CSC 498R: Internet of Things

Lecture 04: Wireless Networks

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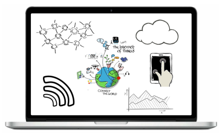
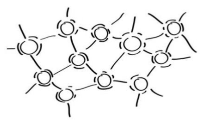
IoT Components



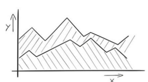
- Things we connect: **Hardware, sensors *and* actuators**



- Connectivity
  – Medium we use to connect things

- Platform
  – Processing and storing collected data
    - Receive and send data via standardized interfaces or API
    - Store the data
    - Process the data.

- Analytics
  – Get insights from gathered data



- User Interface

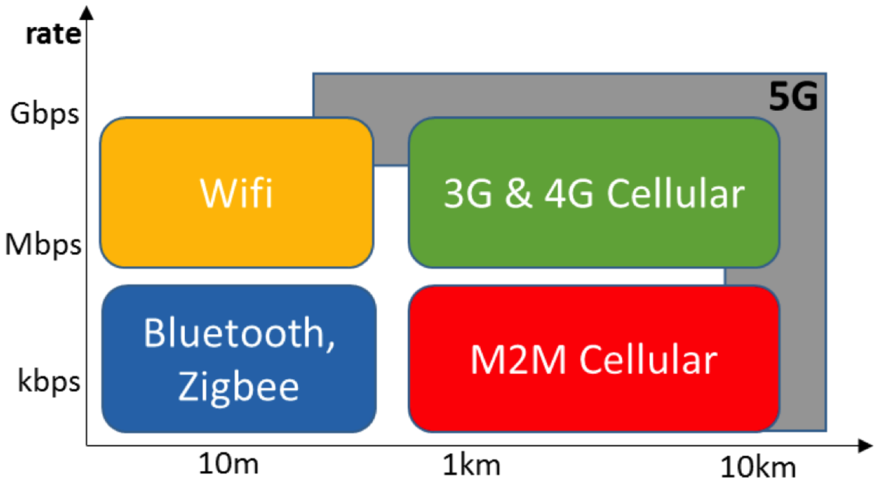
Topics

- Basics of Wireless Networking
- Communication Protocols
- Machine-to-Machine Communications

IoT Network Protocols

- An IoT network may have the following technologies:
  - Wireless Personal Area Network (WPAN) such as Zigbee, Bluetooth, 6LowPAN etc.
  - Wireless Local Area Network (WLAN) includes Wi-Fi on slightly larger wireless network area scale
- Mobile communication technologies like 2G, 3G,4G and LTE for large scale networks

Wireless Technologies



Networking Layer Comparison

	TCP/IP Protocol Stack			Z-Wave	ZigBee	6LoWPAN	
Application	HTTP, RTP, FTP, etc.			Device & Command Classes	Application Profile(s)	HTTP	
Transport	TCP	UDP	ICMP	Routing Layer	Application Support SL	UDP	ICMP
Network	IP			Transfer Layer	NWK Layer	IPv6 with 6LoWPAN	
Data Link	Ethernet MAC			Proprietary MAC	IEEE802.15.4 MAC	IEEE802.15.4 MAC	
Physical	Ethernet PHY			Proprietary PHY	IEEE802.15.4 PHY	IEEE802.15.4 PHY	

Holistic View of Wireless Technologies

- Cellular (2G to 4G)
  - WiMax {long range wireless}
- WiFi
- WSN's
- Near Field Communications
- The focus in this *lecture* is on WiFi technologies and MAC layer issues!!

RFID in Brief

- RFID uses radio waves to transfer data from an electronic tag (RFID tag or label), attached to an object, through a reader to identify and track the object.
- The tag's information are stored electronically.
- Some RFID tags can be read from several meters away and beyond the line of sight of the reader.

RFID in Brief

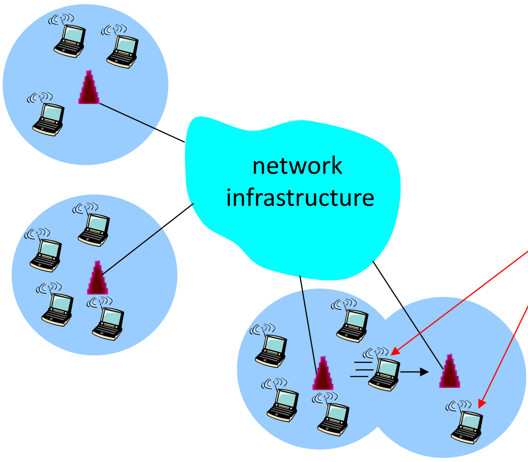
- An RFID reader transmits an encoded radio signal to interrogate the tag.
- With a small RF transmitter and receiver, the RFID tag receives the message and responds with its identification information.
- Many RFID tags have no battery. Instead, the tag uses the radio energy transmitted by the reader as its energy source.

LAN, WLAN and WSN Terminology

- 802.3
  - Ethernet CSMA/CD
- 802.11a/b/g/n/ac
  - WiFi CSMA/CA
- 802.15.4:
  - ZigBee, 802.11-based
  - Lower data rates, lower power

  } WSNs
- Bluetooth:
  - TDMA
  - Wireless Personal Area Networks (PANs) that provide secure, globally unlicensed short-range radio communication.
  - Clusters with max of 8: cluster head + 7 nodes
- WBAN (Wireless Body Area Networks)
  - Generally 802.15.4 or TDMA medical PANs

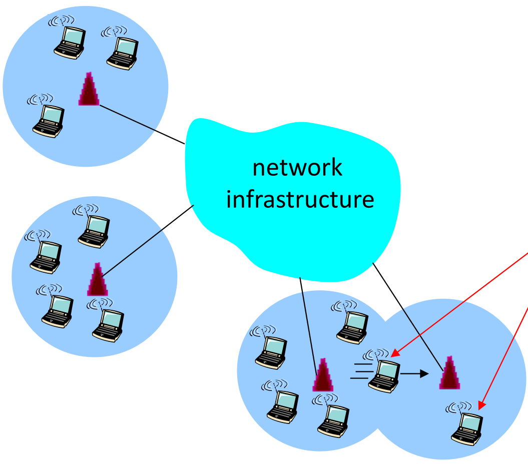
Elements of a Wireless Network



Wireless hosts

- laptop, PDA, smart phone
- run applications
- may be stationary (non-mobile) or mobile
  - wireless does *not* always mean mobility

Elements of a Wireless Network



Base station (BS)

- typically connected to wired network
- relay - responsible for sending packets between wired network and wireless host(s) in its "area"
  - e.g., cell towers, 802.11 access points

Wireless Local Area Networks (WLANs)

- The proliferation of laptop computers and other mobile devices (PDAs and cell phones) created an *obvious* application level demand for wireless local area networking.
- Companies jumped in, quickly developing *incompatible* wireless products in the 1990's.
- Industry decided to entrust standardization to IEEE committee that dealt with wired LANs
  – *Namely, the IEEE 802 committee!!*

Number	Topic
802.1	Overview and architecture of LANs
802.2 ↓	Logical link control
802.3 *	Ethernet
802.4 ↓	Token bus (was briefly used in manufacturing plants)
802.5	Token ring (IBM's entry into the LAN world)
802.6 ↓	Dual queue dual bus (early metropolitan area network)
802.7 ↓	Technical advisory group on broadband technologies
802.8 †	Technical advisory group on fiber optic technologies
802.9 ↓	Isochronous LANs (for real-time applications)
802.10 ↓	Virtual LANs and security
802.11 *	Wireless LANs
802.12 ↓	Demand priority (Hewlett-Packard's AnyLAN)
802.13	Unlucky number. Nobody wanted it
802.14 ↓	Cable modems (defunct: an industry consortium got there first)
802.15 *	Personal area networks (Bluetooth) 802.15.4 ZigBee
802.16 *	Broadband wireless WiMAX
802.17	Resilient packet ring

IEEE 802 Standards Working Groups

The important ones are marked with *. The ones marked with ↓ are hibernating

WiFi

- Wi-Fi is a Wireless Local Area Network (WLAN) technology based on the IEEE 802.11 standards.
- Wi-Fi devices and Access Points (APs) have a wireless communication range of about 30 meters indoors.

IEEE 802.11

- The following IEEE 802.11 standards exist or are in development to support the creation of technologies for wireless local area networking:
  - 802.11a - 54 Mbps standard, 5 GHz signaling (ratified 1999)
  - 802.11b - 11 Mbps standard, 2.4 GHz signaling (1999)
  - 802.11c - operation of bridge connections (moved to 802.1D)
  - 802.11d - worldwide compliance with regulations for use of wireless signal spectrum (2001)
  - 802.11e - Quality of Service (QoS) support (ratified in 2005)
  - 802.11f - Inter-Access Point Protocol recommendation for communication between access points to support roaming clients (2003)
  - 802.11g - 54 Mbps standard, 2.4 GHz signaling (2003)
  - 802.11h - enhanced version of 802.11a to support European regulatory requirements (2003)
  - 802.11i- security improvements for the 802.11 family (2004)
  - 802.11j - enhancements to 5 GHz signaling to support Japan regulatory requirements (2004)
  - 802.11k - WLAN system management (in progress)

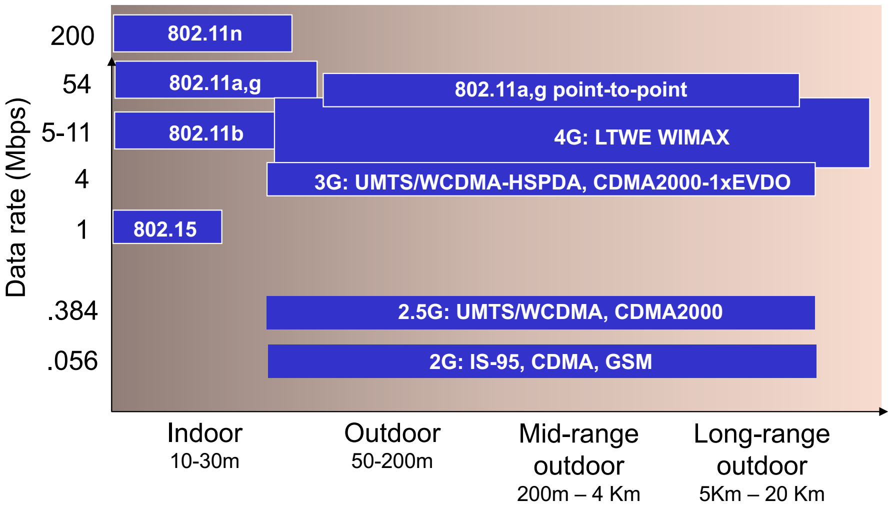
IEEE 802.11

- The following IEEE 802.11 standards exist or are in development to support the creation of technologies for wireless local area networking:
  - 802.11m - maintenance of 802.11 family documentation
  - 802.11n - OFDM version at 248 Mbps; MIMO version up to 600 Mbps
    - Formally voted into the standard in September 2009!
  - 802.11p- Wireless Access for the Vehicular Environment
  - 802.11r - fast roaming support via Basic Service Set transitions
  - 802.11s - ESS mesh networking for access points
  - 802.11t - Wireless Performance Prediction - recommendation for testing standards and metrics
  - 802.11u - internetworking with 3G / cellular and other forms of external networks
  - 802.11v - wireless network management / device configuration
  - 802.11w - Protected Management Frames security enhancement
  - 802.11x- skipped (generic name for the 802.11 family)
  - 802.11y - Contention Based Protocol for interference avoidance

IEEE 802.11 new

- Newest defined standards:
  - 802.11ac – [VHT] Wireless network bearer operating below 6GHz to provide data rates of at least 1Gbps per second for multi-station operation and 500 Mbps on a single link.
  - 802.11ad - Wireless network bearer providing very high throughput (up to 7 Gbps) at frequencies up to 60GHz.
  - 802.11af - Wi-Fi in TV spectrum white spaces (often called White-Fi)

Wireless Link Standards



Evolution of IEEE802.11

TABLE I

THE EVOLUTION OF THE 802.11 STANDARDS

Protocol	Year Introduced	Maximum Data Transfer Speed	Frequency	Highest Order Modulation	Channel Bandwidth	Antenna Configurations
802.11a	1999	54 Mbps	5 GHz	64 QAM	20 MHz	1x1 SISO
802.11b	1999	11 Mbps	2.4 GHz	11 CCK	20 MHz	1x1 SISO
802.11g	2003	54 Mbps	2.4 GHz	64 QAM	20 MHz	1x1 SISO
802.11n	2009	65 to 600 Mbps	2.4 or 5 GHz	64 QAM	20 and 40 MHz	Up to 4x4 MIMO
802.11ac	2012	78 Mbps to 3.2 Gbps	5 GHz	256 QAM	20, 40, 80 and 160 MHz	Up to 8x8 MIMO; MU-MIMO

Wireless Link Characteristics

- Differences from wired link…
  - Decreased signal strength: radio signal attenuates as it propagates through matter (path loss).
  - Interference from other sources: standardized wireless network frequencies (e.g., 2.4 GHz) shared by other devices (e.g., phone); devices (motors) interfere as well.
  - Multipath propagation: radio signal reflects off objects ground, arriving at destination at slightly different times. {known as multipath fading}
- …. makes communication across (even a point to point) wireless link much more difficult.

Classification of Wireless Networks

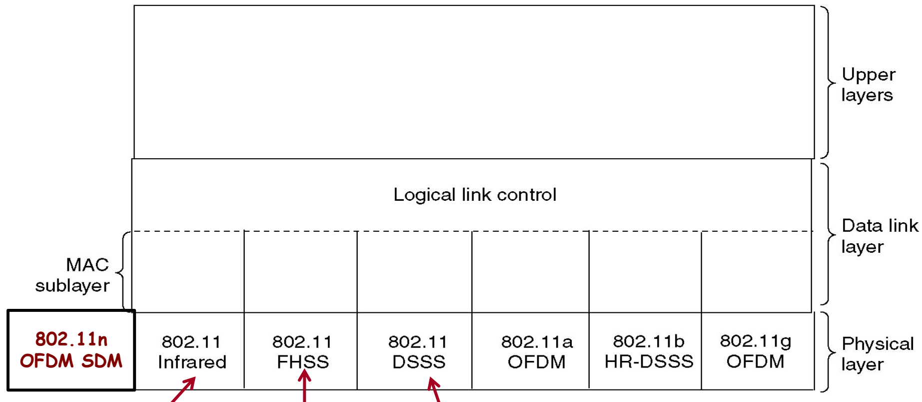
- Base Station
  - All communication via an Access Point (AP) {hub topology}.
  - Other nodes can be fixed or mobile.
- Infrastructure Wireless
  - AP is connected to the wired Internet.

Classification of Wireless Networks

- Ad Hoc Wireless
  - Wireless nodes communicate directly with one another.
  - Mesh Networks
    - Have a relatively stable topology and usually involve multi-hop routing.
- MANETs (Mobile Ad Hoc Networks)
  - ad hoc nodes are mobile.
  - VANETs (Vehicular Ad-Hoc Networks)
    - A technology that uses moving cars as nodes in a network to create a mobile network.

Wireless Network Taxonomy

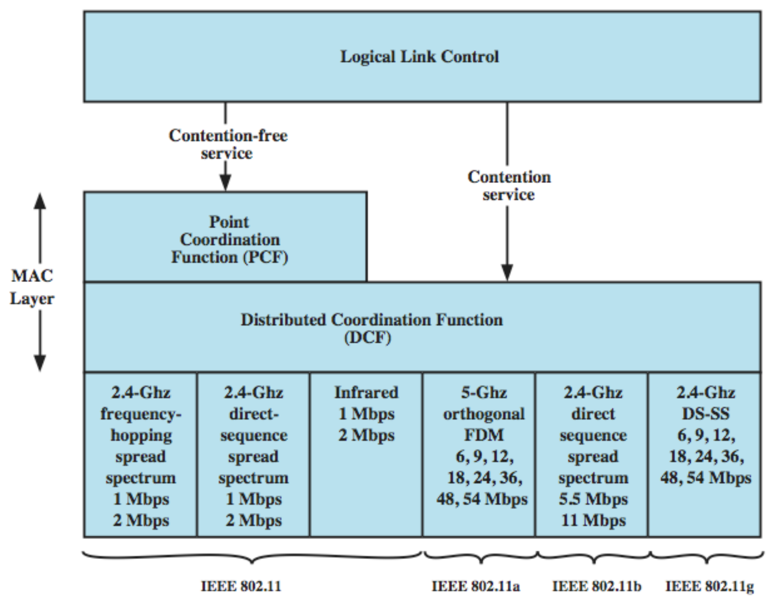
	single hop	multiple hops
Infrastructure (e.g., APs)	Host connects to base station (WiFi, WiMAX, cellular) which connects to larger Internet	Host may have to relay through several wireless nodes to connect to larger Internet: Mesh Net
No Infrastructure	No base station, no connection to larger Internet (Bluetooth, ad hoc nets)	No base station, no connection to larger Internet. May have to relay to reach other wireless nodes. MANET, VANET



Part of the 802.11 protocol stack.

The 802.11 Protocol Stack

Ordinary 802.11 products are no longer being manufactured.



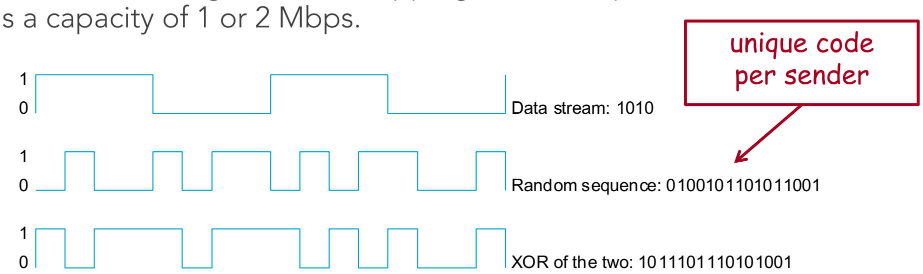
Media Access Control

IEEE 802.11 Physical Layer

- Physical layer conforms to OSI (seven options)
  - 1997: 802.11 infrared, FHSS, DSSS {FHSS and DSSS run in the 2.4GHz band}
  - 1999: 802.11a OFDM and 802.11b HR-DSSS
  - 2003: 802.11g OFDM
  - 2009: 802.11n OFDM and MIMO
  - 2012: 802.11ac OFDM, MIMO and channel bonding
- 802.11 Infrared
  - Two capacities: 1 Mbps or 2 Mbps.
  - Range is 10 to 20 meters and cannot penetrate walls.
  - Does not work outdoors.
- 802.11 FHSS (Frequence Hopping Spread Spectrum)
  - The main issue is multipath fading.
  - [P&D] The idea behind spread spectrum is to spread the signal over a wider frequency to minimize the interference from other devices.
  - 79 non-overlapping channels, each 1 Mhz wide at low end of 2.4 GHz ISM band.
  - The same pseudo-random number generator used by all stations to start the hopping process.
  - Dwell time: min. time on channel before hopping (400msec).

IEEE 802.11 Physical Layer

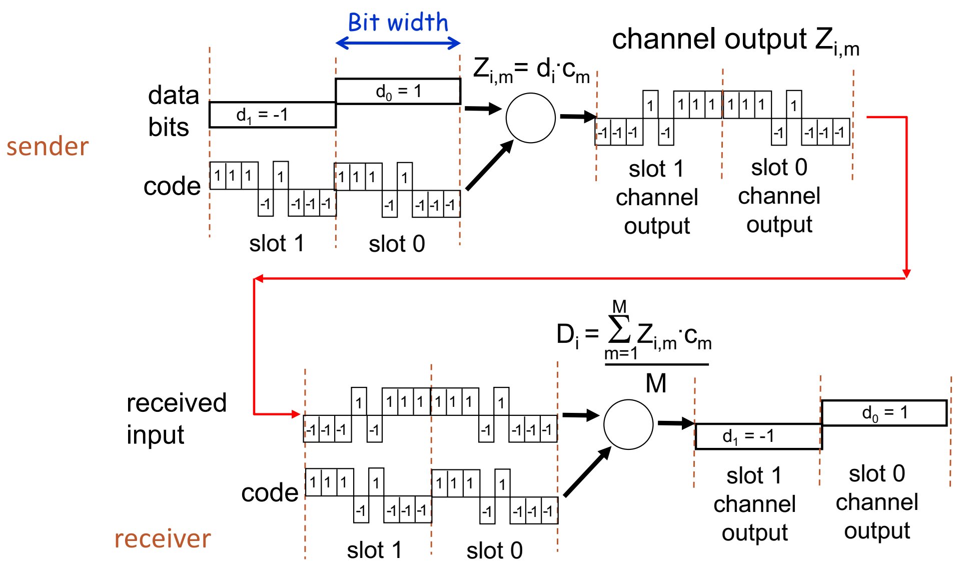
- 802.11 DSSS (Direct Sequence Spread Spectrum)
  - The main idea is to represent each bit in the frame by multiple bits in the transmitted signal (i.e., it sends the XOR of that bit and n random bits).
  - Spreads signal over entire spectrum using pseudo-random sequence (similar to CDMA see Kurose & Ross Chap 6).
  - Each bit transmitted using an 11-bit chipping Barker sequence, PSK at 1Mbaud.
  - This yields a capacity of 1 or 2 Mbps.



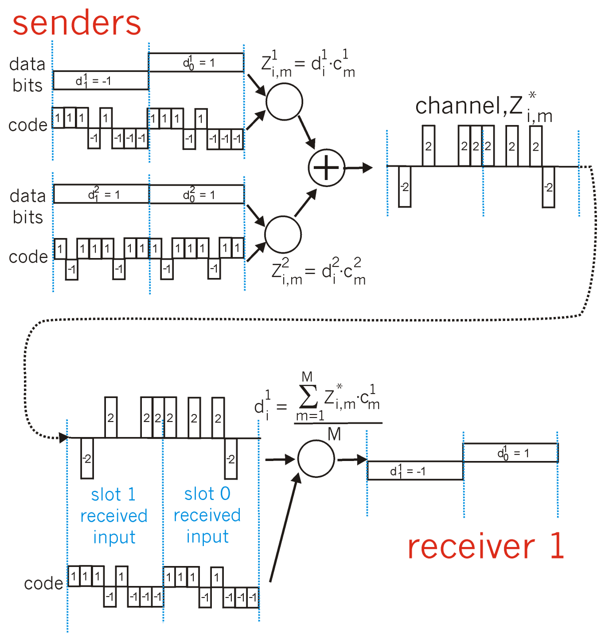
Example 4-bit chipping sequence

Code Division Multiple Access (CDMA)

- Used in several wireless broadcast channels (cellular and satellite) standards.
- A unique "code" is assigned to each user; i.e., code set partitioning.
- All users share the same frequency, but each user has its own chipping sequence (i.e., unique code) to encode data.
- encoded signal = (original data) X (chipping sequence)
- decoding: inner-product of encoded signal and chipping sequence
- Allows multiple users to "coexist" and transmit simultaneously with minimal interference (if codes are "orthogonal")



CDMA Encode/Decode



CDMA: Two-Sender Interference

IEEE 802.11 Physical Layer

- 802.11a OFDM (Orthogonal Frequency Divisional Multiplexing)
  - Compatible with European HiperLan2.
  - **54 Mbps** in wider 5.5 GHz band ➔ transmission range is limited.
  - Uses 52 FDM sub-channels (48 for data; 4 for synchronization).
  - Encoding is complex (PSM up to 18 Mbps and QAM above this capacity).
  - E.g., at 54 Mbps 216 data bits encoded into into 288-bit symbols.
  - More difficulty penetrating walls.

  ** net achievable throughput in the mid-20 Mbps!!

IEEE 802.11 Physical Layer

- 802.11b HR-DSSS (High Rate Direct Sequence Spread Spectrum)
  - **11a and 11b** shows a split in the standards committee.
  - **11b** approved and hit the market before **11a.**
  - Up to **11 Mbps** in 2.4 GHz band using 11 million chips/sec.
  - Note in this bandwidth, this protocol has to deal with interference from microwave ovens, cordless phones and garage door openers.
  - Range is 7 times greater than **11a.**
  - 11b and 11a are incompatible!!

    ** net achievable throughput in 6 Mbps range!!

IEEE 802.11 Physical Layer

- 802.11g OFDM (Orthogonal Frequency Division Multiplexing)
  - Tries **to combine the best of both 802.11a and 802.11b.**
  - Supports bandwidths up to **54 Mbps**.
  - Uses 2.4 GHz frequency for greater range.
  - Is backward compatible with 802.11b.
- Note – common for products to support 802.11a/b/g in a single NIC

Data Rate (Mbps)	802.11b	802.11a	802.11g
1	90+	—	90+
2	75	—	75
5.5(b)/6(a/g)	60	60+	65
9	—	50	55
11(b)/12(a/g)	50	45	50
18	—	40	50
24	—	30	45
36	—	25	35
48	—	15	25
54	—	10	20

Data Rate vs Distance (m)

IEEE 802.11 Physical Layer

- 802.11n OFDM version at 248 Mbps
- Physical Layer Changes:
  - Multiple-Input-Multiple-Output (MIMO)
  - maximum of 600 Mbps with the use of four spatial streams at a channel width of 40 MHz.
  - Spatial Division Multiplexing (SDM)
- MAC Layer Changes:
  - Frame aggregation into single block for transmission.

IEEE 802.11 Physical Layer

- 802.11ac OFDM version up to 6.93 Gbps
- Physical Layer Changes:
  – 5 GHz band
  – Multiple-Input-Multiple-Output (MIMO) with up to eight spatial streams
  – MU MIMO {Multi User MIMO} behaves like a switch
  – Increased channel bandwidth
    - Up to 80 MHz with option of 160 MHz or two 80 MHz blocks
  – 256 QAM optional

Larger than Ethernet frame →

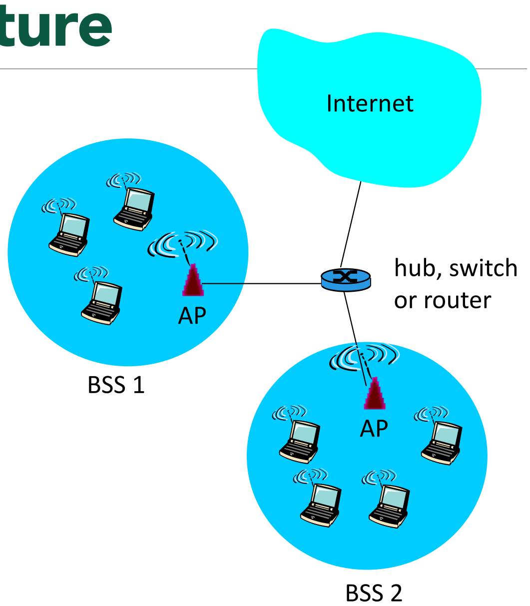
octets	2	2	6	6	6	2	6	0 to 2312	4
	FC	D/I	Address	Address	Address	SC	Address	Frame body	CRC

FC = Frame control
D/I = Duration/Connection ID
SC = Sequence control

IEEE 802.11 MAC Frame Format

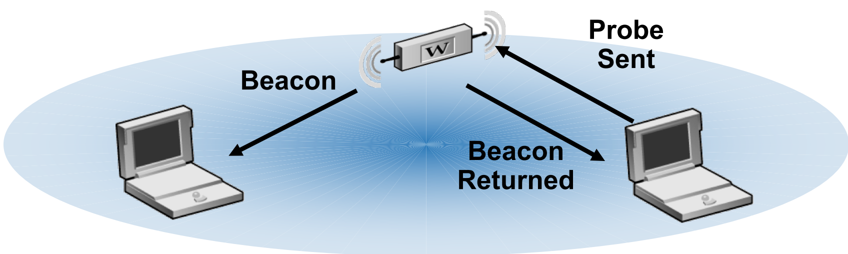
802.11 LAN Architecture

- Wireless host communicates with base station
  - base station = access point (AP)
- Basic Service Set (BSS) (aka "cell") in infrastructure mode contains:
  - wireless hosts
  - access point (AP): base station
  - ad hoc mode: hosts only



802.11 Management Functions

- Channel Selection
- Scanning
- Station (user) Authentication and Association
- Beacon Management
- Power Management Mode

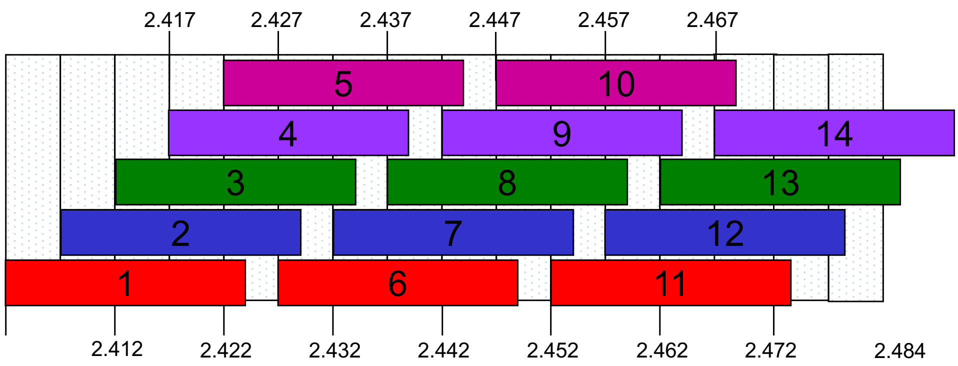


Channels and AP Association

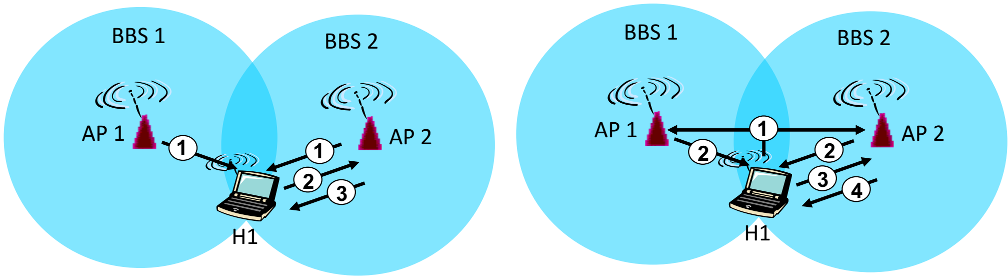
- 802.11b: 2.4GHz-2.485GHz spectrum divided into 11 channels (overlapping frequencies).
  - AP admin chooses frequency for AP.
  - Interference is possible: The channel can be same as that chosen by a neighbor AP!
- Wireless nodes must associate with an AP.
  - Node scans channels, listening for beacon frames containing AP's name (SSID) and MAC address.
  - Node makes choice for AP association {default is best RSSI}.
  - may perform authentication [K&R Chapter 8].
  - will typically run DHCP to get IP address in AP's subnet.

802.11 Overlapping Channels

- 802.11b/g transmission occurs on one of 11 overlapping channels in the 2.4GHz North American ISM band.



802.11: Passive/Active Scanning



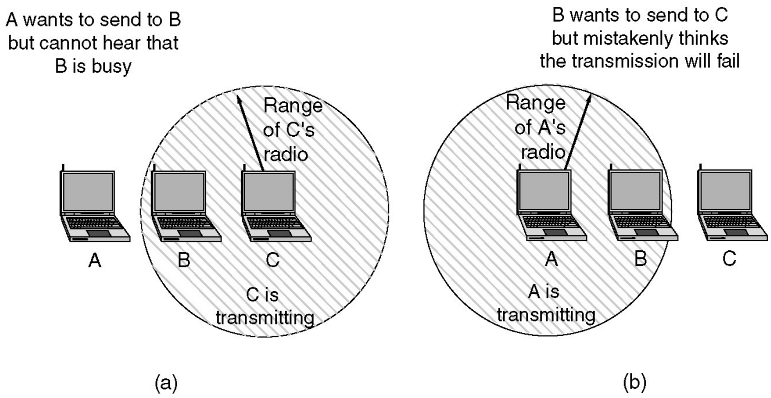
Passive Scanning
(1) beacon frames sent from APs.
(2) association **Request** frame sent: H1 to selected AP.
(3) association **Response** frame sent: AP to H1.

Active Scanning
(1) Probe **Request** frame broadcast from H1.
(2) Probe **Response** frame sent from APs.
(3) Association **Request** frame sent: H1 to selected AP.
(4) Association **Response** frame sent: AP to H1.

802.11 MAC Layer Protocol

- In 802.11 wireless LANs, "seizing the channel" does not exist as in 802.3 wired Ethernet.
- Two additional problems:
  - Hidden Terminal Problem
  - Exposed Station Problem
- To deal with these two problems 802.11 supports two modes of operation:
  - DCF (Distributed Coordination Function)
  - PCF (Point Coordination Function).
- All implementations must support DCF, but PCF is optional.

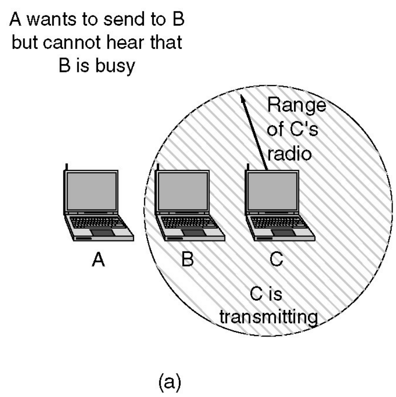
802.11 Problems



- (a) Hidden terminal problem. (b) The exposed station problem.

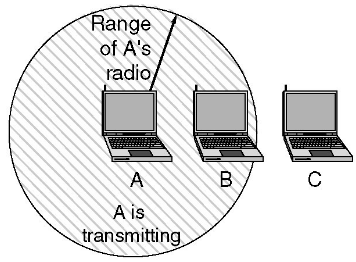
The Hidden Terminal Problem

- Wireless stations have transmission ranges and not all stations are within radio range of each other.
- Simple CSMA will not work!
- C transmits to B.
- If A "**senses**" the channel, it will not hear C's transmission and falsely conclude that A can begin a transmission to B.



The Exposed Station Problem

- This is the inverse problem.
- B wants to send to C and listens to the channel.
- When B hears A's transmission, B falsely assumes that it cannot send to C.



(b)

Distribute Coordination Function (DCF)

CSMA/CA (*CSMA* with *C*ollision *A*voidance) uses one of two modes of operation:

- virtual carrier sensing
- physical carrier sensing

The two methods are supported by:

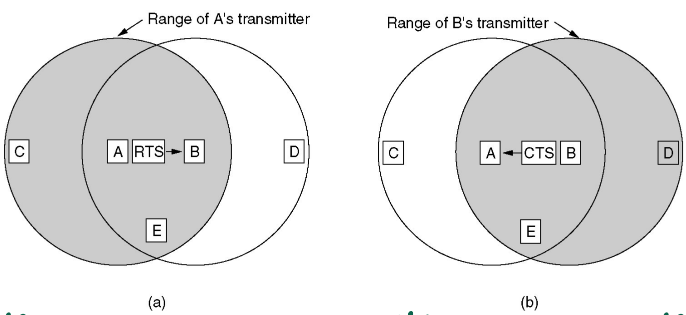
1. ***MACAW*** (Multiple Access with Collision Avoidance for Wireless) with virtual carrier sensing.
2. 1-persistent physical carrier sensing.

Wireless LAN Protocols

- MACA protocol reduces hidden and exposed terminal problems:
- Sender broadcasts a Request-to-Send (RTS) and the intended receiver sends a Clear-to-Send (CTS).
- Upon receipt of a CTS, the sender begins transmission of the frame.
- RTS,CTS help determine who else is in range or busy (Collision Avoidance).
  - Can a collision still occur?

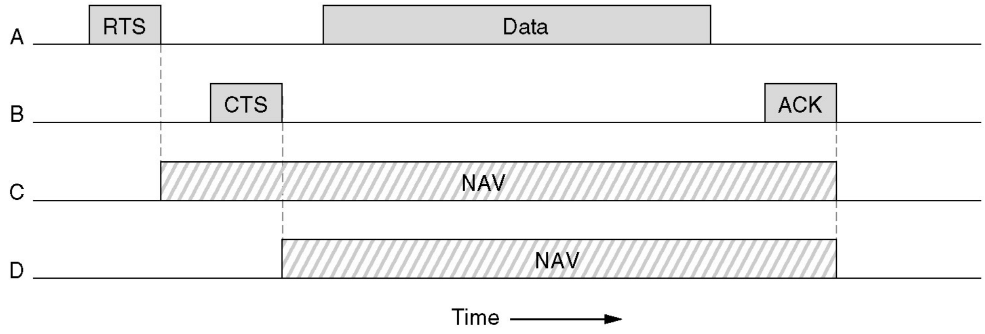
Wireless LAN Protocols

- MACAW added ACKs, Carrier Sense, and BEB done per stream and not per station.



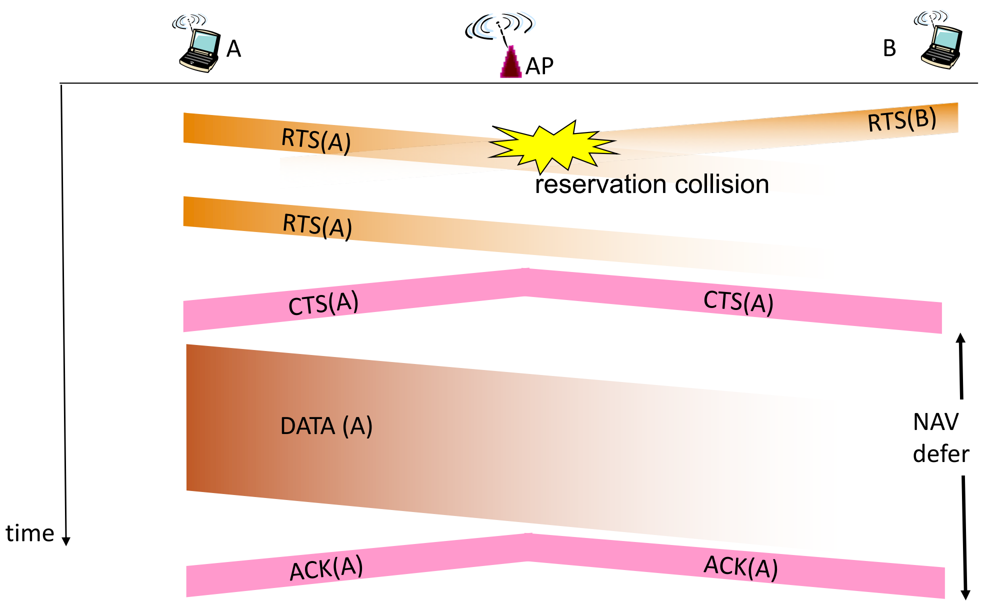
(a) A sending an RTS to B, (b) B responding with a CTS to A.

Virtual Channel Sensing in CSMA/CA



The use of virtual channel sensing using CSMA/CA.

- C (in range of A) *receives the RTS and based on information in RTS creates a* ***virtual channel busy*** NAV (Network Allocation Vector).
- D (in range of B) *receives the CTS and creates a shorter* NAV



Collision Avoidance: RTS-CTS Exchange

Virtual Channel Sensing in CSMA/CA

What is the advantage of RTS/CTS?

RTS is 20 bytes, and CTS is 14 bytes.

MPDU can be 2300 bytes.

- "virtual" implies source station sets the duration field in data frame or in RTS and CTS frames.
- Stations then adjust their NAV accordingly!

1-Persistent Physical Carrier Sensing

- The station **senses** the channel when it wants to send.
- If idle, the station transmits.
  - A wireless station does not sense the channel while transmitting.
- If the channel is busy, the station defers until idle and then transmits **(1-persistent)**.
- Upon collision (no ACK received), wait a *random time* using binary exponential backoff **(BEB)**.

IEEE 802.11 MAC Protocol: CSMA/CA

802.11 sender

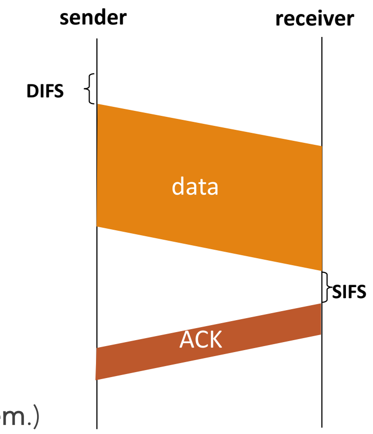
1 if sense channel idle for **DIFS** then
Transmit entire frame (no CD).

2 if sense channel busy then
Choose a random backoff time.
When channel is busy, counter is frozen.
Timer counts down while channel idle and
transmit when timer expires.
if no ACK, increase random backoff interval, repeat 2.

802.11 receiver

- if frame received OK

return ACK after **SIFS (ACK needed due to hidden terminal problem.**)

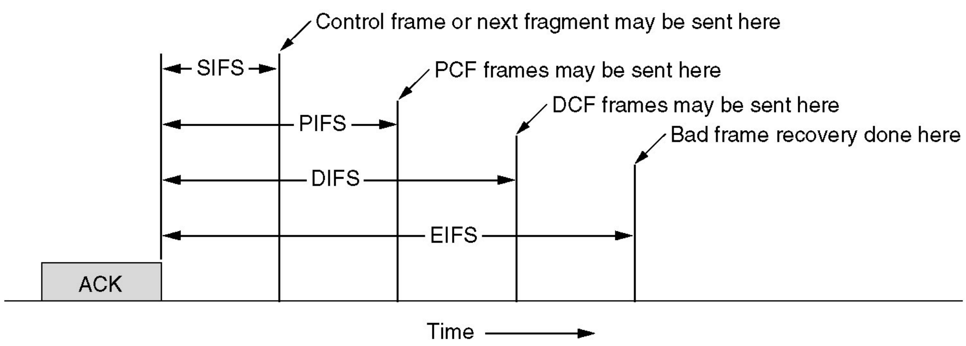


Point Coordinated Function (PCF)

- PCF uses a base station (BS) to poll other stations to see if they have frames to send.
- No collisions occur.
- Base station sends beacon frame periodically.
- Base station can tell another station to sleep to save on batteries and base station holds frames for sleeping station.
- Subsequently, BS awakens sleeping node via beacon frame.

DCF and PCF Co-Existence

- Distributed and centralized control can co-exist using InterFrame Spacing.
- SIFS (Short IFS):: the time waited between packets in an ongoing dialog (RTS,CTS,data, ACK, next frame)
- PIFS (PCF IFS):: when no SIFS response, base station can issue beacon or poll.
- DIFS (DCF IFS):: when no PIFS, any station can attempt to acquire the channel.
- EIFS (Extended IFS):: lowest priority interval used to report bad or unknown frame.



Interframe Spacing in 802.11.

Inter-frame Spacing in 802.11

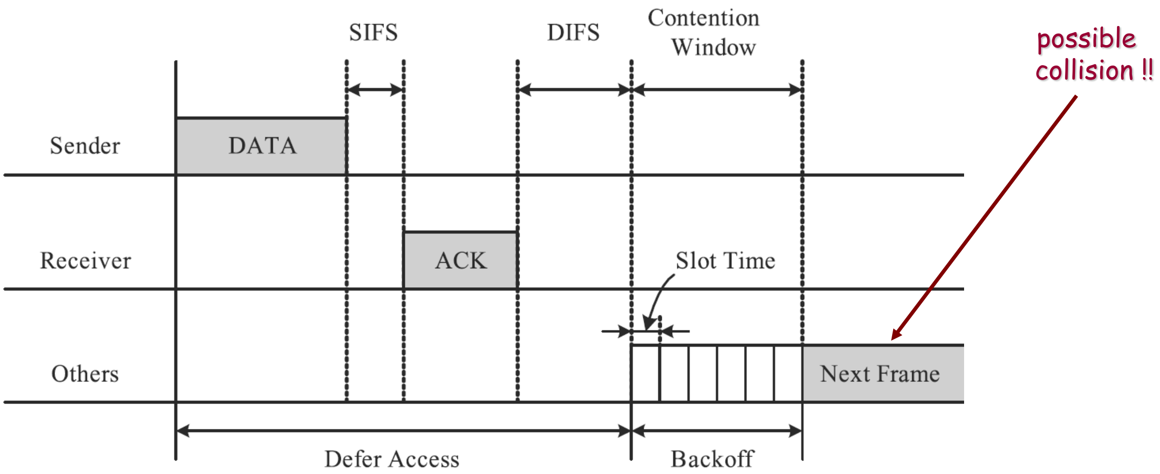


Fig. 1 CSMA/CA protocol of IEEE 802.11 MAC DCF.

Basic CSMA/CA

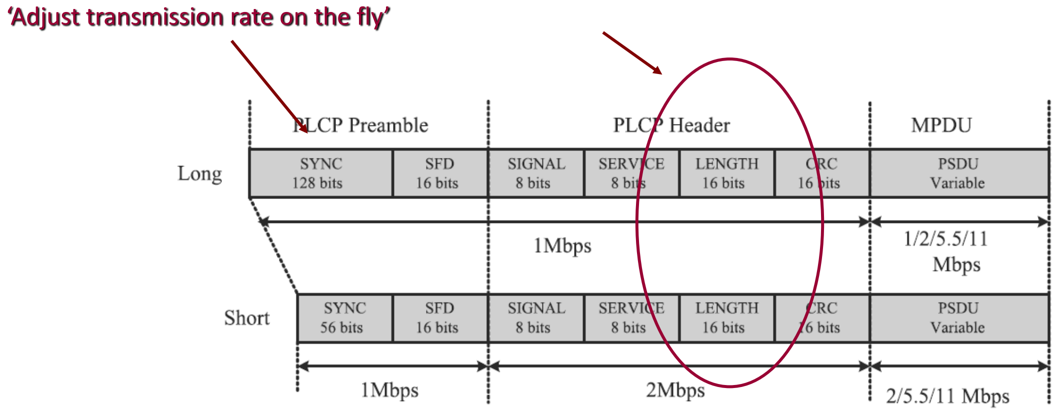


Fig. 2 IEEE 802.11b HR/DSSS PHY framing structure.

802.11b Physical Layer

2	2	6	6	6	2	6	0 - 2312	4
frame control	duration	address 1	address 2	address 3	seq control	address 4	payload	CRC

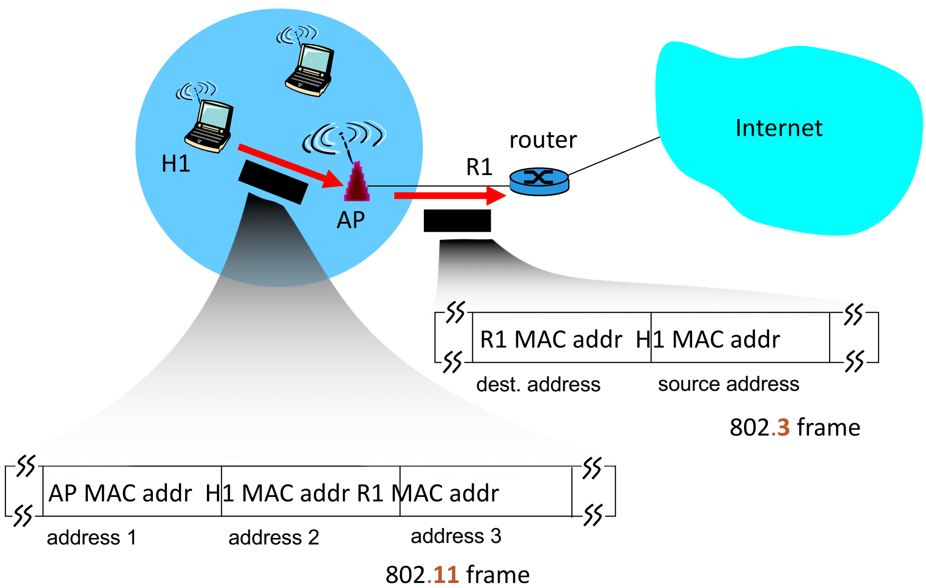
Address 1: MAC address of wireless host or AP to receive this frame

Address 2: MAC address of wireless host or AP transmitting this frame

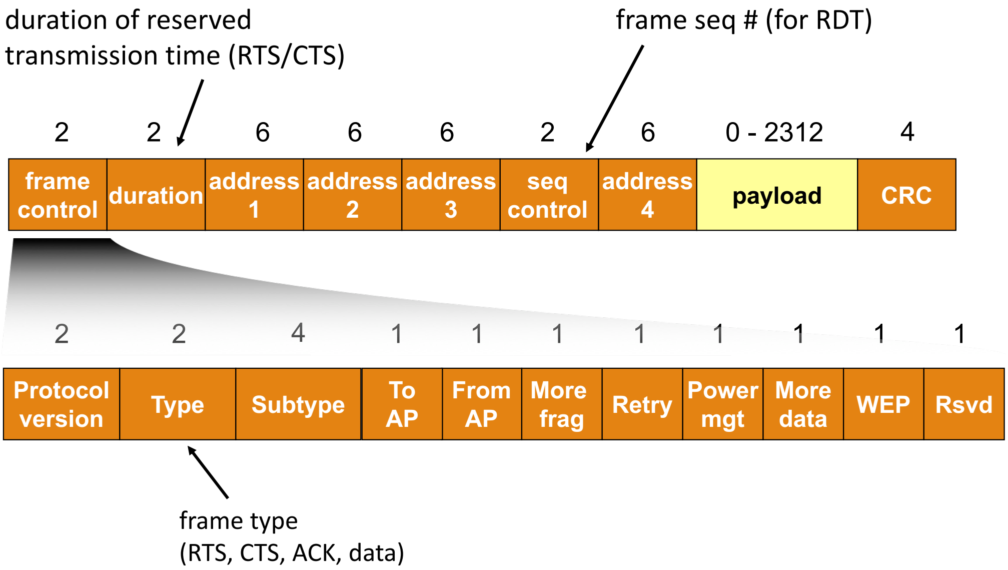
Address 3: MAC address of router interface to which AP is attached

Address 4: used only in ad hoc mode

802.11 Frames – Addresses



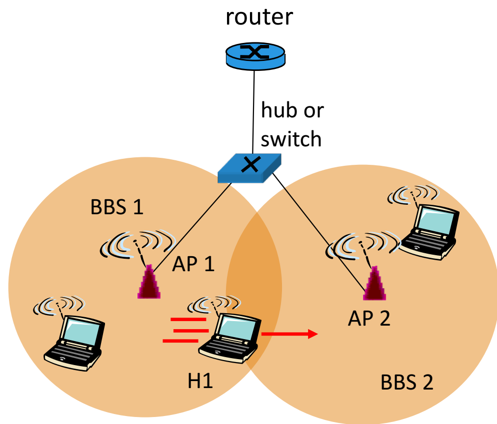
802.11 Frame – Addresses



802.11 Frame Addresses (more)

Addressing

- H1 remains in same IP subnet
  - IP address can remain same.
- Switch: Which AP is associated with H1?
  - Uses self-learning
  - Switch will see frame from H1 and “remember” which switch port can be used to reach H1.



Wireless Network Details

- All APs (or base stations) will periodically send a beacon frame (10 to 100 times a second).
- Beacon frames are also used by DCF to synchronize and handle nodes that want to sleep.
  - Node sets Power management bit to indicate going to sleep and timer wakes node up for next beacon.
  - The AP will buffer frames intended for a sleeping wireless client and wakeup for reception with beacon frame.

Wireless Network Details

- AP downstream/upstream traffic performance is asymmetric.
- AP has buffers for downstream/upstream queueing.
- Wireless communication quality between two nodes can be asymmetric due to multipath fading

Dynamic Rate Adaptation

- 802.11b, g and n use dynamic rate adaptation based on frame loss (algorithms internal to wireless card at the AP).
  – e.g. for 802.11b choices are: 11, 5.5, 2 and 1 Mbps
- Standard 802.11 retries:
  – 7 retries for RTS and CTS
  – 4 retries for Data and ACK frames
- RTS/CTS may be turned off by default. [Research has shown that RTS/CTS degrades performance when hidden terminal is not an issue].

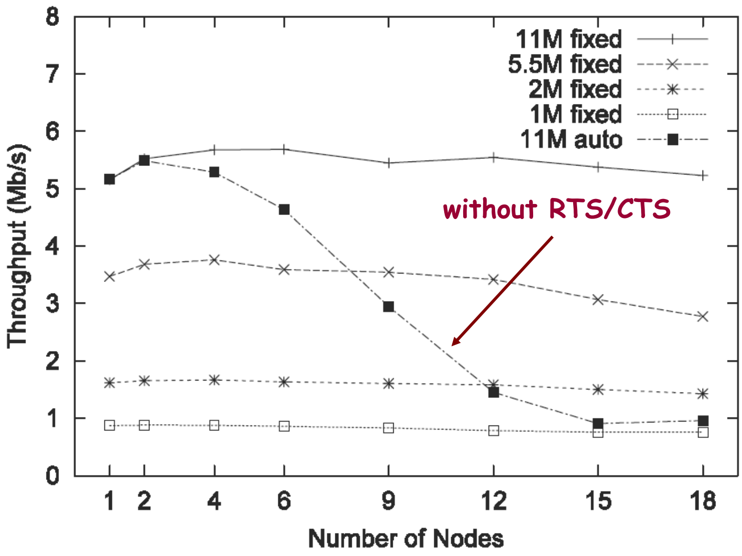
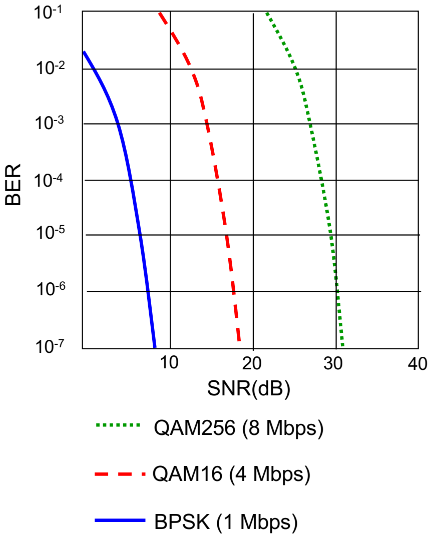


Fig. 7 Throughputs with node contentions.

Node Contention

Wireless Link Characteristics

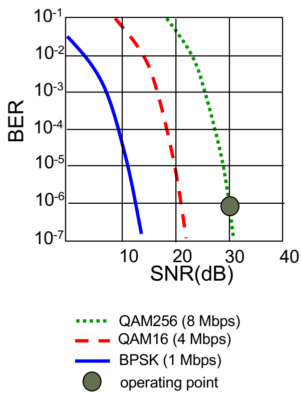
- SNR: signal-to-noise ratio
- larger SNR – easier to extract signal from noise.
- SNR versus BER tradeoffs
- Given a physical layer: increase power -> increase SNR-> decrease BER.
- Given a SNR: choose physical layer that meets BER requirement, aiming for highest throughput.
- SNR may change with mobility: dynamically adapt physical layer (modulation technique, rate).



Mobile Node Example:

1. SNR decreases, BER increases as node moves away from base station.
2. When BER becomes too high, switch to lower transmission rate but with lower BER.

Idea:: lower maximum data rate for higher throughput.



Note – Performance Anomaly paper shows there are other issues when wireless flows contend at AP !

Rate Adaptation versus Distance

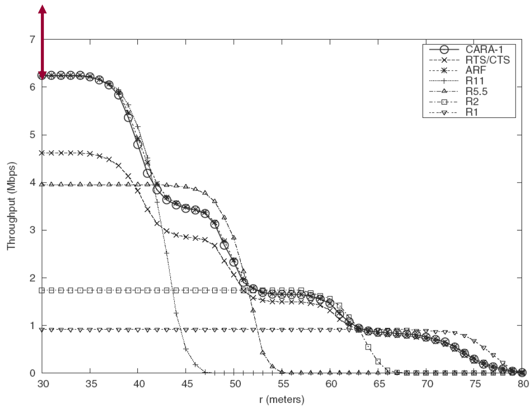
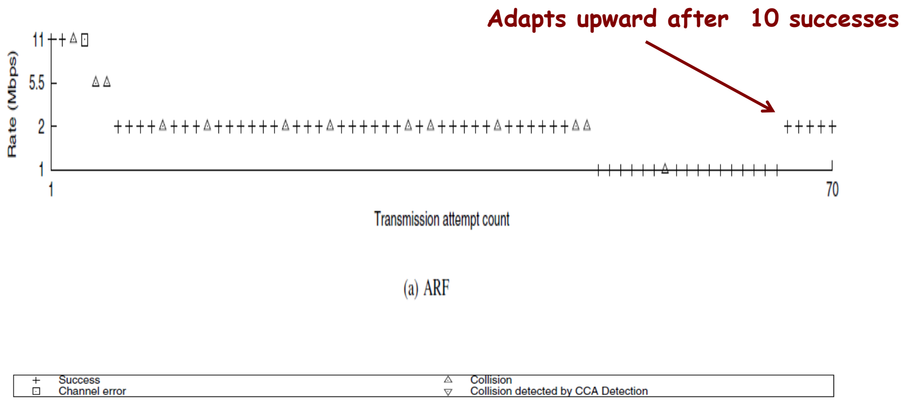


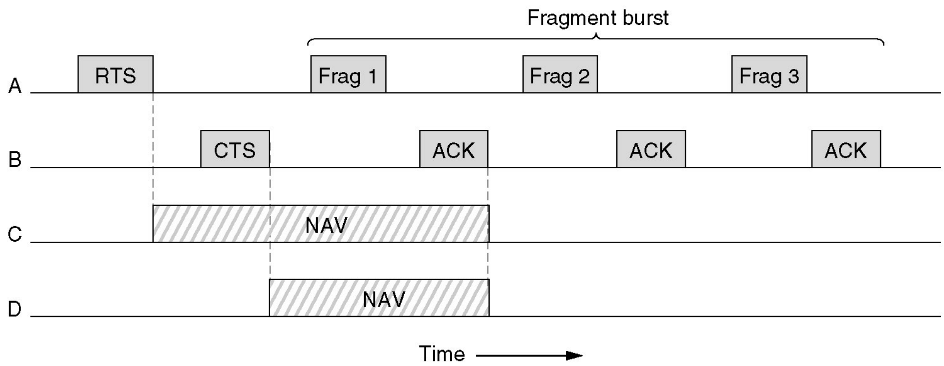
Fig. 6. Throughput comparison of our proposed rate adaptation scheme (CARA-1) against RTS/CTS, ARF, and single-rate schemes for one-to-one topology networks with various distance (r)

ARF – Original Rate Adaptation



(a) ARF

Fragmentation in 802.11



- High wireless error rates → long packets have less probability of being successfully transmitted.
- Solution: MAC layer fragmentation with stop-and-wait protocol on the fragments.

Wireless Networks Summary

- Terminology, WLAN types, IEEE Standards
  - Infrastructure, ad hoc, MANET, Base Station, Access Point, single and multi-hop
- IEEE 802.11a/b/g/n/ac
  - Differences in data rate and transmission technologies
  - FHSS, DSSS, CDMA, OFDM, HR-DSSS, MIMO

Wireless Networks Summary

- 802.11 AP Management Functions
  - Association with AP, active and passive scanning, beacon frames
- 802.11 MAC Sub-Layer
  - Overlapping channels
  - Hidden terminal problem, exposed station problem
  - DCF
    - CSMA/CA
    - MACAW

Wireless Networks Summary

- 802.11 MAC Sub-Layer (cont.)
  - RTS/CTS
  - PCF
    - Beacons, DIFS, SIFS, sleeping nodes
  - Frame Details
    - PLCP preamble and header
    - 3 or 4 Address fields used in 802.11
  - SNR vs BER issues
  - Dynamic Rate Adaptation
  - Frame Fragmentation