Wireless Local Area Networks (WLANs) based on IEEE 802.11 Standard *aka* Wi-Fi

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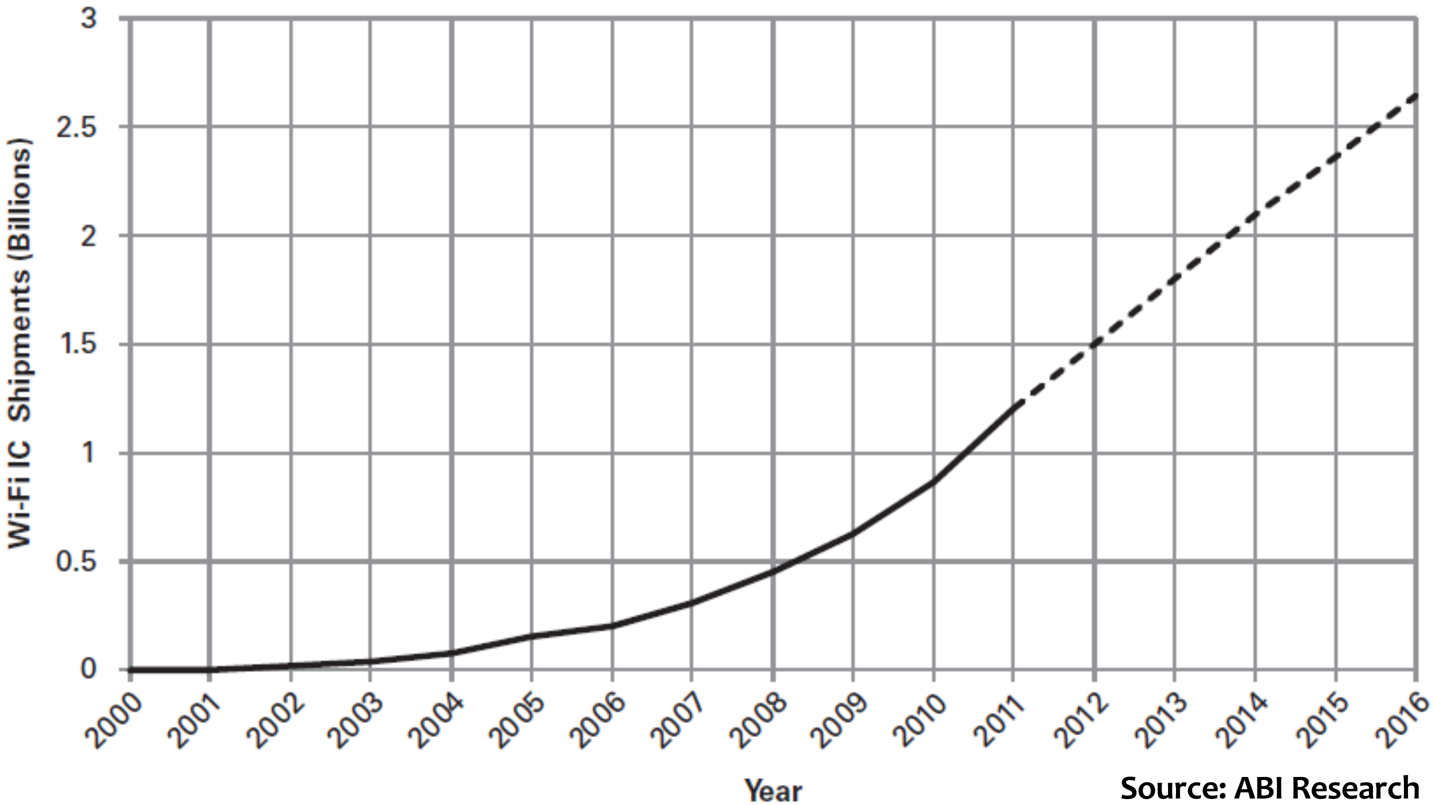
Wireless Local Area Networks (WLANs)

- Offers clear benefits over wired LANs:
  - Avoid the inconvenience and cost of running cables
  - Flexible network connectivity: get connectivity where desired instead of having to connect at locations wired network allows

- IEEE 802.11 has become the *de facto* standard for WLANs
  - Survived the competition from other proposed WLAN technologies and standards (e.g., HiperLAN)

- Now WLANs are synonymous with 802.11 based WLANs (also called *Wi-Fi*)
  - Wi-Fi is to wireless LANs as Ethernet is to wired LANs

The Success of Wi-Fi



- Contributing factors:
  - **Operation in license exempt (unlicensed) spectrum bands ➔** no barrier to deployment
  - Continually evolving **standards** aimed at higher data rates and enhanced functionality
  - **Low cost commodity hardware** from reaching economies of scale

(Partial) History of 802.11 WLANs

1985
- US Federal Communications Commission (FCC) allowed unlicensed use of ISM bands

1997
- First version of 802.11 standard published

1999
- 802.11b and 802.11a amendments supporting higher data rates up to 54Mbps
- Wi-Fi Alliance formed to certify interoperability between IEEE 802.11 devices from different manufacturers

2003
- 802.11g amendment using 802.11a OFDM PHY and supporting up to 54Mbps data rates

2007
- 802.11-2007 (a new release of the standard) that includes amendments a, b, d, e, g, h, i & j

2009
- 802.11n amendment with high throughput improvements via MIMO, channel bonding and frame aggregation

2012
- 802.11-2012 (a new release of the standard) that includes amendments k, n, p, r, s, u, v, w, y and z
- 802.11ad amendment to enable very high throughput operation in frequencies around 60GHz ➔ 802.11ay

2013 -
- 2013: 802.11ac amendment with very high throughput enhancements including multi-user MIMO ➔ 802.11ax
- 2014: 802.11af amendment supporting operation in Television White Spaces (TVWS)
- 2016: 802.11ah for sub 1GHz operation in license-excempt bands
- 802.11-2016 (a new release of the standard) that includes amendments ac, ad, af, aa and ae

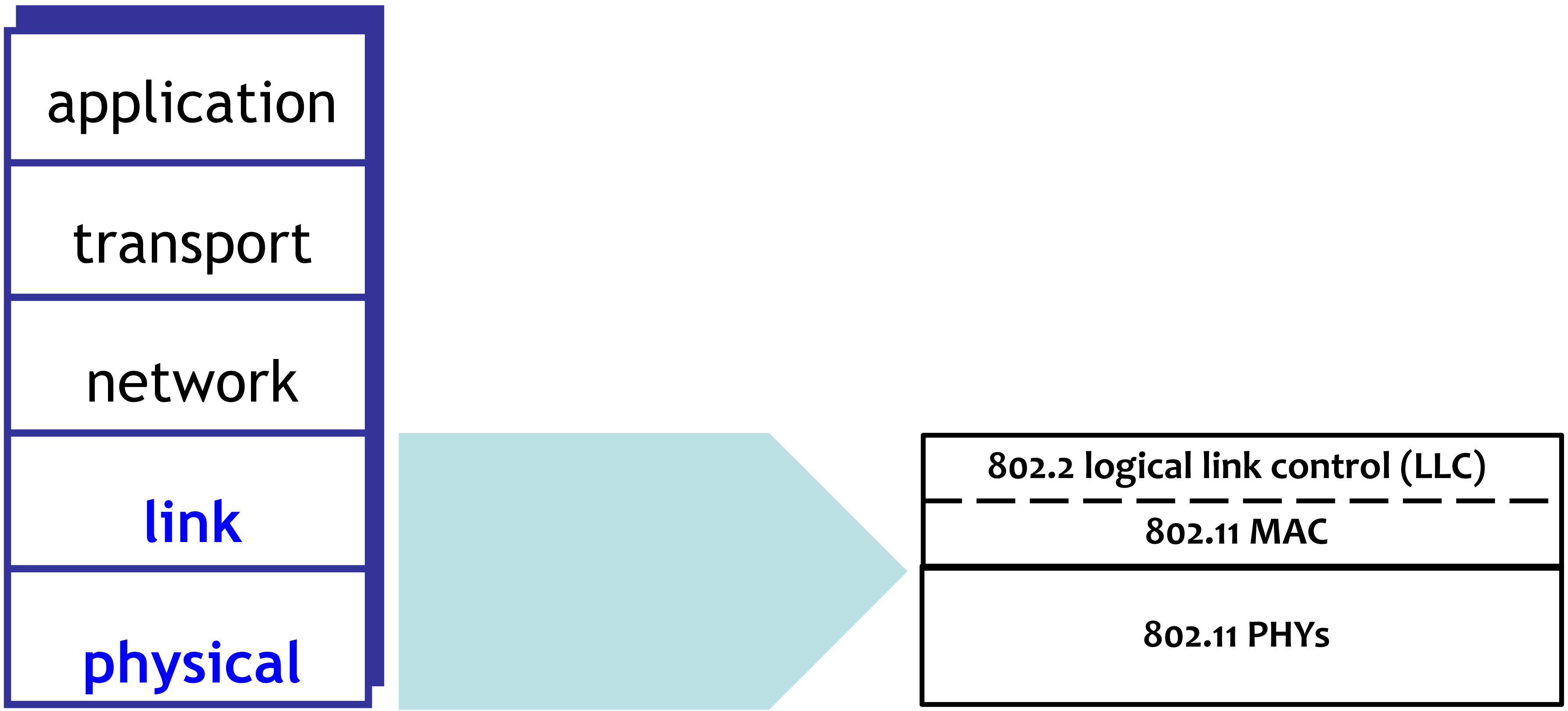
Useful 802.11 Links

- Get latest 802.11 standards via:
  - http://ieeexplore.ieee.org/browse/standards/get-program/page/series?id=68
- Official IEEE 802.11 working group project timelines:
  - http://grouper.ieee.org/groups/802/11/Reports/802.11_Timelines.htm

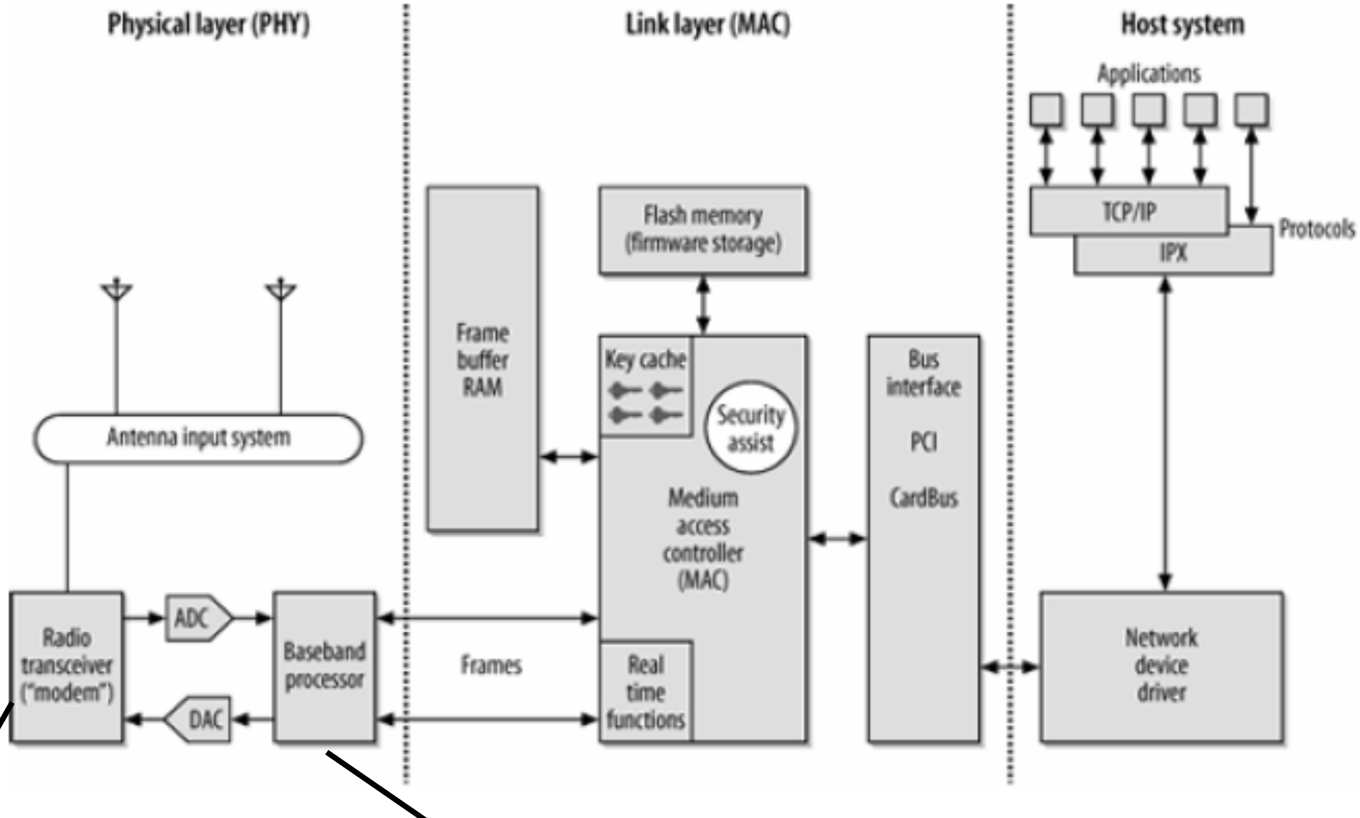
IEEE 802.11 Standard Overview

- Defines multiple physical layers (PHYs) and a common medium access control (MAC) layer for WLANs
- Member of IEEE 802 family of local area networking (LAN) and metropolitan area networking (MAN) standards
  - Inherits the 802 reference model and 48-bit universal addressing scheme

802.11 in the TCP/IP Internet Protocol Stack



A Typical Implementation of 802.11 Network Interface



Frequency conversion
Amplifier

Shielding

(De)modulation
Physical carrier sensing

802.11 Medium Access Control (MAC) Overview

- 802.11 adopted the distributed MAC protocol based on carrier sense multiple access (CSMA) from Ethernet (the wired counterpart of 802.11)
  - listen/sense medium (carrier) and transmit if idle

- Ethernet uses a CSMA variant called *CSMA with collision detection (CSMA/CD)*
  - Each Ethernet device can receive its own transmission and detect collisions
  - Upon collision detection: stop transmission ➔ random backoff ➔ retry

802.11 Medium Access Control (MAC) Overview

- 802.11 uses a different variant called *CSMA with collision avoidance (CSMA/CA)*
  - Coz half-duplex wireless interfaces do not allow receiving one's own transmission
  - Moreover, collisions occur on receiver side

- Idea: be conservative in attempting a transmission
  - 802.11 devices on finding a busy medium defer by different randomly chosen periods (counting down only when medium is idle)

Overview of 802.11 Physical Layers (PHYs)

	802.11 (1997)	802.11b (1999)	802.11a (1999)	802.11g (2003)	802.11n (2009)	802.11ac (2013)
PHY technology	IR, FHSS and DSSS in 2.4 GHz	DSSS/CCK	OFDM	OFDM & DSSS/CCK	SDM/OFDM	SDM/OFDM and MU-MIMO
Data rates (Mbps)	1, 2	1, 2, 5.5, 11	6-54	1-54	6.5-600	6.5-6933.3
Frequency band (GHz)	2.4	2.4	5	2.4	2.4 and 5	5
Channel widths (MHz)	25	25	20	25	20 and 40	20, 40, 80 and 160

Key

IR: Infrared

FHSS: Frequency Hopping Spread Spectrum

DSSS: Direct Sequence Spread Spectrum

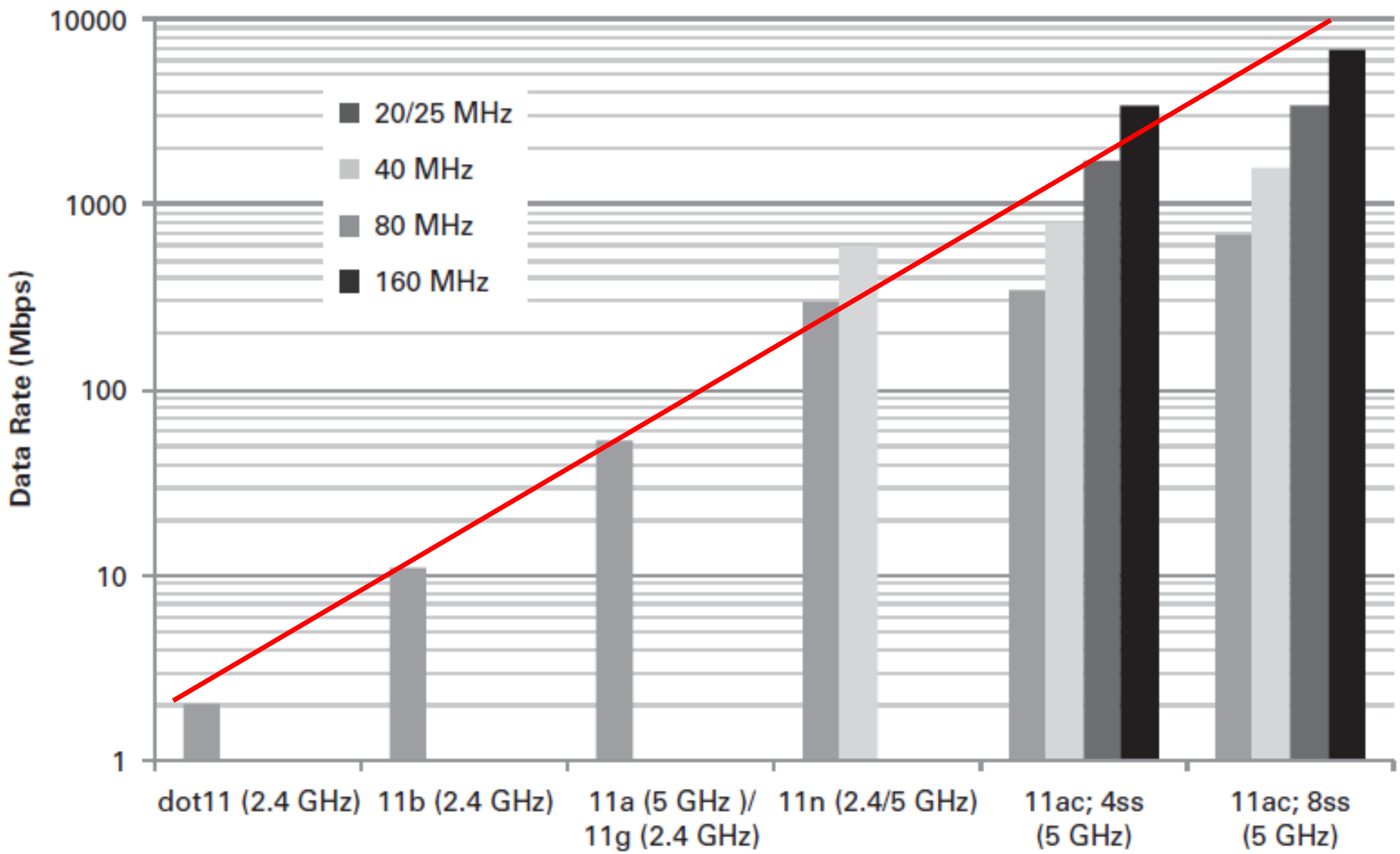
CCK: Complementary Code Keying

OFDM: Orthogonal Frequency Division Multiplexing

SDM: Spatial Division Multiplexing

MU-MIMO: Multi-User MIMO

Exponentially Increasing 802.11 PHY Data Rates



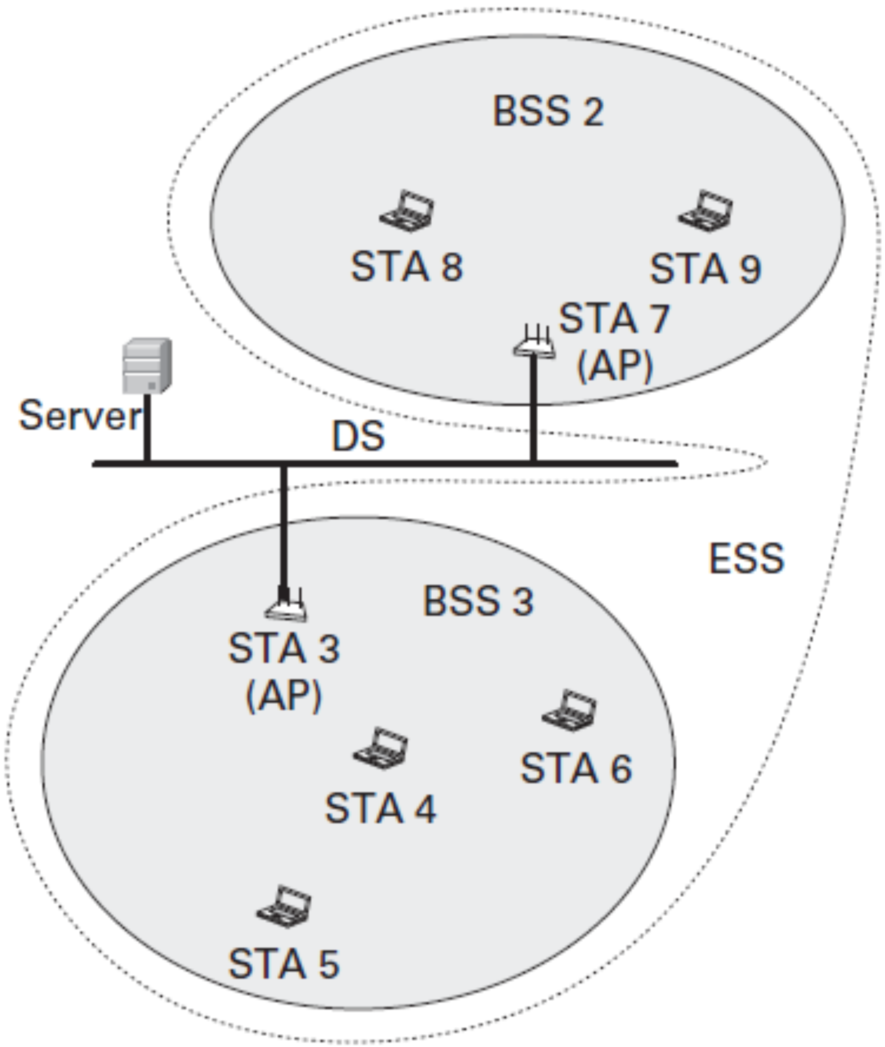
Note that the y-axis is in *log-scale*

802.11 Network Architecture

- Individual 802.11 devices referred to as **stations**
- Basic building block: **basic service set (BSS)**
  - Essentially, a set of stations

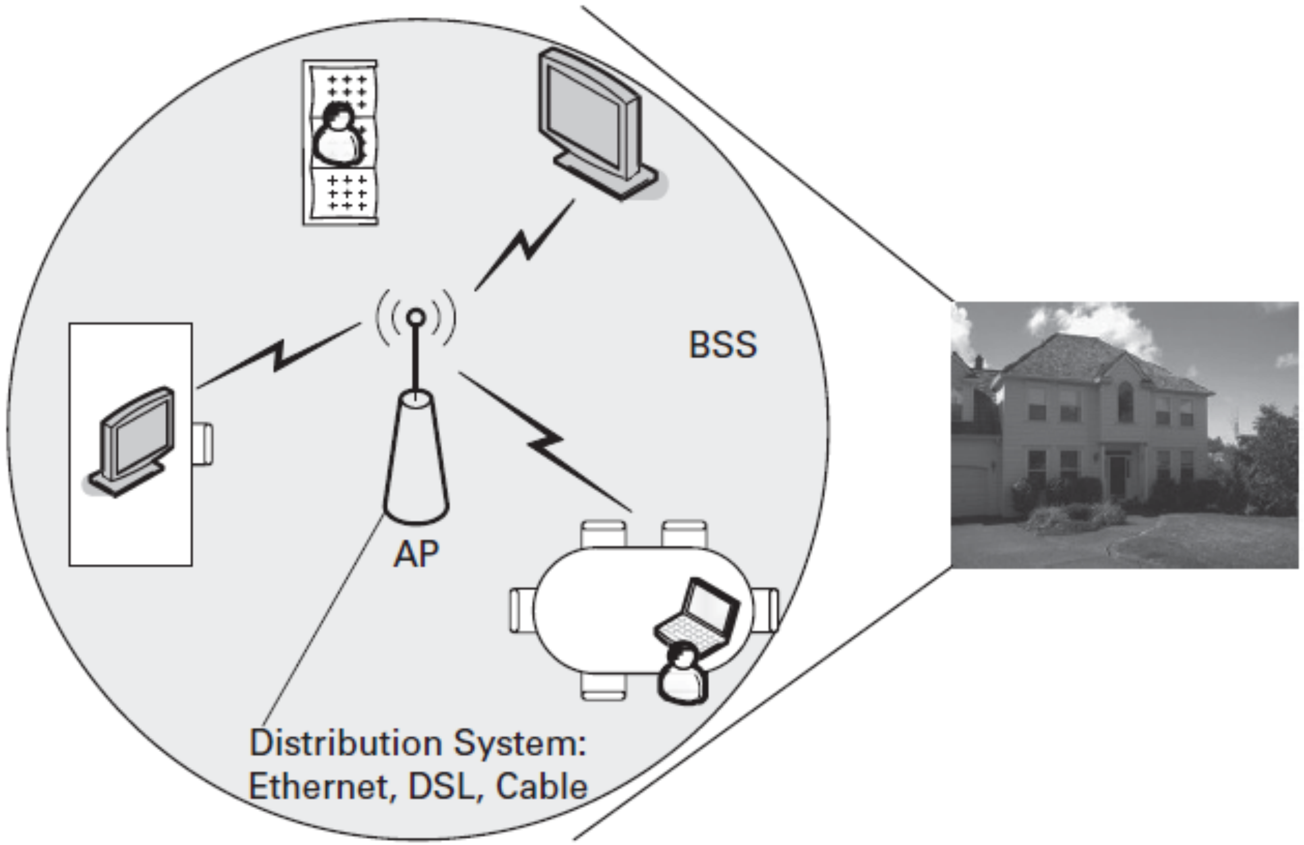
Infrastructure BSS

- Special station called **access point (AP)** manages the BSS and connects with other infrastructure BSSs and network infrastructure via a **distributed system (DS)**
- **Extended service set (ESS)**: a set of infrastructure BSSs interconnected by DS
  - Stations within an ESS can address directly at the MAC layer



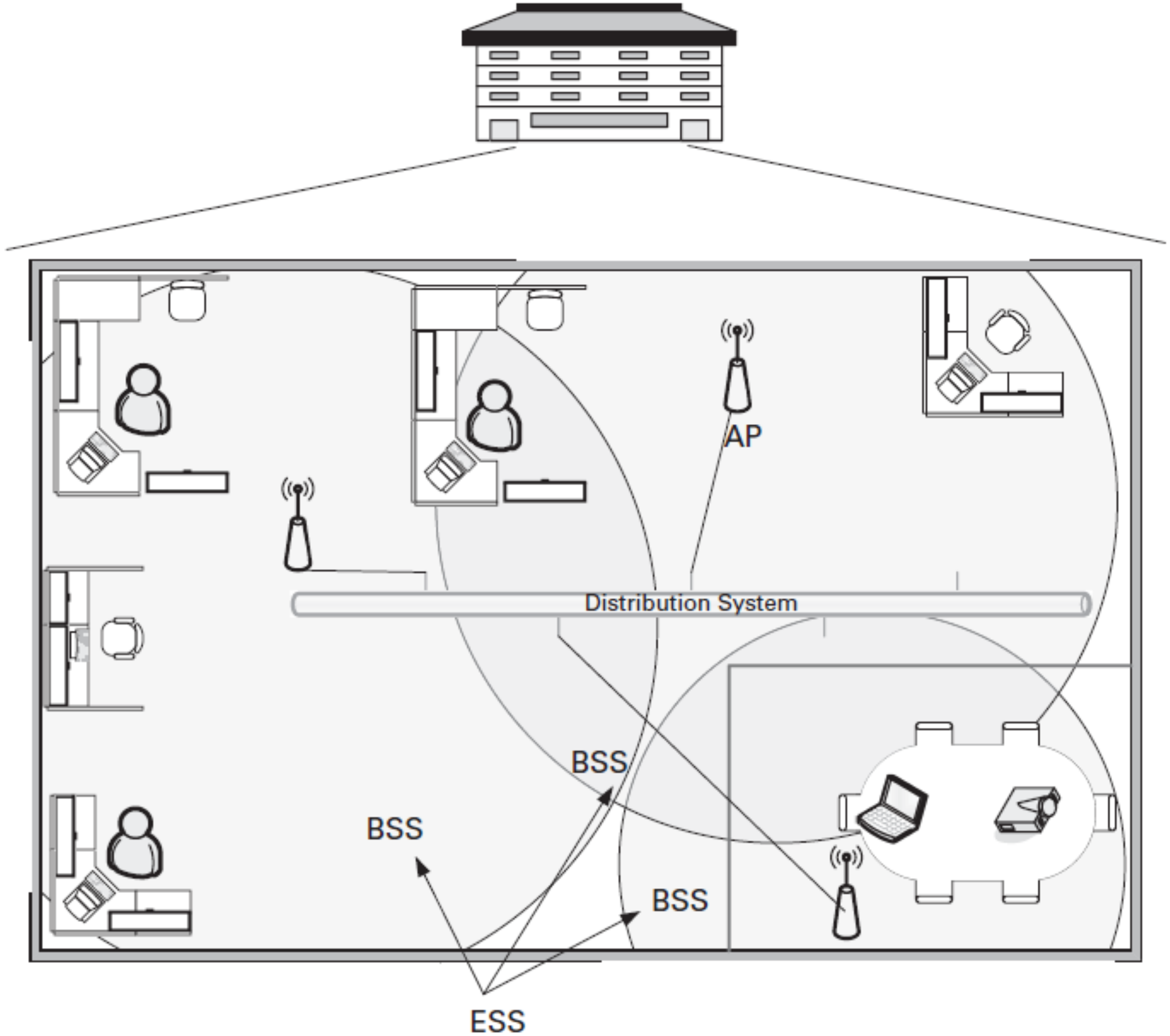
802.11 WLAN Deployment Scenarios (1)

- **Home** scenario
  - Single BSS, but there can be several other nearby similar BSSs that can cause interference



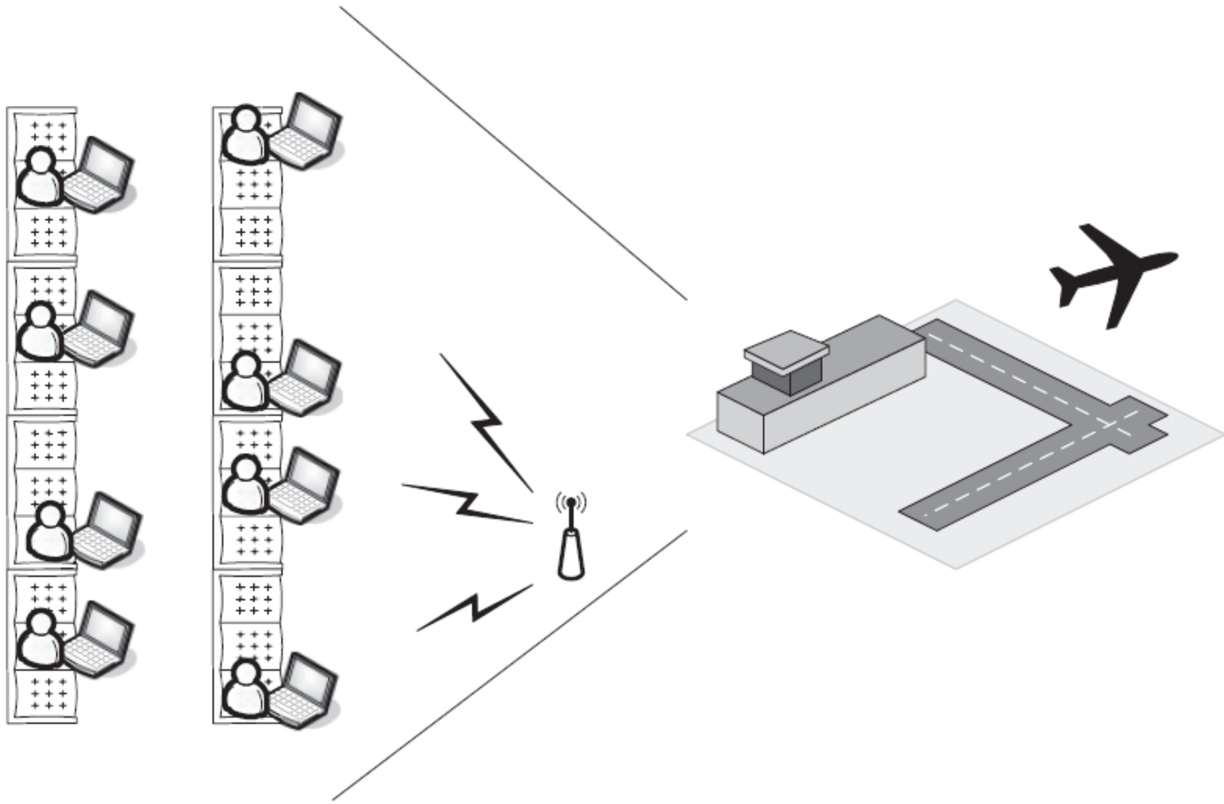
802.11 WLAN Deployment Scenarios (2)

- **Enterprise** wireless access scenario
  - ESS with multiple BSSs



802.11 WLAN Deployment Scenarios (3)

- **Hotspots**: airports, coffee shops, hotels, libraries, WLAN deployments in public areas of cities by municipalities
  - Can be indoor or outdoor



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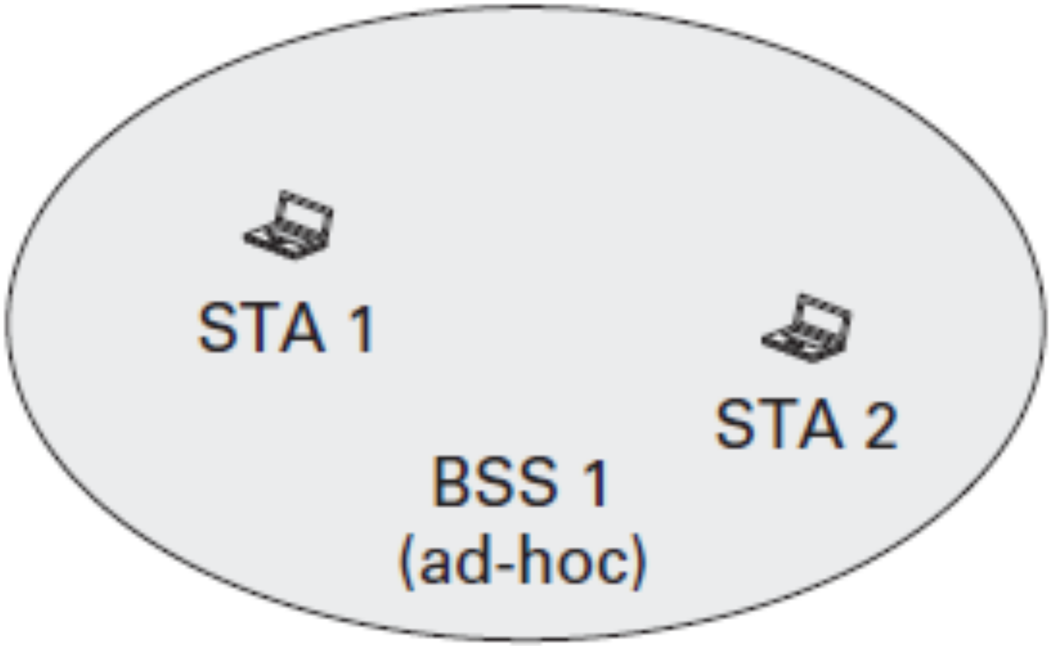
802.11 WLAN Deployment Scenarios (4)

- City-wide / Community / neighbourhood mesh networks
  - Essentially, ***multihop*** version of infrastructure WLAN

- Long-distance Wi-Fi for enabling low cost Internet access in rural and developing regions

Independent BSS (IBSS)

- Stand-alone BSS in which stations form an ad-hoc network, independent of any network infrastructure



Wi-Fi Direct (1)

- Developed by the Wi-Fi alliance for direct communication between Wi-Fi devices
  - Could be achieved via IBSS in 802.11 standard
  - But Wi-Fi direct aims to achieve this in a form that is similar to that of commonly used infrastructure BSS

- Wi-Fi Direct operation:
  - One device takes the role of group owner (GO), similar to that of AP
  - Rest of the devices associate with GO as they would with an AP

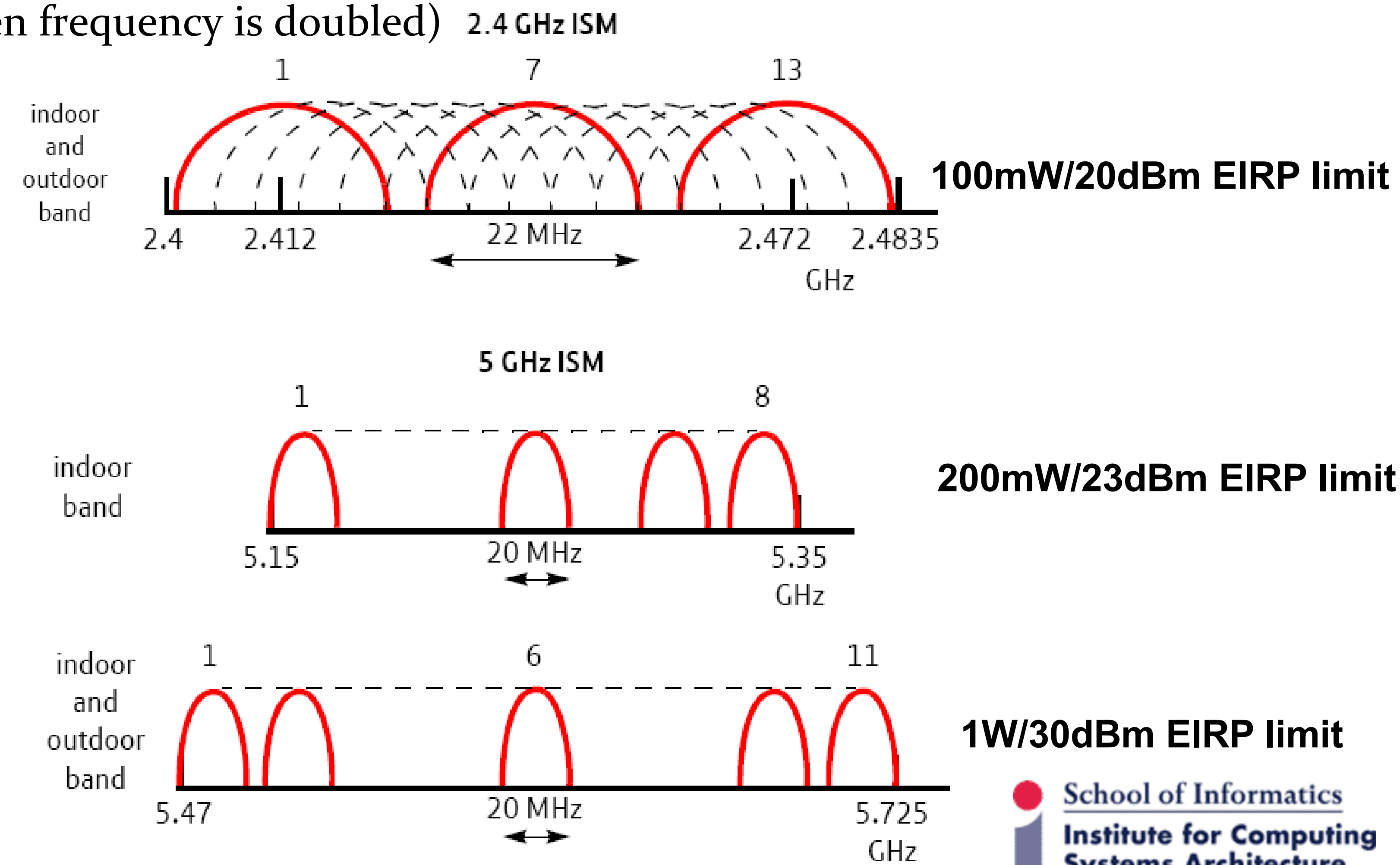
Wi-Fi Direct (2)

- Differences with infrastructure BSS in vanilla 802.11:
  - GO does not provide access to a distribution system
  - GO can be mobile, battery operated device and can enter a low power sleep state when idle

- Wi-Fi Direct standard
  - Builds on the 802.11 specification
  - Additional protocols for:
    - ➢ device discovery
    - ➢ group owner election
    - ➢ protocol for absence from session channel (to save power, for example)

802.11a/b/g Channels (UK)

- Both 2.4GHz and 5GHz bands used by 802.11 are unlicensed (license-exempt)
  - 2.4GHz band used for 802.11b/g relatively more crowded whereas shorter range in 5GHz 802.11a bands (recall: increase in free-space loss by 6dB when frequency is doubled)



Source: Kawade-Hodgkinson'07

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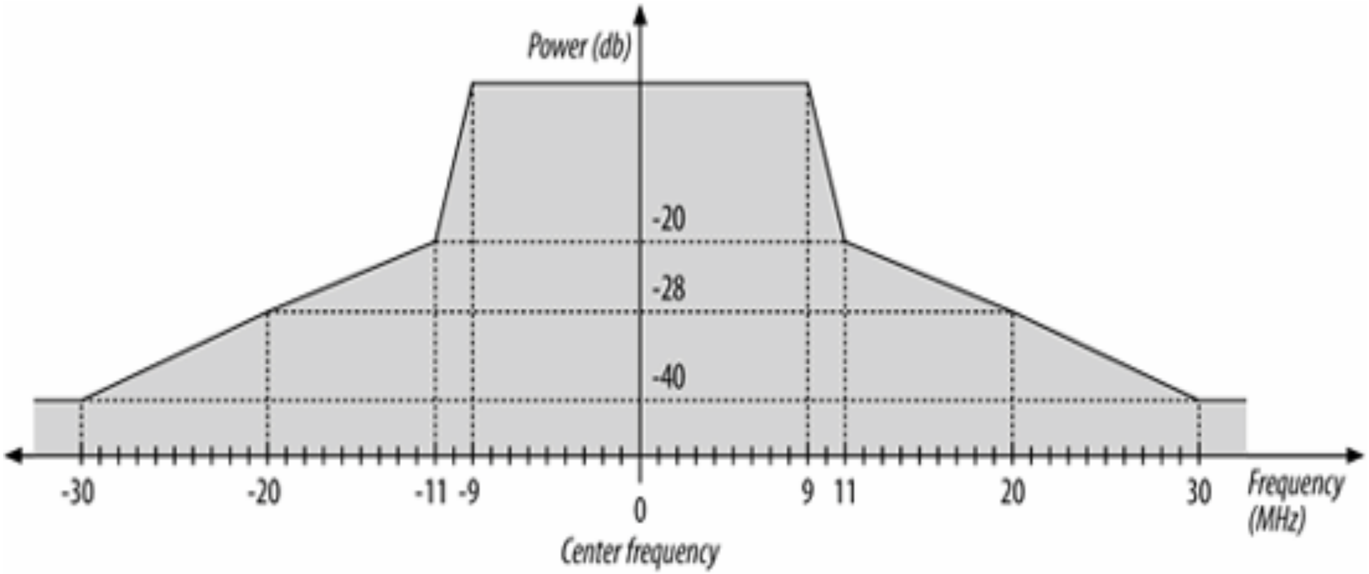
Transmit Spectrum Mask

- To limit power leakage into adjacent channels



Transmit spectrum mask for 802.11a

802.11b

- Based on Direct Sequence Spread Spectrum (DSSS)
- Like CDMA but with common chipping sequence (spreading code) for all users

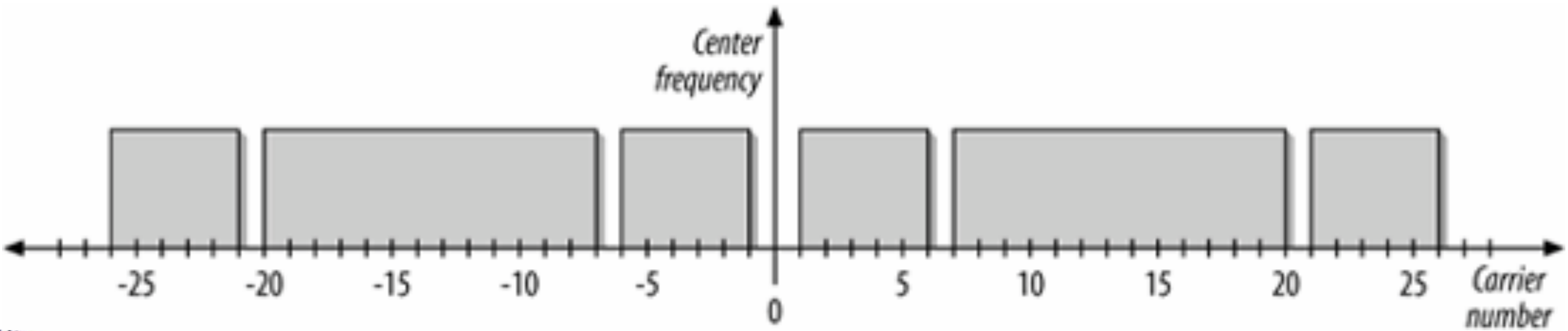
Bit-rate (Mbps)	Modulation and coding rate (R)	Data bits per symbol[b]
1	BPSK, R=1/11	1
2	QPSK, R=1/11	2
5.5	CCK[a], R=4/8	1
11	CCK, R=4/8	2

[a] Complementary Code Keying

[b] Symbol (chipping) rate is 1 Mega symbols(11 Mega chips) per second

802.11a/g

- Based on OFDM (Orthogonal Frequency Division Multiplexing), which is more spectrally efficient and robust to multipath fading
- Total 52 subcarriers for a 20MHz channel
  - 48 subcarriers used for data and the remaining 4 are pilot subcarriers for synchronization



802.11a/g Bit-Rates

Bit-rate (Mbps)	Modulation and coding rate (R)	Coded bits per sub-carrier[a]	Coded bits per symbol	Data bits per symbol[b]
6	BPSK, R=1/2	1	48	24
9	BPSK, R=3/4	1	48	36
12	QPSK, R=1/2	2	96	48
18	QPSK, R=3/4	2	96	72
24	16-QAM, R=1/2	4	192	96
36	16-QAM, R=3/4	4	192	144
48	64-QAM, R=2/3	6	288	192
54	64-QAM, R=3/4	6	288	216

[a] Coded bits per sub-carrier is dependent on the modulation scheme used (BPSK, QPSK, 16-QAM, or 64-QAM).

[b] The data bits per symbol is determined by the rate of the convolutional code.

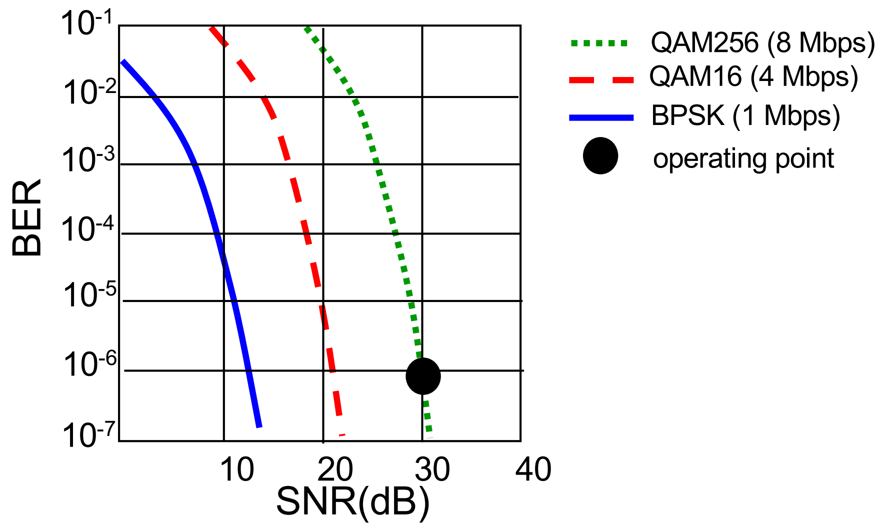
250,000 symbols per second across 48 subcarriers (that together make up a symbol)

Role of Bit-Rate and Frame Length Selection for Efficient *and* Reliable Transmission

- Recall:
  - Throughput = bit-rate * (1-FER) = bit-rate * (1- BER)^L, where L is the frame length
  - Higher bit-rates require higher SNR to keep BER under a desirable threshold (e.g., 10^{-5})
- But channel (and hence, channel quality metrics such as SNR) are time varying
- So need to adapt bit-rate with SNR (or other easily measurable channel quality metrics at transmitter side such as FER)

Adaptive Bit-Rate Selection (or simply, Rate Adaptation)

- Mechanism not specified in standard, instead left to vendor/user discretion
- Issues:
  - Channel quality measurement
  - Responsiveness in dynamic environments
  - Separating channel induced losses from collision/interference losses
    - ➢ Because rate adaptation appropriate only for channel losses



1. SNR decreases (e.g., as node moves away from AP), BER increases
2. When BER becomes too high, switch to lower bit-rate with lower BER

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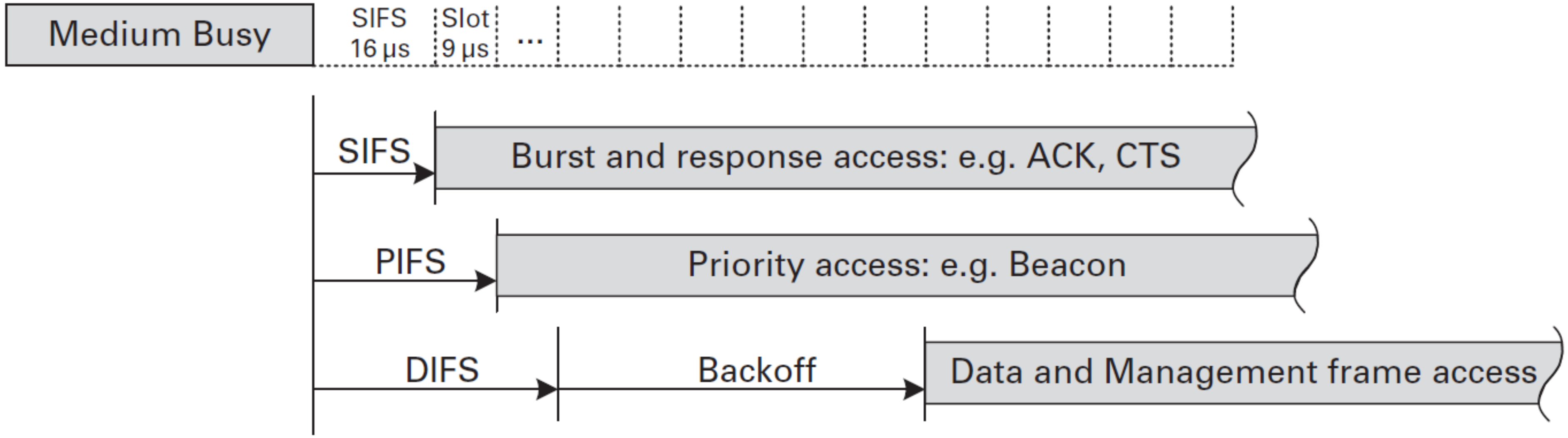
802.11 Multiple Access Overview

- Core mechanism is distributed and based on contention based random access
  - Called Distributed Coordination Function (DCF)
- Collision detection (CD) at transmitter as in Ethernet (or 802.3) not possible due to half-duplex radios and receiver-side interference
  - Need acknowledgement (ACK) from receiver; missing ACK used to infer collisions and other types of frame losses (e.g., channel induced bit errors)
  - Need to transmit collided frames in entirety
- So adopt a collision avoidance approach
  - Specifically, carrier sense multiple access with collision avoidance (CSMA/CA)
  - Still bears similarity with Ethernet's CSMA/CD approach due to use of CSMA and exponential backoff (upon frame transmission failure)

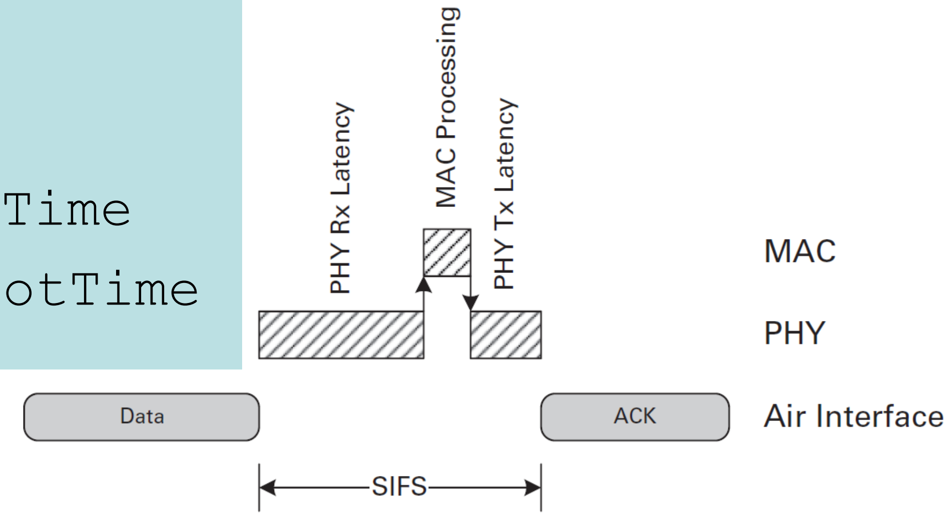
802.11 Multiple Access Ingredients

- CSMA
  - Sense if medium idle (e.g., via signal energy detection)
    - This physical carrier sensing referred to as Clear Channel Assessment (CCA) in 802.11
- Collision avoidance via:
  - Random backoffs
  - Inter frame spaces (IFSs)
  - Virtual carrier sensing using Network Allocation Vector (NAV) to complement physical carrier sensing (CCA)
  - (Optional) RTS/CTS mechanism to mitigate hidden terminal problem
- Loss recovery / reliability via:
  - Receiver ACKs for successful frame transmissions
  - Failed frames retransmitted with exponential backoffs
  - Multiple physical layer bit-rates, each using different modulation and coding scheme (MCS)
  - Option of frame fragmentation for shorter sized frames

Inter Frame Spaces for *Prioritised* Channel Access



- Short inter-frame space (**SIFS**) = `aSIFSTime` = 16µs with 802.11a/g/n/ac PHYs
- Slot time = `aSlotTime` = 9µs with 802.11a/g/n/ac PHYs
- PCF IFS (**PIFS**) = `aSIFSTime` + `aSlotTime`
- DCF IFS (**DIFS**) = `aSIFSTime` + 2*`aSlotTime`



802.11 CSMA/CA Protocol

I. When a station has a frame to transmit:

1. If medium busy, then choose a random backoff counter between 0 and CW (initially, CW_{min}) slots; CW_{min} = 15 with 802.11a/g/n/ac PHYs
   a. Random backoff counter *counts down to zero only during idle slots* (i.e., medium idle for DIFS period); pauses otherwise. When counter reaches 0, then transmit frame
2. Else: if medium stays idle for another DIFS period and backoff counter is 0, then transmit frame

II. On the receiver side:

– If frame received correctly then transmit ACK after SIFS period

III. If no ACK received at transmitter then:

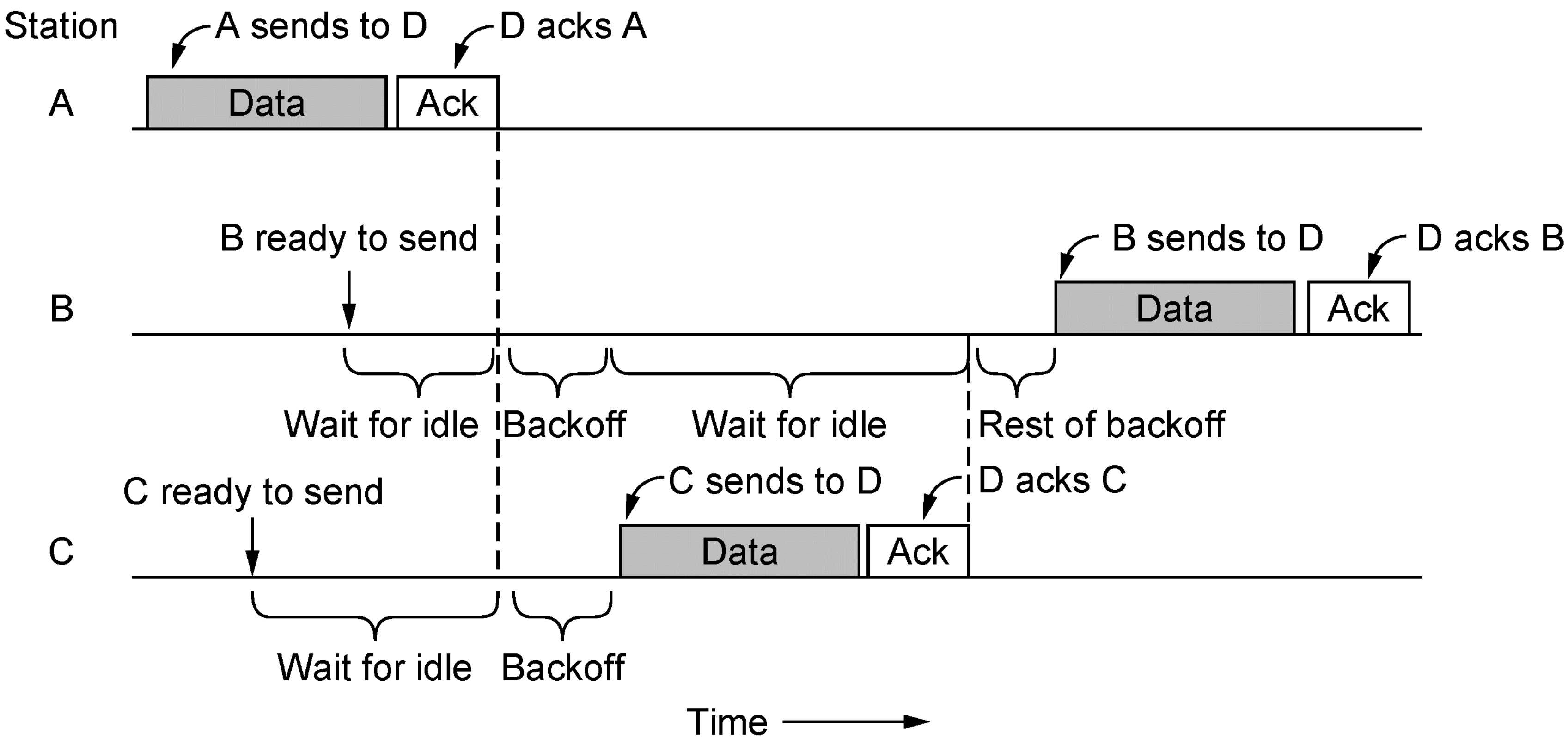
a. *Double* the backoff interval CW unless CW = CW_{max} (1023 with 802.11a/g/n/ac PHYs) 🡸 *exponential* backoff

b. Attempt a retransmission by following step 1.a until frame transmission successful or max. retransmission limit reached

IV. If ACK received at transmitter and has another frame to transmit, then follow step 1 regardless of medium busy or idle (i.e., random backoff, countdown and transmit)

– Note that ACK frames use a lower PHY data rate compared to the corresponding data frame for extra reliability

802.11 CSMA/CA Protocol Illustrated



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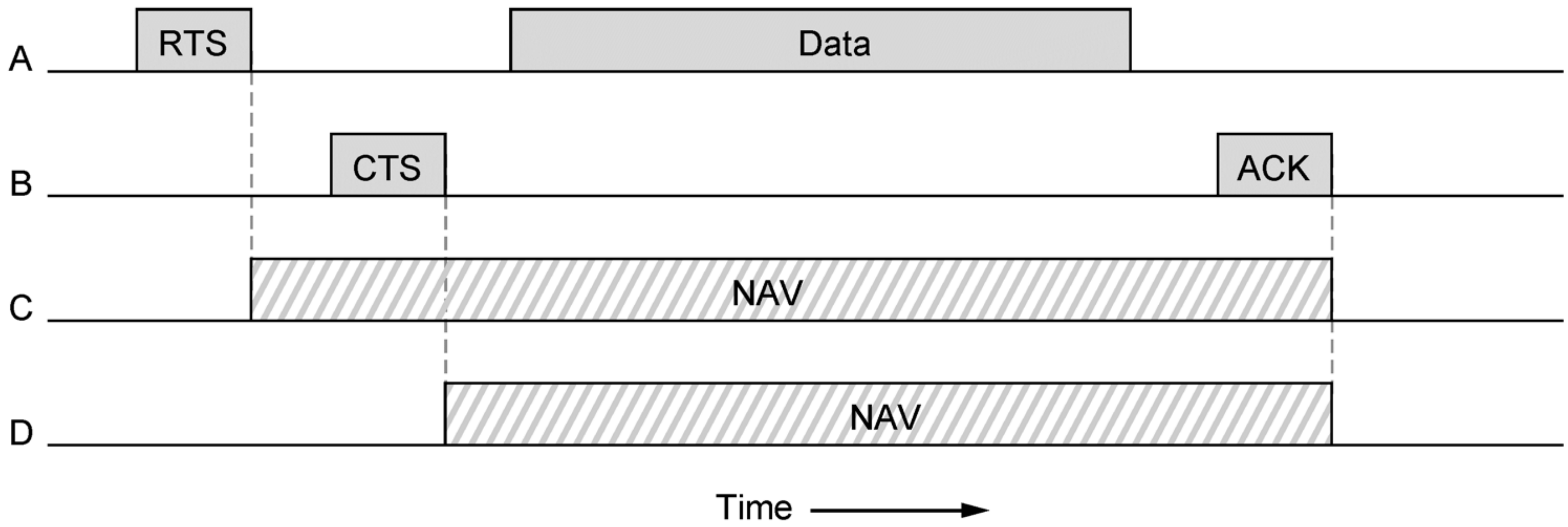
Virtual Carrier Sensing

- Via a "virtual medium busy timer" variable called **Network Allocation Vector (NAV)** maintained independently and internally at each node (AP or station)
- Every node's NAV keeps track *its notion of medium usage* by looking at the value of duration field in overheard frames (even those not destined to it)
- Non-zero NAV is taken to mean medium is busy regardless of what physical carrier sensing (CCA) sees
  - Can be seen as MAC level carrier sensing
- E.g.,
  - Upon hearing a DATA frame, NAV extended (at least) till the time required for completion of ACK transmission corresponding to the DATA frame
  - As a result, each hearing node (not just the intended receiver) considers the medium to be busy even if it does not hear the following ACK frame

RTS/CTS Mechanism

- Optional, to mitigate hidden terminal problem
- Leverages NAVs



- Idea: use short control frames, request-to-send (RTS) and clear to send (CTS), upfront to reserve the medium around transmitter *and* receiver for the ensuing data frame transmission
- Example in above figure:
  - A wants to transmit frame to B; C within range of A (and possibly B) but D only within range of B

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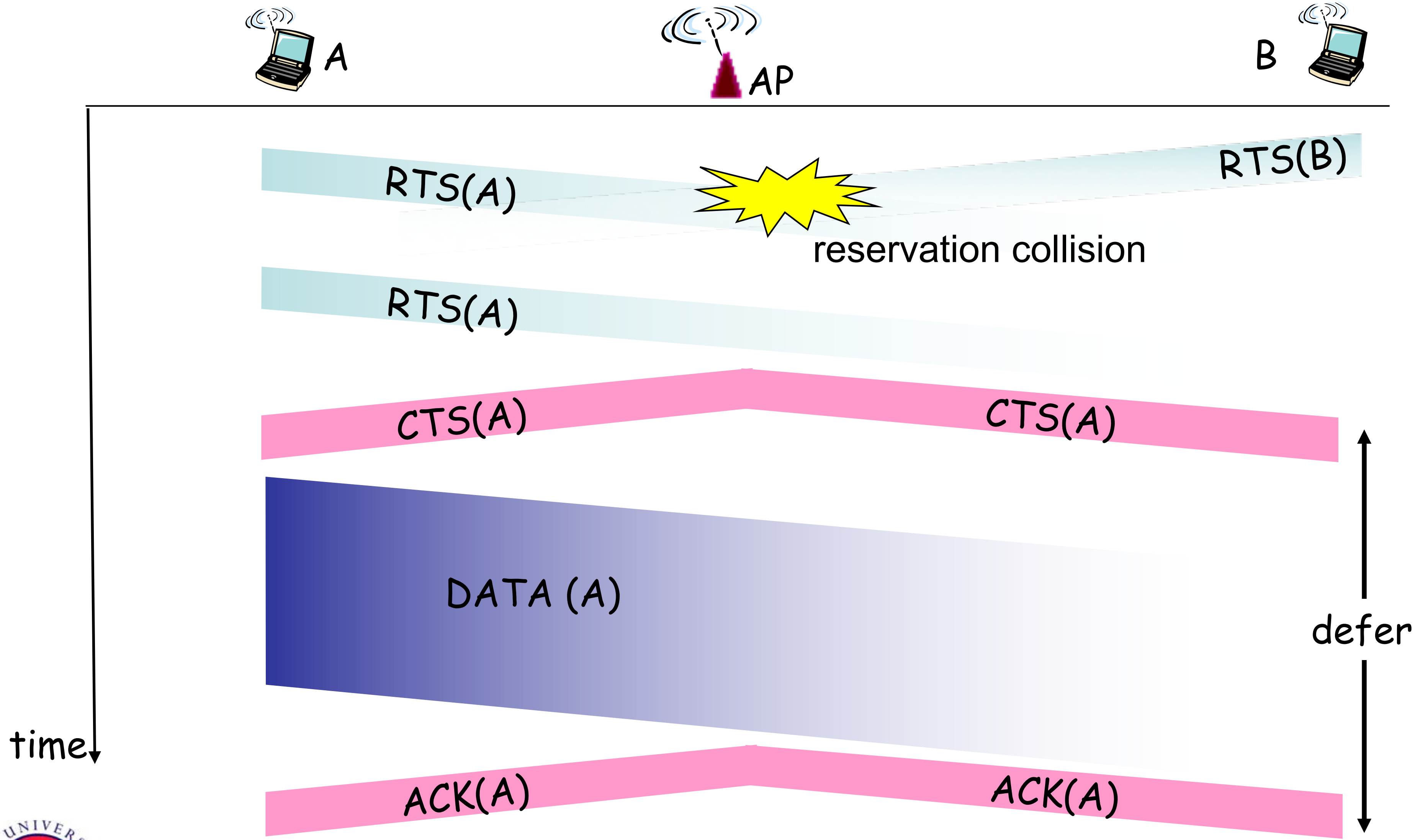
RTS/CTS frames can also experience collisions; dealt the same way as with DATA frames



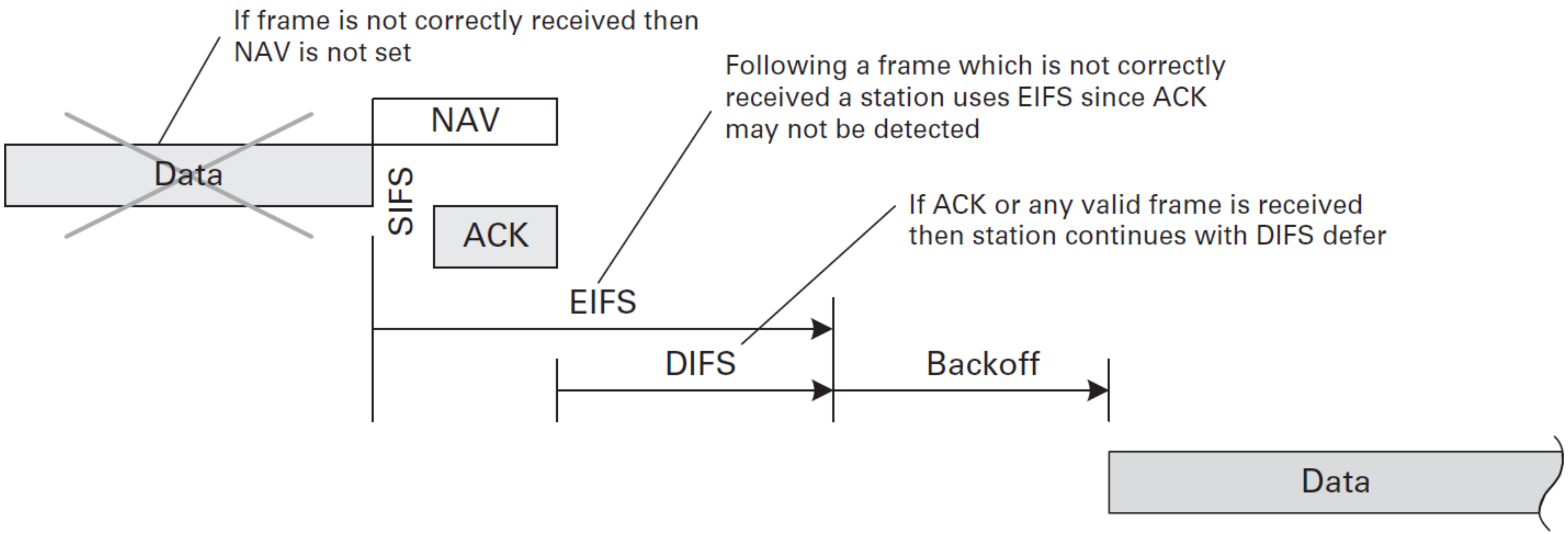
RTS/CTS Mechanism: Discussion

- Not found to be very useful in practice
  - Not helpful for shorter frames or AP frames
  - Does not help with exposed terminals
- Physical/virtual carrier sensing can largely prevent potential hidden terminal collisions; besides, unsuccessful transmitters are automatically slowed down with basic CSMA/CA because of stop-and-wait ARQ mechanism with exponential backoffs
- So additional benefit from using RTS/CTS for hidden terminals marginal, especially when considering the extra delay and handshake overhead
- This changes with newer high throughput 802.11 standards (e.g., 802.11n/ac) with very large aggregated frames

Extended Inter-Frame Space (EIFS)

- Another mechanism to protect against hidden nodes
- EIFS = `aSIFSTime` + `ACKTxTime` + DIFS

  where `ACKTxTime` is the time required to transmit an ACK at the lowest mandatory PHY data rate



Finding, joining and leaving a BSS

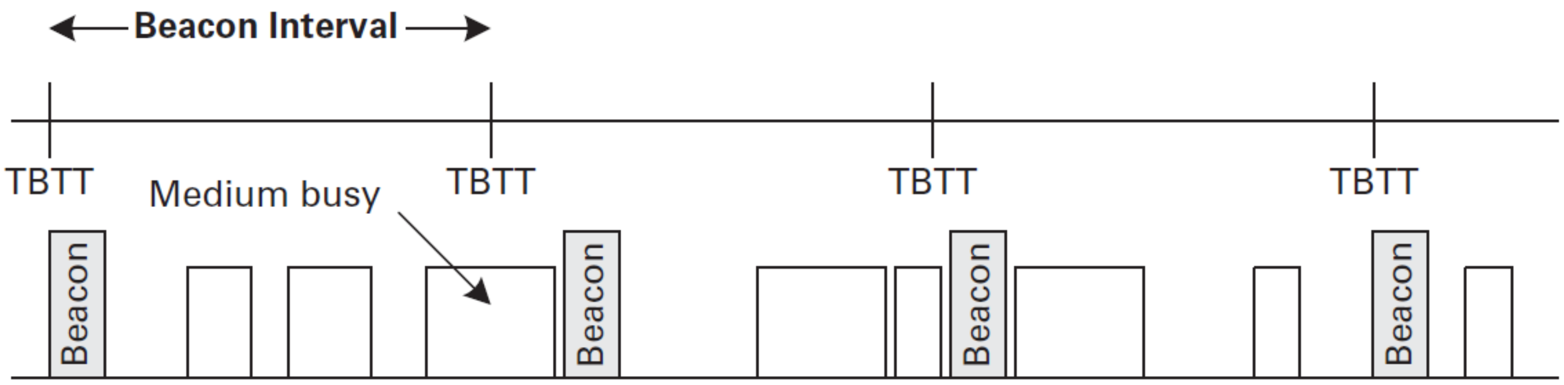
- **Scanning** for a station to discover a BSS and its attributes
  1. Passive
  2. Active
- **(Re-/Dis-)Association**
  - By associating with an AP, a station becomes a member of the BSS represented by the AP
  - By disassociating, it leaves the BSS
  - In an ESS with multiple BSSs, a station can move from one BSS and reassociate with another BSS

Beacons

- Each AP periodically broadcasts beacon frames, typically every 100ms
- Each beacon carries regulatory info, capability info, and info for managing the BSS:
  - Network/ESS identifier (SSID)
  - AP/BSS identifier (BSSID)
  - Country code info
  - Maximum allowable transmit power
  - Allowed channels
  - time reference
  - time till next beacon
  - bit-rates supported
  - security settings
  - power-saving capabilities
  - QoS support
  - …

Target Beacon Transmission Time (TBTT)

- Beacons scheduled every TBTT
- Actual transmission time of beacons depends on whether channel is idle at scheduled time



AP and Station Channel Assignment

- Each AP operates on a channel in a band (e.g., 2.4GHz, 5GHz)
- The channel used by an AP depends on its hardware capability and channel assignment procedure in use (default setting, manual configuration, automatic and adaptive channel selection)
- Channel used by a station implicitly chosen depending on the AP it associates with
- Neighboring APs (and their associated stations) could interfere with each other depending on their channels of operation

Passive Scanning

- A station looks for beacon transmissions in *all* channels, by repeating the following process:
  - dwelling for some time in each channel, then switching to another channel

- Passive (receive only) operation

- Compatible with all regulatory domains

- May need to follow it up with active scanning if additional info required

Active Scanning

- Actively probe for a BSS using `Probe Request` and `Probe Response` messages
- A station transmits `Probe Request` frames on each of the channels it is seeking a BSS, including the following addresses in the request:
  - SSID: specific or wild card
  - BSSID: specific or wild card
  - Destination Address (DA): broadcast MAC address (FF:FF:FF:FF:FF:FF)
- AP receiving a `Probe Request` responds with a `Probe Response` if its SSID and BSSID match with that in request
- Multiple APs may respond to a `Probe Request`

802.11 Association

- Note that scanning (passive or active) may lead to discovery of one or more APs (BSSs)
- **AP selection problem:** selecting an AP if more than one discovered
  - AP selection mechanism left unspecified in the standard
  - Could be based on signal strength, load, etc.
- Before a station can send/receive data, it must:
  - *Associate* with the selected AP
  - Then get an IP address (in the associated AP's subnet), typically via DHCP

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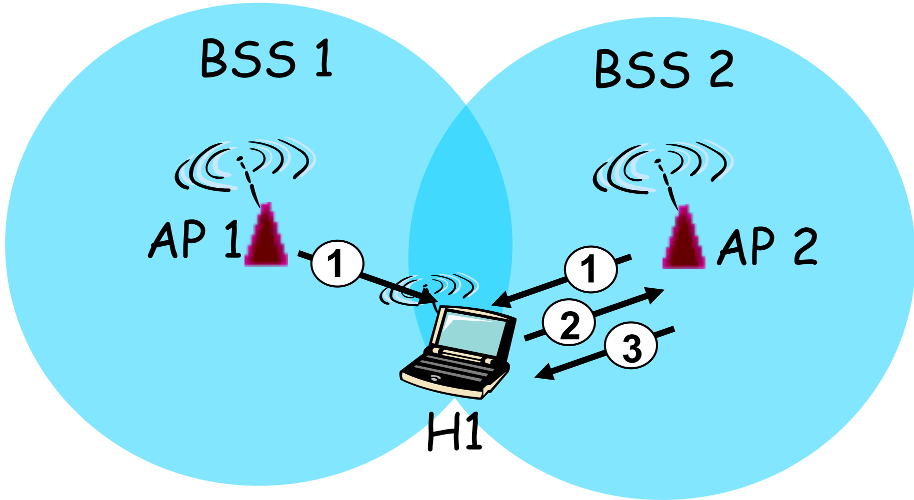
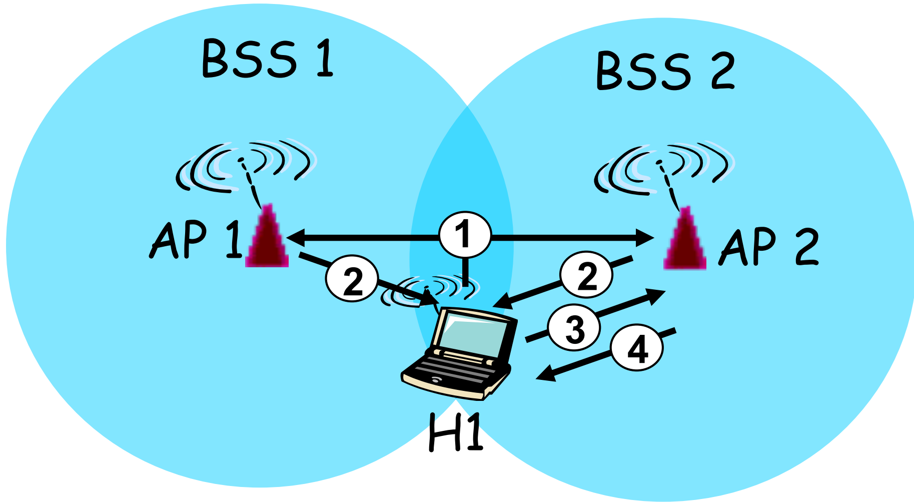
Scanning + Association Illustrated





Passive Scanning:

(1) Beacon frames sent periodically from APs

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

(3) Association Response frame sent from Selected AP to H1

Active Scanning:

(1) Probe Request frame broadcast from H1

(2) Probe Response frames sent from APs

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

(4) Association Response frame sent from Selected AP to H1

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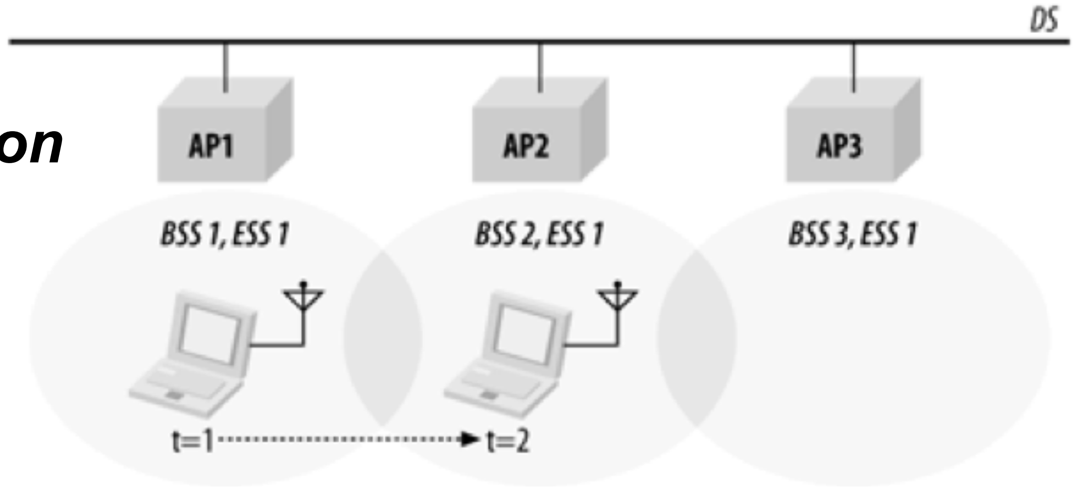
Reassociation and Disassociation

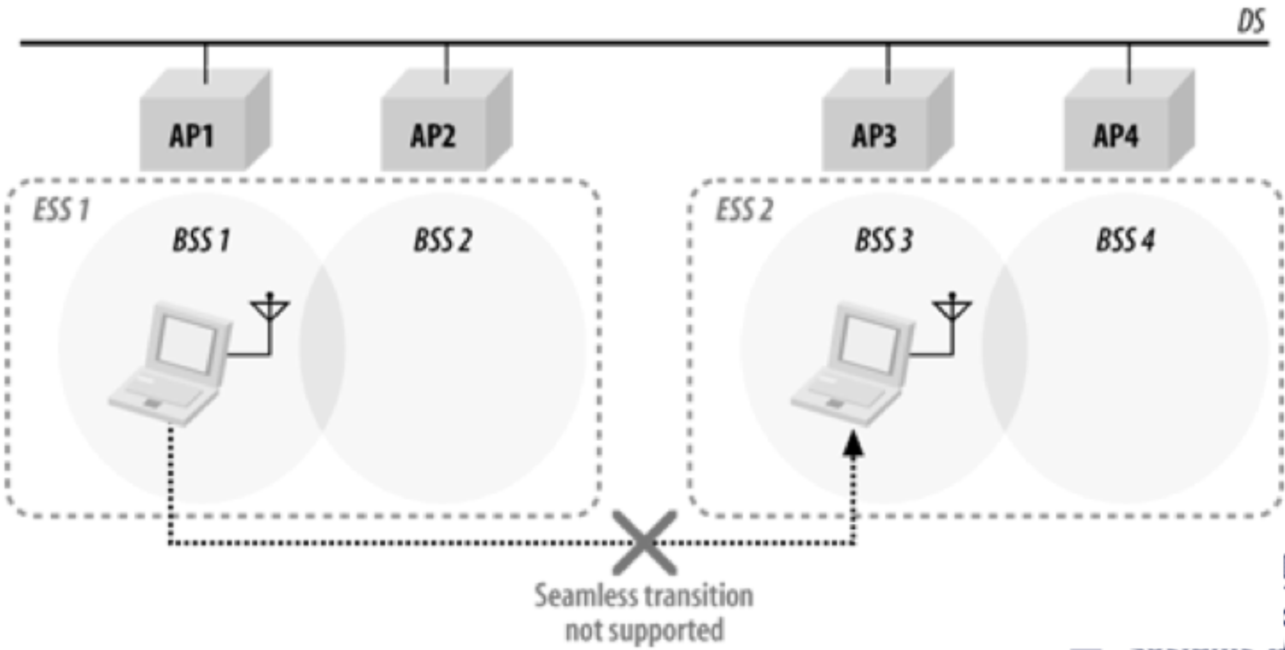
- Reassociation
  - Happens when:
    - Station moves to a new BSS served by an AP different from the one it is associated with
    - To change attributes of station association such as station capability info
  - Initiated by station (Reassociation Request to AP seeking a Reassociation Response)
- Disassociation
  - When leaving the network or loss of communication
  - Explicitly performed (by either AP or station) by sending Disassociation frame and seeking acknowledgement
  - Implicitly via timeout at AP

802.11 Mobility Support

BSS Transition

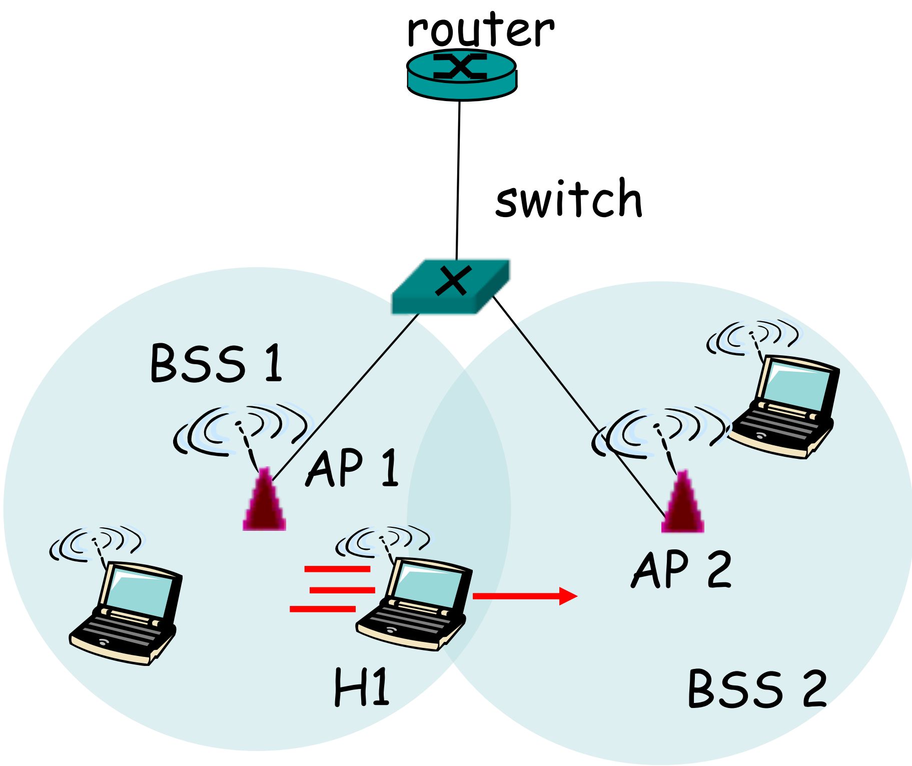


ESS Transition



802.11 Mobility Within Same Subnet (Intra-ESS)

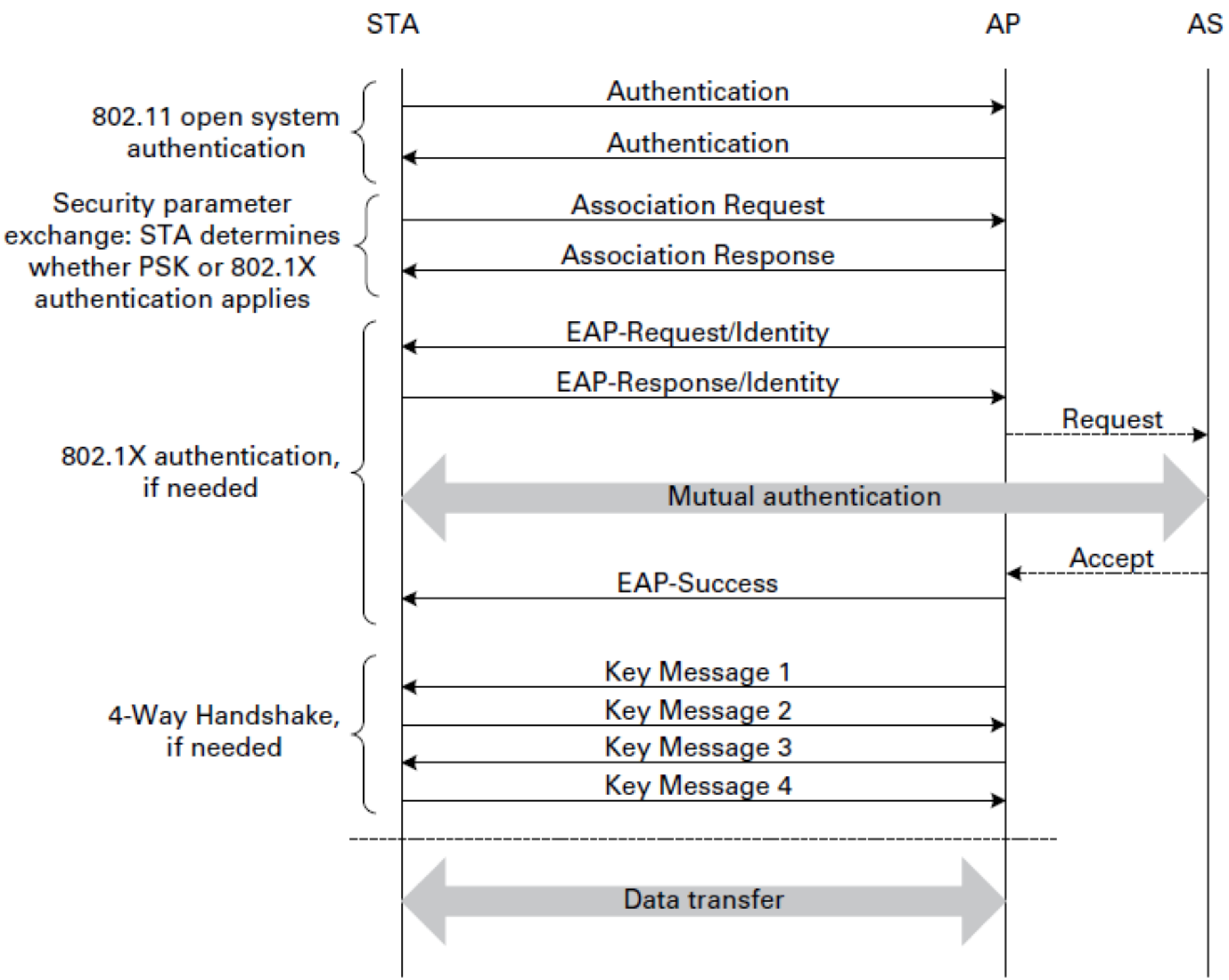
- H1 remains in same IP subnet: IP address can remain same
- Switch: H1 associated with which AP?
  - self-learning: switch will see incoming frames from H1 and “remember” which switch port can be used to reach H1



802.11 Authentication

- Establish the identity of the station before it is allowed to communicate
- Broadly speaking, two authentication methods:
  1. Open system authentication (*prior* to Association)
     - Station joining the BSS sends an Authentication frame requesting open system authentication
     - AP responds with an Authentication frame with status "success"
  2. Shared key authentication
     - Initially, Wired Equivalent Privacy (WEP) which was found to be insecure in 2001
     - Currently used approach from the 802.11i (WPA2) amendment from 2004
       - Authentication *after* Association

Authentication and Association Process Illustrated



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802.1X Authentication

- Station to access a BSS authenticates with an **authentication server (AS)** using **extensible authentication protocol (EAP)**
  - AS may be co-located with AP or on a separately located server

- Multiple options for the authentication method:
  - EAP-Transport Layer Security (EAP-TLS) often used
  - Lightweight Extensible Authentication Protocol (LEAP)
  - EAP-MD5

802.11i Operation

- Following Association Request/Response exchange:
  - AP sends an `EAP Request` challenging the station to identify itself
  - Station responds with an `EAP Response` that is forwarded to the AS
  - EAP authentication exchange between station and AS via AP to mutually authenticate each other and derive a **Master Key (MK)** known to both
    - ➢ A second key called **Pairwise Master Key (PMK)** is generated from MK
  - On successful authentication of station:
    - ➢ AS informs this to AP along with PMK
    - ➢ AP then forwards `EAP-Success` to station ➔ AP and station mutually authenticated and have a shared key
  - If authentication fails:
    - ➢ AS informs the AP which sends an `EAP-Failure` message to station followed by Disassociation frame

Transient Keys

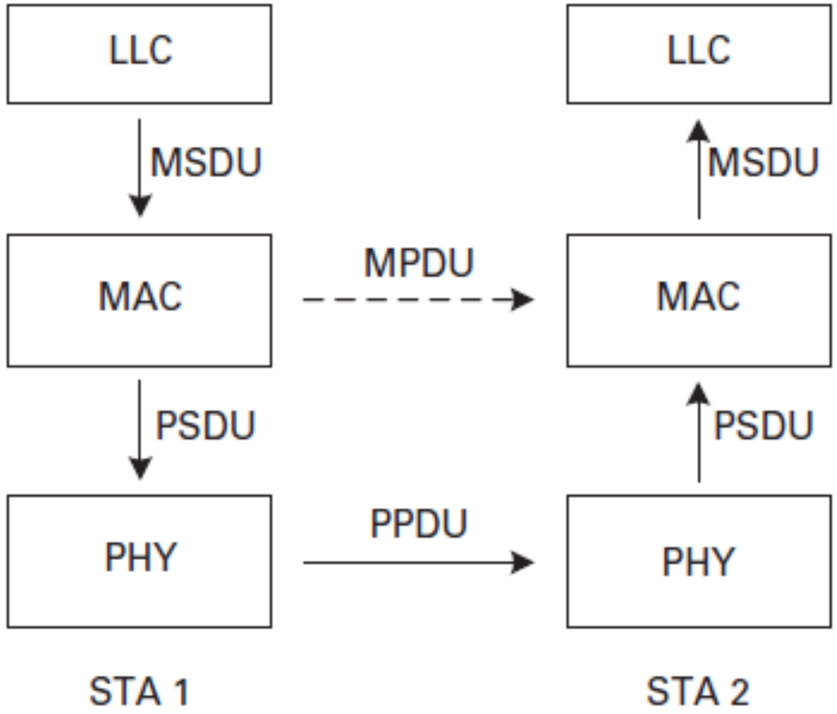
- Data frames are encrypted using transient keys, regenerated using PMK periodically (typically, every 24 hours)
- **Pairwise transient key (PTK)** to protect traffic between AP and station
- **Group transient key (GTK)** to protect broadcast and multicast traffic from AP

Transient Key Generation

- Four/two-way handshake for station and AP to derive PTK/GTK
  - **Key Message 1 (AP to station):** station derives PTK using ANonce from AP + locally generated SNonce + knowledge of PMK
  - **Key Message 2 (station to AP):**
    - AP derives PTK using SNonce from station + previously locally generated ANonce + knowledge of PMK
    - AP confirms that station knows PTK using the message integrity check (MIC) in message generated using PTK by station
  - **Key Message 3 (AP to station):** GTK encrypted using PTK + MIC sent to station
  - **Key Message 4 (station to AP):** confirms receipt of GTK and authentication of AP

MAC and PHY Data Units

- Service Data Unit (SDU) refers to data transferred between layers
  - MAC SDU (MSDU)
  - PHY SDU (PSDU)
- Protocol Data Unit (PDU) refers to data exchanged by peer entities of the same layer
  - MAC PDU (MPDU) = MAC header + MSDU + trailer (frame check sequence) = PSDU
  - PHY PDU (PPDU) = Preamble + PHY header + PSDU



MAC Frame Format

Octets	2	2	6	6	6	2	6	2	4	Variable	4
	Frame Control	Duration/ ID	Address 1	Address 2	Address 3	Sequence Control	Address 4	QoS Control	HT Control	Frame Body	FCS

MAC Header (Frame Control through HT Control)

B0 B1	B2 B3	B4 B7	B8	B9	B10	B11	B12	B13	B14	B15
Protocol Version	Type	Subtype	To DS	From DS	More Frag	Retry	Pwr Mgt	More Data	Protected Frame	Order

Frame Control field

- Protocol Version subfield always set to 00

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Frame Type and Subtypes

Type	Type description	Subtype	Subtype description
00	Management	0000	Association Request
		0001	Association Response
		0010	Reassociation Request
		0011	Reassociation Response
		0100	Probe Request
		0101	Probe Response
		0110–0111	Reserved
		1000	Beacon
		1001	ATIM
		1010	Disassociation
		1011	Authentication
		1100	Deauthentication
		1101	Action
		1110	Action No Ack
		1111	Reserved
01	Control	0100	Beamforming Report Poll
		0101	VHT NDP Announcement
		0111	Control Wrapper
		1000	Block Ack Request
		1001	Block Ack
		1010	PS-Poll
		1011	RTS
		1100	CTS
		1101	ACK
		1110	CF-End
		1111	CF-End + CF-Ack
10	Data	0000	Data
		0001	Data + CF-Ack
		0010	Data + CF-Poll
		0011	Data + CF-Ack + CF-Poll
		0100	Null (no data)
		0101	CF-Ack (no data)
		0110	CF-Poll (no data)
		0111	CF-Ack + CF-Poll (no data)
		1000	QoS Data
		1001	QoS Data + CF-Ack
		1010	QoS Data + CF-Poll
		1011	QoS Data + CF-Ack + CF-Poll
		1100	QoS Null (no data)
		1101	Reserved
		1110	QoS CF-Poll (no data)
		1111	QoS CF-Ack + CF-Poll (no data)

To/From DS

From DS	To DS	Meaning
0	0	Indicates: • a data frame direct from one station to another within the same IBSS • a data frame direct from one non-AP station to another non-AP station within the same BSS • all management and control frames
0	1	A data frame destined for the distribution system (DS) or being sent by a station associated with an AP to the Port Access Entity in that AP
1	0	A data frame exiting the DS or being sent by the Port Access Entity in an AP
1	1	A data frame using the four-address format (not defined in the standard)

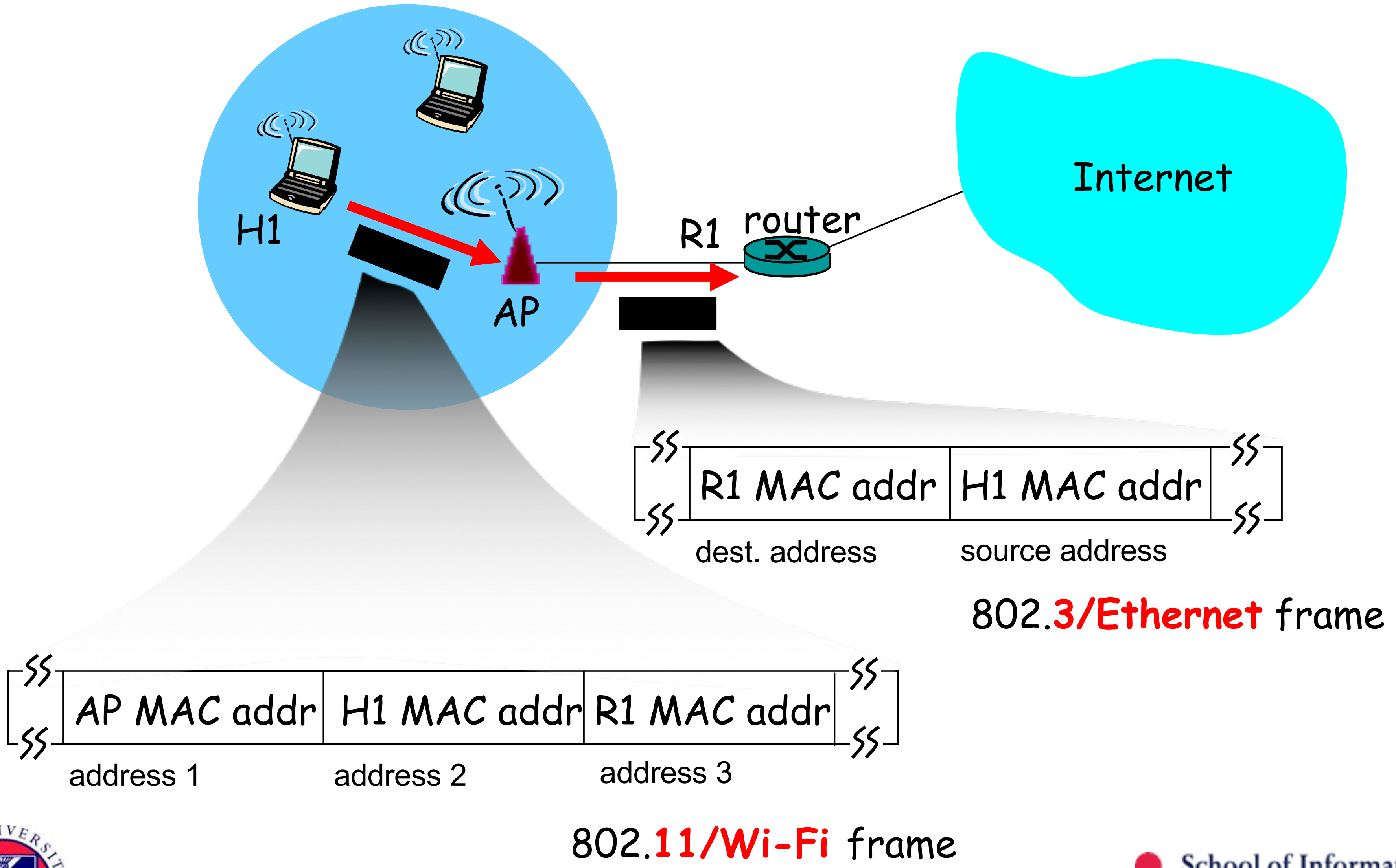
Duration and Address Fields

- Duration/ID:
  - If less than 32,768 then interpreted as a duration in µs to update NAV
  - If the two high order bits are set in PS-Poll frame then low order 14 bits are interpreted as association identifier (AID)
- Address 1: receiver address, present in all frames
- Address 2: transmitter address, present in all frames except CTS and ACK
- Address 3: present in data and management frames
  - In data frame, dependent on To/From DS settings and MSDU/A-MSDU
  - In management frame, address 3 contains BSSID
- Address 4: present only in data frames and only when both From/To DS bits are set

Octets	2	2	6	6	6	2	6	2	4	Variable	4
	Frame Control	Duration/ ID	Address 1	Address 2	Address 3	Sequence Control	Address 4	QoS Control	HT Control	Frame Body	FCS

MAC Header (Frame Control through HT Control)

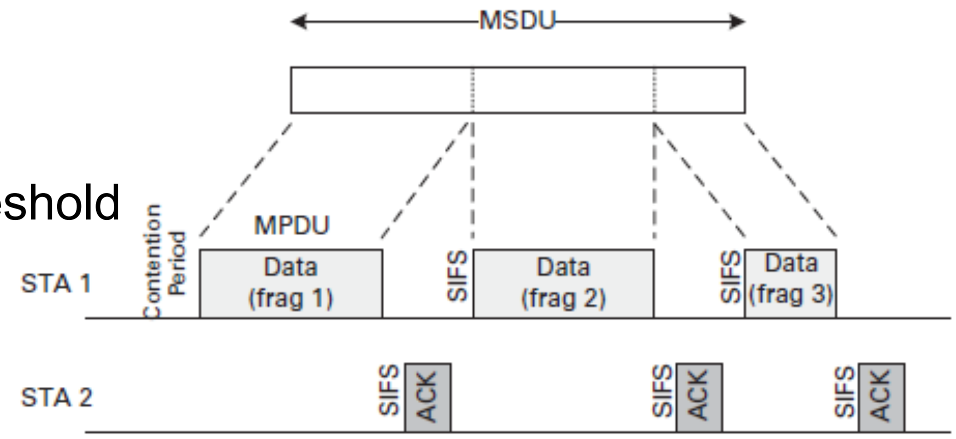
A Use of "Address 3"



Fragmentation

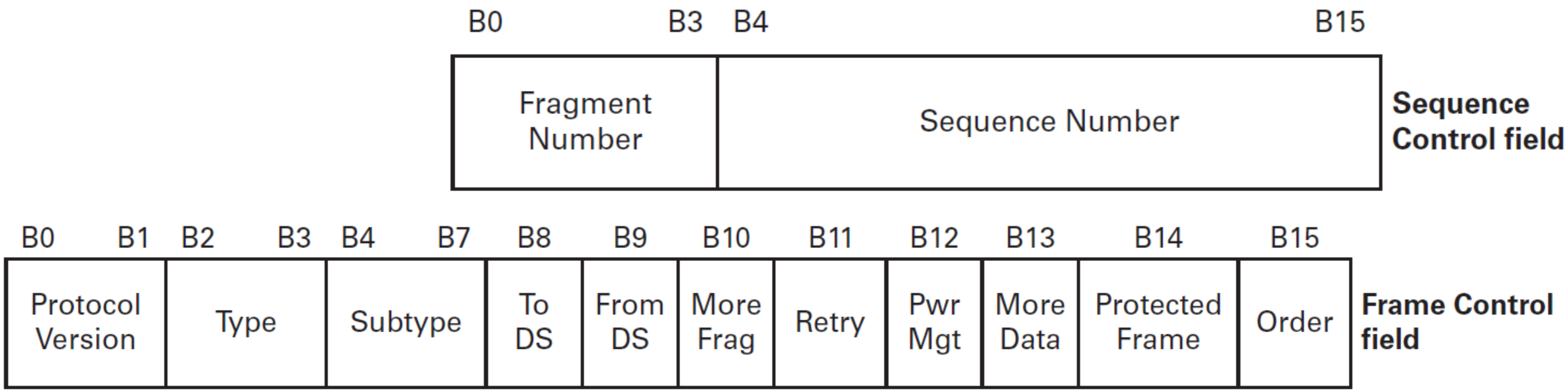
- Allows a large MSDU to be divided into smaller data fragments, each encapsulated in a MPDU
- Individual MPDUs containing the fragments of a MSDU can be sent separately, or in a burst upon gaining access to channel as shown here
- MSDU is fragmented if it is

longer than dot11FragmentationThreshold



Sequence Control Field

- Duplicate detection via:
  - Sequence numbers for duplicate detection
    - Start from 0 and are assigned from a modulo-4096 counter
  - Retry subfield
    - Set to 1 in any data or management frame that is a retransmission
    - Set to 0 in all other frames
    - Receiver uses this bit while eliminating duplicate frames
- When a MSDU is fragmented, MPDUs with fragments are given different fragment numbers in sequence starting from 0 but share the same sequence number
  - More Fragments subfield set to 1 in all data or management frames if another fragment to follow, otherwise set to 0



Power Management

- 802.11 radio interface that is idle and listening consumes nearly as much power as when receiving and marginally lower than when it is transmitting
- Turning off the radio altogether leads to greater power savings
  - Which is essentially how stations can save power using 802.11 power management features
- Broadly speaking, a station can be in one of two modes:
  - Power Save (PS) mode: in this mode, a station alternates between Awake state and Doze (Sleep) state
  - Active mode (i.e., always awake)
- AP always in active mode
- A station indicates its mode to its AP via the "Pwr Mgt" bit in Frame Control field

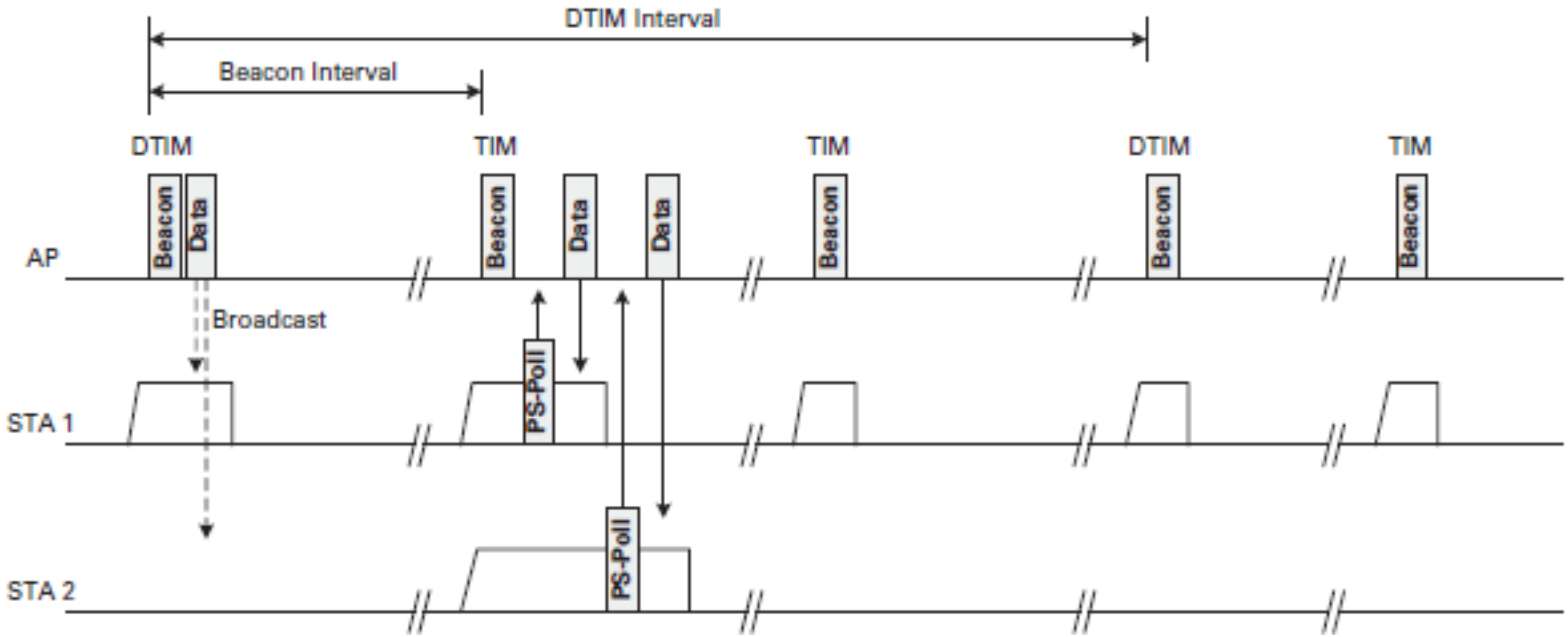
Unicast Traffic and Traffic Indication Map (TIM)

- AP buffers frames addressed to stations in PS mode
- Traffic indication map (TIM) in every beacon frame used to indicate buffered traffic to a station in PS mode
  - TIM is a partial virtual bitmap: each bit represents a station on the BSS
  - A station identified in the TIM by the bit position indexed by its association ID (AID)
  - First bit (AID = 0) used for group addressed (broadcast/multicast traffic)
- All stations in PS mode wake up periodically to receive beacon frames
- If a station has buffered frames waiting at the AP as indicated via TIM then
  - It remains awake and polls AP to receive one or more buffered frames ("More Data" bit in Frame Control field), then go back to doze state

Group Addressed Traffic and Delivery TIM (DTIM)

- AP also delivers group addressed (broadcast/multicast) traffic at predictable intervals to allow stations in PS mode to receive
- Delivery TIM (DTIM) in every *n*th beacon frame
  - Indicates group addressed traffic will be delivered immediately following the beacon with DTIM
- DTIM Count in a beacon frame indicates #beacons until next DTIM
  - DTIM Count = 0 in beacon frame with DTIM
  - All non-DTIM beacons have non-zero DTIM Count
- DTIM interval is the interval between beacons carrying DTIM
- Multiple buffered group addressed frames are delivered one after another using the "More Data" bit in a similar way to delivery of multiple buffered unicast frames

802.11 PS Mode Illustrated



- In this example:
  - DTIM Count = 0 in 1st Beacon
  - DTIM Count = 2 in 2nd Beacon
  - DTIM Count = 1 in 3rd Beacon
  - DTIM Count = 0 in 4th Beacon

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Automatic Power Save Delivery (APSD)

- Introduced in 802.11e amendment (2005)
- AP buffers frames until the station wakes up when it needs to send frames to the AP
- Allows more flexible and fine-grained sleep schedule
  - Works well for interactive applications like VoIP with bidirectional traffic pattern
  - A VoIP phone can send and receive frames every 20ms and sleep in between (instead of having to wake up at beacon frame arrival times, which are typically every 100ms)

WNM-Sleep Mode

- Introduced in 802.11u amendment (2011)
- Allows a station to miss DTIMs without missing associated group addressed traffic
- To support a station using this mode (indicated to AP via TFS request frame), AP converts group addressed frames to equivalent unicast frame addressed to that station

802.11 Power Management: Discussion

- Even if a station wakes up to receive every beacon, significant energy savings possible, especially when at times of no buffered traffic
  - E.g., ~250 microseconds (=0.25ms) wakeup period to receive beacon frames every beacon interval (typically 100ms) ➔ **sleep more than 99% of the time!**

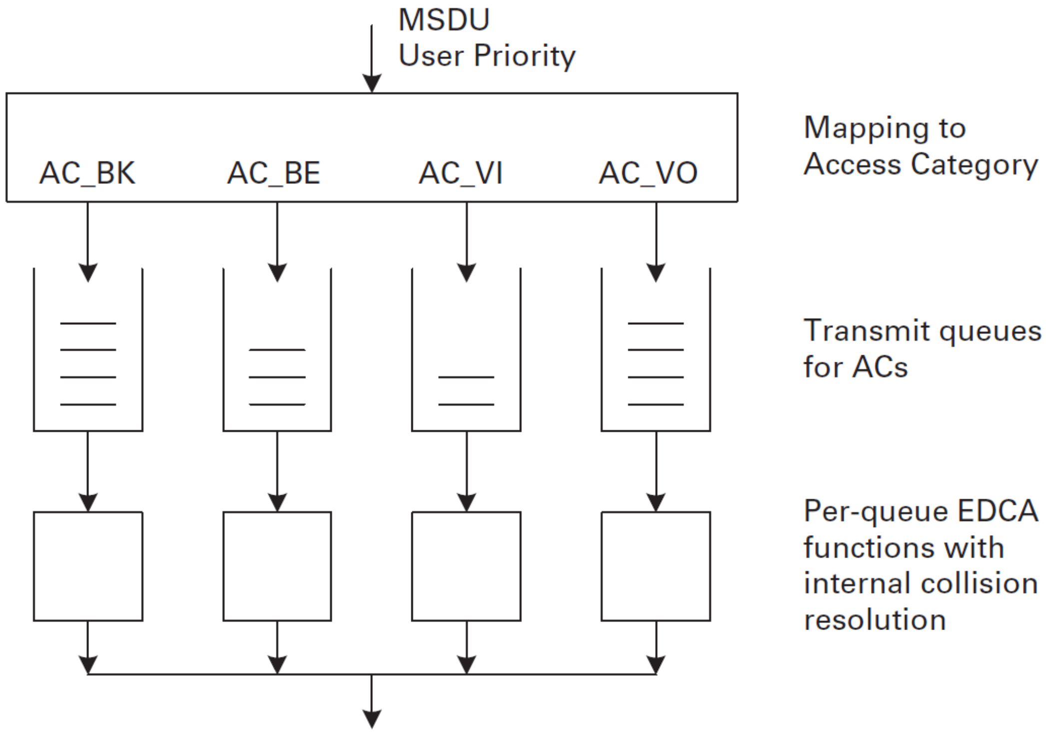
- Standard does not define which beacon frames a station should receive ➔ even greater power savings can be achieved at the expense of increased latency

Enhanced Distributed Channel Access (EDCA)

- Introduced in 802.11e amendment (2005) to support prioritised Quality of Service (QoS)
- Defines four access categories (ACs) representing four different traffic types: background, best effort, video and voice traffic
- Other key new features introduced in 802.11e:
  - Transmit opportunity (TXOP) concept
  - QoS Data frame = regular Data frame + QoS Control field
  - Block acknowledgements

EDCA Schematic

- Each AC has:
  - a logically separate queue at MAC layer
  - different settings for access parameters (contention window, inter-frame space, etc.)

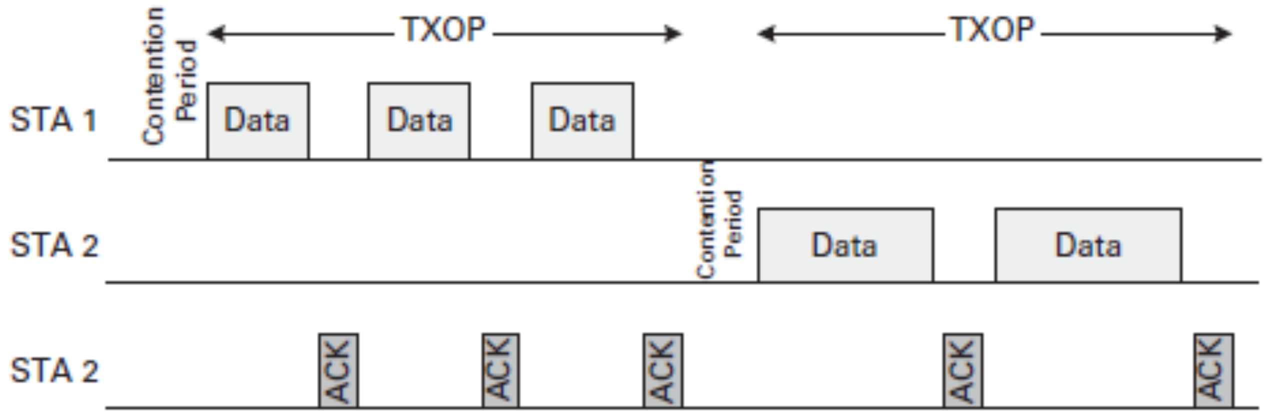


Priority	802.ID user priority	802.ID Designation	AC	Designation
Lowest	1	BK	AC_BK	Background
	2	–		
	0	BE	AC_BE	Best effort
	3	EE		
	4	CL	AC_VI	Video
	5	VI		
Highest	6	VO	AC_VO	Voice
	7	NC		

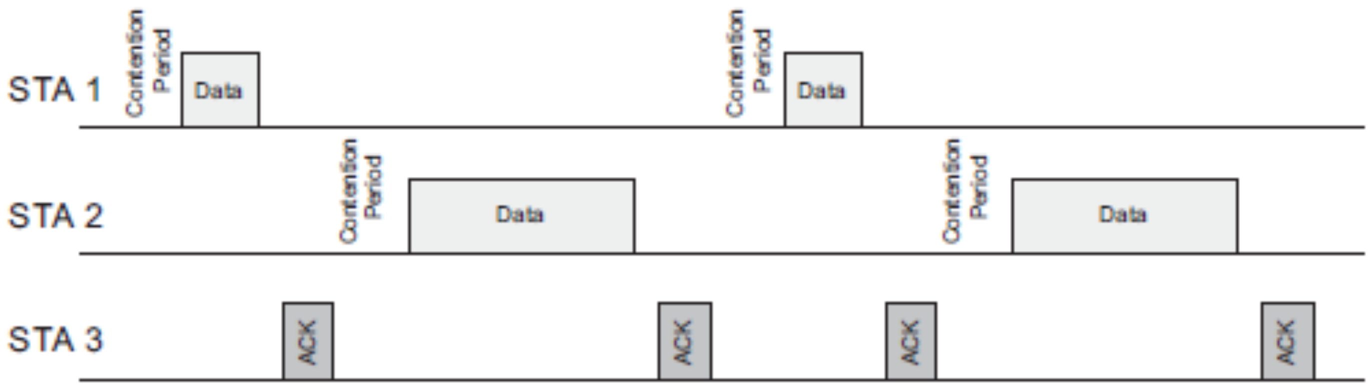
Transmit Opportunity (TXOP)

- A bounded period during which a station may transfer data of a particular traffic class (AC)
- Obtained using the access parameters of the traffic class (AC) that will use it
- Once obtained, station may continue to transmit and receive frames provided frame sequence duration does not exceed TXOP limit for that AC
- TXOP = 0 (the default prior to 802.11e) ➔ after a transmission of MSDU or management frame, a station needs to compete again for channel access
- Collision detect via a short frame exchange (e.g., RTS/CTS) required at the beginning of TXOP

TXOP Illustrated



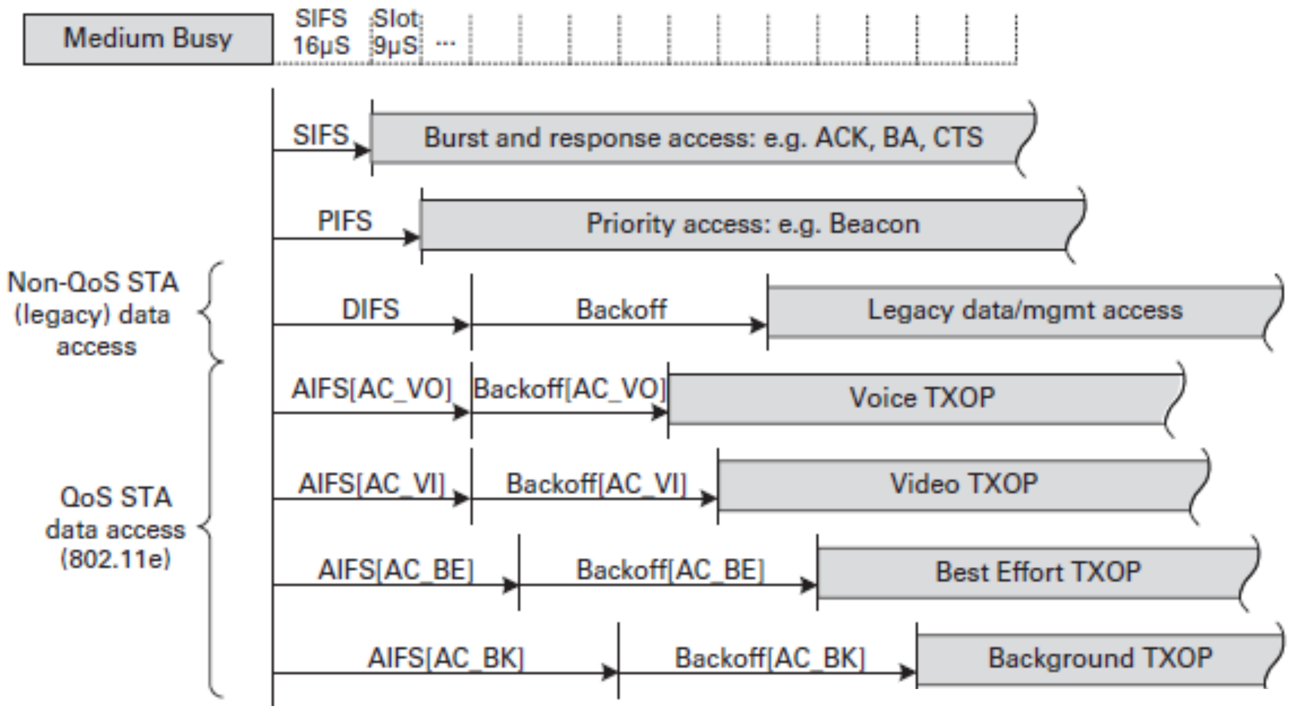
- TXOP promotes resource (air time) fairness
- Note that vanilla 802.11 fair in terms of transmission opportunities (throughput) even when links use multiple different PHY data rates



EDCA Access Parameters

- DIFS in the vanilla DCF protocol replaced by arbitration inter-frame space (AIFS):

AIFS [AC] = `aSIFSTime` + AIFSN [AC] * `aSlotTime`

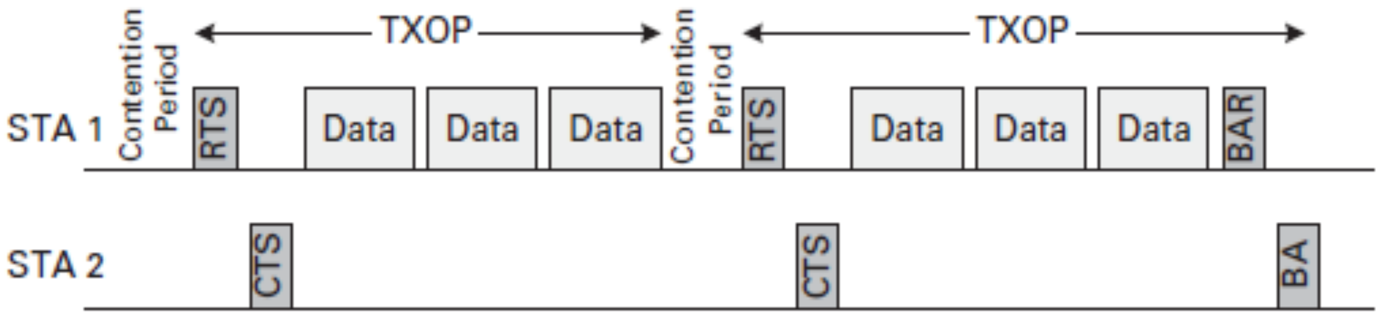


Default parameters for 802.11a/g/n PHYs

AC	CWmin	CWmax	AIFSN	TXOP limit
AC_BK	31	1023	7	0
AC_BE	31	1023	3	0
AC_VI	15	31	2	3.008 ms
AC_VO	7	15	2	1.504 ms
legacy	15	1023	2	0

Block Acknowledgements

- Allows transfer of a block of frames that are together acknowledged with a single Block Acknowledgement (BA) frame instead of ACK for each individual frame
- Two options:
  1. **Immediate block ACK**: After sending a block of frames, *possibly spanning multiple TXOPs*, sender sends a block acknowledgement request (BAR) frame soliciting a block ack (BA) from receiver



  2. **Delayed block ACK**: BAR sent in one TXOP and BA can come back in a separate, later TXOP

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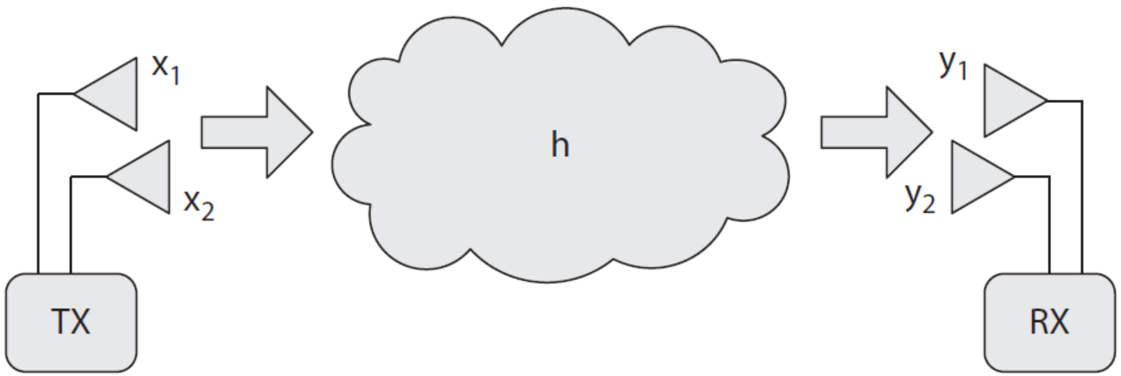
802.11n

- Goal: achieving **100Mbps+ throughput above data link layer**
- Key features:
  - Higher PHY data rates via:
    - Spatial division multiplexing (SDM) using MIMO
    - 40MHz operation
  - MAC efficiency improvement via:
    - Frame aggregation
    - Block acknowledgement enhancement

MIMO and SDM

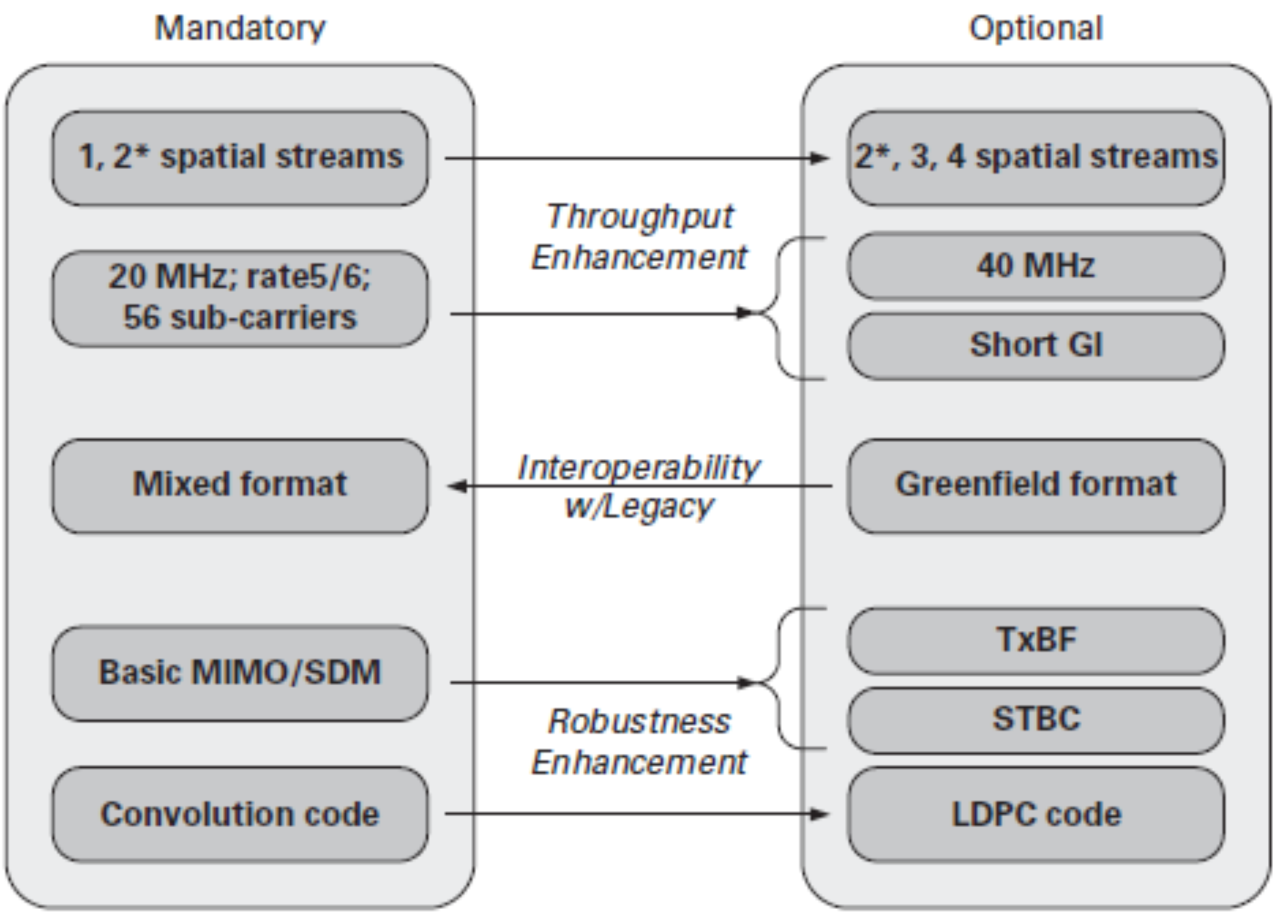
- Multiple input, multiple output (MIMO) system: transmitter with multiple antennas transmitting to a receiver with multiple receive antennas
  - Contrast with single input single output (SISO) system in which both transmitter and receiver have only one antenna
- Spatial division multiplexing (SDM): A MIMO system used to transmit independent data streams (or spatial streams) on different antennas
  - Spatial streams: streams of bits transmitted over separate spatial dimensions
  - *k* spatial streams require *k* antennas
  - *NxN* MIMO system has *N* Tx antennas and *N* Rx antennas



Other Enhancements in 802.11n

- Robustness improvements via:
  - Spatial diversity through the use of multiple antennas
  - Space-time block coding (STBC)
  - Fast link adaptation
  - Low density parity check (LDPC) codes
  - Transmit beamforming (TxBF)
- Other enhancements:
  - Shorter guard interval (GI)
  - Greenfield preamble
  - Reverse direction MAC protocol (subleasing TXOP)
  - Reduced inter-frame space (RIFS)

802.11n PHY Features



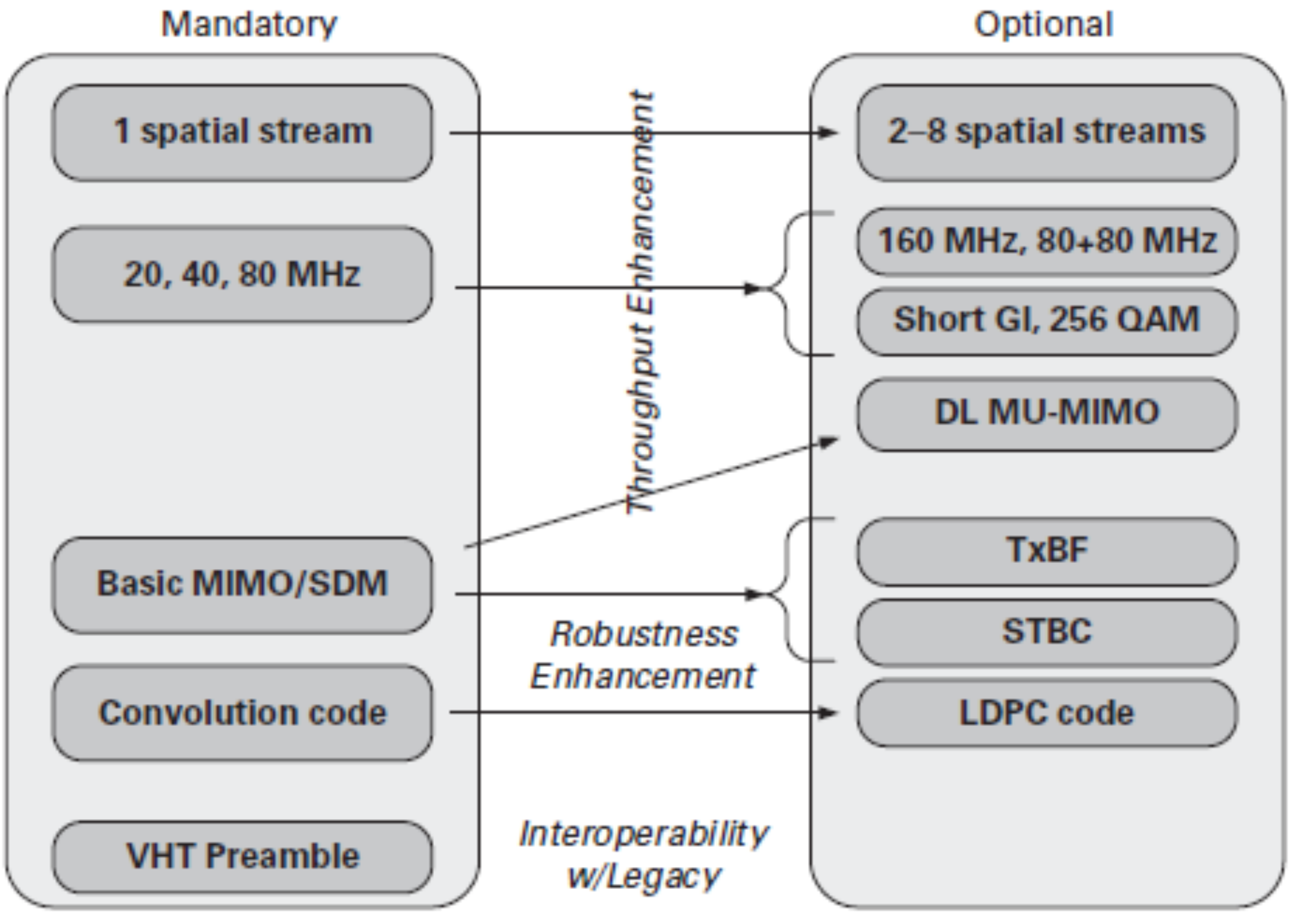
* 2 spatial streams mandatory for AP only

802.11n PHY Data Rates

MCS Index	Spatial Streams	Modulation Scheme	Coding Rate	20MHz w/ LGI	40MHz w/ LGI
0	1	BPSK	1/2	6.50	13.50
1	1	QPSK	1/2	13.00	27.00
2	1	QPSK	3/4	19.50	40.50
3	1	16-QAM	1/2	26.00	54.00
4	1	16-QAM	3/4	39.00	81.00
5	1	64-QAM	2/3	52.00	108.00
6	1	64-QAM	3/4	58.50	121.50
7	1	64-QAM	5/6	65.00	135.00
8	2	BPSK	1/2	13.00	27.00
9	2	QPSK	1/2	26.00	54.00
10	2	QPSK	3/4	39.00	81.00
11	2	16-QAM	1/2	52.00	108.00
12	2	16-QAM	3/4	78.00	162.00
13	2	64-QAM	2/3	104.00	216.00
14	2	64-QAM	3/4	117.00	243.00
15	2	64-QAM	5/6	130.00	270.00

802.11ac PHY Features

- 802.11ac Goals:
  - Single link throughput at least 500Mbps
  - Multi-station throughput of at least 1Gbps



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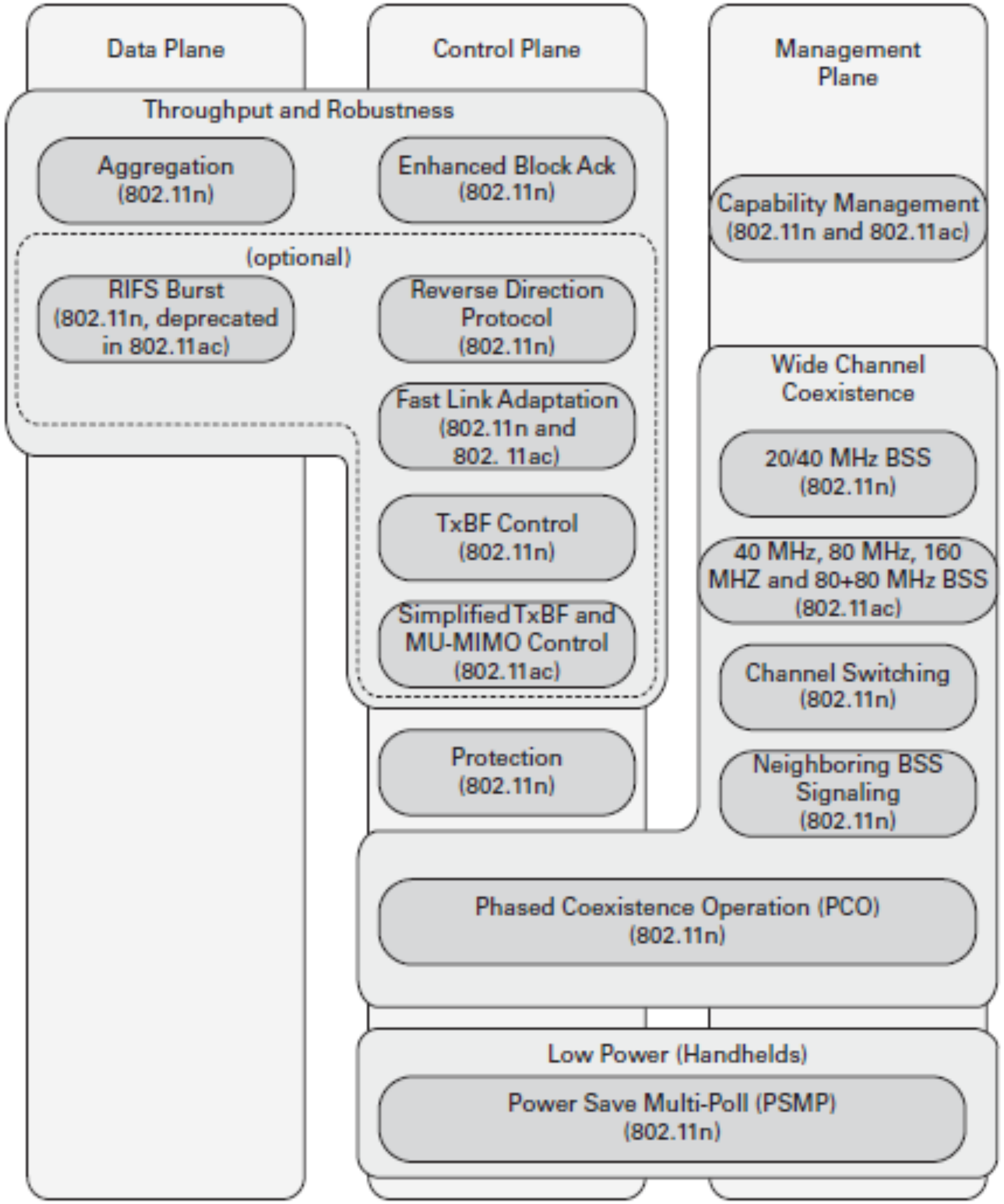
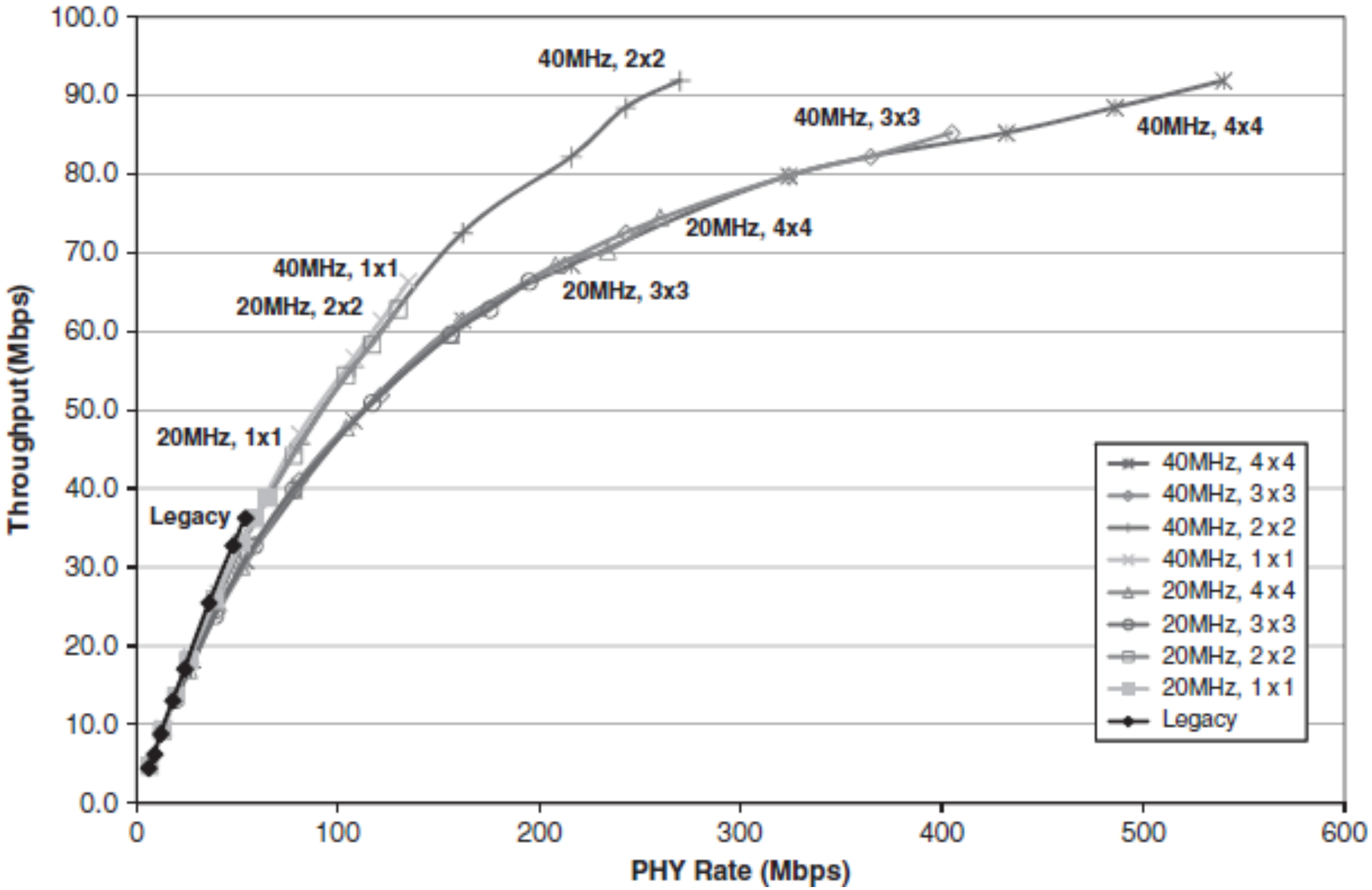
802.11n and 802.11ac MAC Enhancements



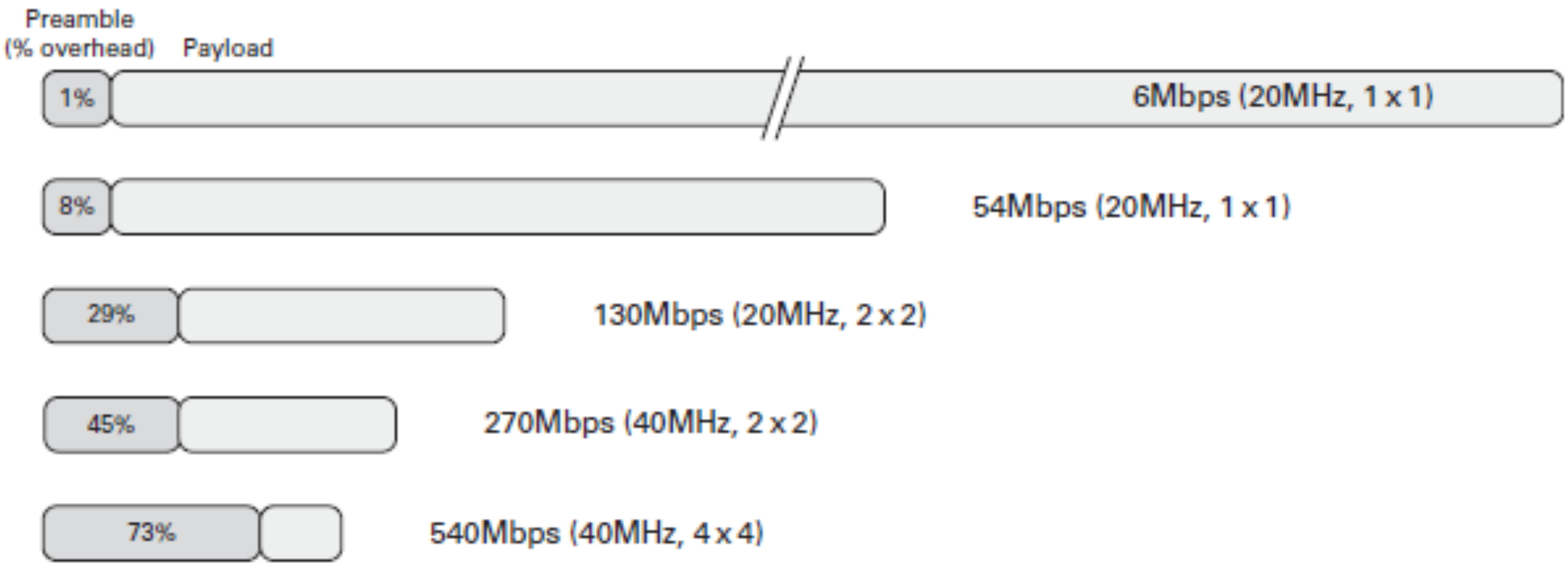
802.11n Throughput without MAC Changes



- 3ms TXOP limit, block ack, 10% PER

Overhead Increase at Higher PHY Data Rates

- Relative preamble overhead for a 1500 byte frame at different PHY data rates



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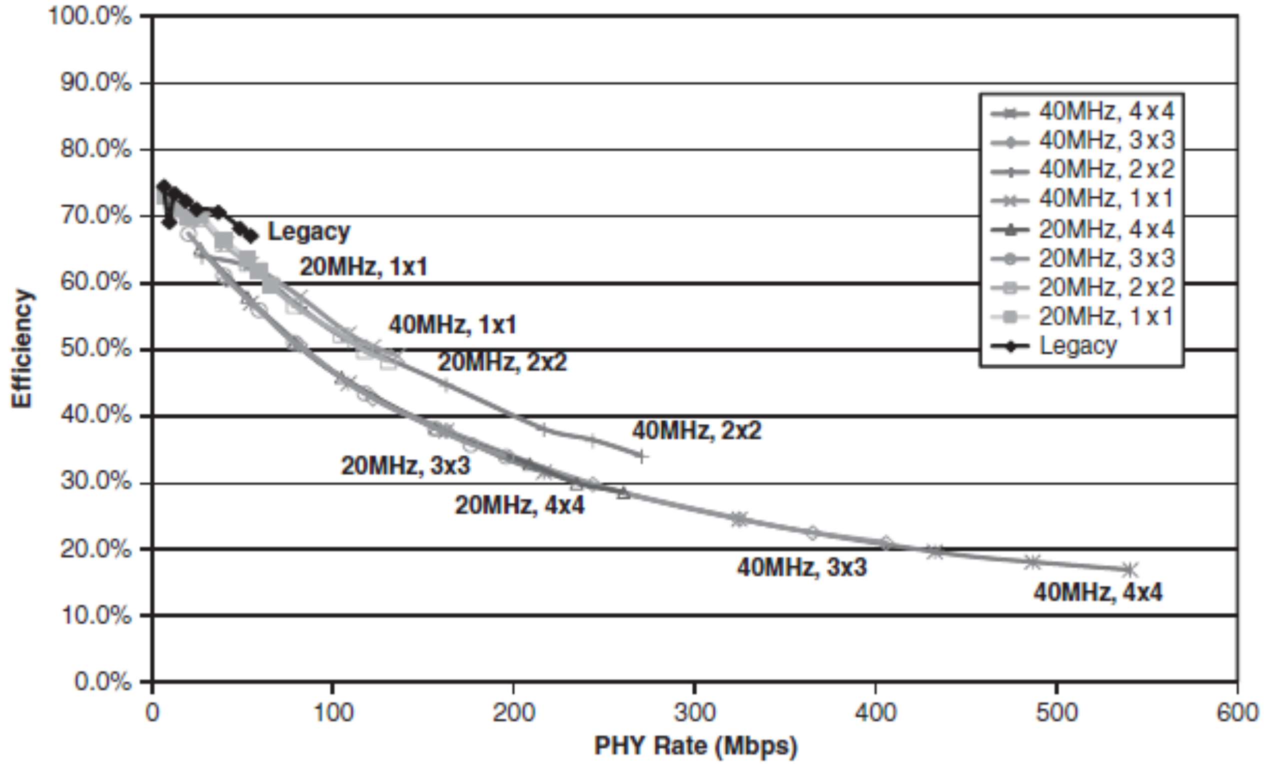
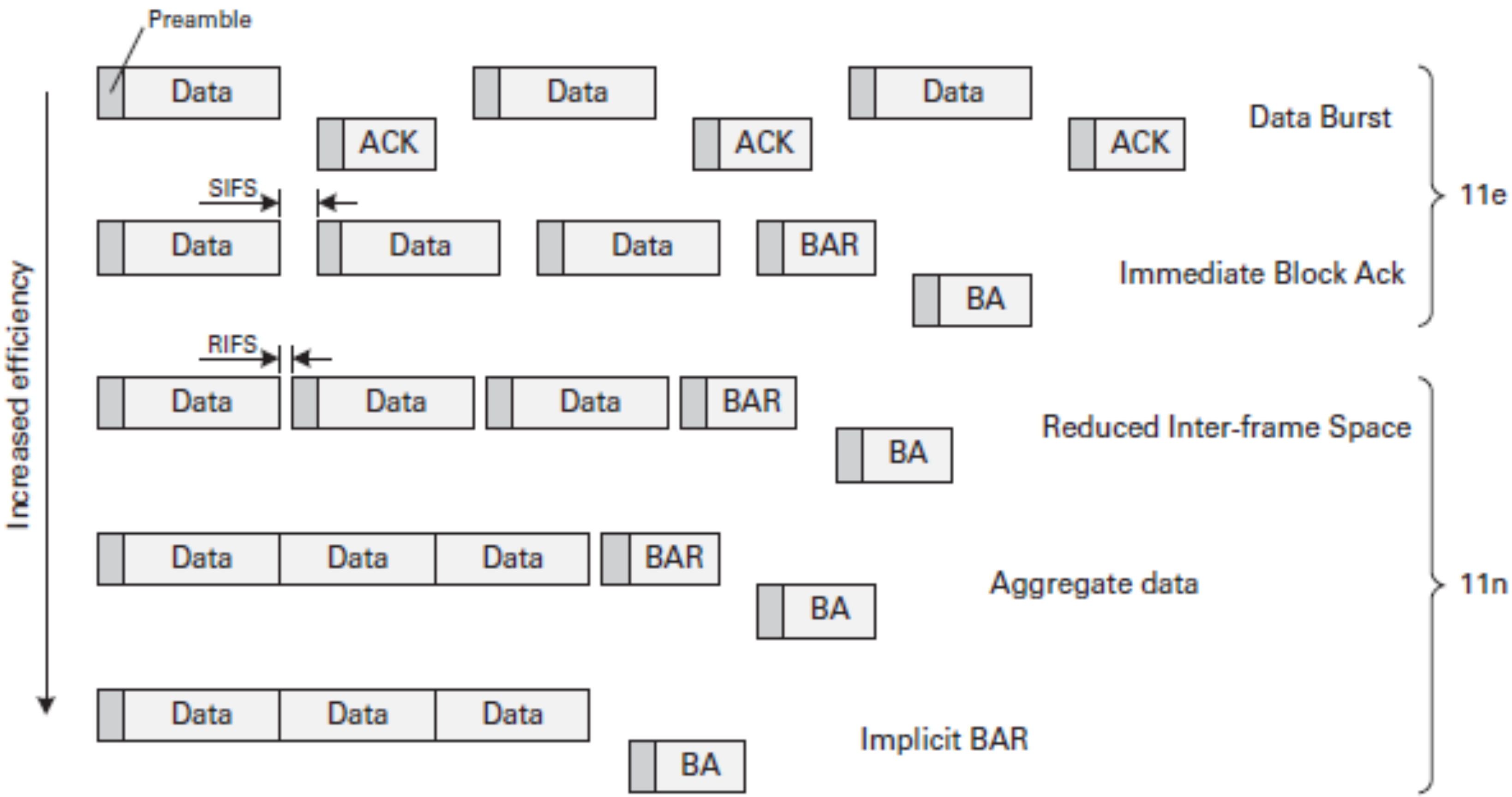
802.11n MAC Efficiency without MAC Changes



- 3ms TXOP limit, block ack, 10% PER

MAC Throughput Enhancements



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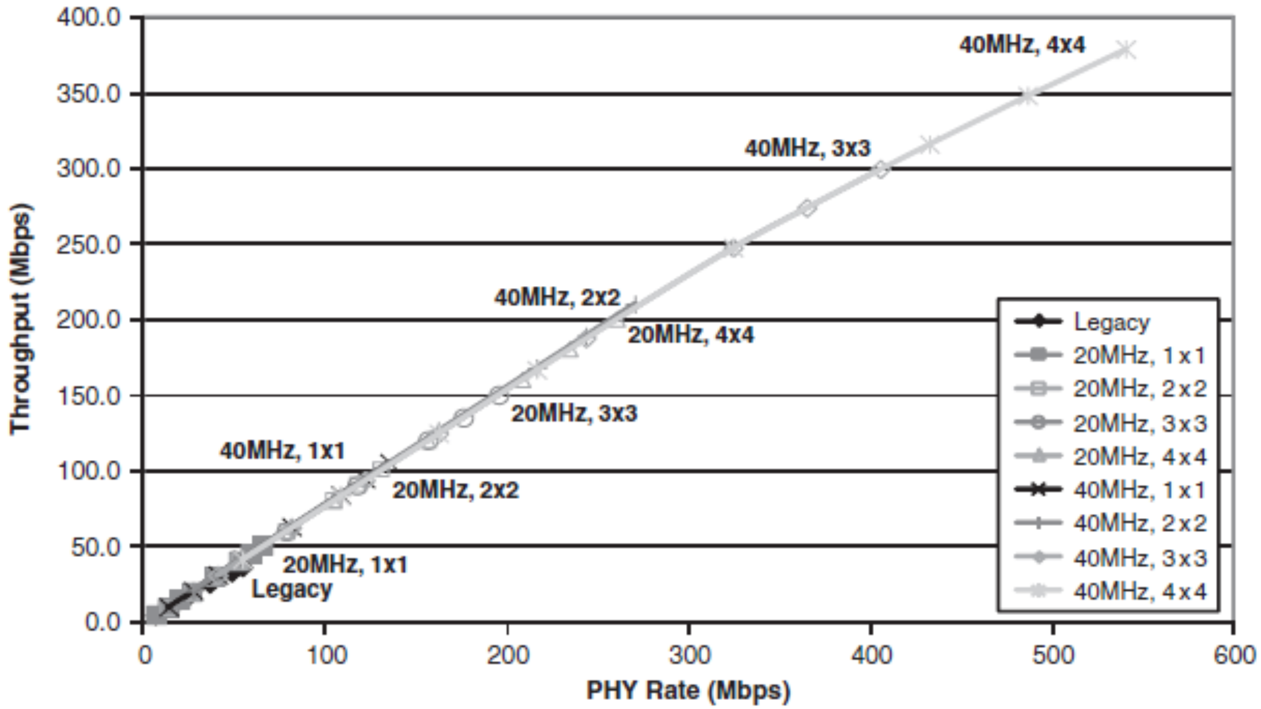
802.11 Throughput with MAC Enhancements



- 3ms TXOP limit, block ack, 10% PER

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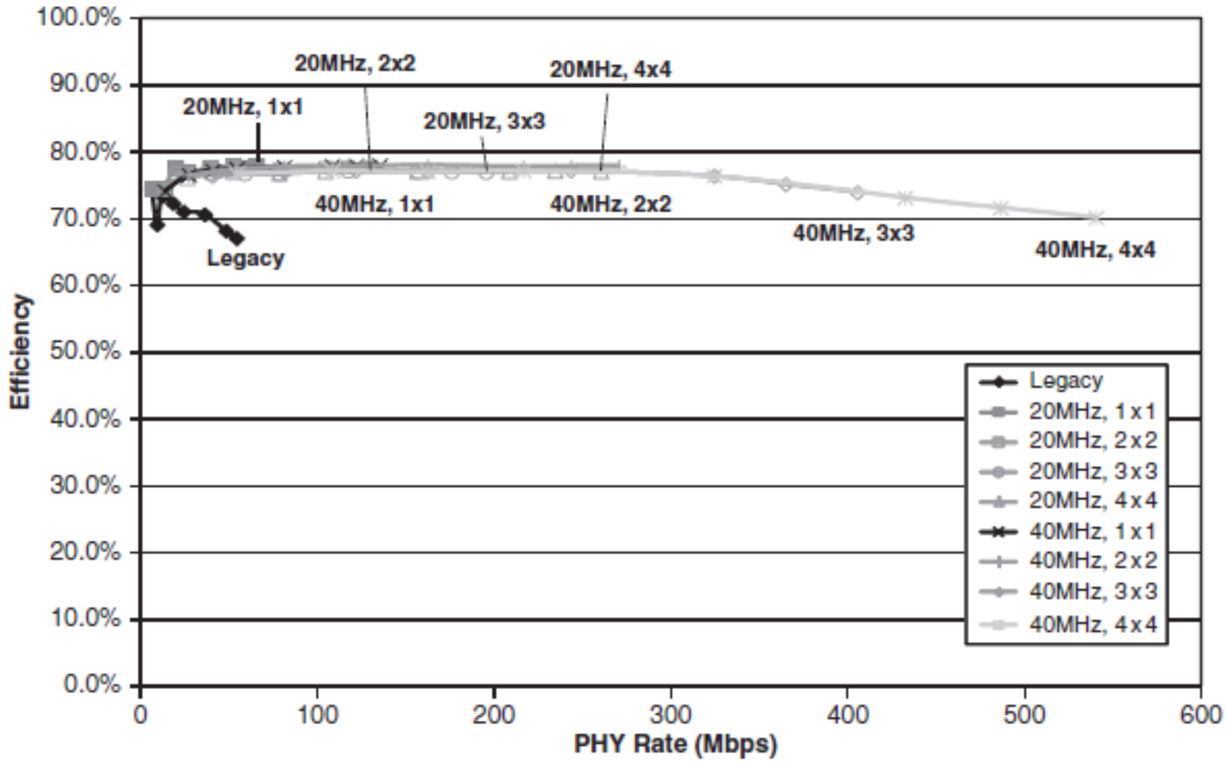
MAC Efficiency with MAC Enhancements



- 3ms TXOP limit, block ack, 10% PER

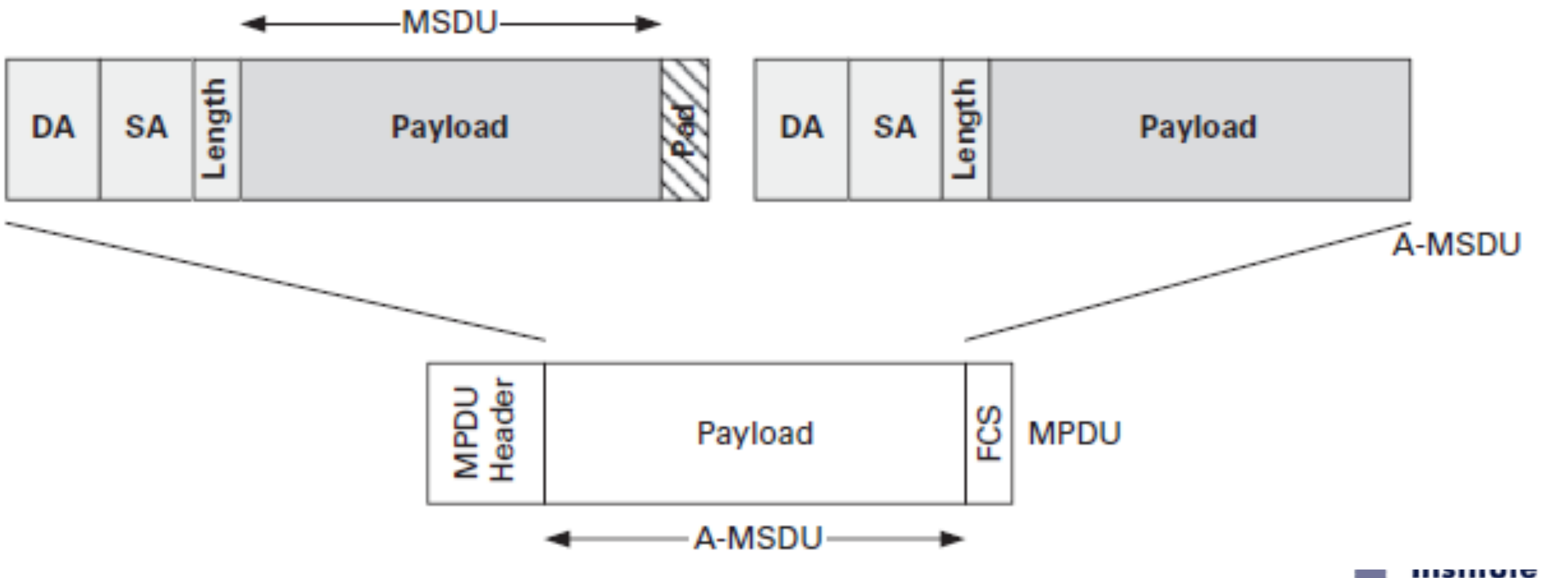
802.11n Frame Aggregation

- Two types:
  - MSDU aggregation (A-MSDU) at the *top* of the MAC
  - MPDU aggregation (A-MPDU) at the *bottom* of the MAC

- In both cases, subframes must be destined to the same receiver and should belong to the same service category

Aggregate MSDU (A-MSDU)

- Multiple MSDUs from LLC aggregated and encapsulated within a single MPDU
- Maximum length = 3839/7935 bytes depending on receiver buffer size (4KB/8KB)



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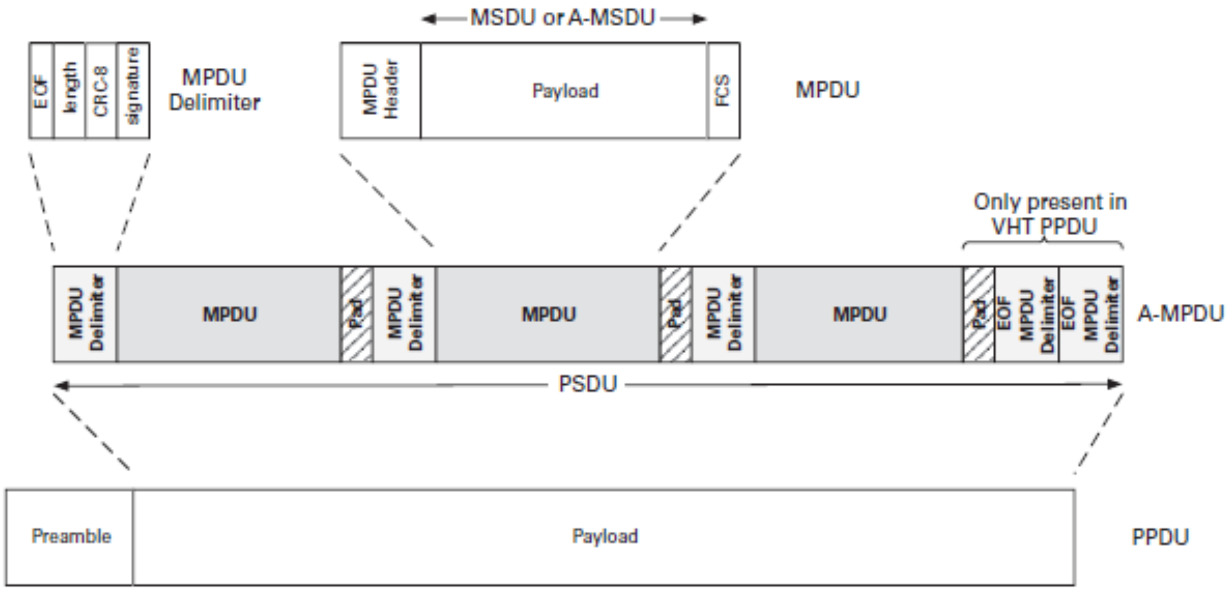
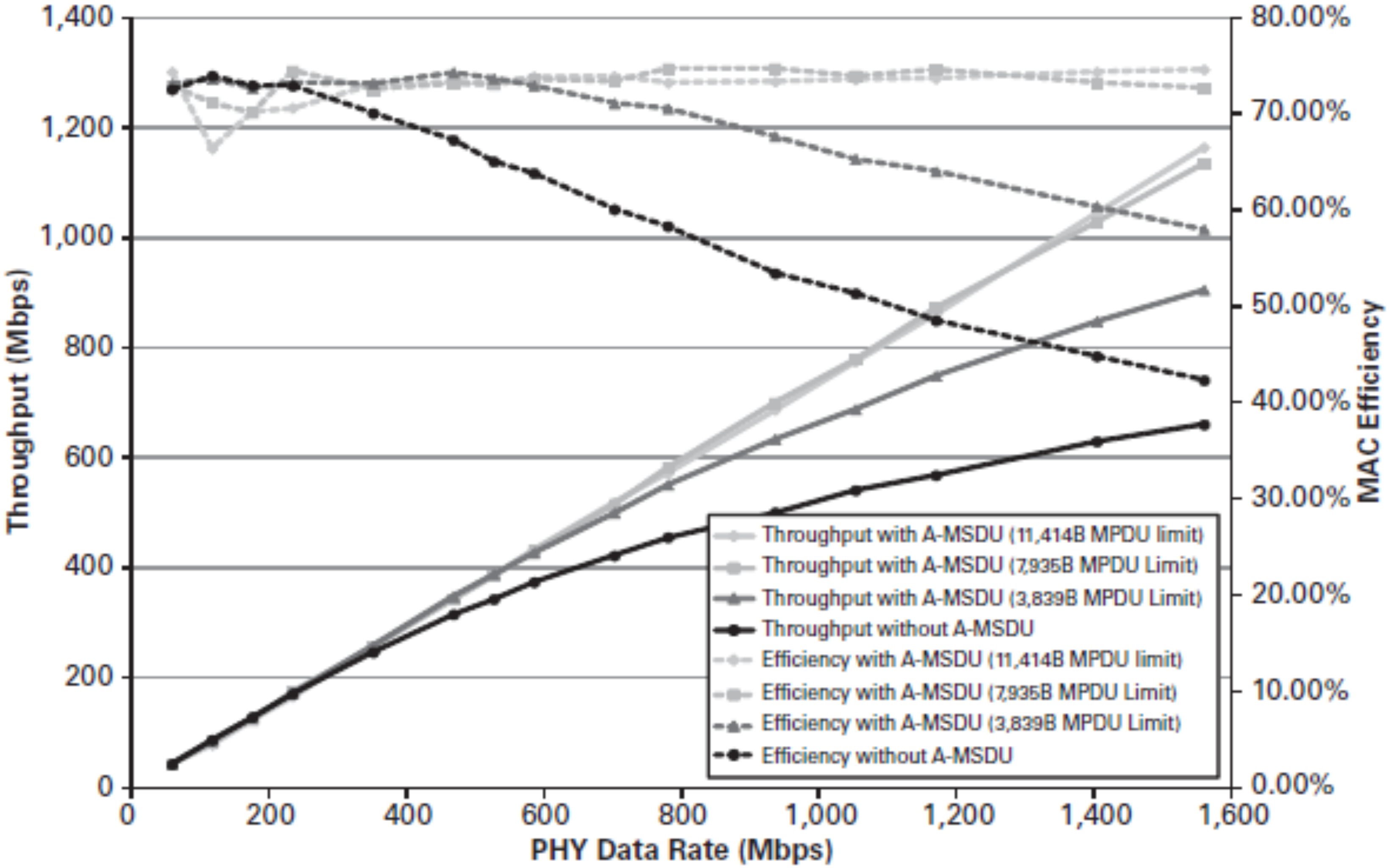
Aggregate MPDU (A-MPDU)

- Multiple MPDUs are aggregated together and encapsulated within a single PSDU (A-MPDU)
- Maximum A-MPDU length with 802.11n can be 8191; 16383; 32, 767, or 65,535 bytes



Need both A-MSDU and A-MPDU with 802.11ac



HT Control Field

- To carry .11n and .11ac specific information in MAC header

HT Control field

B0	B1 – B29	B30	B31
VHT	HT Control Middle	AC Constraint	RDG/ More PPDU

HT Control Middle: HT variant

B1 – B15	B16 – B17	B18 – B19	B20 – B21	B22 – B23	B24	B25 – B28	B29
Link Adaptation Control	Calibration Position	Calibration Sequence	Reserved	CSI/Steering	NDP Announce-ment	Reserved	DEI

HT Control Middle: VHT variant

B1	B2	B3 – B5	B6 – B8	B9 – B23	B24 – B26	B27	B28	B29
Reserved	MRQ	MSI/ STBC	MFSI/ GID-L	MFB	GID-H	Coding Type	FB Tx Type	Unsolicited MFB