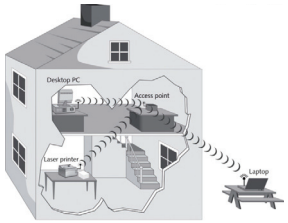
IEEE 802.11 Wireless LANs
Part I: Basics



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Audio/Video recordings of this class lecture are available at:
http://www.cse.wustl.edu/~jain/cse574-16/

1. IEEE 802.11 Features
2. IEEE 802.11 Physical Layers
3. IEEE 802.11 MAC
4. IEEE 802.11 Architecture
5. Frame Format
6. Power Management

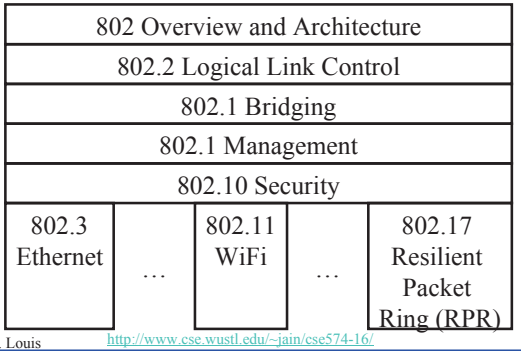
Note: This is 1st of 2 lectures on WiFi. The 2nd lecture covers recent developments such as high-throughput WiFi, white spaces, etc.

IEEE 802.11 vs. WiFi

- IEEE 802.11 is a standard
- WiFi = "Wireless Fidelity" is a trademark
- Fidelity = Compatibility between wireless equipment from different manufacturers
- WiFi Alliance is a non-profit organization that does the compatibility testing (WiFi.org)
- 802.11 has many options and it is possible for two equipment based on 802.11 to be incompatible.
- All equipment with "WiFi" logo have selected options such that they will interoperate.

IEEE Standards Numbering System

- IEEE 802.* and IEEE 802.1* standards (e.g., IEEE 802.1Q-2011) apply to all IEEE 802 technologies:
  - IEEE 802.3 Ethernet
  - IEEE 802.11 WiFi
  - IEEE 802.16 WiMAX



IEEE Standards Numbering (Cont)

- IEEE 802.11* (e.g., 802.11i) standards apply to all WiFi devices but may not apply to ZigBee devices which are based on 802.15,
- Standards with all upper case letters are base standards, e.g., IEEE 802.1AB-2009
- Standards with lower case are additions/extensions/revisions. Merged with the base standard in its next revision. e.g., IEEE 802.1w-2001 was merged with IEEE 802.1D-2004
- Standards used to be numbered, sequentially, e.g., IEEE 802.1a, …, 802.1z, 802.1aa, 802.1ab, …
- Recently they started showing base standards in the additions, e.g., IEEE 802.1Qau-2010

IEEE 802.11 Features

- Original IEEE 802.11-1997 was at 1 and 2 Mbps. Newer versions at 11 Mbps, 54 Mbps, 108 Mbps, 200 Mbps,…
- All versions use "License-exempt" spectrum
- Need ways to share spectrum among multiple users and multiple LANs Þ *Spread Spectrum* (CDMA)
- Three Phys:
  - Direct Sequence (**DS**) spread spectrum using ISM band
  - Frequency Hopping (**FH**) spread spectrum using ISM band
  - Diffused Infrared (850-900 nm) bands
- Supports multiple priorities
- Supports time-critical and data traffic
- Power management allows a node to doze off

ISM Bands

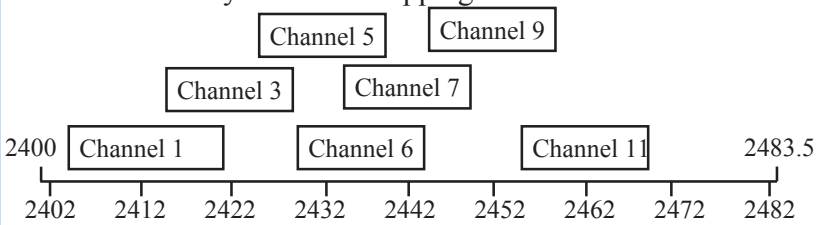
- Industrial, Scientific, and Medical bands. License exempt

From	To	Bandwidth	Availability
6.765 MHz	6.795 MHz	30 kHz	
13.553 MHz	13.567 MHz	14 kHz	Worldwide
26.957 MHz	27.283 MHz	326 kHz	Worldwide
40.660 MHz	40.700 MHz	40 kHz	Worldwide
433.050 MHz	434.790 MHz	1.74 MHz	Europe, Africa, Middle east, Former Soviet Union
902.000 MHz	928.000 MHz	26 MHz	America, Greenland
2.400 GHz	**2.500 GHz**	**100 MHz**	**Worldwide**
5.725 GHz	**5.875 GHz**	**150 MHz**	**Worldwide**
24.000 GHz	24.250 GHz	250 MHz	Worldwide
61.000 GHz	61.500 GHz	500 MHz	
122.000 GHz	123.000 GHz	1 GHz	
244 GHz	246 GHz	2 GHz	

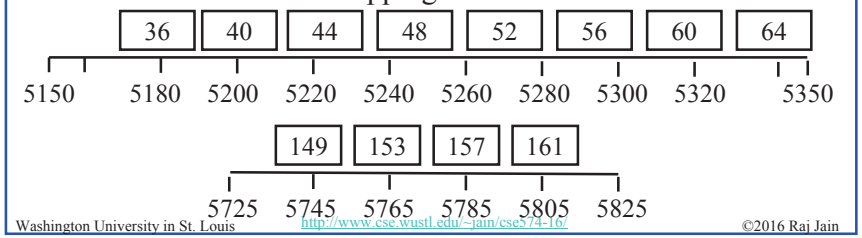
Ref: http://en.wikipedia.org/wiki/ISM_band

North American Channels

2.4 GHz Band: 14 5-MHz Channels. Only 12 in USA.
20 MHz Þ Only 3 non-overlapping channels



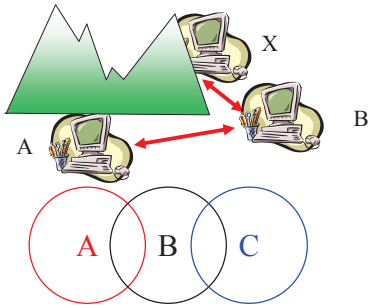
5 GHz Band: 12 non-overlapping channels



IEEE 802.11 Physical Layers

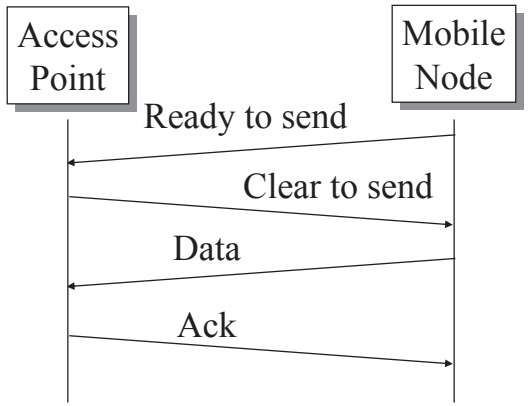
- Issued in several stages
- First version in 1997: IEEE 802.11
  - Includes MAC layer and three physical layer specifications
  - Two in 2.4-GHz band and one infrared
  - All operating at 1 and 2 Mbps
  - No longer used
- Two additional amendments in 1999:
  - IEEE 802.11a-1999: 5-GHz band, 54 Mbps/20 MHz, **OFDM**
  - IEEE 802.11b-1999: 2.4 GHz band, 11 Mbps/22 MHz
- Fourth amendment:
  - IEEE 802.11g-2003 : 2.4 GHz band, 54 Mbps/20 MHz, **OFDM**

Hidden Node Problem



- A can hear B, B can hear C, but C cannot hear A.
- C may start transmitting while A is also transmitting
  - A and C can't detect collision.
- CSMA/CD is not possible
  - Only the receiver can help avoid collisions

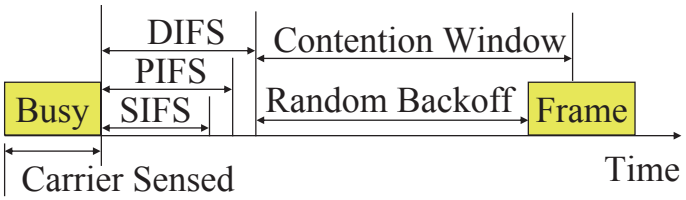
4-Way Handshake



IEEE 802.11 MAC

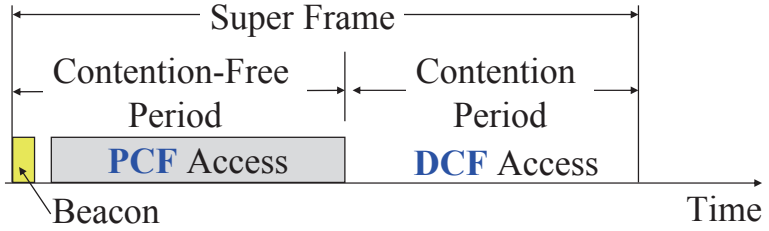
- Carrier Sense Multiple Access with Collision Avoidance (**CSMA/CA**)
- Listen before you talk. If the medium is busy, the transmitter backs off for a random period.
- Avoids collision by sending a short message:
  Ready to send (**RTS**)
  RTS contains dest. address and duration of message.
  Tells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

IEEE 802.11 Priorities



- Initial interframe 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**)

Time Critical Services



- Timer critical services use **Point Coordination Function**
- The point coordinator allows only one station to access
- Coordinator sends a beacon frame to all stations. Then uses a polling frame to allow a particular station to have contention-free access
- Contention Free Period (CFP) varies with the load.

IEEE 802.11 DCF Backoff

- MAC works with a single FIFO Queue
- Three variables:
  - Contention Window (CW)
  - Backoff count (BO)
  - Network Allocation Vector (NAV)
- If a frame (RTS, CTS, Data, Ack) is heard, NAV is set to the duration in that frame. Stations sense the media after NAV expires.
- If the medium is idle for DIFS, and backoff (BO) is not already active, the station draws a random BO in [0, CW] and sets the backoff timer.
- If the medium becomes busy during backoff, the timer is stopped and a new NAV is set. After NAV, back off continues.

IEEE 802.11 DCF Backoff (Cont)

- Initially and after each successful transmission:

$$CW = CW_{min}$$

- After each unsuccessful attempt

$$CW = \min\{2CW + 1, CW_{max}\}$$

Example: CWmin=3, CWmax=127

3, 7, 15, 31, 63, 127, 127, 127, …

Typical Parameter Values

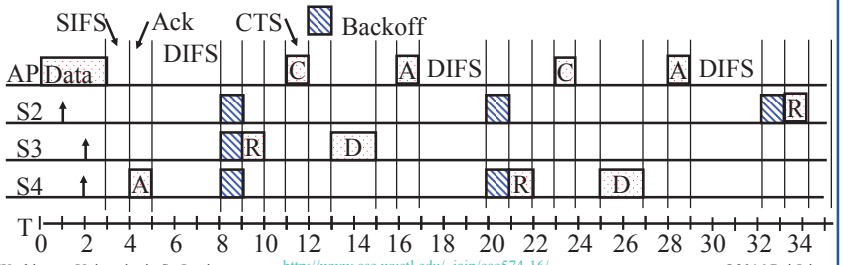
- For DS PHY: Slot time = 20 us, SIFS = 10 us, CWmin = 31, CWmax = 1023
- For FH PHY: Slot time = 50 us, SIFS = 28 us, CWmin = 15, CWmax = 1023
- 11a: Slot time = 9 us, SIFS= 16 us, CWmin= 15, CWmax=1023
- 11b: Slot time = 20 us, SIFS = 10 us, CWmin= 31, CWmax=1023
- 11g: Slot time = 20 us or 9 us, SIFS = 10 us, CWmin= 15 or 31, CWmax=1023
- PIFS = SIFS + 1 slot time
- DIFS = SIFS + 2 slot times

Virtual Carrier Sense

- Every frame has a "Duration ID" which indicates how long the medium will be busy.
  - RTS has duration of RTS + SIF + CTS + SIF + Frame + SIF + Ack
  - CTS has duration of CTS + SIF + Frame + SIF + Ack
  - Frame has a duration of Frame + SIF + ACK
  - ACK has a duration of ACK
- All stations keep a "**Network Allocation Vector (NAV)**" timer in which they record the duration of the each frame they hear.
- Stations do not need to sense the channel until NAV becomes zero.

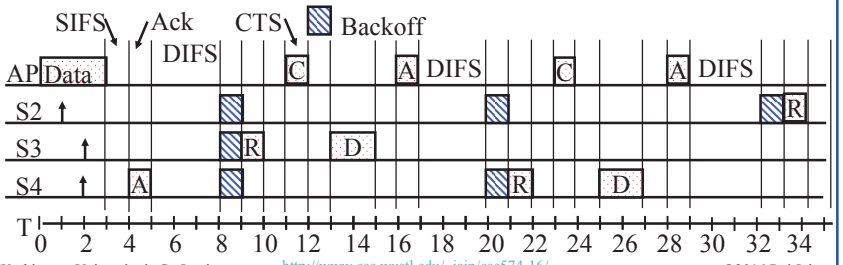
DCF Example

- Example: Slot Time = 1, CWmin = 5, DIFS=3, PIFS=2, SIFS=1
- T=1 Station 2 wants to transmit but the media is busy
- T=2 Stations 3 and 4 want to transmit but the media is busy
- T=3 Station 1 finishes transmission.
- T=4 Station 1 receives ack for its transmission (SIFS=1)
  Stations 2, 3, 4 set their NAV to 1.
- T=5 Medium becomes free
- T=8 DIFS expires. Stations 2, 3, 4 draw backoff count between 0 and 5.
  The counts are 3, 1, 2

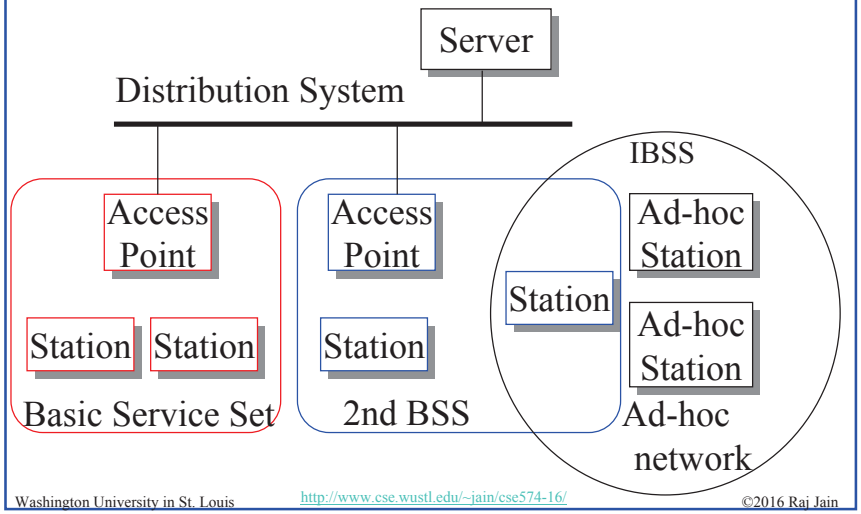


DCF Example (Cont)

- T=9 Station 3 starts transmitting. Announces a duration of 8 (RTS + SIFS + CTS + SIFS + DATA + SIFS + ACK). Station 2 and 4 pause backoff counter at 2 and 1 resp. and wait till T=17
- T=15 Station 3 finishes data transmission
- T=16 Station 3 receives Ack.
- T=17 Medium becomes free
- T=20 DIFS expires. Station 2 and 4 notice that there was no transmission for DIFS.
  Stations 2 and 4 start their backoff counter from 2 and 1, respectively.
- T=21 Station 4 starts transmitting RTS



IEEE 802.11 Architecture



IEEE 802.11 Architecture (Cont)

- **Basic Service Area (BSA)** = Cell
- Each BSA may have several access points (APs)
- **Basic Service Set (BSS)**
  = Set of stations associated with one AP
- **Distribution System (DS)** - wired backbone
- **Extended Service Area (ESA)** = Multiple BSAs interconnected via a distribution system
- **Extended Service Set (ESS)**
  = Set of stations in an ESA
- **Independent Basic Service Set (IBSS)**: Set of computers in **ad-hoc mode**. May not be connected to wired backbone.
- Ad-hoc networks coexist and interoperate with infrastructure-based networks

Frame Format

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

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

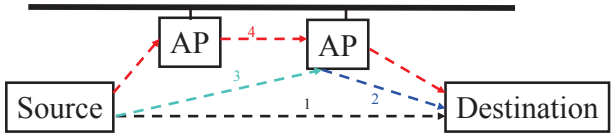
- Type: Control, management, or data
- Sub-Type: Association, disassociation, re-association, probe, authentication, de-authentication, CTS, RTS, Ack, …
- Retry/retransmission
- Going to Power Save mode
- More buffered data at AP for a station in power save mode
- Wireless Equivalent Privacy (Security)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

MAC Frame Fields

- **Duration/Connection ID**:
  - If used as duration field, indicates time (in μs) channel will be allocated for successful transmission of MAC frame. Includes time until the end of Ack
  - In some control frames, contains 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

802.11 Frame Address Fields

- All stations filter on "Address 1"

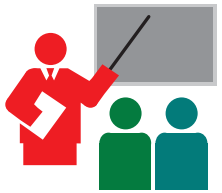


	To Distribution System	From Distribution System	Address 1	Address 2	Address 3	Address 4
1	0	0	Destination Address	Source Address	BSS ID	-
2	0	1	Destination Address	BSS ID	Source Address	-
3	1	0	BSS ID	Source Address	Destination Address	-
4	1	1	Receiver Address	Transmitter Address	Destination Address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

802.11 Power Management

- Station tells the base station its mode: Power saving (PS) or active
- Mode changed by power mgmt bit in the frame control header.
- All packets destined to stations in PS mode are buffered
- AP broadcasts list of stations with buffered packets in its beacon frames: Traffic Indication Map (TIM)
- Subscriber Station (SS) sends a PS-Poll message to AP, which sends one frame. More bit in the header Þ more frames.
- With 802.11e unscheduled Automatic Power Save Delivery (APSD): SS transmits a data or null frame with power saving bit set to 0. AP transmits all buffered frames for SS.
- With Scheduled APSD mode:AP will transmit at pre-negotiated time schedule. No need for polling.
- Hybrid APSD mode: PS-poll for some. Scheduled for other categories

Summary



1. 802.11 uses Frequency hopping, Direct Sequence CDMA, OFDM
2. 802.11 PHYs: 802.11, 802.11a, 802.11b, 802.11g
3. Allows both: Ad-Hoc vs. Infrastructure-based
4. 802.11 supports single FIFO Q. Uses SIFS, PIFS, DIFS

Homework 5

- Two 802.11 stations get frames to transmit at time t=0. The 3rd station (AP) has just finished transmitting data for a long packet at t=0 to Station 1. The transmission parameters are: Slot time=1, SIFS=1, DIFS=3, CWmin=5, CWmax=7. Assume that the pseudo-random number generated are 1, 3. The data size for both stations is 3 slots. Draw a transmission diagram. At what time the two packets will get acknowledged assuming no new arrivals.

Reading List

- IEEE 802.11 Tutorial, http://wow.eecs.berkeley.edu/ergen/docs/ieee.pdf
- A Technical Tutorial on the IEEE 802.11 Protocol, http://www.sss-mag.com/pdf/802_11tut.pdf

Wikipedia Links

- http://en.wikipedia.org/wiki/Wireless_LAN
- http://en.wikipedia.org/wiki/IEEE_802.11
- http://en.wikipedia.org/wiki/Channel_access_method
- http://en.wikipedia.org/wiki/Direct-sequence_spread_spectrum
- http://en.wikipedia.org/wiki/Wi-Fi
- http://en.wikipedia.org/wiki/Distributed_Coordination_Function
- http://en.wikipedia.org/wiki/Carrier_sense_multiple_access
- http://en.wikipedia.org/wiki/Multiple_Access_with_Collision_Avoidance_for_Wireless
- http://en.wikipedia.org/wiki/Beacon_frame
- http://en.wikipedia.org/wiki/IEEE_802.11
- http://en.wikipedia.org/wiki/IEEE_802.11_(legacy_mode)
- http://en.wikipedia.org/wiki/IEEE_802.11_RTS/CTS
- http://en.wikipedia.org/wiki/List_of_WLAN_channels
- http://en.wikipedia.org/wiki/Point_Coordination_Function
- http://en.wikipedia.org/wiki/Service_set_(802.11_network)
- http://en.wikipedia.org/wiki/Wi-Fi_Alliance

Acronyms

- Ack Acknowledgement
- AP Access Point
- APSD Automatic Power Save Delivery
- BO Backoff
- BSA Basic Service Area
- BSS Basic Service Set
- BSSID Basic Service Set Identifier
- CA Collision Avoidance
- CD Collision Detection
- CDMA Code Division Multiple Access
- CFP Contention Free Period
- CRC Cyclic Redundancy Check
- CSMA Carrier Sense Multiple Access
- CTS Clear to Send
- CW Congestion Window
- CWmax Maximum Congestion Window

Acronyms (Cont)

- CWmin Minimum Congestion Window
- DA Destination Address
- DCF Distributed Coordination Function
- DIFS DCF Inter-frame Spacing
- DS Direct Sequence
- ESA Extended Service Area
- ESS Extended Service Set
- FH Frequency Hopping
- FIFO First In First Out
- GHz Giga Hertz
- IBSS Independent Basic Service Set
- ID Identifier
- IEEE Institution of Electrical and Electronics Engineers
- IFS Inter-frame spacing
- ISM Instrumentation, Scientific and Medical
- LAN Local Area Network

Acronyms (Cont)

- MAC Media Access Control
- MHz Mega Hertz
- MIMO Multiple Input Multiple Output
- NAV Network Allocation Vector
- OFDM Orthogonal Frequency Division Multiplexing
- PCF Point Coordination Function
- PHY Physical Layer
- PIFS PCF inter-frame spacing
- PS Power saving
- QoS Quality of Service
- RA Receiver Address
- RTS Ready to Send
- SA Source Address
- SIFS Short Inter-frame Spacing

Acronyms (Cont)

- SS Subscriber Station
- TA Transmitter's Address
- TIM Traffic Indication Map
- WiFi Wireless Fidelity
- WLAN Wireless Local Area Network

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Related Modules

Introduction to 5G,
http://www.cse.wustl.edu/~jain/cse574-16/j_195g.htm

Low Power WAN Protocols for IoT,
http://www.cse.wustl.edu/~jain/cse574-16/j_14ahl.htm

Introduction to Vehicular Wireless Networks,
http://www.cse.wustl.edu/~jain/cse574-16/j_08vwn.htm

Internet of Things,
http://www.cse.wustl.edu/~jain/cse574-16/j_10iot.htm

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