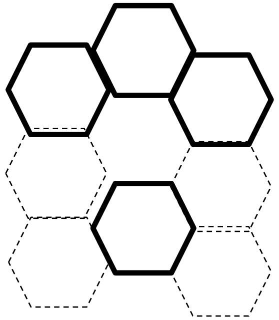
1. **Peak Data Rate**: max rate per user under ideal conditions. 10 Gbps for mobiles, 20 Gbps under certain conditions.
2. **User experienced Data Rate**: 95% Rate across the coverage area per user. 100 Mbps in urban/suburban areas. 1 Gbps hotspot.
3. **Latency**: Radio contribution to latency between send and receive
4. **Mobility**: Max speed at which seamless handover and QoS is guaranteed
5. **Connection Density**: Devices per km^2
6. **Energy Efficiency**: Network bits/Joule, User bits/Joule
7. **Spectrum Efficiency**: Throughput per Hz per cell
8. **Area Traffic Capacity**: Throughput per m^2



Student Questions

- ❑ What creates a "hotspot"? Why can't there be many spread out?

Hotspots are also arranged in a hexagonal pattern but may not be everywhere.



- ❑ Why do we need both Peak Data Rate and User experienced Data Rate?

User experience excludes overhead.

Additional Capabilities for 5G

1. **Spectrum and Bandwidth Flexibility**: Ability to operate at different frequencies and channel bandwidths
2. **Reliability**: High availability
3. **Resilience**: Continue working in the face of disasters
4. **Security and Privacy**: Confidentiality, Integrity, Authentication, Protection against hacking, denial of service, man-in-the-middle attacks
5. **Operational Lifetime**: Long battery life

Ref: ITU-R Recommendation M.2083-0, "IMT Vision – Framework and overall objectives of the future development of IMT for 2020 and beyond," Sep. 2015, 21 pp., https://www.itu.int/dms_pubrec/itu-r/rec/m/R-REC-M.2083-0-201509-I!!PDF-E.pdf

Student Questions

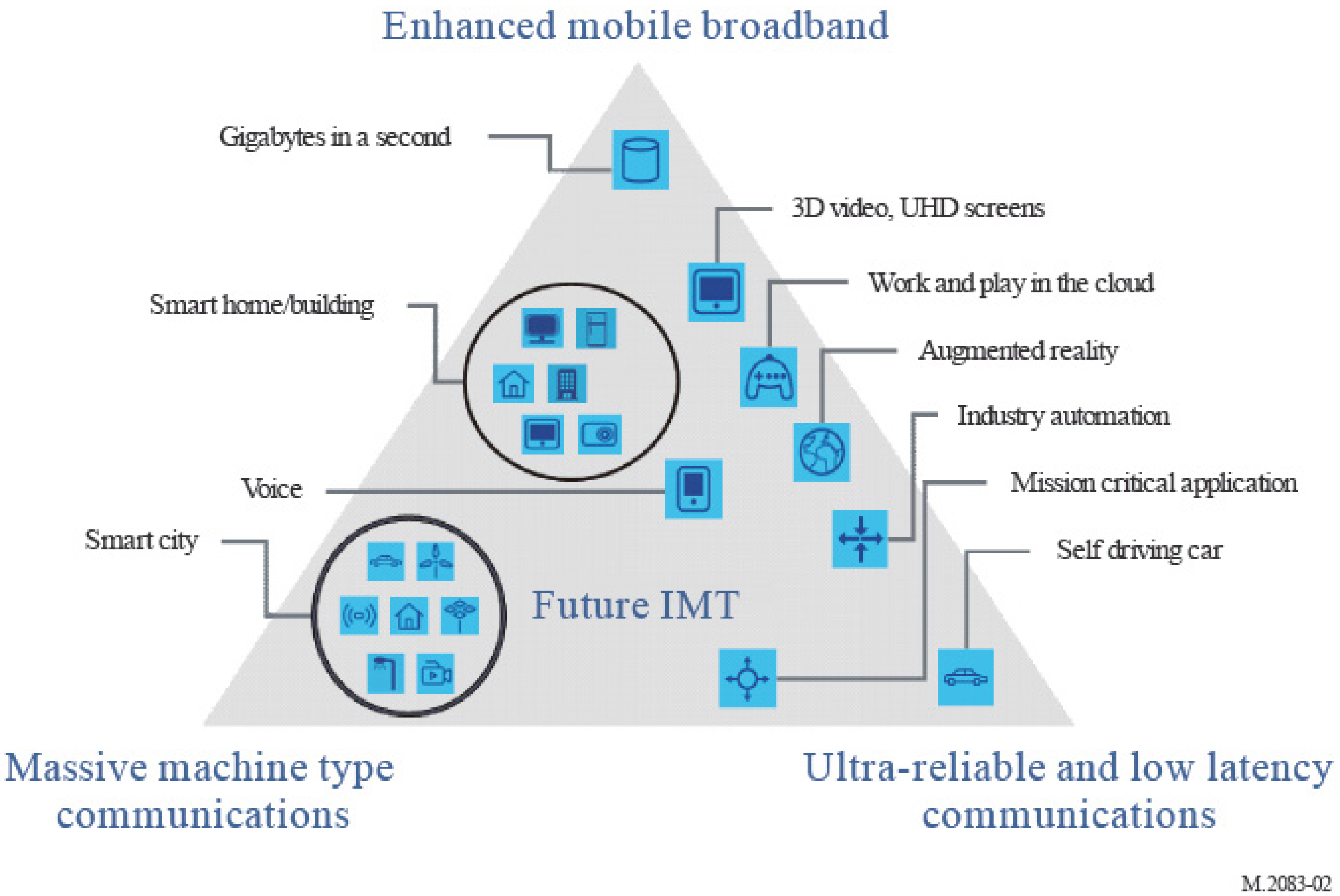
5G Applications

Three Key Application Areas:

1. **Enhanced Mobile Broadband (eMBB)**: Better mobile phones and hot spots. High data rates, high user density. Human centric communications
2. **Ultra-Reliable and Low-Latency Communications (URLLC)**: Vehicle-to-Vehicle communication, Industrial IoT, 3D Gaming. Human and Machine centric communication
3. **Massive Machine Time Communications (mMTC)**: A large number of devices, low data rate, and low power. IoT with a long battery lifetime. Addition to GSM, LoRa, Zigbee, etc. Machine-centric communication.

Student Questions

5G Applications (Cont)


Enhanced mobile broadband
Gigabytes in a second
3D video, UHD screens
Work and play in the cloud
Smart home/building
Augmented reality
Industry automation
Voice
Mission critical application
Smart city
Self driving car
Future IMT
Massive machine type communications
Ultra-reliable and low latency communications
M.2083-02

Ref: ITU-R M.2083-0, "IMT Vision – Framework and overall objectives of the future development of IMT for 2020 and beyond," Sep. 2015. https://www.itu.int/dms_pubrec/itu-r/rec/m/R-REC-M.2083-0-201509-I!!PDF-E.pdf

Student Questions

Spectrum for 5G

- ❑ World Radio-communications Conference (WRC) determines the spectrum requirements
- ❑ Two Frequency Ranges (FRs)
  - ➢ **FR1**: Sub 6-GHz. Several new bands in this range.
  - ➢ **FR2**: 24.25-52.6 GHz (mm-Waves)
    ⇒ Good for high throughput in small cells
  - ➢ NR can use both paired and unpaired spectrum
    NR specs list 26 operating bands for FR1 and 3 for FR2.

Student Questions

- ❑ Would later generations of wireless technology ever run out of available frequency ranges?

They will keep moving in higher frequency bands. There is plenty of room at this point. Also, spectral efficiency will ensure that we use smaller bandwidth.

- ❑ Does the specification require that all devices (i.e. smart phones) work in both FR1 and FR2?

No.

- ❑ What is paired and unpaired spectrum? Is it the same as an aggregated spectrum?

Paired=Uplink & Download bands
Unpaired=Either direction

Above 6 GHz

- **Free-space loss** increases proportionately to the square of frequency and the square of the distance. 88 dB loss with 30 GHz at 20 m
  ⇒ 10-100 m cell radius
- **Outdoor-to-Indoor**: Glass windows add 20-40 dB
- **Mobility**: Doppler shift is proportional to frequency and velocity. Multipath results in varying Doppler shifts
  ⇒ Lower mobility
- **Wide Channels**: Duplex filters cover only 3-4% of center frequency ⇒ Need carrier aggregation.
- **Antenna**: 8x8 array at 60 GHz is only 2cm x 2cm. A/D and D/A converters per antenna element may be expensive
- 2 Gbps to 1 km is feasible using mm waves

Ref: ITU-R M2376-0, "Technical Feasibility of IMT in bands above 6 GHz," July 2015, http://www.itu.int/dms_pub/itu-r/opb/rep/R-REP-M.2376-2015-PDF-E.pdf

Student Questions

- Has there been attempted solutions to the glass window problem in the recent year? Or is this an inevitability of the frequency?

Every material has different light and radio-frequency properties. They will find other materials that either stop most RF or allow most RF as required.

- What are the requirements for 5G infrastructure besides the new antenna?

ITU does not set infrastructure requirements. Only performance. New Antenna is not a requirement from ITU.

❖ Why are A/D and D/C expensive above 6 GHz?

High-frequency ⇒ High resolution

Above 6 GHz (Cont)

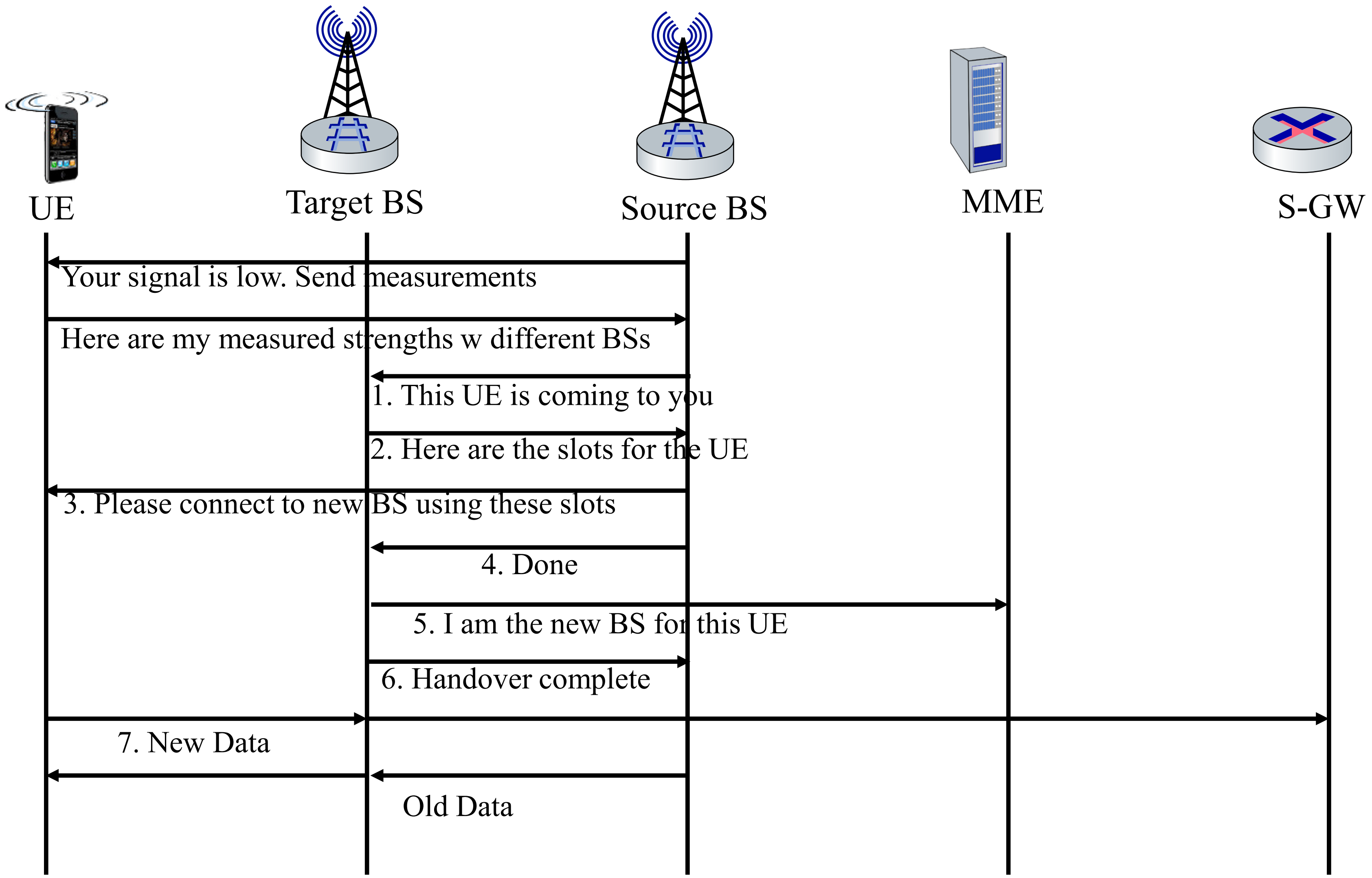
- 100s MHz ⇒ **Multi-gigabit** data rates
- **Dense spatial reuse**
- Lower latency
- Need analog beamforming with a narrow beam width
- **Adaptive beam steering** and switching to avoid blockage from hand, body, or foliage
- Need different antenna configurations in the mobile
- **Directional antennas** with adaptable 3D beamforming and beam tracking

Student Questions

- Could you explain why we need different antenna configurations in the mobile?
- *Designing antennas is a research field in Electrical Engineering.*
- What is analog beamforming?

Digital = Using FFT
Analog = using analog circuits

Handover: In the Same LTE



Your signal is low. Send measurements

Here are my measured strengths w different BSs

1. This UE is coming to you

2. Here are the slots for the UE

3. Please connect to new BS using these slots

4. Done

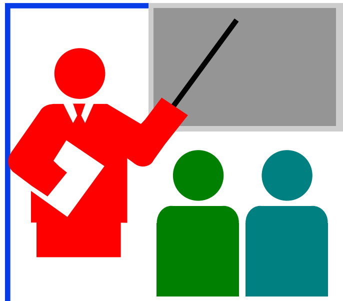
5. I am the new BS for this UE

6. Handover complete

7. New Data

Old Data

Student Questions



Review: 4G/5G

1. ITU-T sets requirements for the next generation of telecommunication networks every 10 years.
2. 4G requirements are specified in IMT-Advanced document. LTE is pre-4G technology. LTE-Advanced was approved as 4G.
3. Orthogonal Frequency Division Multiplexing Access (OFDMA) is used for media access control
4. All generations of telecommunications allow mobiles to sleep to improve battery life.
5. 5G extends improves performance over 4G by a factor of 10

Read Sections 7.4-7.8 and do R12-R31.

Student Questions

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http://www.cse.wustl.edu/~jain/cse473-23/i_7wmn.htm

Student Questions

Related Modules

CSE 567: The Art of Computer Systems Performance Analysis
https://www.youtube.com/playlist?list=PLjGG94etKypJEKjNAa1n_1X0bWWNyZcof

CSE473S: Introduction to Computer Networks (Fall 2011),
https://www.youtube.com/playlist?list=PLjGG94etKypJWOSPMh8Azcgy5e_10TiDw

CSE 570: Recent Advances in Networking (Spring 2013)

https://www.youtube.com/playlist?list=PLjGG94etKypLHyBN8mOgwJLHD2FFIMGq5

CSE571S: Network Security (Spring 2011),
https://www.youtube.com/playlist?list=PLjGG94etKypKvzfVtutHcPFJXumyyg93u

Video Podcasts of Prof. Raj Jain's Lectures,
https://www.youtube.com/channel/UCN4-5wzNP9-ruOzQMs-8NUw

Student Questions