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Researching the Internet of the Future

Networking II

WLANs

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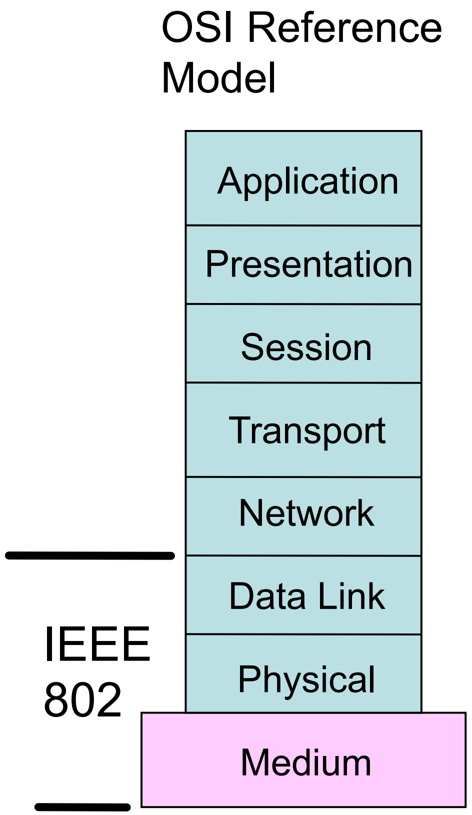
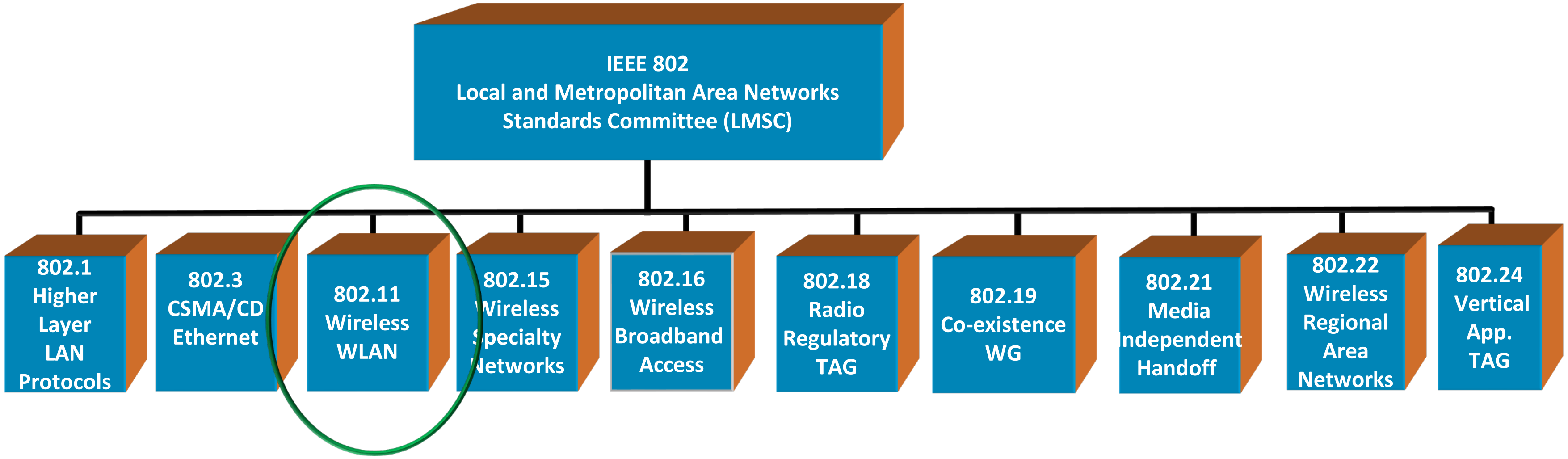
The IEEE 802.11 Working Group is one of the most active WGs in 802

- Focus on **link and physical layers** of the network stack
- Leverage IETF protocols for upper layers





IEEE 802.11 WG Voting Members: 300+

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Type of Groups in 802.11

Type of Group	Description
WG	Working Group
SC	Standing Committee
TG	Task Group
SG	Study Group
TIG	Topic Interest Group
AHG	Ad Hoc Group

IEEE 802.11 Wireless LAN

802.11b

- 2.4 GHz unlicensed spectrum
- up to 11 Mbps
- direct sequence spread spectrum (DSSS) in physical layer
  - all hosts use same chipping code

802.11a

- 5-6 GHz range
- up to 54 Mbps

802.11g

- 2.4 GHz range
- up to 54 Mbps

802.11n: multiple antennae

- 2.4-5 GHz range
- up to 200 Mbps

- all use CSMA/CA for multiple access
- all have base-station and ad-hoc network versions

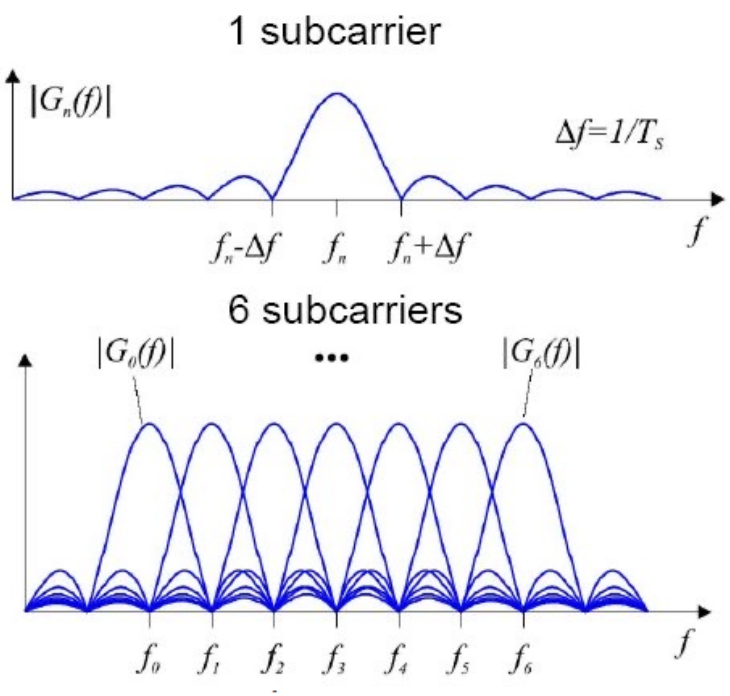
IEEE 802.11–1997

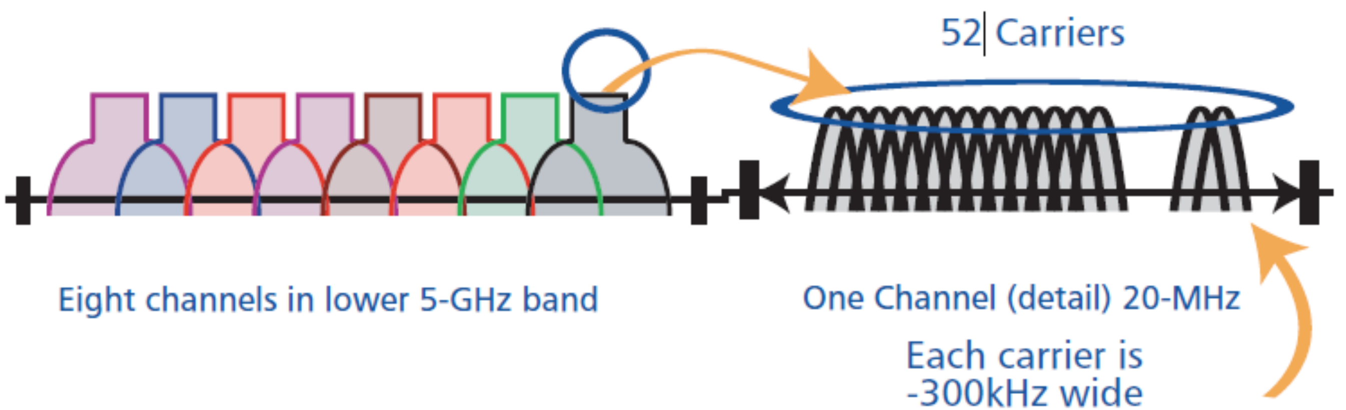
- The ORIGINAL wireless protocol.
  - Security implemented via WEP
    - Wired Equivalent Privacy (Legacy)
- Provided Bandwidth
  - 1 or 2 Mbit/s due to use of CSMA/CA
- Relatively Unpopular
- Low interoperability due to loose specifications
- Used DSSS
- Considered Legacy and no longer used

IEEE 802.11a

- One of two amendments to the original 802.11 specification released simultaneously
- Provided up to 54 Mbit/s bandwidth
- Uses OFDM
  - Orthogonal Frequency-Division Multiplexing
    - Transmits a signal over several sub signals for higher efficiency

OFDM





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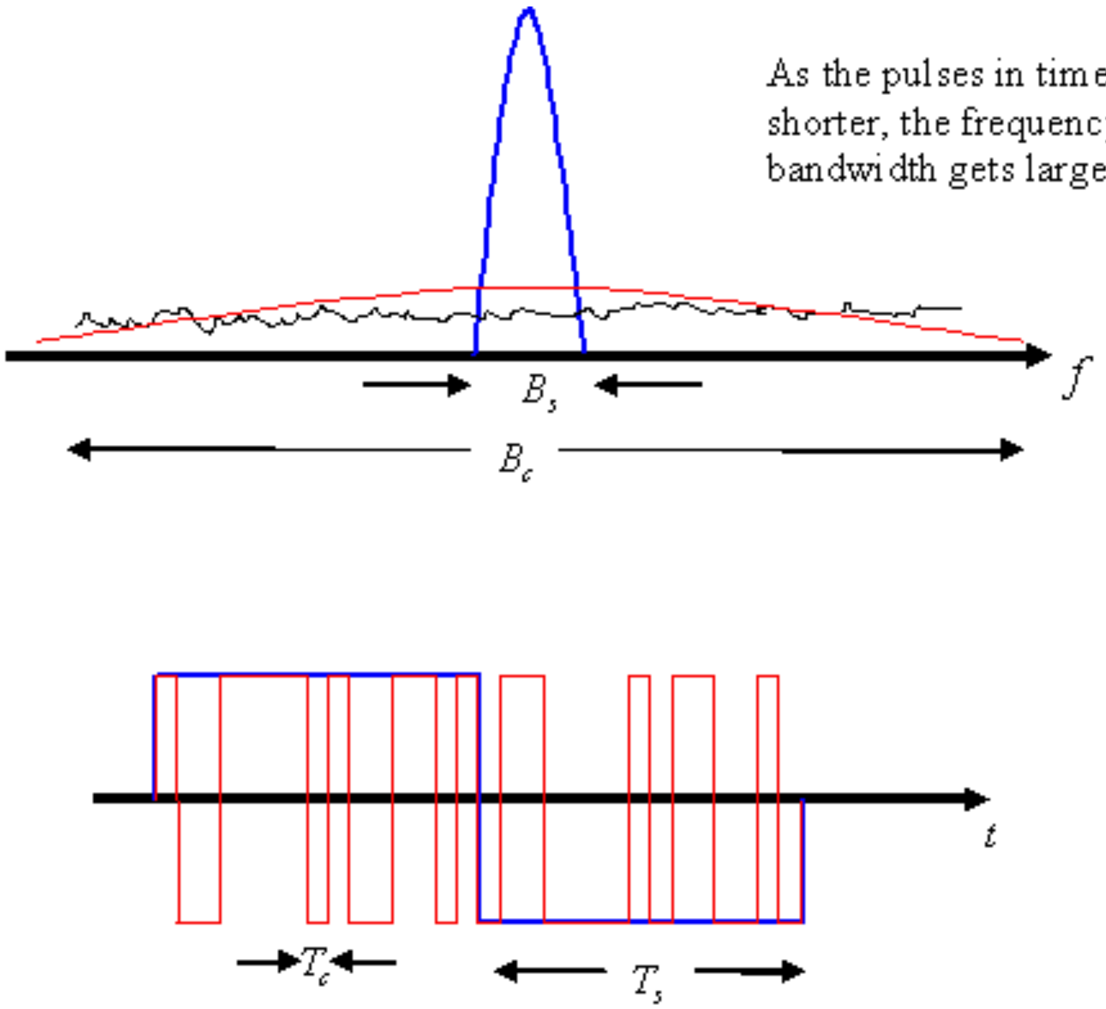
IEEE 802.11b

- Second of two amendments released in 1999
- Provided up to 11 Mbit/s bandwidth
- Uses DSSS
  - Direct-Sequence Spread Spectrum
    - Transmits a signal over several sub signals for higher efficiency

DSSS

As the pulses in time get shorter, the frequency bandwidth gets larger



IEEE 802.11a and b

- Both introduced at the same time
- Both use CSMA/CA
- 802.11a
  - Faster
  - More expensive to manufacture
  - Operated in 5Ghz band
  - Mainly used in industrial settings
- 802.11b
  - Slower
  - Cheaper to manufacture
  - Operated in 2.4Ghz band.
  - Mainly used in residential settings

IEEE 802.11g

- The most common wireless network in use before .11n.
- Operates on 2.4Ghz band
- Provides up 54Mbit/s bandwidth
  - 108Mbit/s with special implementations
- Uses OFDM for modulation
- Adopted quickly after release for cheap and high bandwidth

IEEE 802.11n

- Reference version of the 802.11 family.
- Has rated 600Mbit/s bandwidth
- Introduces MIMO
  - Multiple-Input Multiple-Output
- OFDM Modulation
  - Uses higher frequencies for increased number of carrier waves

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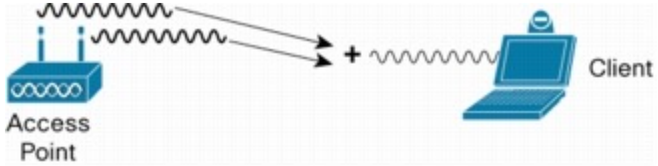
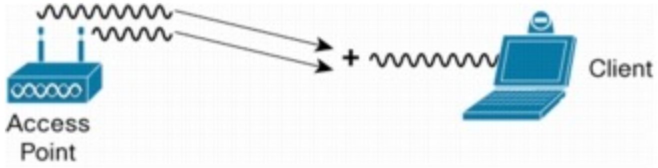
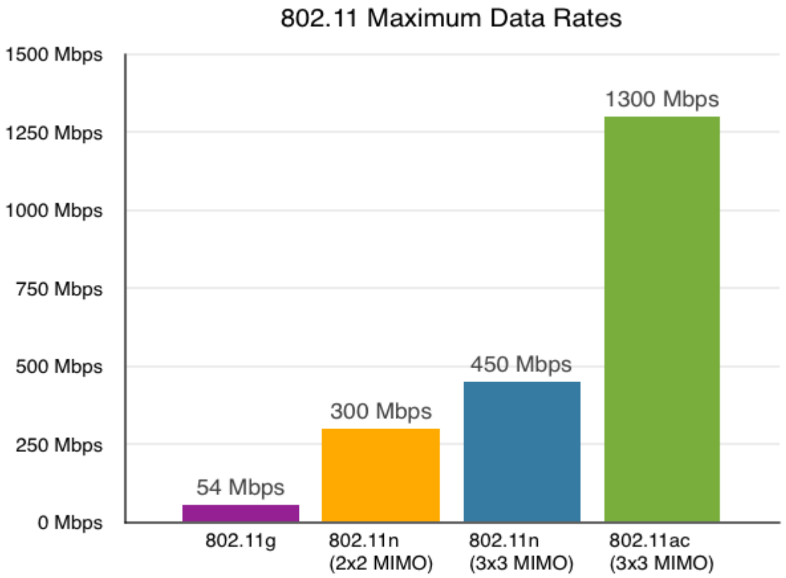
IEEE 802.11n – New Technologies

- Beam Forming
  - Takes advantage of multi-antenna setup
  - Makes signals from separate antenna arrive in sync
  - Out of sync leads to interference



  - In sync leads to greater signal strength





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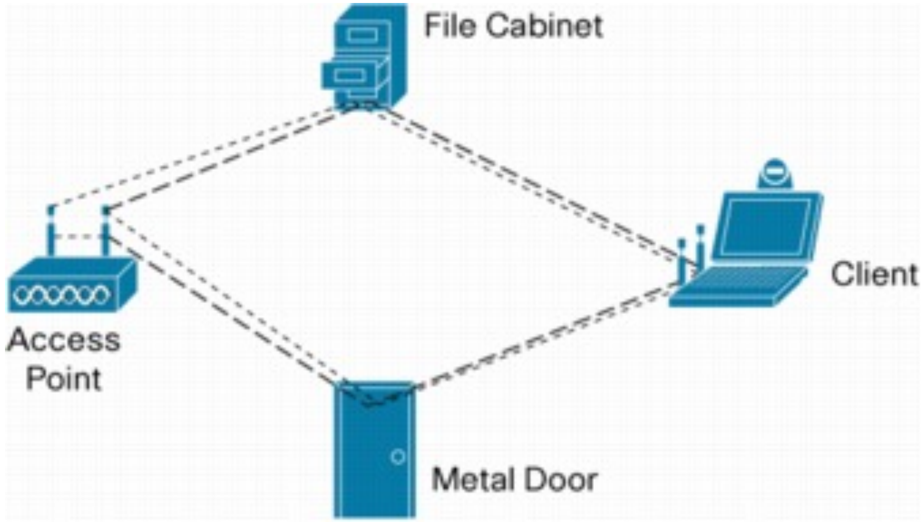
IEEE 802.11n – New Technologies

- Multipath/Spatial Diversity



  - Multiple antenna/radios send/receive signals
  - Different signals reach receivers at different times
  - Use math to combine signals for greater quality
  - Each stream can carry separate data

IEEE 802.11n – New Technologies

- Guard interval reduction
  - Guard interval is a time of radio silence
  - Used to avoid interference
  - 802.11n can reduce guard interval from 800µs to 400µs.
- Frame aggregation
  - Aggregate multiple frames destined for a specific AP and send them together to reduce overhead

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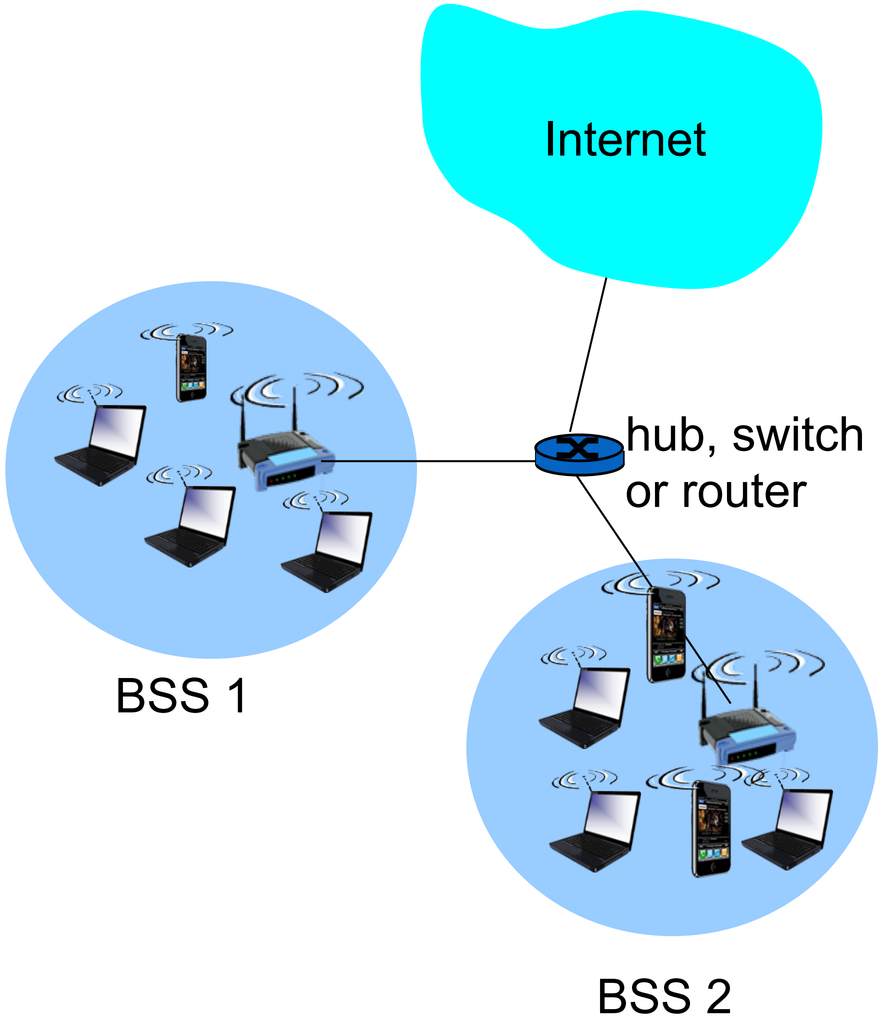
IEEE 802.11 LAN architecture



- 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

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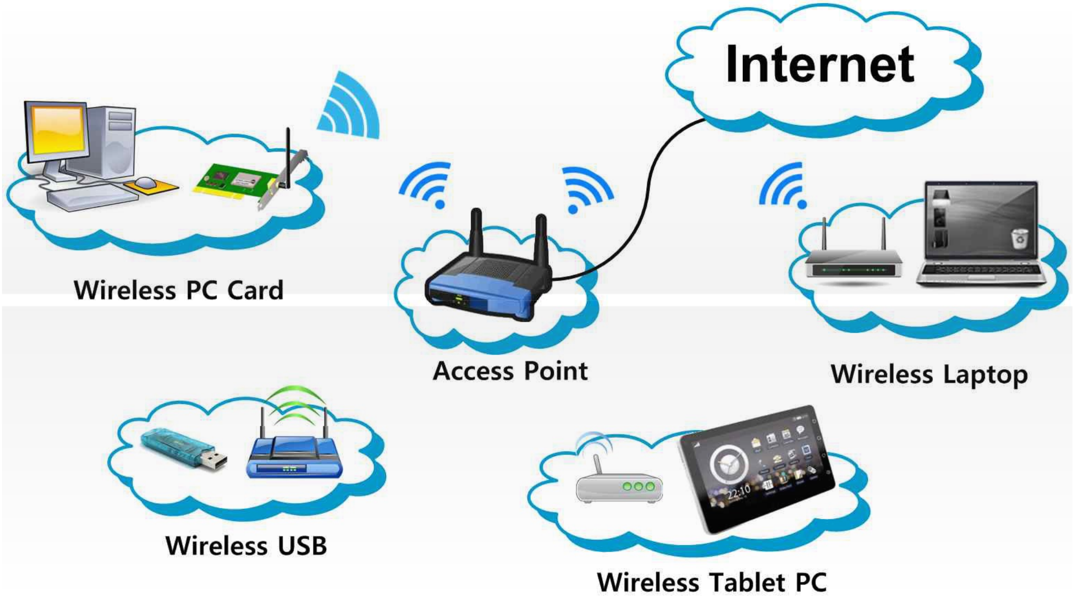
IEEE 802.11 LAN architecture

Infrastructure mode



Infrastructure Mode

- In infrastructure mode, Wi-Fi devices can
  - communicate with each other and
  - communicate with a wired network

- BSS (Basic Service Set)
  - In infrastructure mode, commonly one AP is connected by wire to the Internet, and a set of Wi-Fi devices connect to the AP

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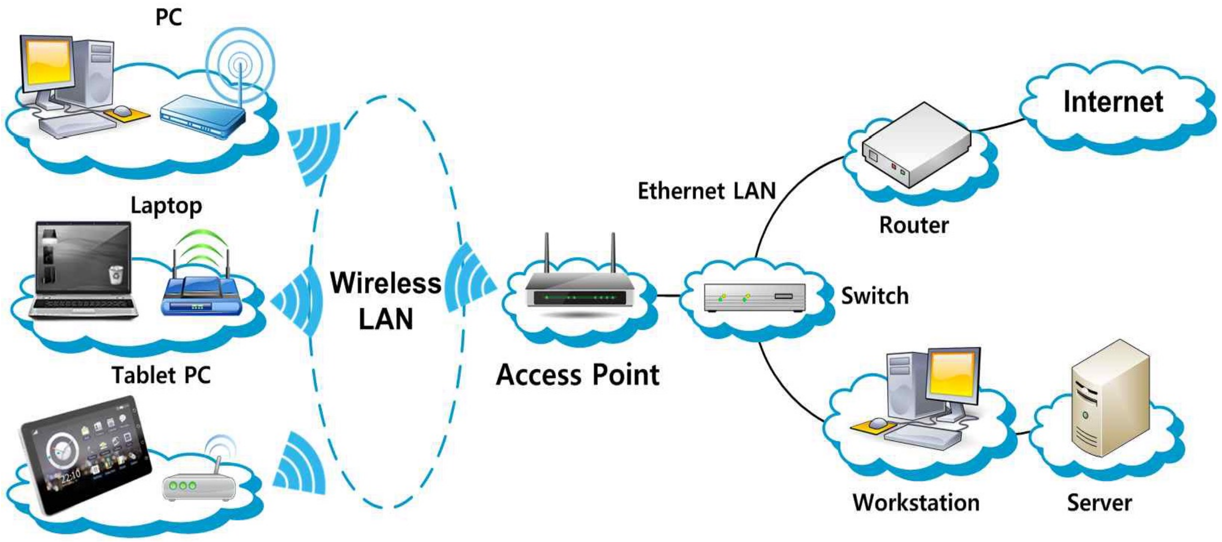
IEEE 802.11 LAN architecture

Another example of Infrastructure mode



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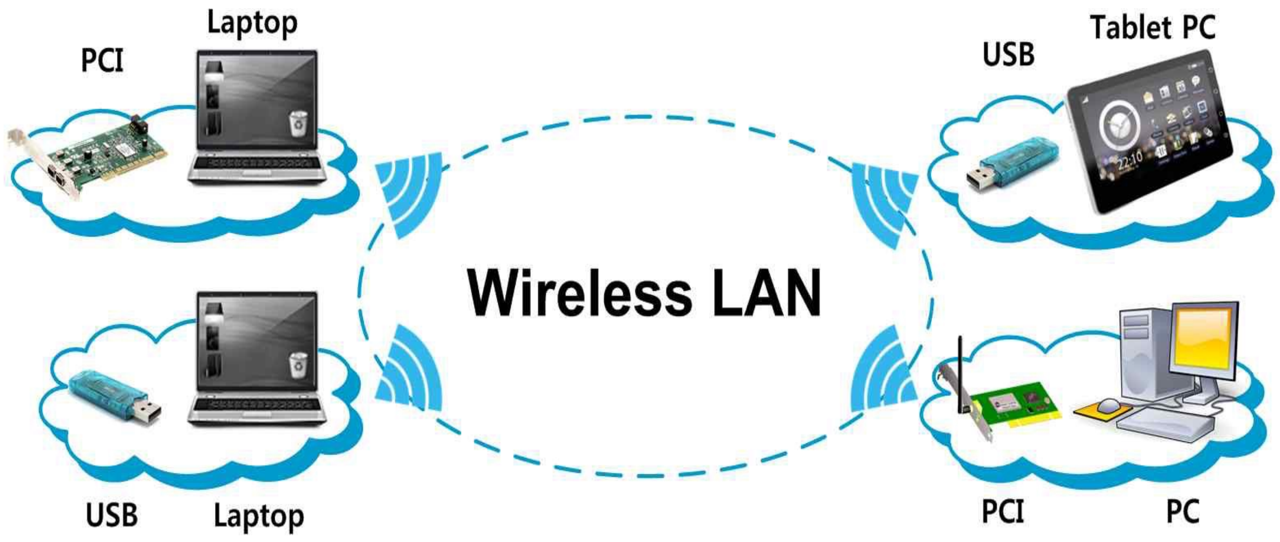
IEEE 802.11 LAN architecture

Ad-Hoc Mode

- Wi-Fi devices or stations communicate directly with each other, without help from an AP (Access Point) ➔ Used where Infrastructure Mode network setup is not needed or not possible
- Also referred to as peer-to-peer mode
- IBSS (Independent Basic Service Set)
  - Ad-hoc mode network is referred to as an IBSS

Example of Ad-Hoc mode



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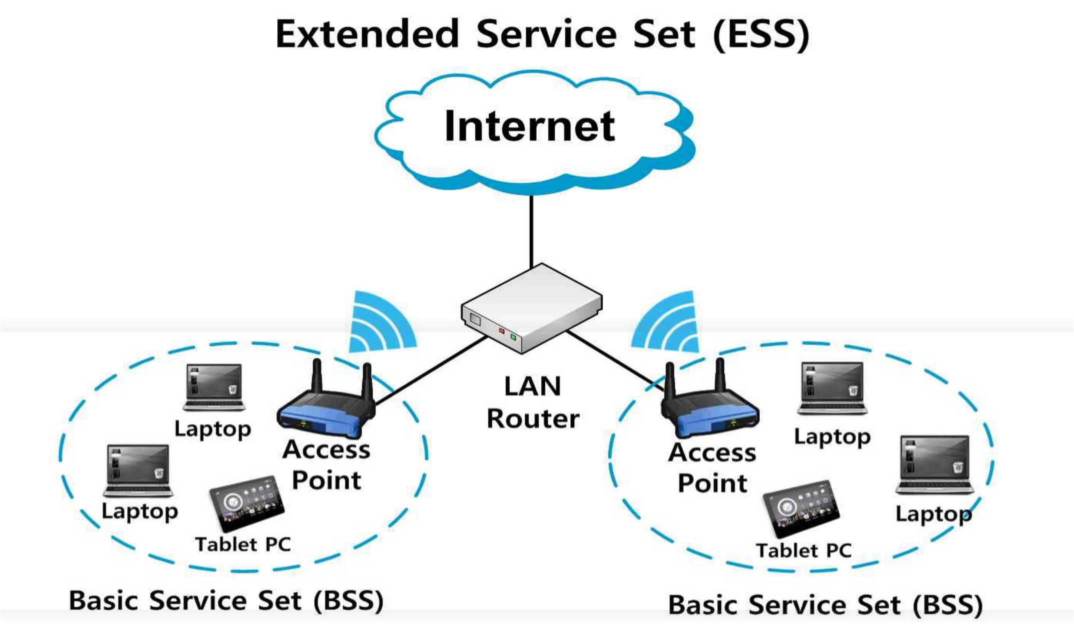
IEEE 802.11 LAN architecture

BSS & ESS

- BSS (Basic Service Set) is the basic building block of an 802.11 WLAN
  - In infrastructure mode, a BSS is formed by a single AP (Access Point) and all associated STAs (stations)
  - AP acts as a Master and controls all STAs within the BSS

- ESS (Extended Service Set) is a set of two or more BSSs that form a single network

➔ Extends the range of Wi-Fi STA mobility



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IEEE 802.11 Versions

IEEE 802.11 Network PHY Standards (1/2)				
802.11 Protocol	Release Date	Frequency	Bandwidth	Stream Data Rate
802.11−1997	Jun. 1997	2.4 GHz	22 MHz	1, 2 Mbps
802.11a	Sep. 1999	5 GHz	20 MHz	6 ~ 54 Mbps
		3.7 GHz		
802.11b	Sep. 1999	2.4 GHz	22 MHz	1 ~ 11 Mbps
802.11g	Jun. 2003	2.4 GHz	20 MHz	6 ~ 54 Mbps
802.11n	Oct. 2009	2.4/5 GHz	20 MHz	7.2 ~ 72.2 Mbps
			40 MHz	15 ~ 150 Mbps

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IEEE 802.11 Versions

IEEE 802.11 Network PHY Standards (2/2)				
802.11 Protocol	Release Date	Frequency	Bandwidth	Stream Data Rate
802.11ac	Dec. 2013	5 GHz	20 MHz	7.2 ~ 96.3 Mbps
			40 MHz	15 ~ 200 Mbps
			80 MHz	32.5 ~ 433.3 Mbps
			160 MHz	65 ~ 866.7 Mbps
802.11ad	2012, 2016	60 GHz	2.16 GHz	Up to 7 Gbps
802.11ay	2017	60 GHz	8 GHz	Up to 100 Gbps

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IEEE 802.11 Versions

IEEE 802.11 Network PHY Standards (1/2)				
802.11 protocol	Frequency	Modulation	Approximate Range	
			Indoor (m)	Outdoor (m)
802.11-1997	2.4 GHz	DSSS, FHSS	20	100
802.11a	5 GHz	OFDM	35	120
	3.7 GHz		–	5000
802.11b	2.4 GHz	DSSS	35	140
802.11g	2.4 GHz	OFDM, DSSS	38	140

IEEE 802.11 Versions

IEEE 802.11 Network PHY Standards (2/2)				
802.11 protocol	Frequency	Modulation	Approximate Range	
			Indoor (m)	Outdoor (m)
802.11n	2.4/5 GHz	OFDM (MIMO-4)*	70	250
802.11ac	5 GHz	OFDM (MIMO-8)*	35	–
802.11ad	60 GHz	OFDM (>10X10 MIMO)	10	10

*MIMO-4 and MIMO-8 represent that the allowable MIMO streams are 4 and 8, respectively.

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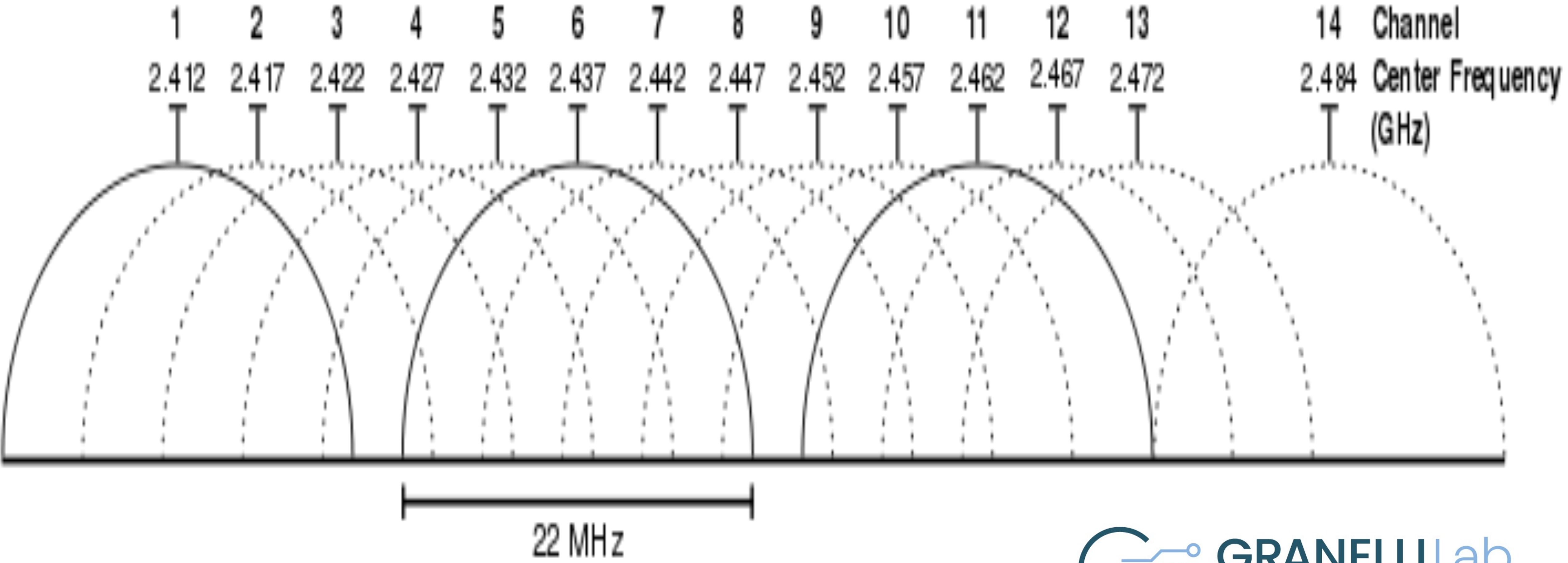
IEEE 802.11b Channels

- 802.11 splits up the frequencies within the band into 14 radio channels, numbered 1–14.
- These are the 14 channels designated in the 2.4 GHz range spaced 5 MHz apart (with the exception of a 12 MHz spacing before Channel 14).
- FCC allows channels 1 through 11 within the U.S. Most of Europe can use channels 1 through 13. In Japan, only 1 choice: channel 14.
- Channel represents a center frequency. Only 5 MHz separation between center frequencies of channels.

5 MHz

Channel	1	2	3	4	5	6	7	8	9	10	11
Center Frequency (GHz)	2.412	2.417	2.422	2.427	2.432	2.437	2.442	2.447	2.452	2.457	2.462

IEEE 802.11b Channels



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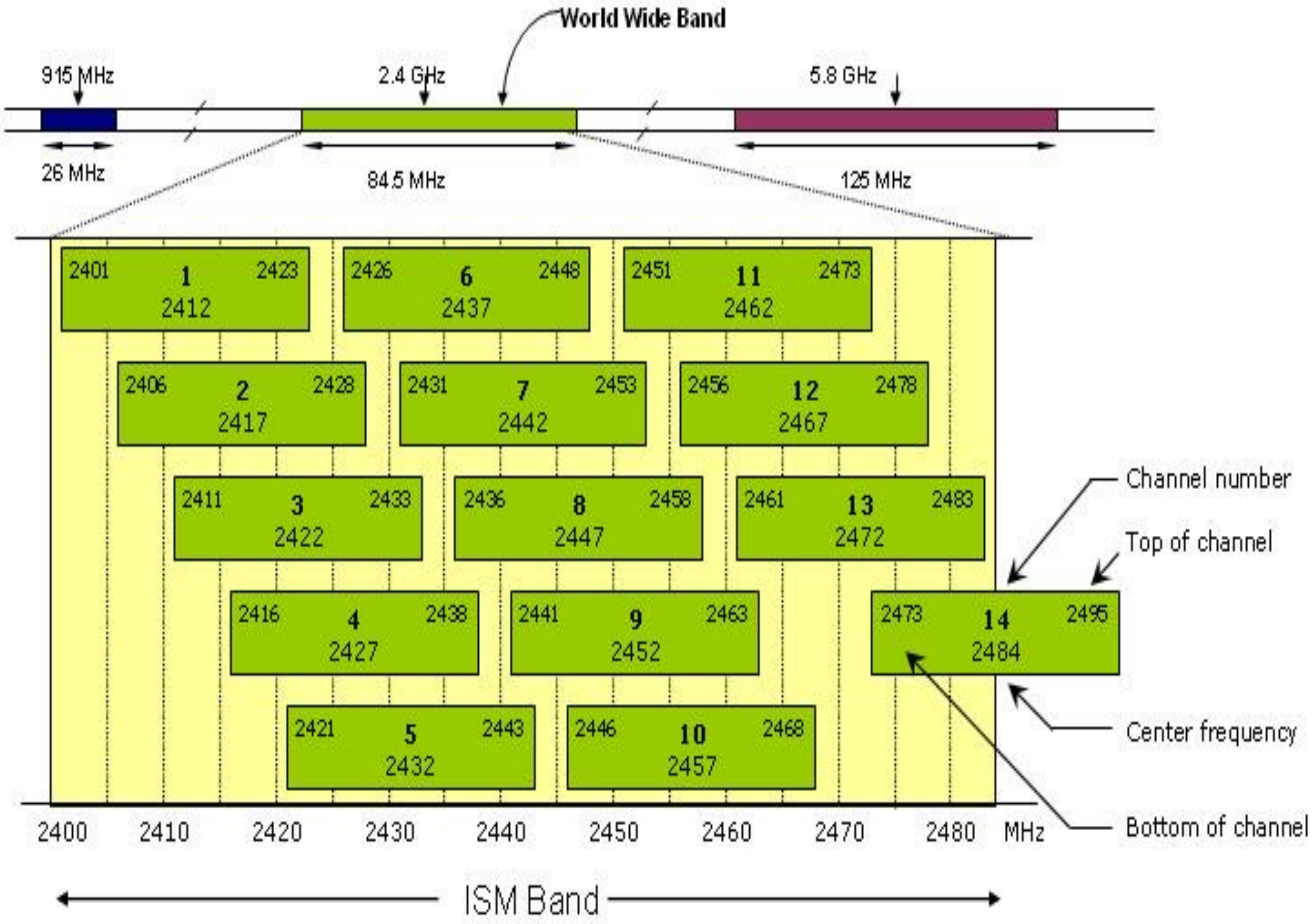
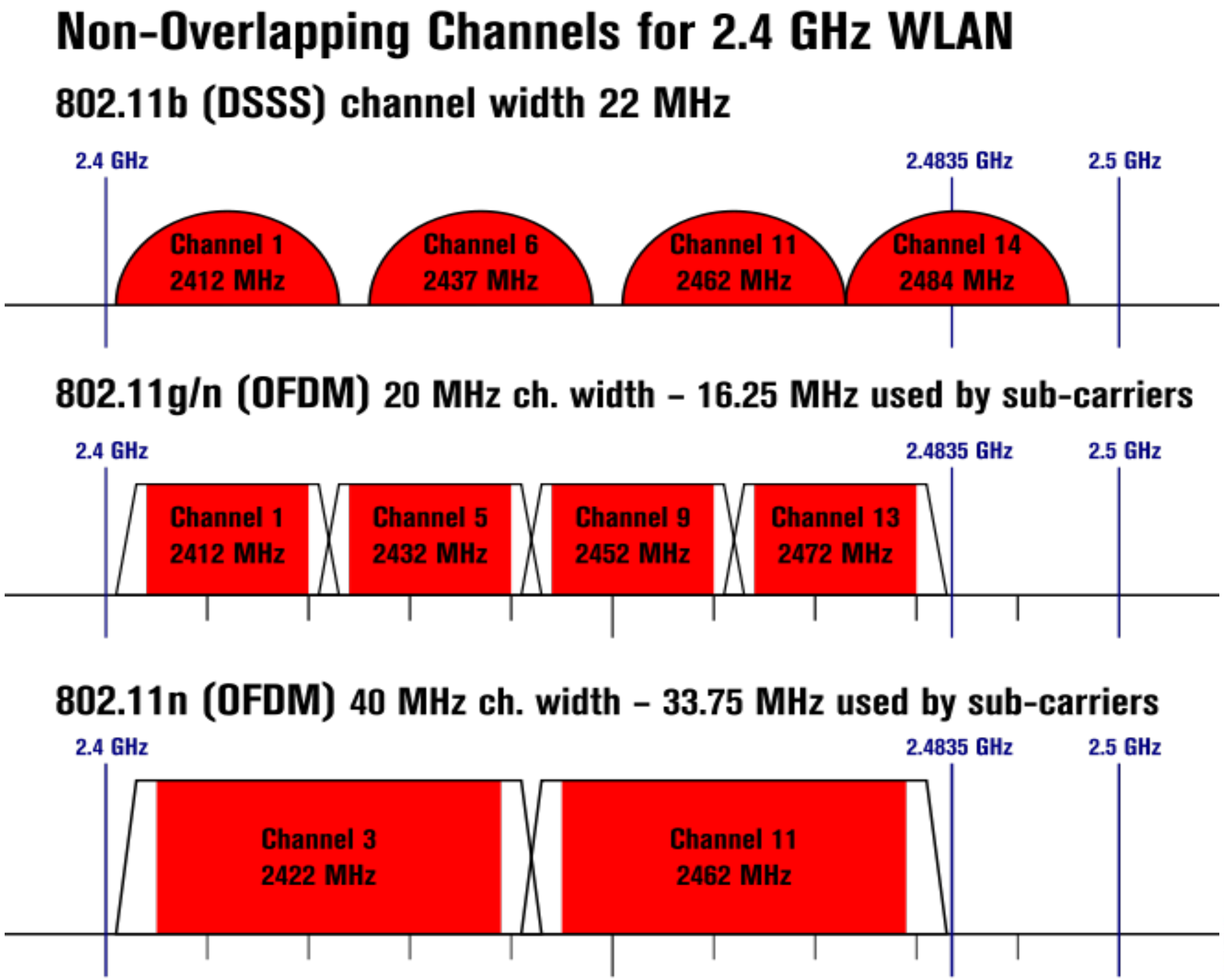
IEEE 802.11b Channels



2.4 GHz (IEEE 802.11b/g/n)



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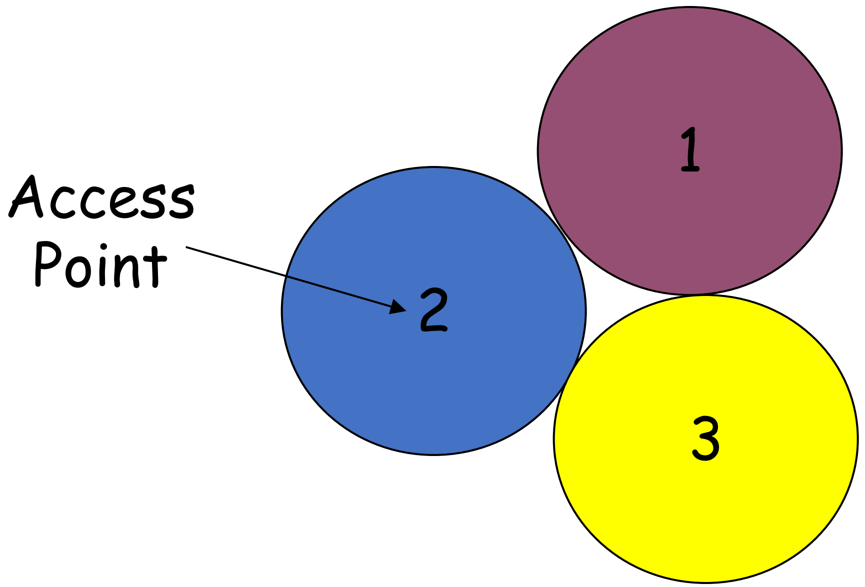
IEEE 802.11b (Cont'd)

Neighboring AP's use different channels to reduce interference. "Reuse cluster" size is equal to 3.



WiFi Direct

Wi-Fi Direct

- Wi-Fi Direct devices can connect directly to one another without access to a traditional network

- Devices can make a one-to-one connection, or a group of several devices can connect simultaneously

- With optional services, users can send files, print documents, play media, and display screens between and among devices

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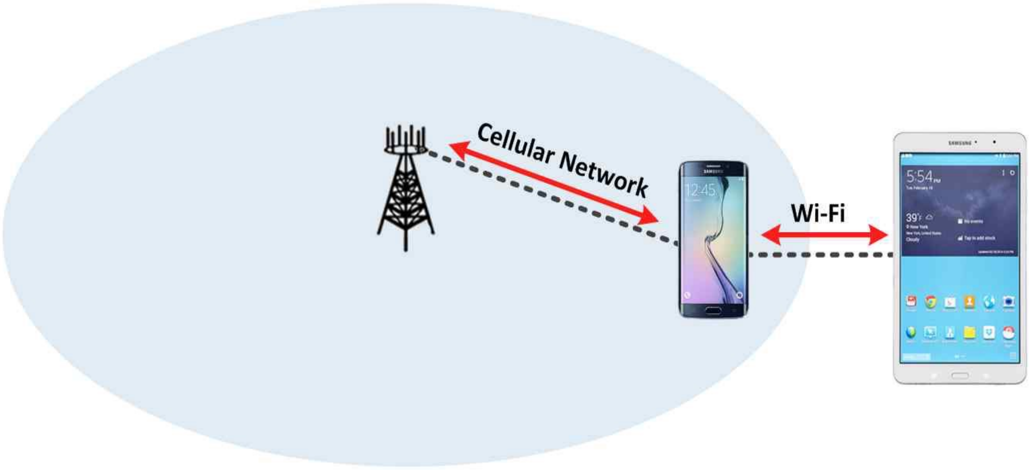
WiFi Tethering (Hotspot)

- Tethering refers to connecting one device to another
- In the context of mobile phones or Internet tablets, tethering allows sharing the Internet connection of the phone or tablet with other devices such as laptops
- A Wi-Fi STA can make connection to the Internet by connecting to a smartphone using Wi-Fi



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IEEE 802.11: Channels, Association

- 802.11b: 2.4GHz–2.485GHz spectrum divided into 11 channels at different frequencies
  - AP admin chooses frequency for AP
  - interference possible: channel can be same as that chosen by neighboring AP!
- host: must *associate* with an AP
  - scans channels, listening for *beacon frames* containing AP's name (SSID) and MAC address
  - selects AP to associate with
  - may perform authentication
  - will typically run DHCP to get IP address in AP's subnet

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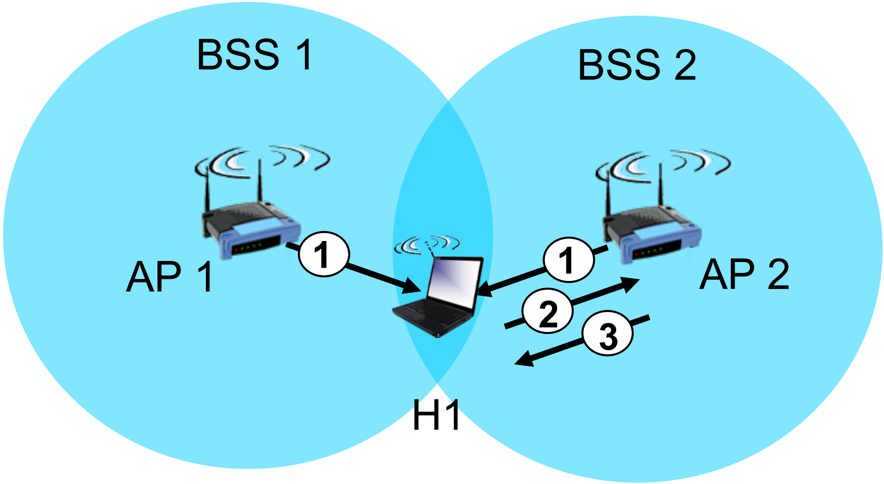
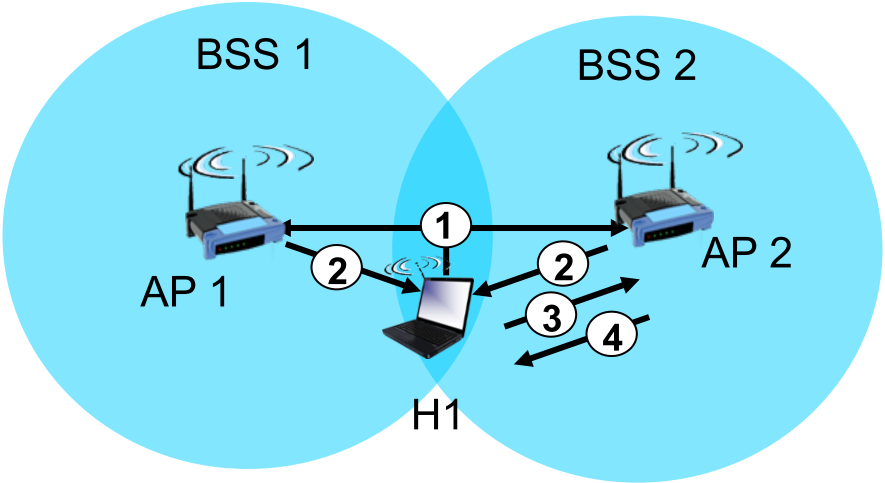
IEEE 802.11: Scanning





passive scanning:

(1) beacon frames sent from APs
(2) association Request frame sent: 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: H1 to selected AP
(4) Association Response frame sent from selected AP to H1

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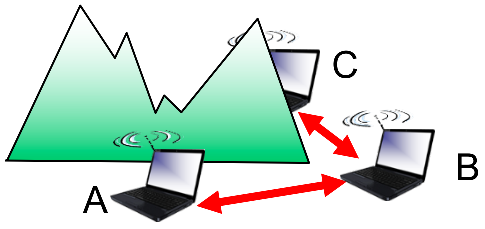
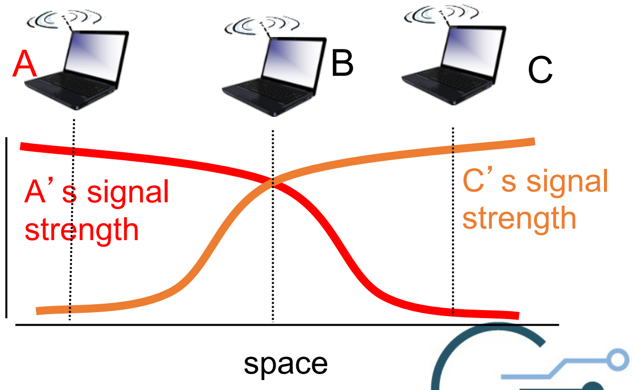
IEEE 802.11: Multiple Access

- avoid collisions: 2⁺ nodes transmitting at same time
- 802.11: CSMA – sense before transmitting
  - don't collide with ongoing transmission by other node
- 802.11: *no* collision detection!
  - difficult to receive (sense collisions) when transmitting due to weak received signals (fading)
  - can't sense all collisions in any case: hidden terminal, fading
  - goal: *avoid collisions:* CSMA/C(ollision)A(voidance)





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IEEE 802.11 MAC: CSMA/CA

802.11 sender

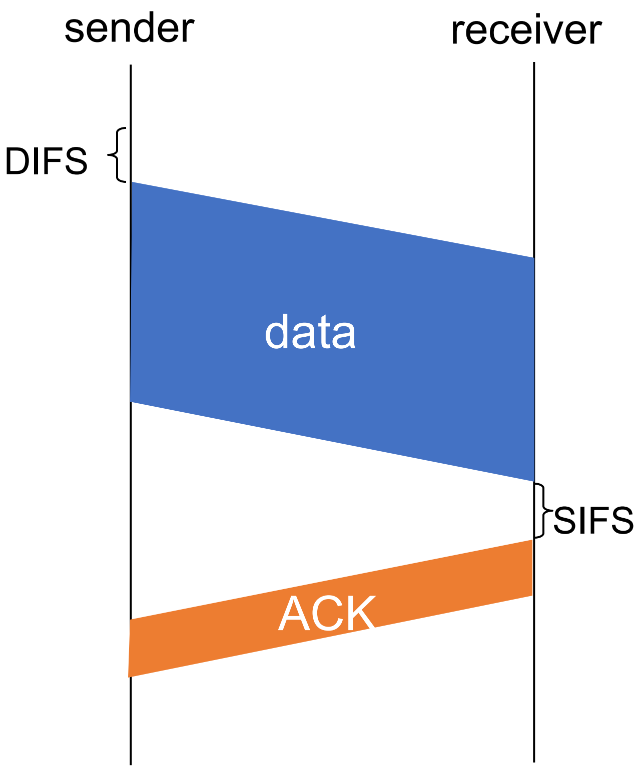
1 if sense channel idle for **DIFS – Distributed Inter Frame Space** then
   transmit entire frame (no CD)

2 if sense channel busy then
   start random backoff time
   timer counts down while channel idle
   transmit when timer expires
   if no ACK, increase random backoff interval, repeat 2

802.11 receiver

– if frame received OK

return ACK after **SIFS – Short Inter Frame Space** (ACK needed due to hidden terminal problem)



Avoiding collisions (more)

idea: allow sender to "reserve" channel rather than random access of data frames: avoid collisions of long data frames

- sender first transmits *small* request-to-send (RTS) packets to BS using CSMA
  - RTSs may still collide with each other (but they're short)
- BS broadcasts clear-to-send CTS in response to RTS
- CTS heard by all nodes
  - sender transmits data frame
  - other stations defer transmissions

avoid data frame collisions completely using small reservation packets!

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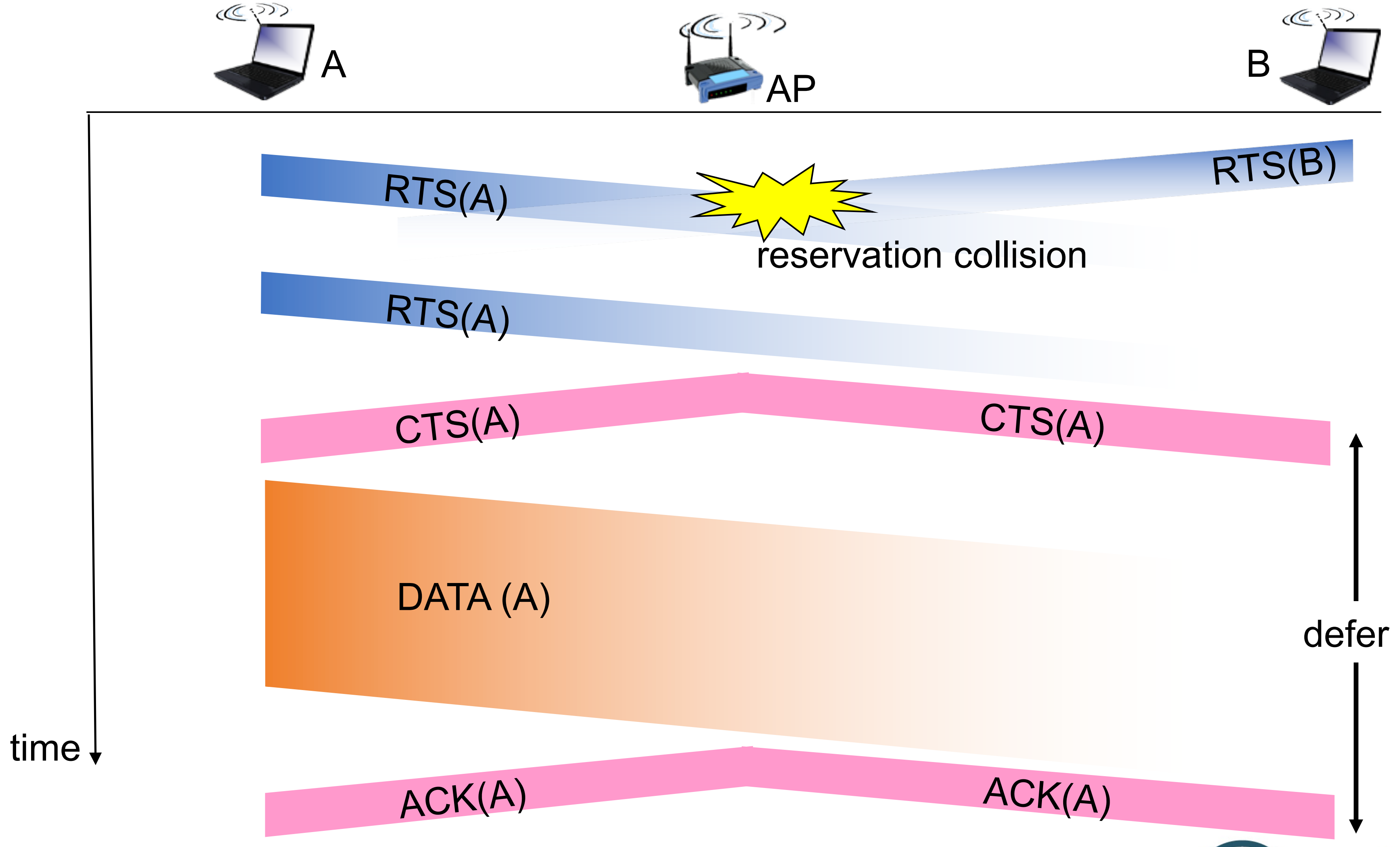
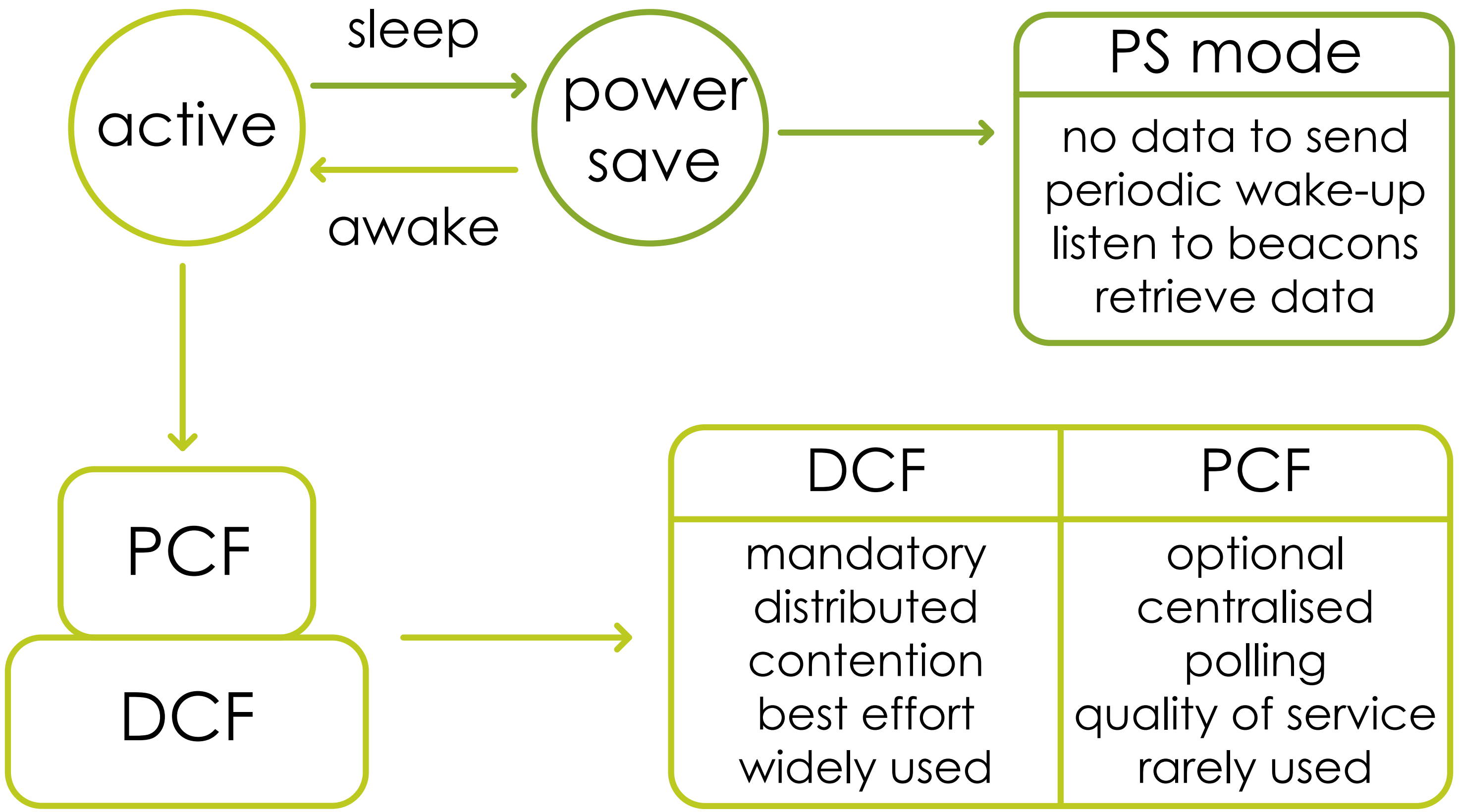
Collision Avoidance: RTS/CTS

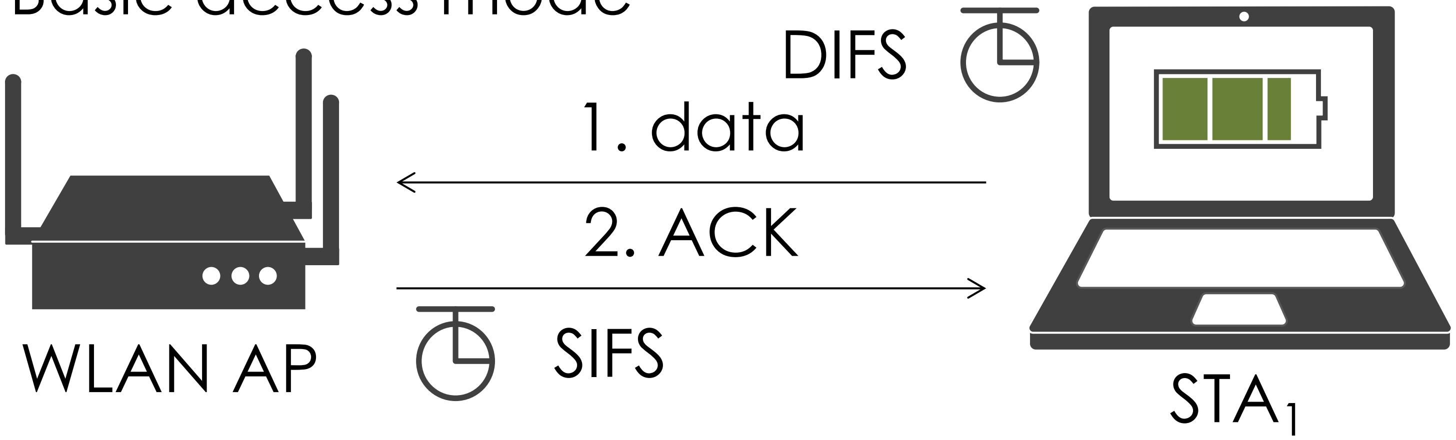


IEEE 802.11a/b/g MAC layer

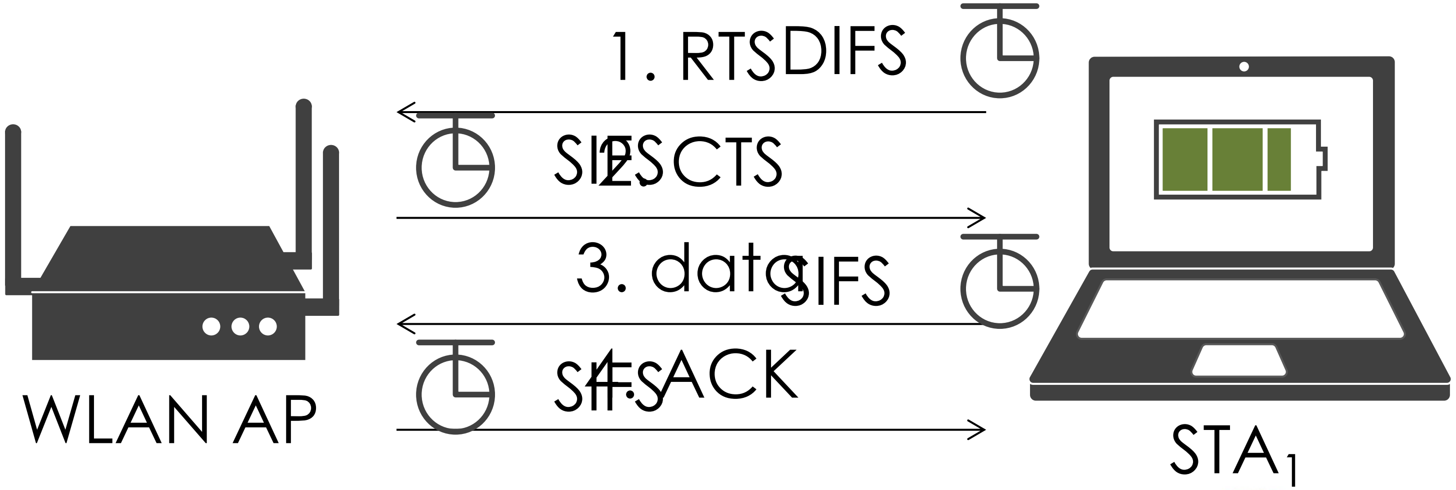


DCF: Access Modes

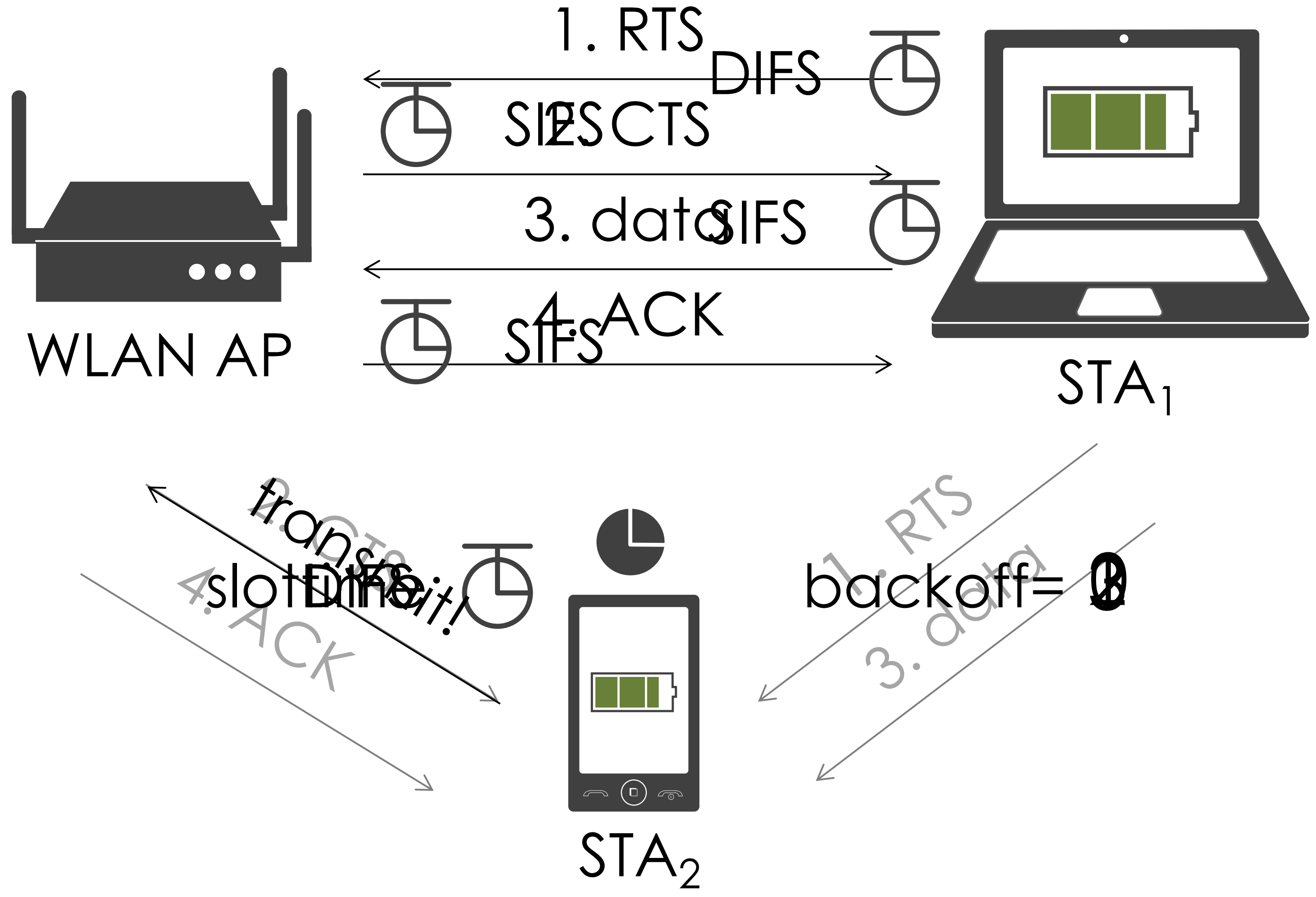
Basic access mode



Collision avoidance access mode

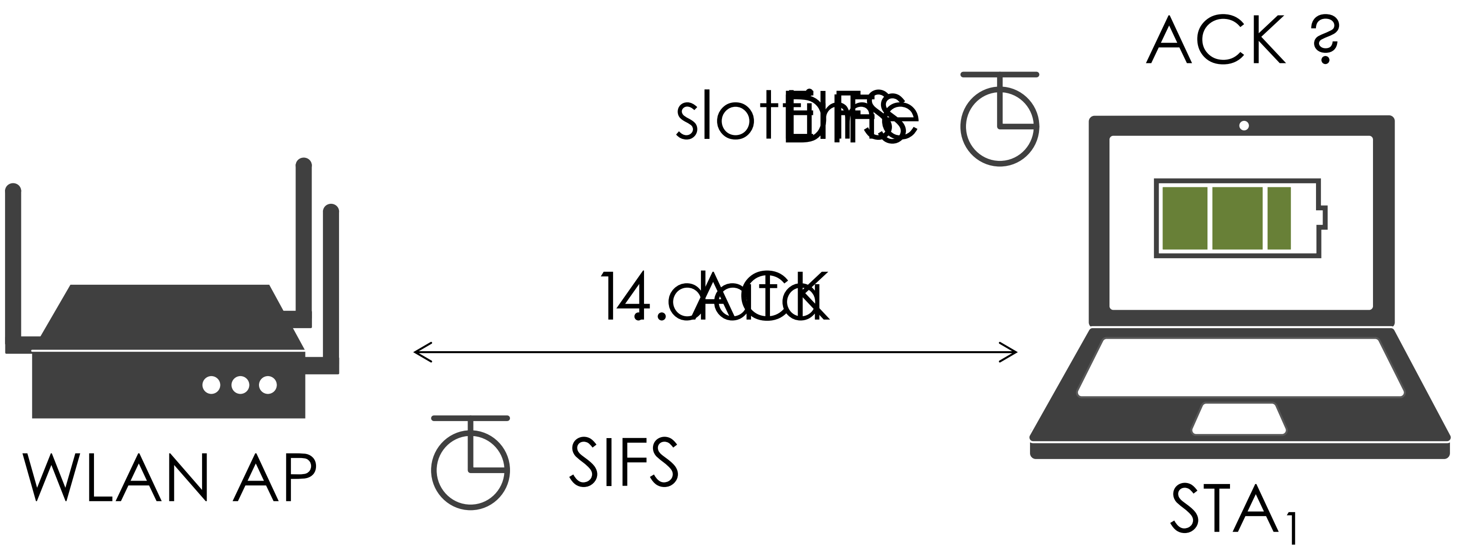


DCF: Virtual Sensing



NAV

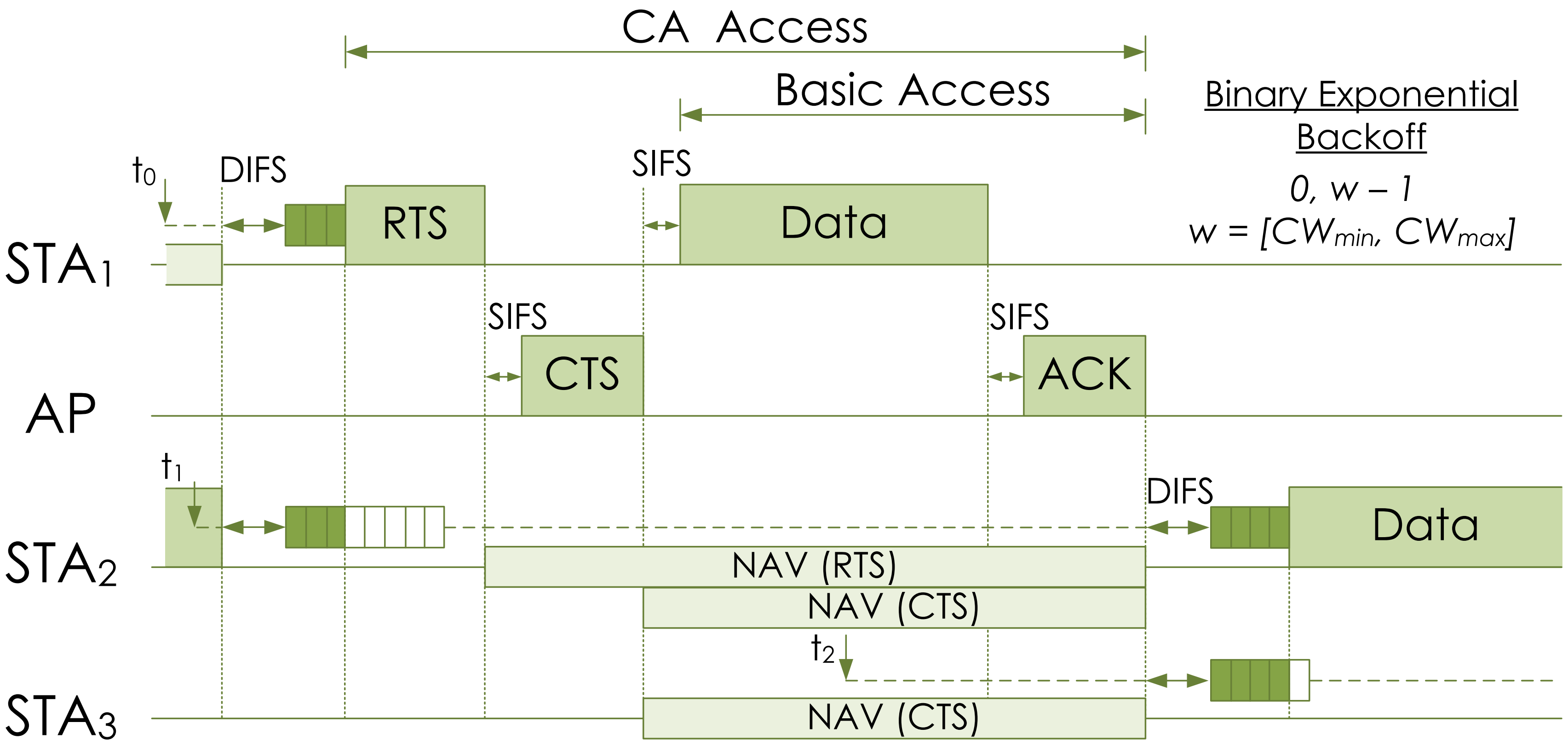
DCF: Binary Exponential Backoff



CW= 32 < 1024

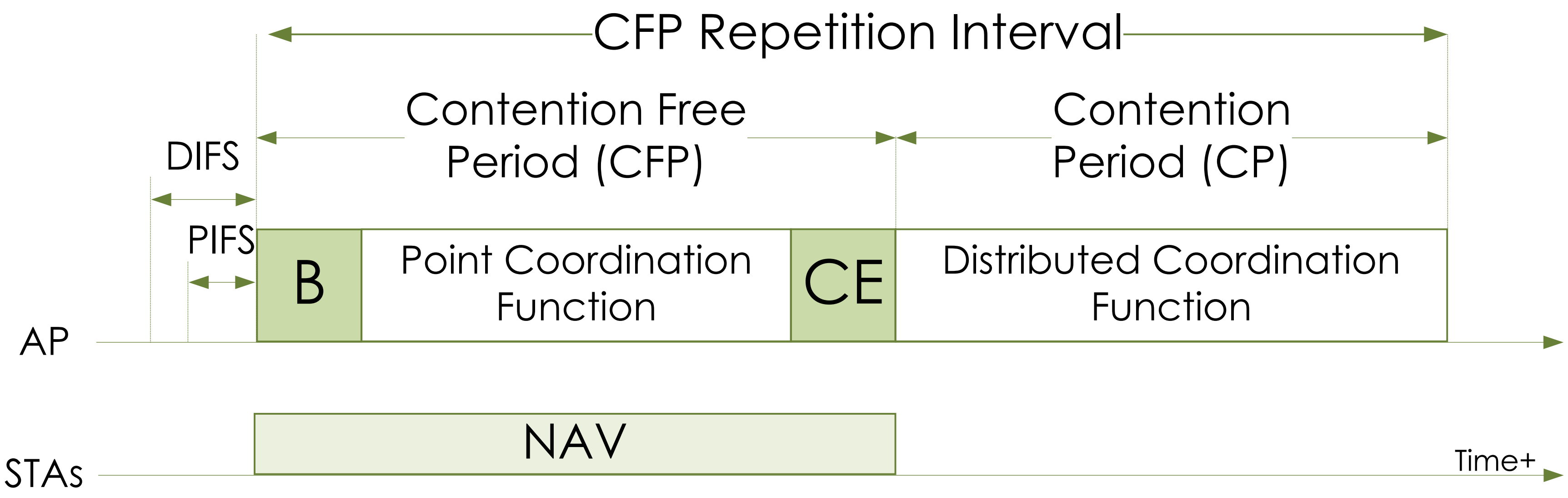
backoff= 0..31

DCF-based Channel Access



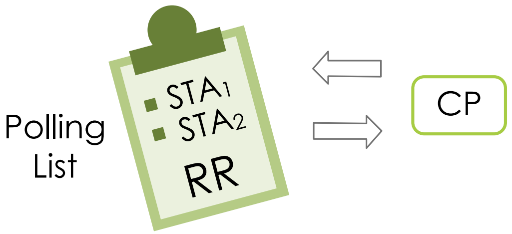
The stations must sense channel activity before transmitting. When the wireless channel is sensed busy, a backoff process of random duration is executed to avoid packet collisions.

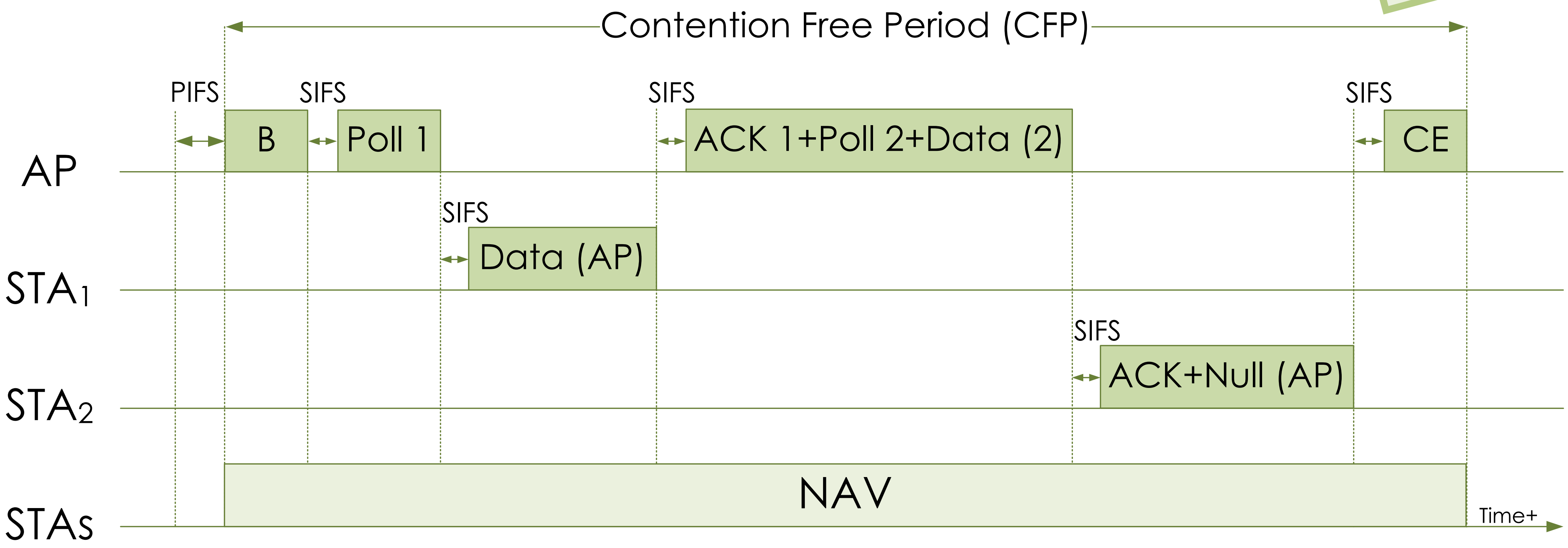
Coexistence of PCF and DCF



When the PCF is executed, the AP announces a periodic super structure in which the channel access time is divided into CFPs, wherein the PCF is used, and CPs, wherein the DCF is employed.

PCF-based Channel Access





The AP delivers data and sequentially polls the mobile stations of the polling list to grant them transmission opportunities. The mobile stations join and leave the polling list via the DCF in CPs.

IEEE 802.11 Frame Format

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

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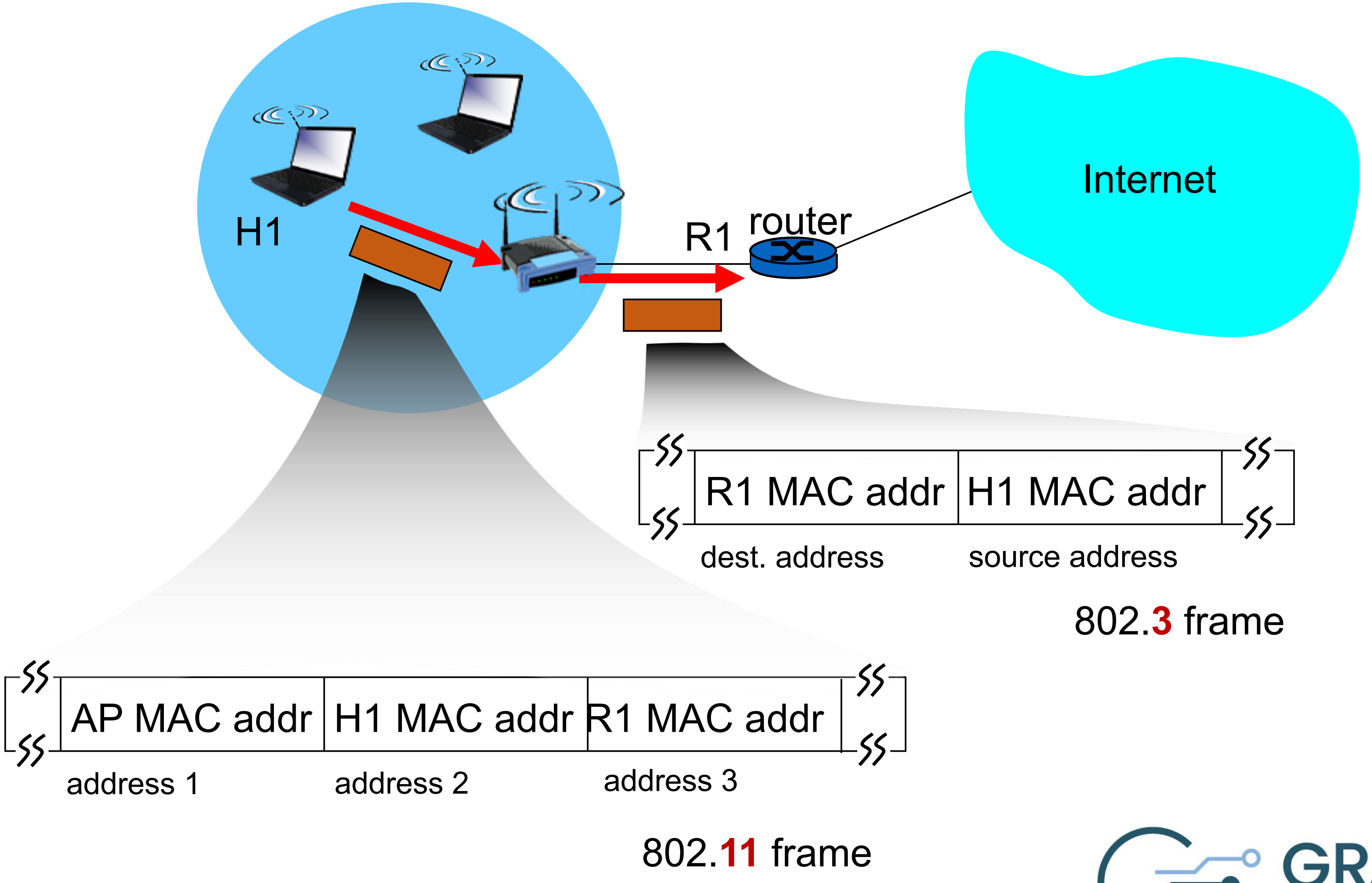
IEEE 802.11 Addressing



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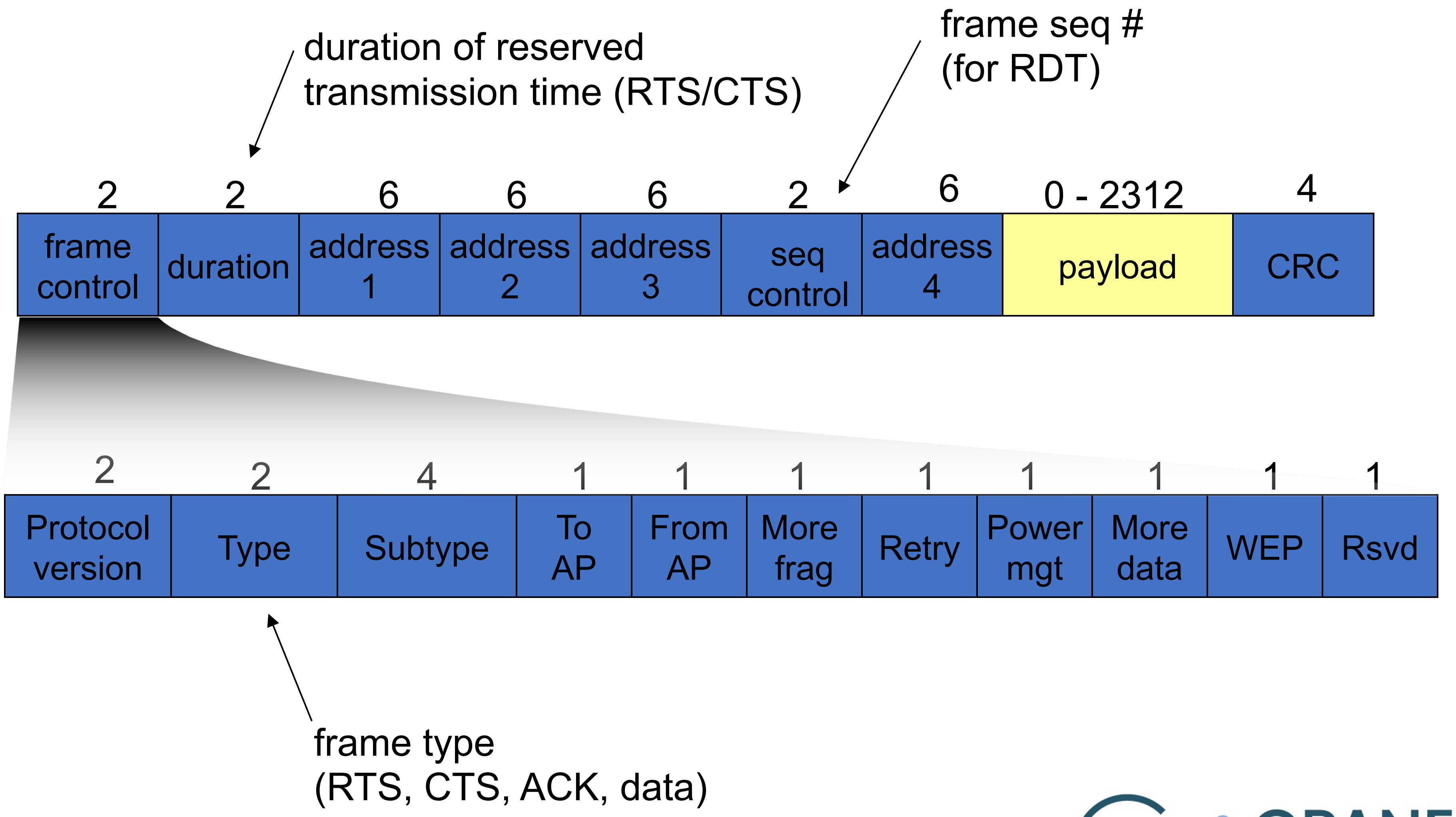
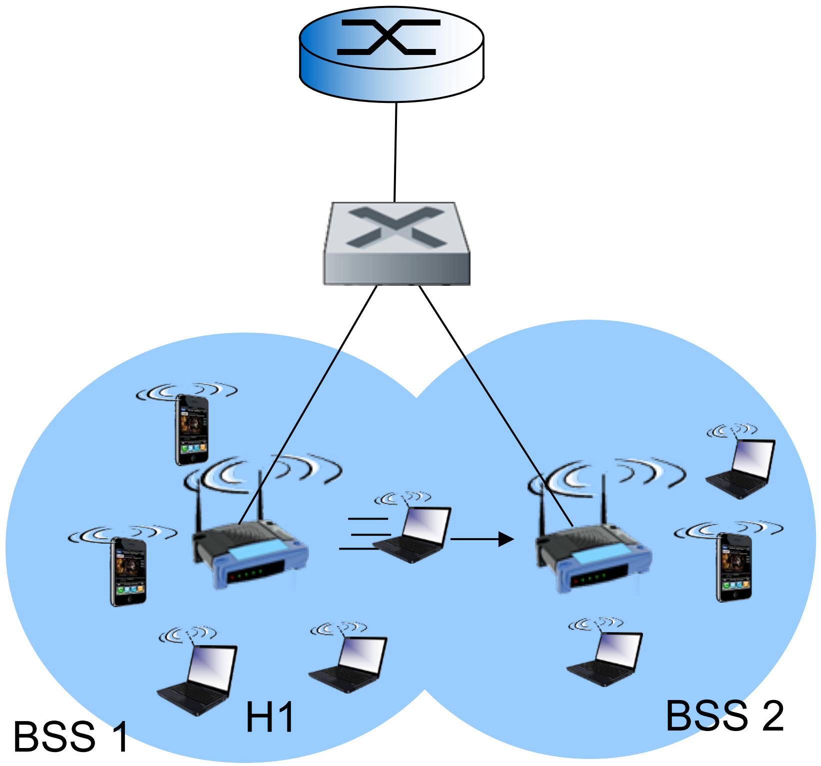
IEEE 802.11 Frame Format (cntd)



Mobility within the same subnet

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



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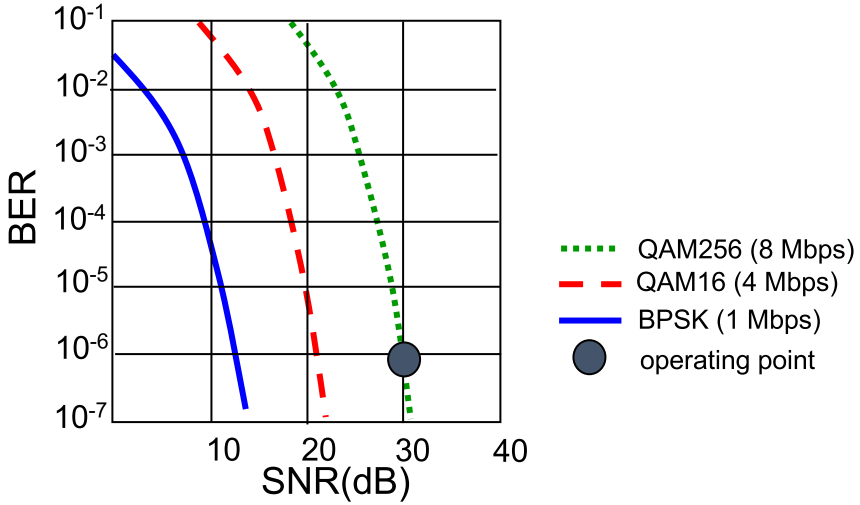
IEEE 802.11 Advanced Capabilities

Rate adaptation

- base station, mobile dynamically change transmission rate (physical layer modulation technique) as mobile moves, SNR varies



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

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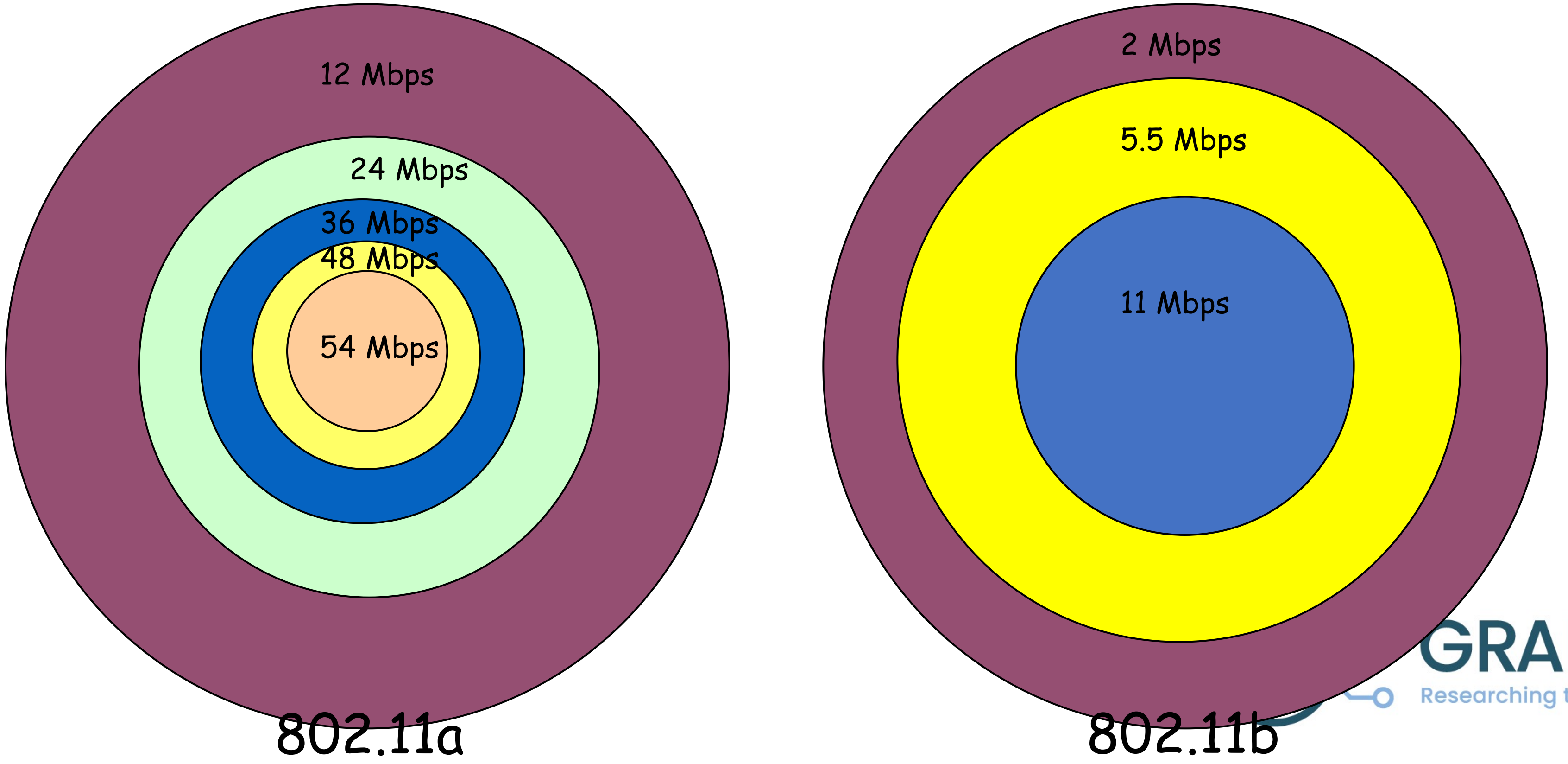
IEEE 802.11 Advanced Capabilities

Rate adaptation

- 802.11 has a rate fall back mechanism, i.e., as the distance between the transmitter and receiver increases, the supported data rate decreases.



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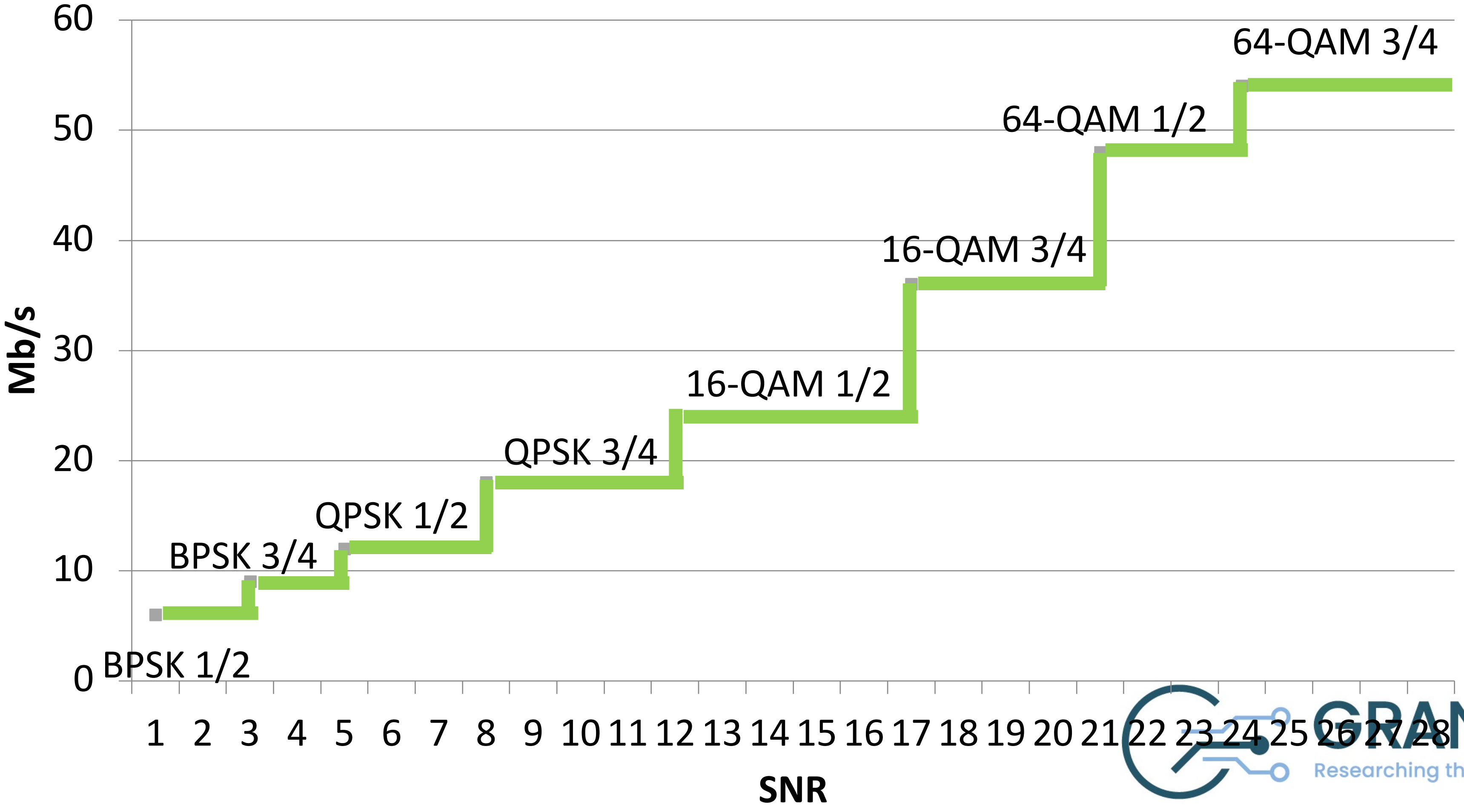
IEEE 802.11 Advanced Capabilities

Rate adaptation

- Bitrates and channel codes



IEEE 802.11 Advanced Capabilities

power management

- node-to-AP: "I am going to sleep until next beacon frame"
  - AP knows not to transmit frames to this node
  - node wakes up before next beacon frame
- beacon frame: contains list of mobiles with AP-to-mobile frames waiting to be sent
  - node will stay awake if AP-to-mobile frames to be sent; otherwise sleep again until next beacon frame

From 1 to 5 – IEEE 802.11 Overview

1997 · 1998 · 1999 · 2000 · 2001 · 2002 · 2003 · 2004 · 2005 · 2006 · 2007 · 2008 · 2009 · 2010 · 2011 · 2012 · 2013

1st Generation

- **802.11a**
- Data rate: 54 Mbps
- Frequency band: 5 GHz
- PHY: OFDM
- Use case: Internet

2nd Generation

- **802.11b**
- Data rate: 11 Mbps
- Frequency band: 2.4 GHz
- PHY: DSSS with CCK WEP
- Use case: Email

3rd Generation

- **802.11g**
- Data rate: 54 Mbps
- Frequency band: 2.4 GHz
- PHY: OFDM
- Wi-Fi starts to become ubiquitous
- Use case: Rich-data Web experience

4th Generation

- **802.11n**
- Data rate: Up to 600 Mbps
- Frequency band: 2.4 GHz & 5 GHz
- PHY: OFDM/MIMO
- Higher throughput
- Enhanced range due to use of MIMO
- Use case: Medium-resolution video streaming

5th Generation

- **802.11ac**
- Data rate: Up to 7 Gbps
(first solutions on market < 1.8 Gbps)
- Frequency band: 5 GHz
- PHY: OFDM/MIMO
- 8 parallel streams
- Use case: Coverage for video "Wired" Compliment

5th Generation

- **802.11ad**
- Data rate: Up to 7 Gbps
- Frequency band: 60 GHz
- PHY: OFDM/MIMO
- Tri-band Wi-Fi
- Use case: short-range app

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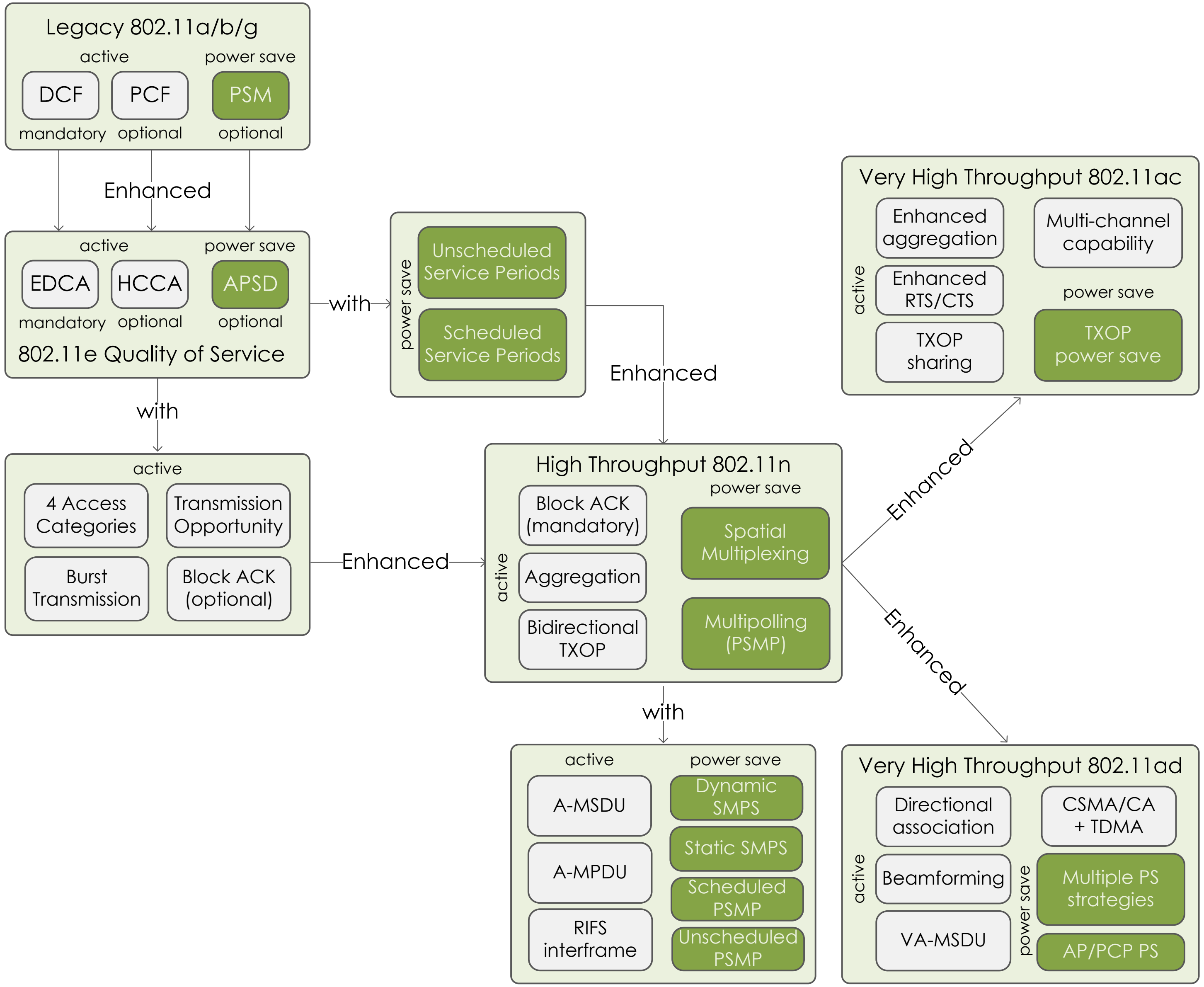
Modern IEEE 802.11 PHY Protocols

Feature	IEEE 802.11g	IEEE 802.11n	IEEE 802.11ac	IEEE 802.11ad
Channel Bandwidth	20 MHz	20/40 MHz	20/40/80/160 MHz	20/40/80/160/2160 MHz
MIMO Support	No support	Up to 4 streams (4 antennas)	Up to 8 streams (8 antennas)	> 10 streams (> 10 antennas)
Modulation	BPSK/QPSK/16-QAM/64-QAM	BPSK/QPSK/16-QAM/64-QAM	BPSK/QPSK/16-QAM/64-QAM/256-QAM	SQPSK/QPSK/16-QAM/64-QAM
Max PHY Rate	54 Mbps	600 Mbps	7000 Mbps	7000 Mbps
Operating Bands	2.4 GHz	2.4, 5 GHz	5 GHz	2.4, 5, 60 GHz
Beamforming	No support	Supported but not standardized	Standardized	Supported
STBC (space–time block codes)	No support	Many modes and options	Minimized in favour of beamforming	Supported
Range (indoor) (m)	20	70	35	10

Modern IEEE 802.11 MAC protocols



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IEEE 802.11 Subgroups

Type	Group	WG & Infrastructure
WG	WG11	The IEEE 802.11 Working Group
SC	AANI	Advanced Access Networking Interface (AANI)
SC	ARC	Architecture
SC	COEX	Coexistence
SC	PAR	PAR review
802 SC	JTC1	ISO/IEC JTC1/SC6

Type	Group	New Work
SC	WNG	Wireless Next Generation
SG	Various	Study Groups
TIG	Various	Topic Interest Groups

Type	Group	Amendments/Revision
TG	AX	High Efficiency Wireless LAN (HEW)
TG	AY	Next Generation 60 GHz (NG60)
TG	AZ	Next Generation Positioning (NGP)
TG	BA	Wake-up Radio
TG	BB	Light Communication (LC)
TG	BC	Enhanced Broadcast Service (BCS)
TG	BD	Enhancements for Next Gen V2X (NGV)
TG	BE	Extremely High Throughput
TG	BF	WLAN Sensing (pending approval)
TG	MD	Revision (REVmd)

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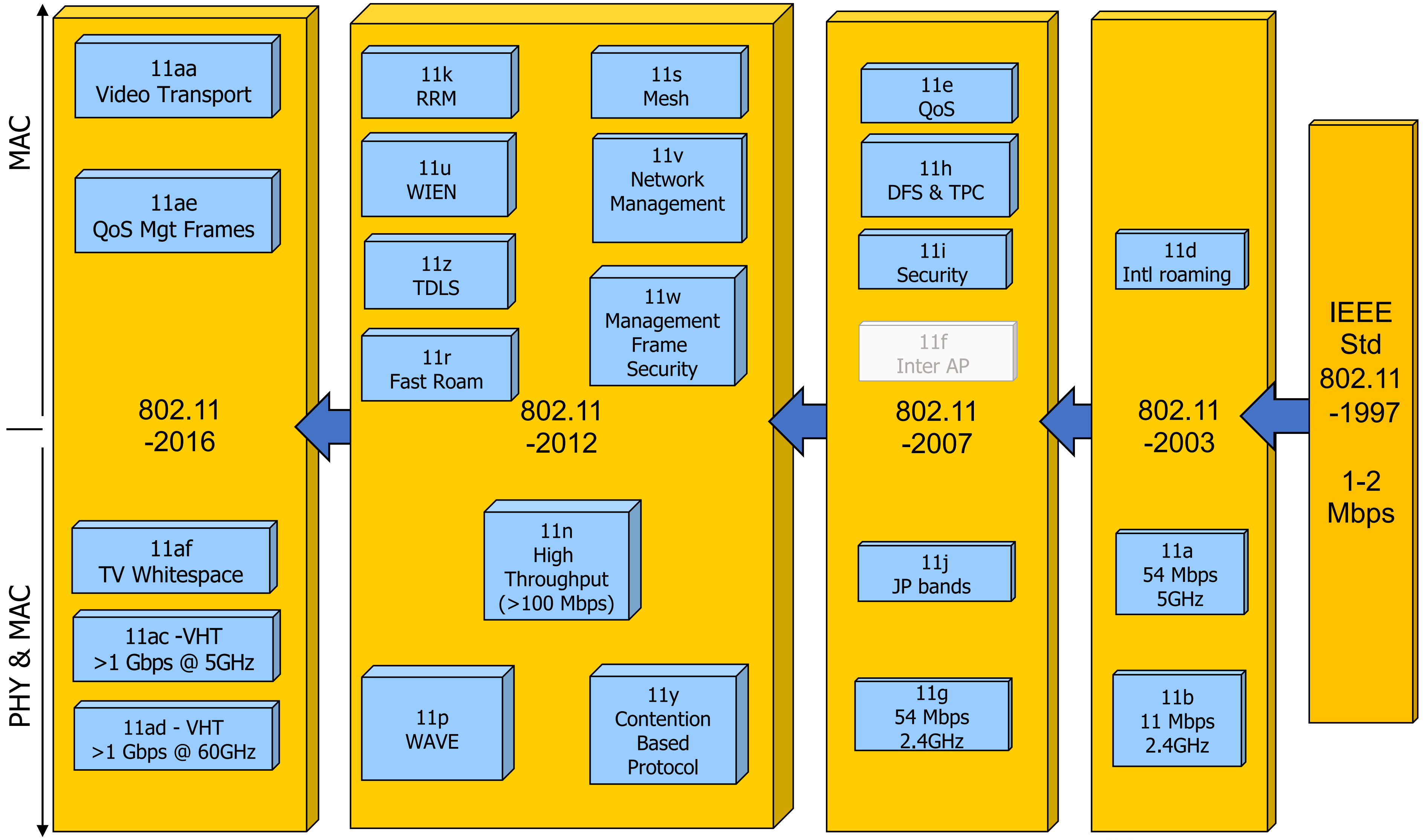
Development of the IEEE 802.11 Standard is ongoing since



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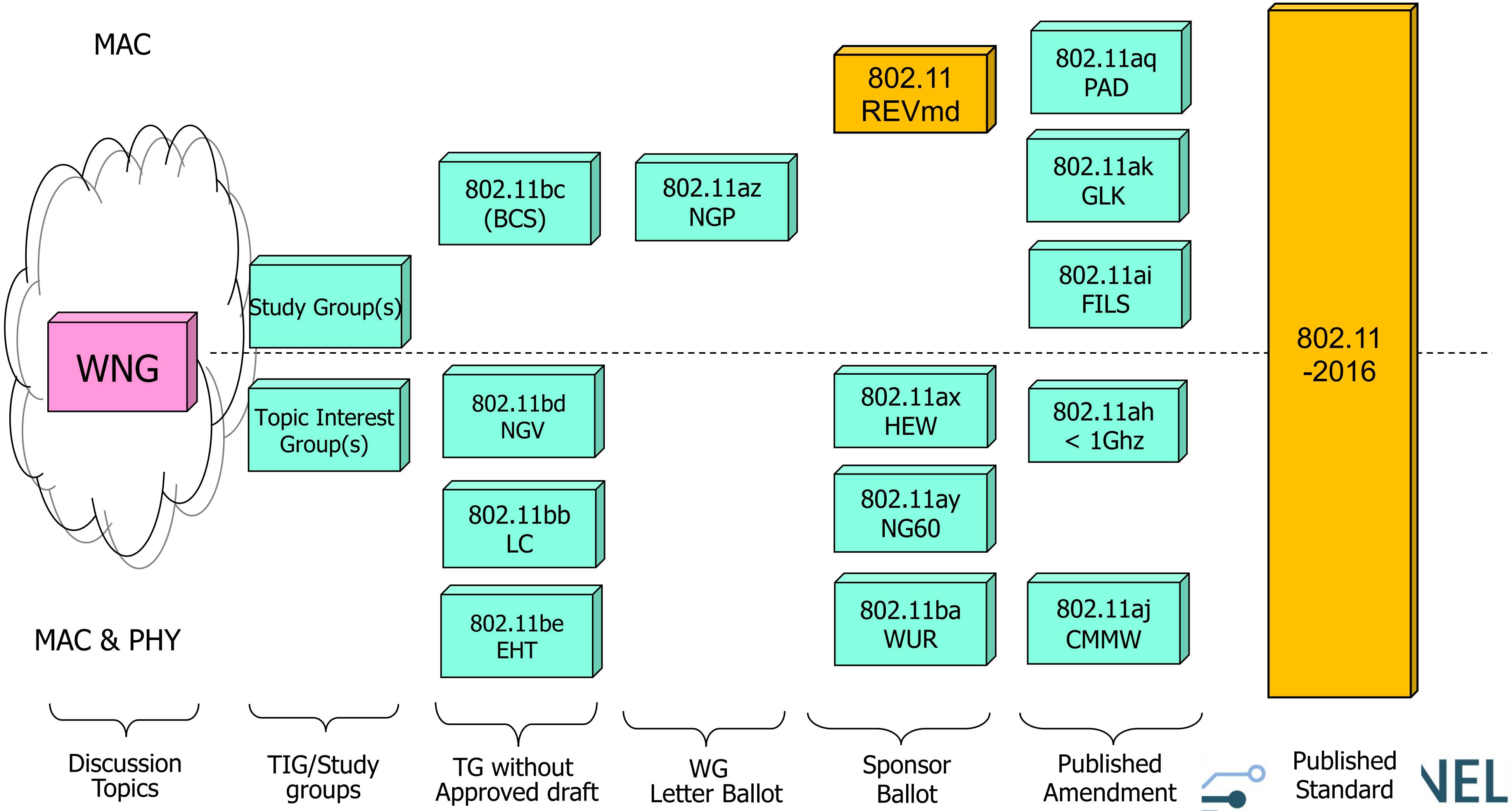
IEEE 802.11 Standards Pipeline



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Market demands and new technology drive IEEE 802.11 innovation

- **Demand for throughput**
  - Continuing exponential demand for throughput **(802.11ax and 802.11ay, 802.11be)**
  - Most (50–80%, depending on the country) of the world's mobile data is carried on 802.11 (Wi-Fi) devices
- **New usage models / features**
  - Dense deployments **(802.11ax)**, Indoor Location **(802.11az)**,
  - Automotive (IEEE Std 802.11p, Next Gen V2X), Internet of Things **(802.11ah)**
  - Low Power applications **(802.11ba)**
  - WLAN Sensing **(802.11bf – pending approval)**
- **Technical capabilities**
  - MIMO (IEEE Std 802.11n, 802.11ac, **802.11ay**) and OFDMA (**802.11ax**)
  - 60 GHz radios **(802.11ay)**
- **Changes to regulation**
  - TV whitespaces (IEEE Std 802.11af), Radar detection (IEEE Std 802.11h), 6GHz **(802.11ax, 802.11be)**
  - Coexistence and radio performance rules (e.g., ETSI BRAN, ITU-R)

New 802.11 Radio technologies are under development to meet expanding market needs and leverage new technologies

- 802.11ax – Increased throughput in 2.4, 5 (and 6) GHz bands. Increased efficiency.
- 802.11ay – Support for 20 Gbps in 60 GHz band.
- 802.11az – 2nd generation positioning features.
- 802.11ba – Wake up radio. Low power IoT applications.
- 802.11bb – Light Communications
- 802.11bc – Enhanced Broadcast Service
- 802.11bd – Enhancements for Next Generation V2X
- 802.11be – Extremely High Throughput
- 802.11bf – WLAN Sensing [pending approval]

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802.11ax is focused on improving performance in dense environments

- Existing 802.11 WLAN systems serve dense deployments: 2019 Super bowl: 24TB* of data carried on WLAN network
- 802.11ax aims to further improve performance of WLAN deployments in dense scenarios
  - Targeting at least 4x improvement in the per-STA throughput compared to 802.11n and 802.11ac.
  - Improved efficiency through spatial (MU MIMO) and frequency (OFDMA) multiplexing.
- Dense scenarios are characterized by large number of access points and large number of associated STAs deployed in geographical limited region
  - e.g. a stadium or an airport.

Access to Internet, latest airlines' announcements, and digital media such as movies and sport events

* https://www.extremenetworks.com/resources/slideshare/wi-fi-engagements-from-super-bowl-liii/

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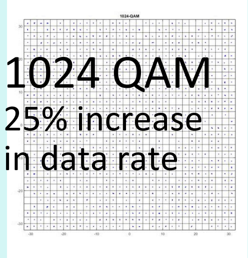
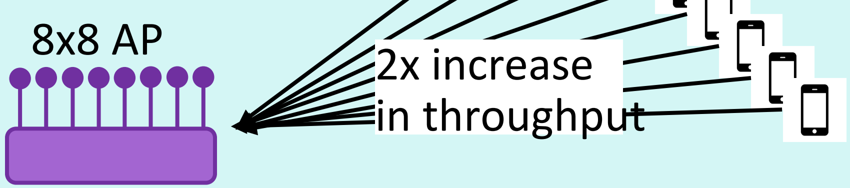
802.11ax Categories of Enhancements

Spectral Efficiency & Area Throughput

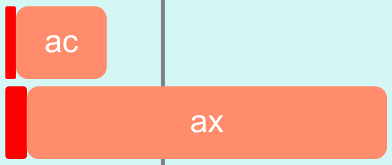


1024 QAM
25% increase in data rate

DL/UL MU-MIMO
w/ 8 clients



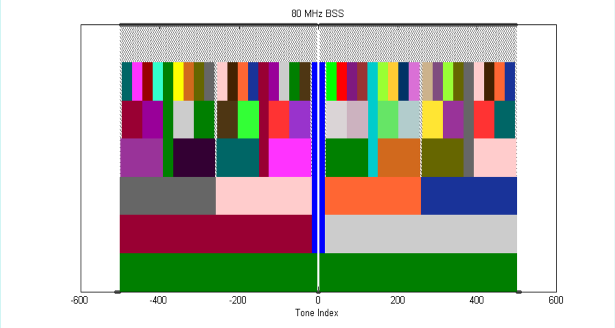
Long OFDM Symbol



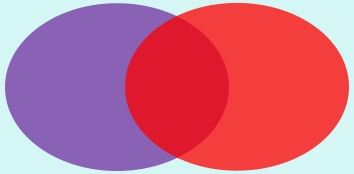
Up to 20% increase in data rate

High Density

OFDMA

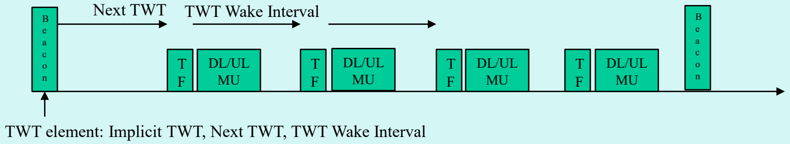


Spatial Reuse

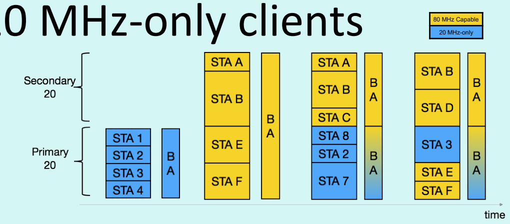


Power Saving

Scheduled sleep and wake times



20 MHz-only clients

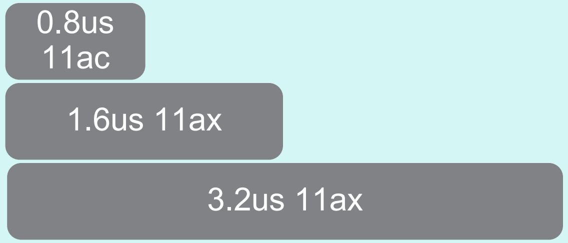


Outdoor / Longer range

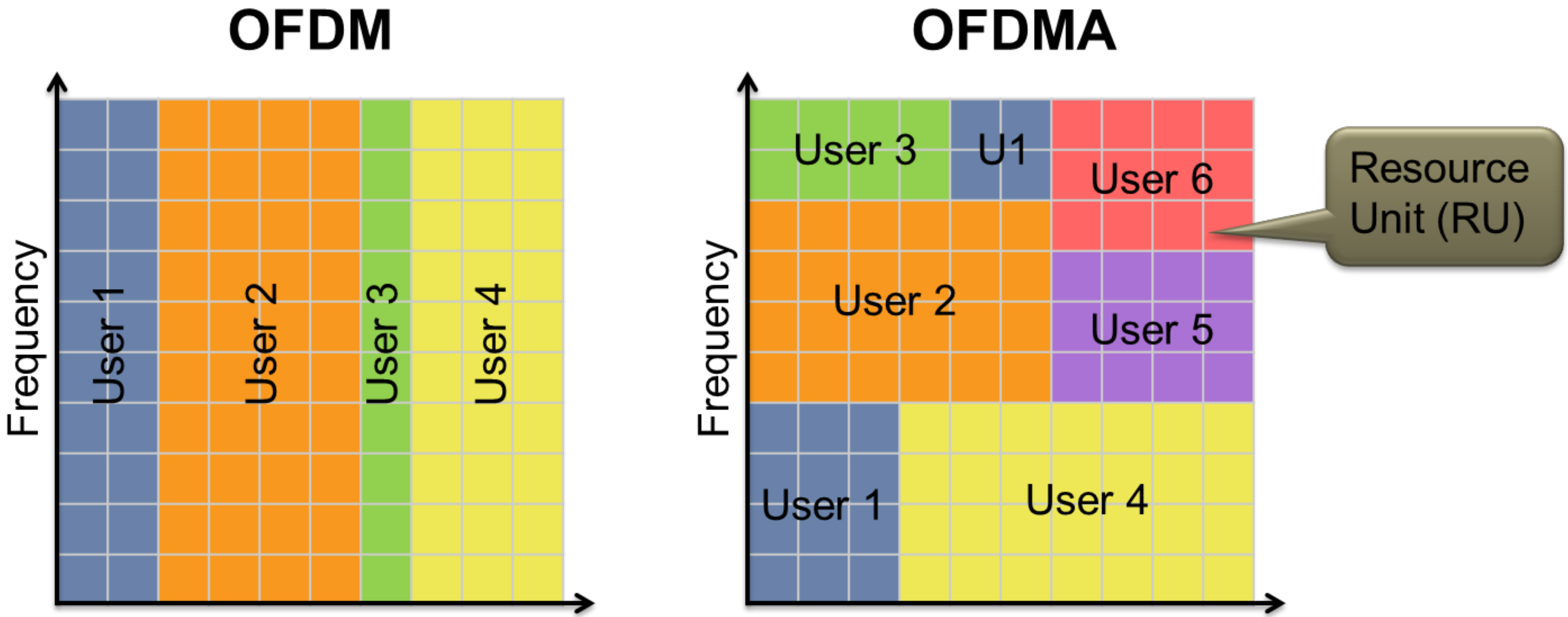
Extended range packet structure

8μs	8μs	4μs	4μs	16μs	4μs					
L-STF	L-LTF	L-SIG	RL-SIG	HE-SIG-A	HE-STF	HE-LTF	...	HE-LTF	Data	PE

Enhanced delay spread protection- long guard interval



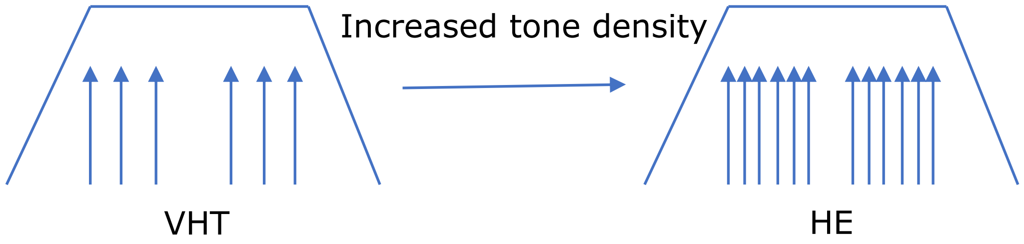
OFDMA enables further AP customization of channel use to match client and traffic demands



Increased efficiency for (high percentage of traffic) short data frames

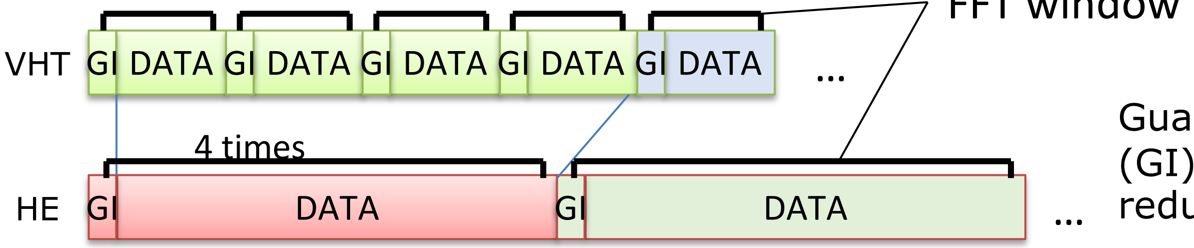
802.11ax Increases link efficiency

Frequency domain
(~5% gain)



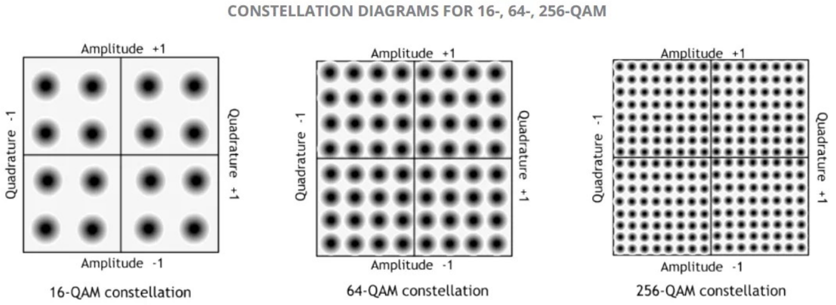
Squeeze more tones in around DC and edge

Time domain
(~15% gain)



Guard interval (GI) overhead reduced

Modulation
(~25% gain)



+ 1024-QAM

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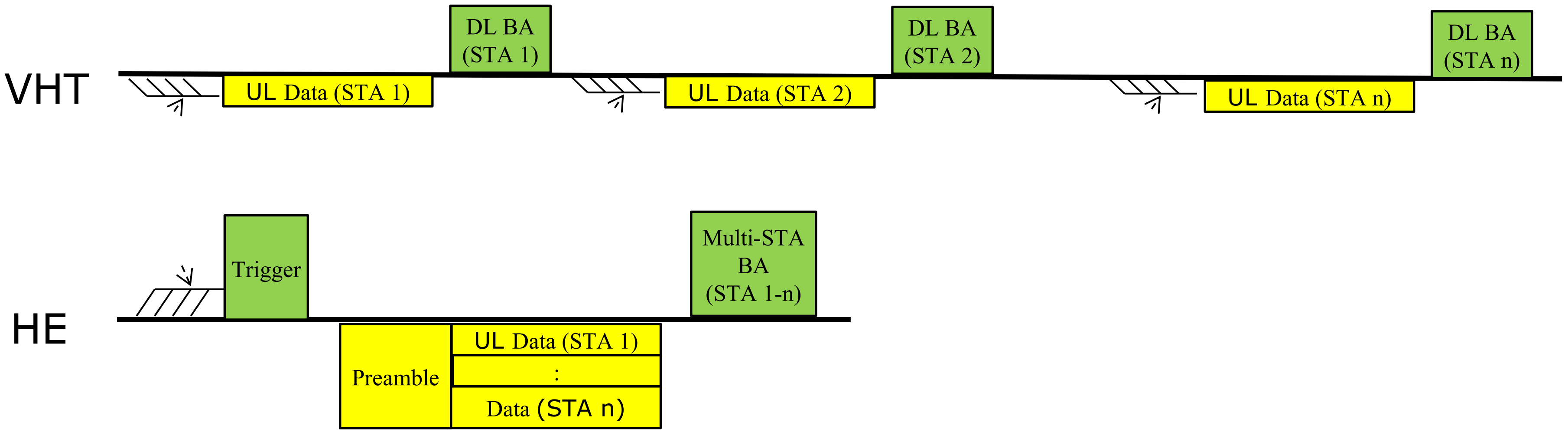
UL/DL multi-user links in 802.11ax will support more efficient UL data

- In a VHT UL sequence, STAs compete for medium access and send sequentially
- In an HE UL sequence, the AP triggers simultaneous transmissions in multiple STAs



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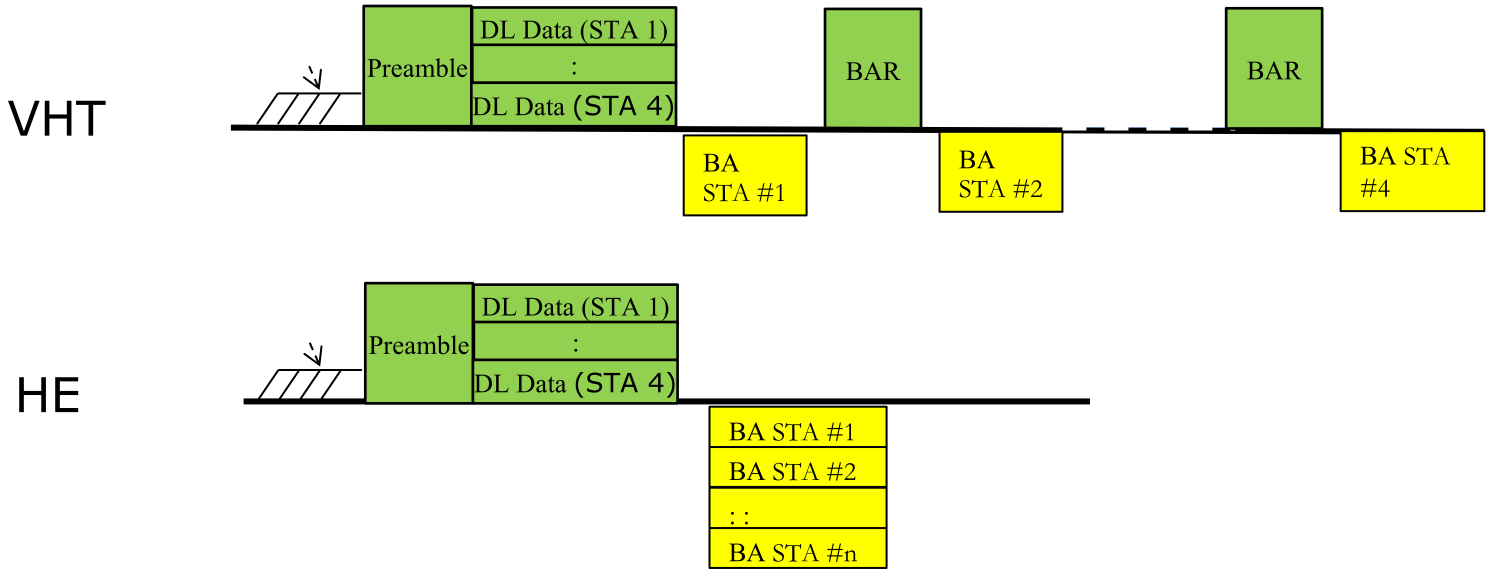
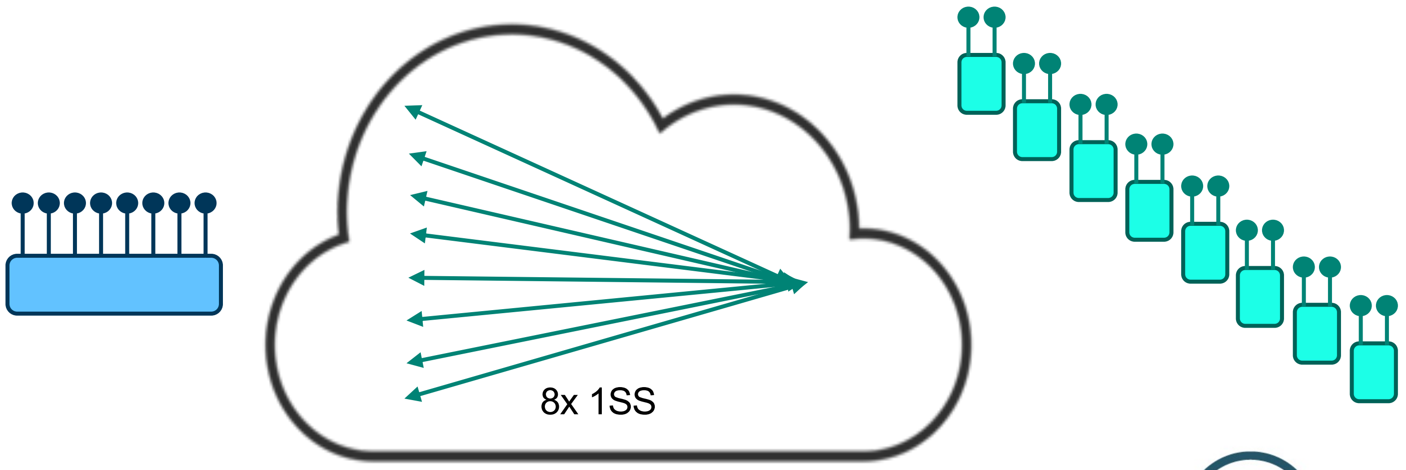
802.11ax Data exchange sequences: Multi-user downlink

- In a VHT DL MU sequence acknowledgements are serialized
- In an HE DL MU sequence acknowledgements are allocated UL resources and transmitted simultaneously



Uplink MU-MIMO

- UL MU-MIMO was initially considered in 802.11ac, but not included due to implementation concerns
- Sounding frames, data frames, etc can be grouped among multiple users to reduce overhead and increase uplink response time



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Various features in 802.11ax will support improved outdoor operation

- Operates in higher delay spread channels than 802.11ac:
  - 802.11ac GI options: 0.4 µs and 0.8 µs
  - 802.11ax GI options: 0.8 µs, 1.6 µs and 3.2 µs
  - GI overhead mitigated with longer OFDM symbol
- Preamble includes repeated L-SIG
- Extended range preamble includes repeated HE-SIG-A
- Dual carrier modulation improves robustness in Data field

802.11ax meets the MAC/PHY requirements for 5G Indoor Hotspot test Environment defined by IMT–2020

- Analysis and simulations confirm that performance of IEEE 802.11ax MAC/PHY meet or exceed 5G requirements for the 5G Indoor Hotspot use case
- Similar studies are underway for the Dense Urban test environment

	Metric	ITU-R Evaluation Method	Minimum Requirement	802.11ax Performance
1	Peak data rate	Analytical	DL/UL : 20/10 Gbps	DL/UL : 20.78 Gbps
2	Peak spectral efficiency	Analytical	DL/UL : 30/15 bits/s/Hz	DL/UL : 58.01 bits/s/Hz
3	User experienced data rate	Analytical for single band and single layer; Simulation for multi-layer	Not applicable for Indoor Hotspot	Not applicable
4	5^{th} percentile user spectral efficiency	Simulation	DL/UL : 0.3/0.21 bits/s/Hz	DL/UL : 0.45/0.52 bits/s/Hz
5	Average spectral efficiency	Simulation	DL/UL : 9/6.75 bits/s/Hz/TRxP	DL/UL : 9.82/13.7 bits/s/Hz/TRxP
6	Area traffic capacity	Analytical	DL : 10 Mbit/s/m^2	Required DL bandwidth = 170 MHz with 3 TRxP/site
7	Mobility	Simulation	UL : 1.5 bits/s/Hz	UL : 9.4 bits/s/Hz
8	Bandwidth	Inspection	100 MHz, scalable	20/40/80/80+80/160 MHz
9	User plane latency	Analytical	DL/UL : 4 ms	DL/UL : 80 us

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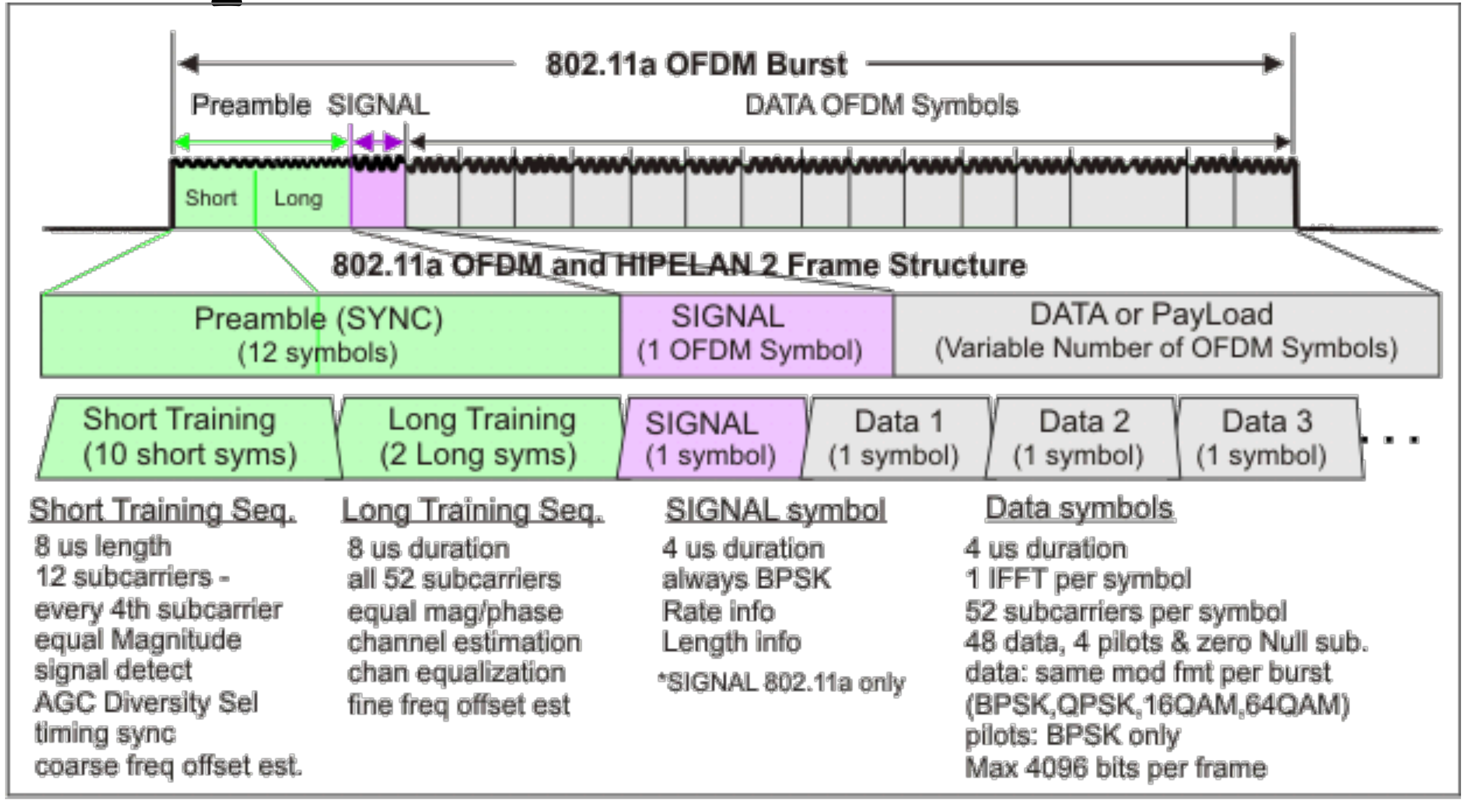
802.11 PHY standards are backwards compatible with prior generations within a spectrum band



802.11a and HIPERLAN/2 Frame Structure

- 802.11a preamble is included in 802.11a, 802.11n, 802.11ac, 802.11ax 5GHz encoded frames
- Common preamble provides backward compatibility and enables preamble detection at low energy levels for improved coexistence

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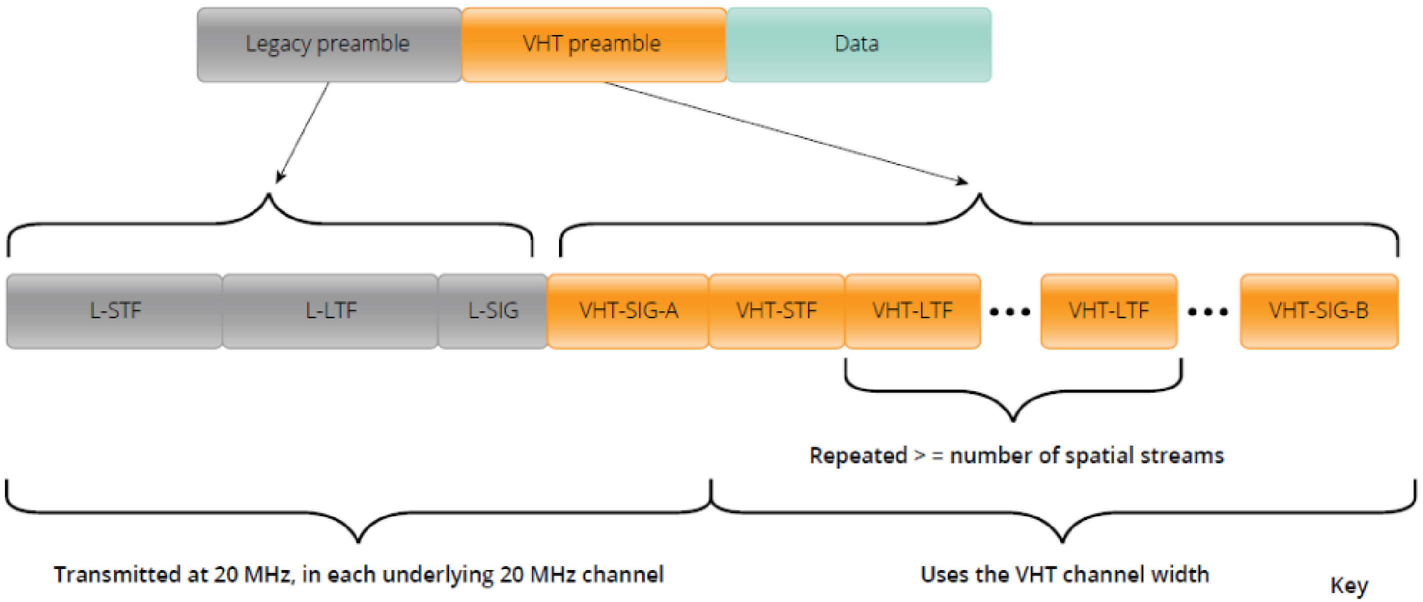
802.11 PHY standards are backwards compatible with prior generations within a spectrum band

VHT PREAMBLE FORMAT



Key

STF	Short Training Field
LTF	Long Training Field
SIG	Signal
L	Legacy (e.g. pre-802.11ac)
HT	High Throughput (e.g. 802.11n)
VHT	Very High Throughput (e.g. 802.11ac)

802.11ay is defining next generation 60 GHz: increased throughput and range

- 20Gbps+ rates are defined
- License- Exempt bands above 45Gbps
- Completion in 2020; First chipsets announced

Use Cases:

- Ultra-Short Range
- 8K UHD - Smart Home
- AR/VR and wearables
- Data Center Inter Rack connectivity
- Video / Mass-Data distribution
- Mobile Offloading and MBO
- Mobile Fronthauling
- Wireless Backhauling (w. multi-hop)
- Office Docking
- Fixed Wireless

Key additions :

- SU/ MU MIMO, up to 8 spatial streams
- Channel bonding
- Channel aggregation
- Non-uniform constellation modulation
- Advanced power saving features

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60 GHz Fixed Wireless Use Case: Affordable 5G Performance

“the 14 GHz of contiguous spectrum in the band offers more bandwidth than any other licensed or unlicensed mmWave band. Further, the 60 GHz band has chipsets and technology currently available on the commercial market.”

“In the U.S., unlicensed mmWave frequencies available for 5G primarily cover the band from 57 – 71 GHz, called the V–Band, or 60 GHz band. This band offers 14 GHz of contiguous spectrum, which is more than all other licensed and unlicensed bands combined7. **This makes the 60 GHz band an excellent alternative to licensed mmWave frequencies for smaller providers, as it can be used to deliver 5G performance for the minimal cost of available 60 GHz infrastructure products.**

https://go.siklu.com/hubfs/Content/White%20Papers/Maravedis%20Industry%20Overview:%205G%20Fixed%20Wireless%20Gigabit%20Services%20Today.pdf

https://www.fiercewireless.com/wireless/60-ghz-band-particularly-appealing-for-fixed-wireless-report

60 GHz Mesh Backhaul Wireless Use Case: Deploying Today

“Leading Wi-Fi and wireless network solution vendor [Cambium Networks](#) announced today that they will be incorporating Facebook’s [Terragraph](#) technology into a new series of Cambium Networks **60 GHz radio products** called cnWave™. The news comes as Terragraph appears to be ramping up go-to-market activities with trials underway in Hungary and most recently in Malaysia.”

“Terragraph is essentially a 60 GHz-based meshed (or multi-hop, multi-point) backhaul radio system for deployment at street level in cities.”

https://wifinowevents.com/news-and-blog/cambium-networks-to-incorporate-facebook-terragraph-tech-into-new-60-ghz-products/

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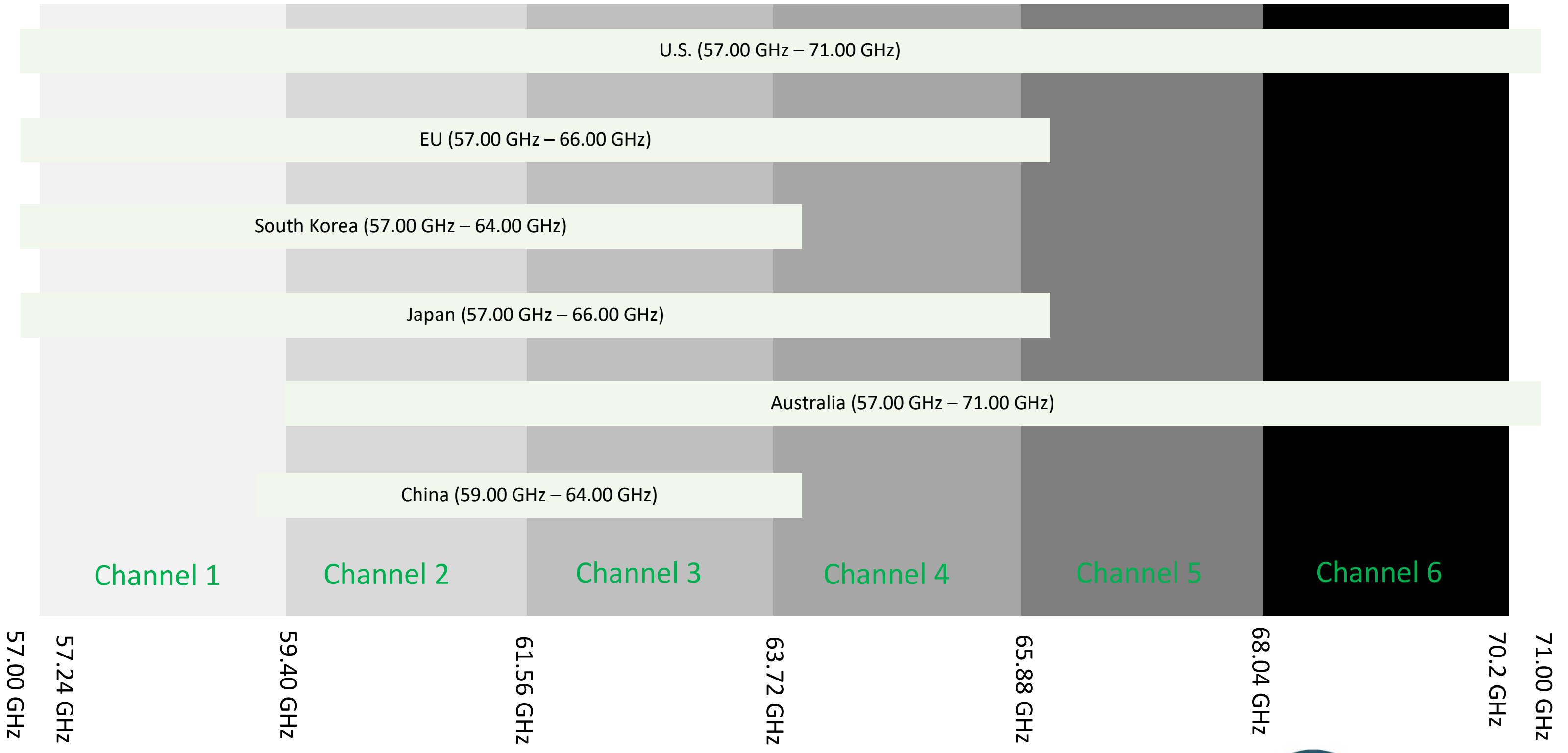
60 GHz Worldwide Spectrum

- Worldwide, unlicensed, spectrum availability
- 4 bands available in EU and Japan
- Recently expanded spectrum in U.S. from 57 – 71GHz, additional countries also considering expansion



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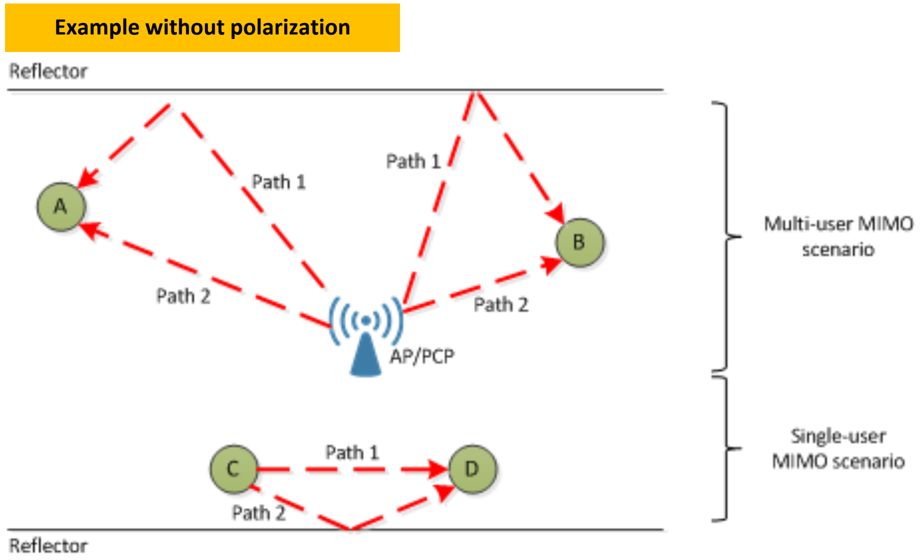
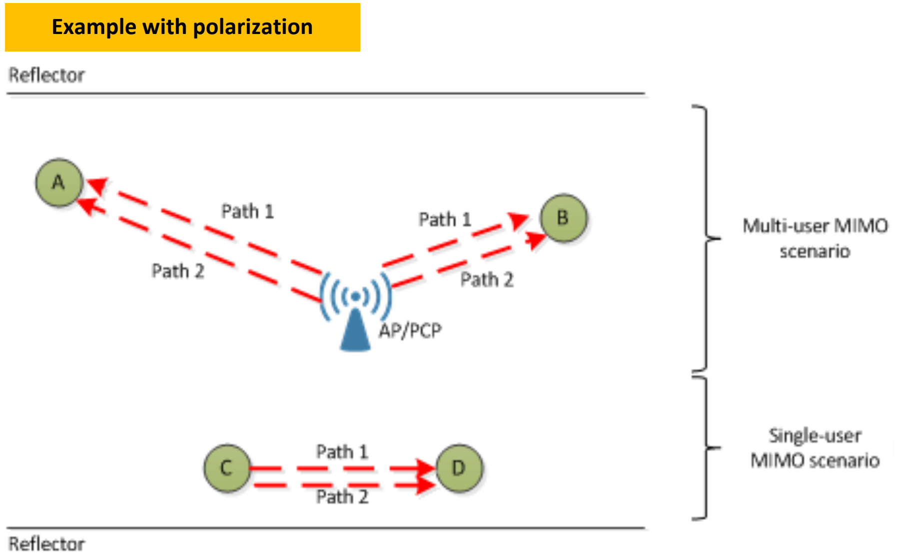
802.11ay builds on 802.11ad with MIMO and channel bonding features

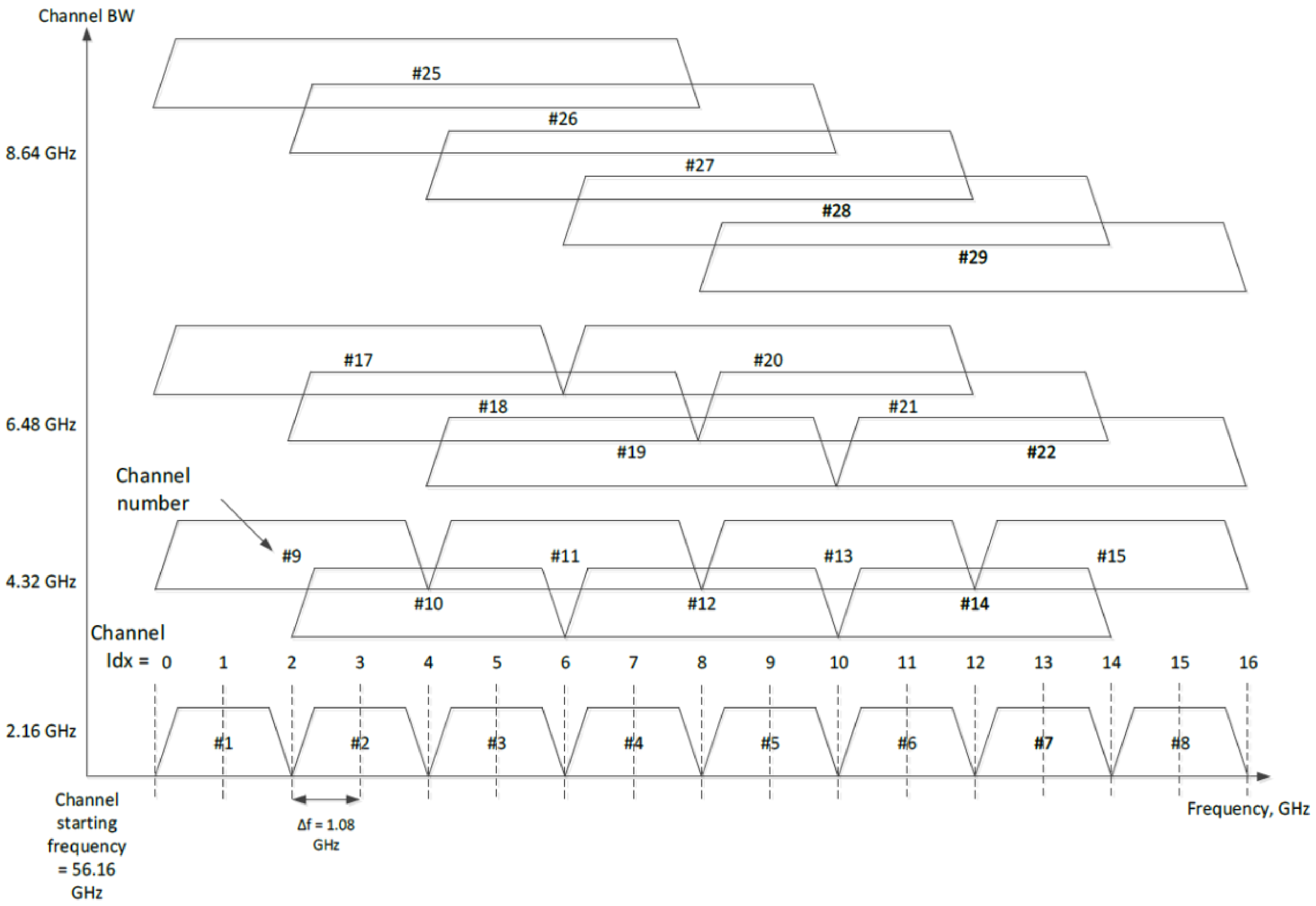
- Channel bonding and aggregation requires new:
  - Channelization
  - Packet format
  - Channel access mechanisms

- Single User and downlink MU MIMO
  - Distribute capacity across users
  - Unique requirements given directionality
  - Exploit antenna polarization
  - Changes to the beamforming protocol





802.11ay defined channelization



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802.11az Next Generation Positioning

- Next Generation Positioning P802.11az project is the evolutionary roadmap of accurate 802.11 location (FTM) appearing first in previous revisions of the 802.11 standard:
  - Accurate indoor Navigation (sub 1m and into the <0.1m domain).
  - Secured (authenticated and private) positioning – open my car with my smartphone, position aware services (money withdrawal).
  - Open my computer with my phone/watch.
  - Location based link adaptation for home usages (connect to best AP).
  - Navigate in extremely dense environments (stadia/airport scenarios).

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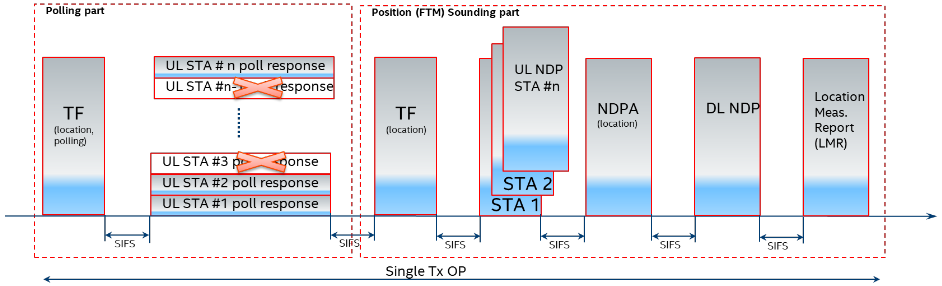
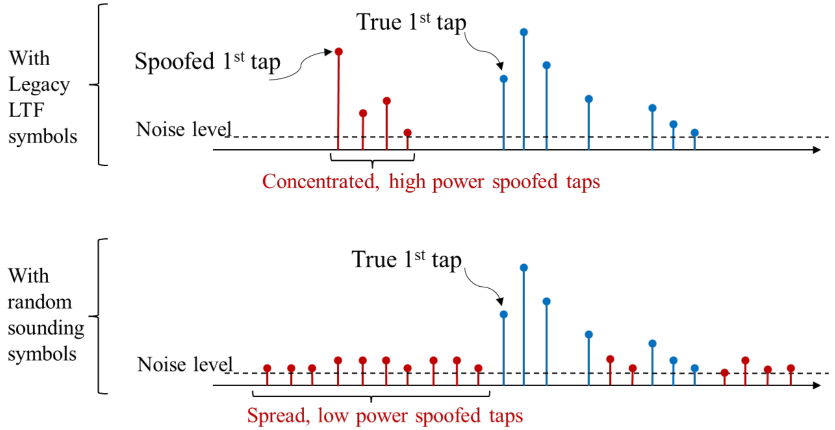
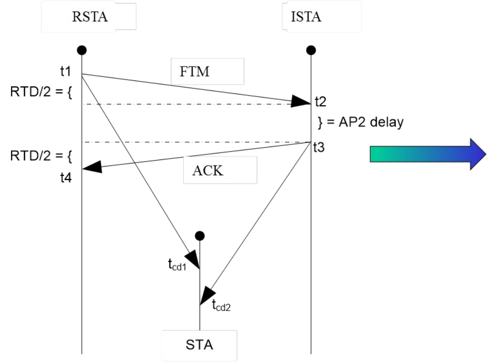
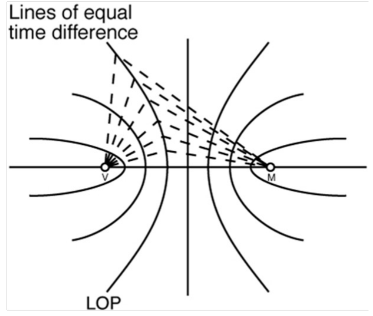
802.11az Key Radio and Positioning Techniques

- Medium efficient operation via dynamic (demand dependent) measurement rate.
- Adaptation to next generation mainstream 802.11ax Trigger Based Operation (MIMO, Trigger Frame, NDP frame)
- Authenticity and privacy and anti-spoofing mechanism via PMF in the unassociated mode and PHY level randomized measurement sequences (HE LTF sequences protection).
- Improved accuracy via MIMO and larger BW available in the <7Ghz band for 11ax.
- MIMO enablement for measurement for improved accuracy especially for NLOS or NNLOS conditions.
- Passive location with fixed overhead independent of number of users



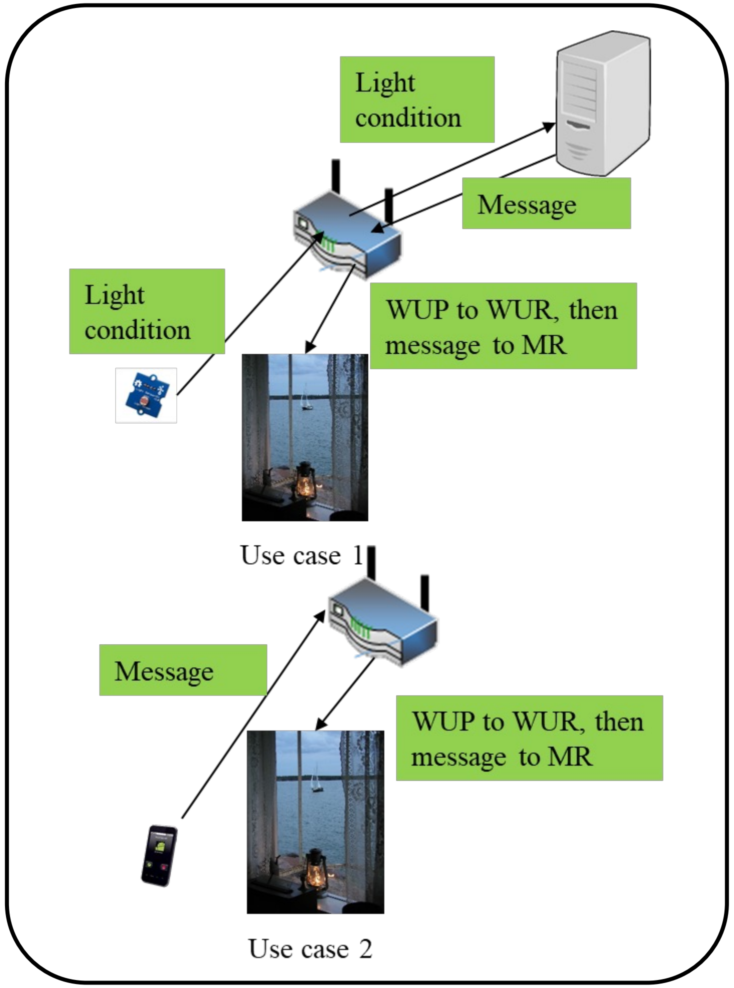




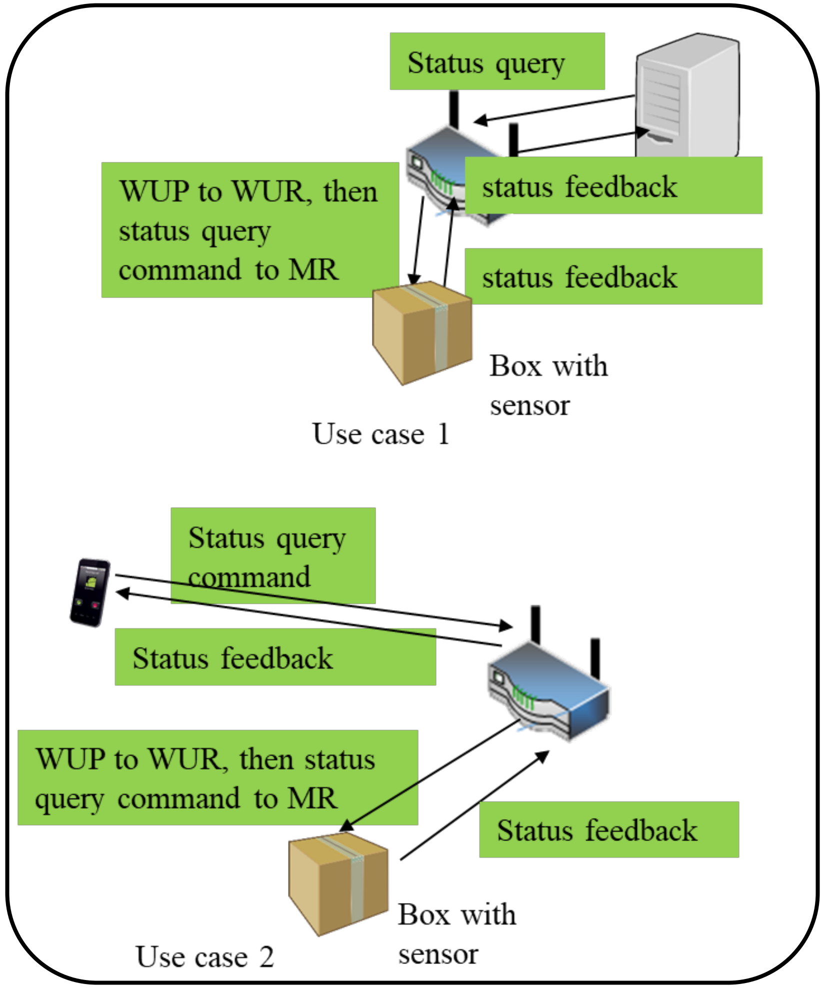


802.11ba Wake-up Radio Main Use Cases

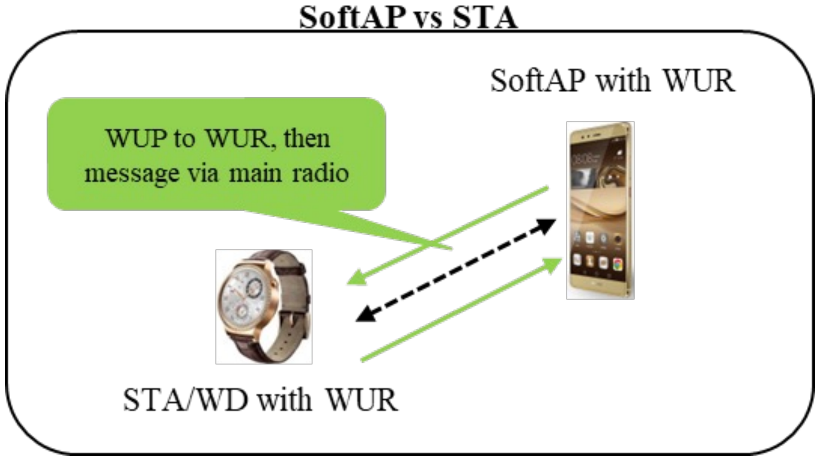
1. Smart Home



2. Warehouse



3. Wearables



WUP: wake-up packet
WUR: wake-up receiver
MR: main radio

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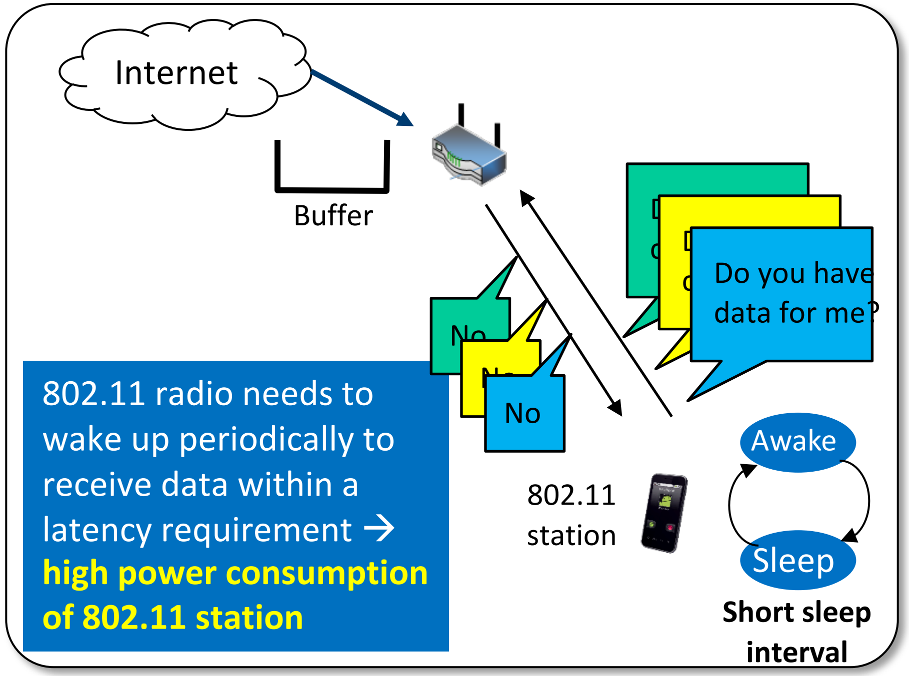
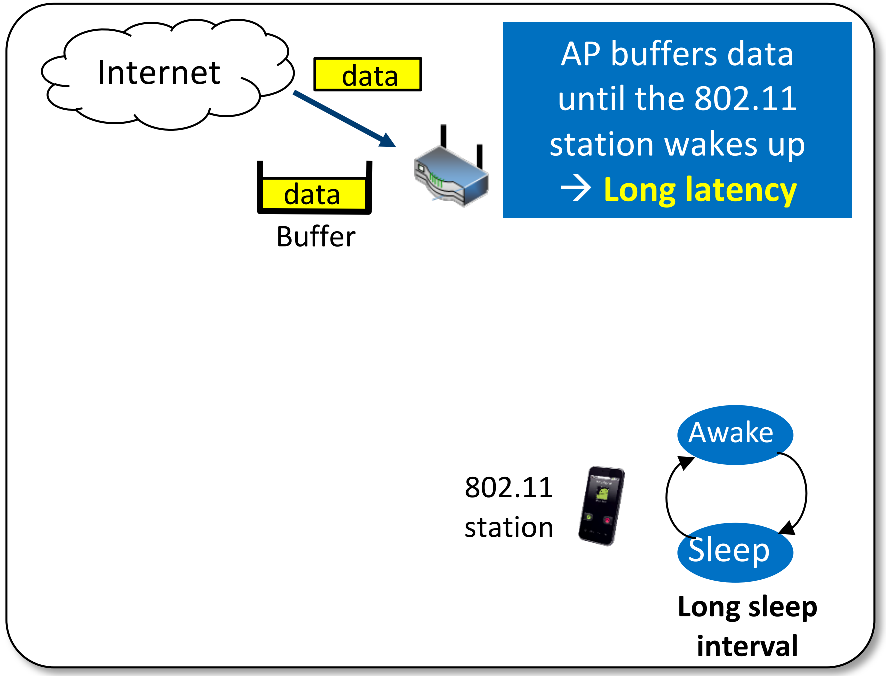
802.11ba improves energy efficiency of stations and maintains low latency





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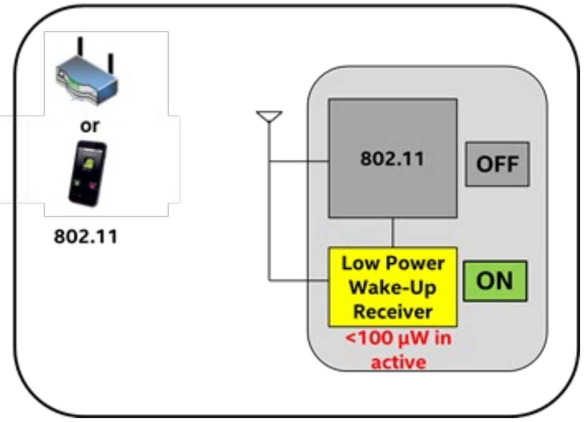
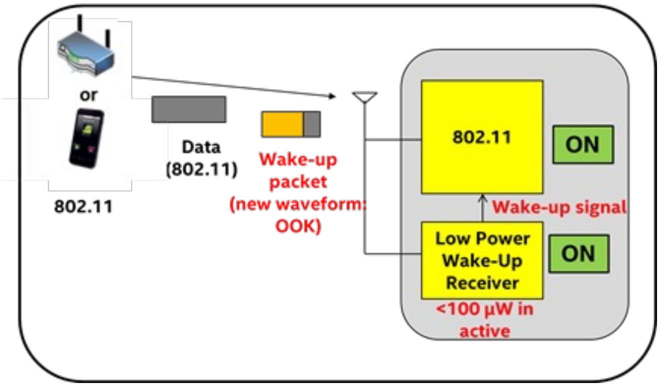
802.11ba Low-power Wake-up Receiver (LP-WUR) as Companion Radio for 802.11

- Comm. Subsystem = Main radio (802.11) + LP-WUR
  - **Main radio (802.11): for user data transmission and reception**
    - Main radio is off unless there is something to transmit
    - LP-WUR wakes up the main radio when there is a packet to receive
    - User data is transmitted and received by the main radio
  - **LP-WUR: <u>not</u> for user data; serves as a simple "wake-up" receiver for the main radio**
    - LP-WUR is a simple <u>receiver</u> (doesn't have a transmitter)
    - Active while the main radio is off
    - Target power consumption < 1 mW in the active state
      - Simple modulation scheme such as On-Off-Keying (OOK)
      - Narrow bandwidth (e.g. < 5 MHz)
    - Target transmission range: LP-WUR = Today's 802.11

No data to receive



Data to receive



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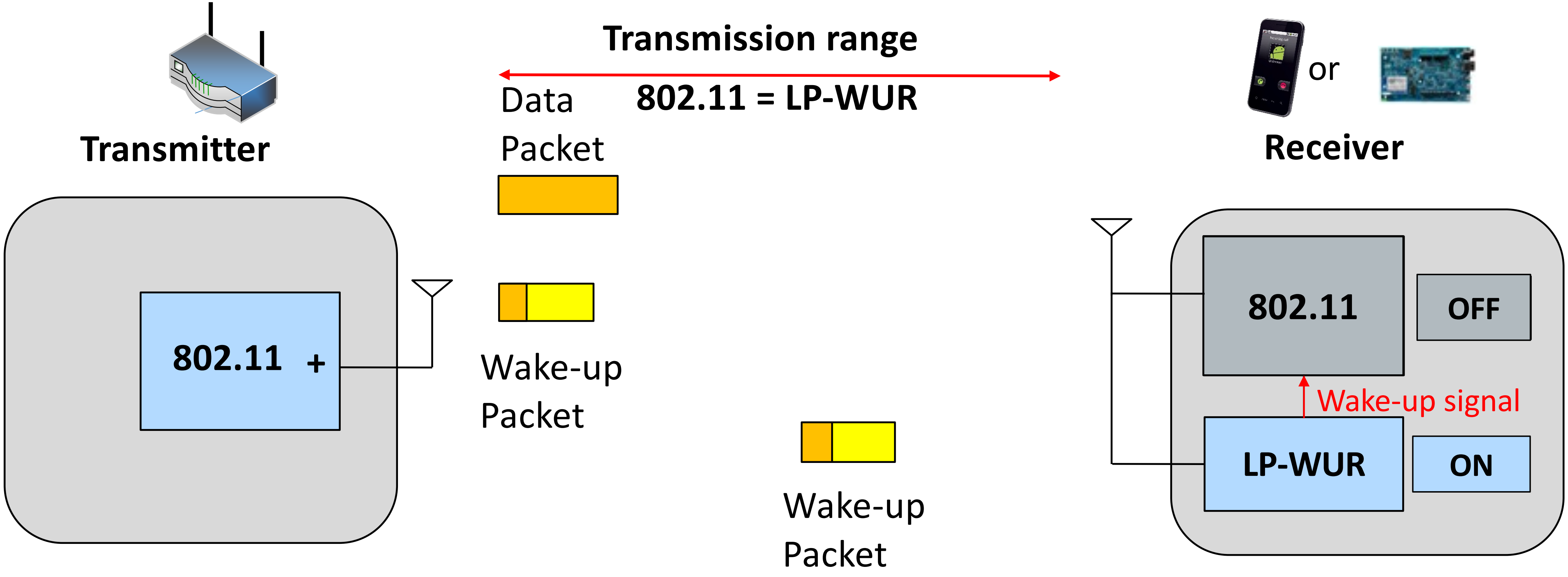
802.11ba Low Power Wake-up Radio Operation



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802.11bb Light Communications

- 5Gbps+ rates are defined
- Light Communications (LC)

Use Cases:

- Industrial wireless applications
- Medical environments
- Enterprise
- Home
- Backhaul
- Vehicle to Vehicle Communication
- Underwater Communication
- Gas Pipeline Communication

Key additions :

- Uplink and downlink operations in 380 nm to 5,000 nm band
- Minimum single-link throughput of 10 Mb/s
- Mode supporting at least 5 Gb/s,
- Interoperability among solid state light sources with different modulation bandwidths.

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802.11bb usage model 1: Industrial wireless

Pre-Conditions

Devices may experience unstable radio frequency (RF) connection due to Electro-Magnetic Interference (EMI) in factories. LC is deployed to provide reliable wireless connectivity for industrial wireless networks.

Environment

All communications are within a large metal building, industrial or automated work cell. The area of these environments range from tens to thousands of square meters, equipped with industrial robot and other equipment. The environment has high levels of EMI. Lighting level of 150 lux is recommended (1500 lux for dedicated work).

Applications

Ultra-high-definition (UHD) video streaming for surveillance or production monitoring (quality control) applications, for video collaboration for team, customer, and supplier meetings. Lightly compressed Video: ~ 1Gbps, delay < 5 ms, 1x10^{-8} PER, 99.9% reliability. Fully connected factory—for real-time communications, application execution, and remote access.Distance between LC APs ranges from 2~20 meters.

Traffic Conditions

Both uplink and downlink traffic is using LC.

High levels of OBSS interference between LC access points (APs) expected due to very high density deployment.

Potential non-LC interference from surrounding environments such as artificial-light.

Multiple LC modules are deployed on the robot/equipment and on the ceiling/walls to provide multiple light links for a robust connectivity in case a single line-of-sight (LOS) link is blocked.

Use Case

An industrial robot is powered on and ready for operation. Operating instructions are transmitted to the robot via LC. The robot is working (e.g., movement) according to the instructions and provides real-time feedback information and/or video monitoring data for quality control to control center also via LC. Upon command, the robot finishes the task and is ready for the next one.

802.11bb usage model 2: Wireless access in medical environments

Pre-Conditions

IEC 60601-1-2 standard recommends the minimum separation distance between medical electrical (ME) equipment and RF wireless communications equipment (e.g., wireless local area network (WLAN)) be 30 cm to avoid performance degradation of the ME equipment. LC is deployed to ensure the performance of all ME equipment.

Environment

The size of a operating theater and MRI room ranges from 30~60 m^2. Multiple LC-APs are deployed on the ceiling to provide specialized illumination. The central ~~il~~luminance of the operating light: 160k and 40k lux. The size of a four beds ward is about 60 m^2, light level: 300 lux on the bed and >100 lux between the beds and in the central area.

Applications

LC-WLAN is used to allow wireless data exchange in medical environments with ME equipment or system.
Medical multimedia and diagnostic information can be transmitted to provide telemedicine services; ME equipment can also be wirelessly controlled via LC.
Provide Intranet/ Internet access, audio or video call for doctors, nurses and patients using LC-based devices.

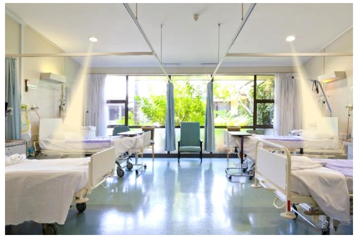
Traffic Conditions

No interference caused by RF radiation.
Both uplink and downlink traffic is ~~are~~ using LC.
High Quality of Service (QoS) and high reliability are required.
Potential non-LC interference from surrounding environments such as artificial-light.

Use Case

Doctors enter an operating theater, turn on the LC enabled LED lights and ME equipment. Doctors can interact with the remote doctors and share information using LC. ME equipment connectivity is also supported by LC. Doctors finish the treatment, then turn off the lights and medical equipment.
A patient is monitored by ME equipment which communicate with the nurses/doctors in control room via LC.

Operating theater



Hospital ward

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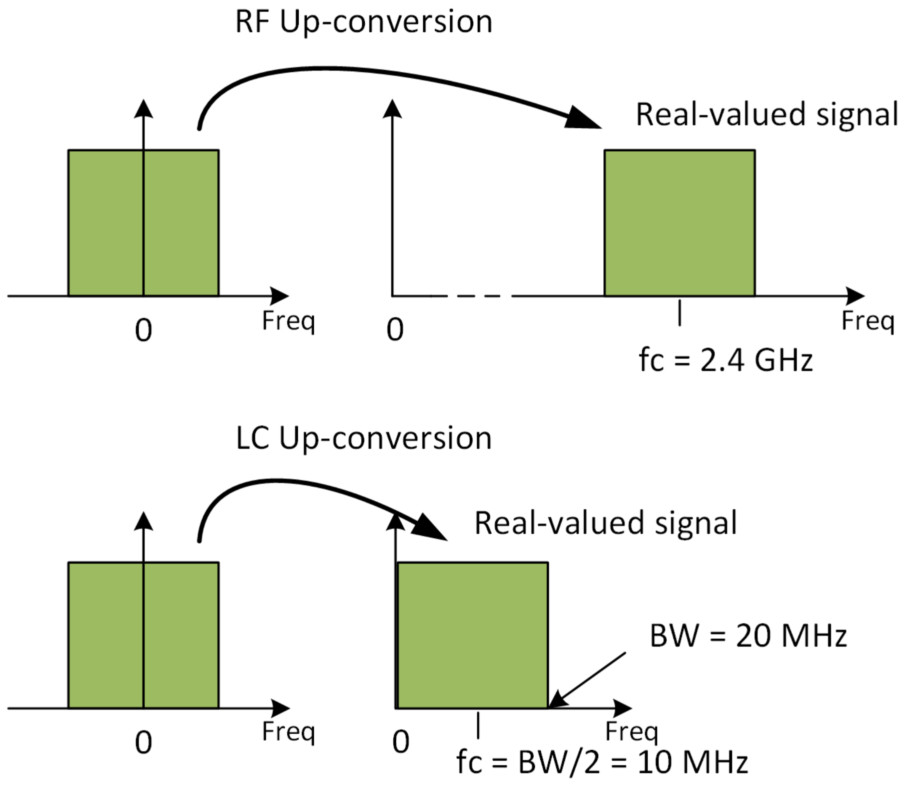
802.11bb uses light spectrum and existing technological capabilities

- RF frontend up-converts baseband signals onto e.g. f_c=2.4 GHz.
- LC frontend up-converts baseband onto low IF e.g. f_c=BW/2 + Δ.
  - Δ is to be agreed depending on signal mask design.
- This way, any complex-valued baseband signal (i.e. any existing IEEE 802.11 PHY) can be used to facilitate LC.



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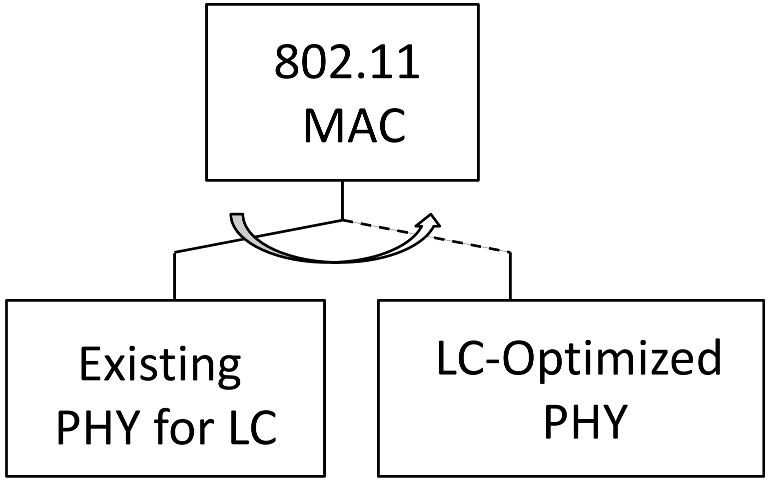
802.11bb uses light spectrum and existing technological capabilities

- 802.11 MAC could integrate existing and optimized PHY



- Use existing 802.11 PHY as a common, mandatory OFDM PHY (except 11ad, ay).
- A legacy preamble is prepended to new LC PHYs. Legacy preamble is sent by using an existing 802.11 OFDM PHY. The switch is set in the legacy signaling field.
    - a) Legacy 802.11 PHY is used (e.g. 11a/g, n, ac, ax) → reuse 802.11 PHY also for LC
    - b) LC–optimized PHY is used (e.g. G.hn/G.vlc) → optimize performance for LC

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802.11bc is defining Enhanced Broadcast Services

- Enhanced Broadcast Services (eBCS) define broadcast service enhancements within an 802.11-based network.
- Client end devices broadcast information to an AP, e.g. in an IoT environment, to other STAs so that any of the receiving APs act as an access node to the Internet.

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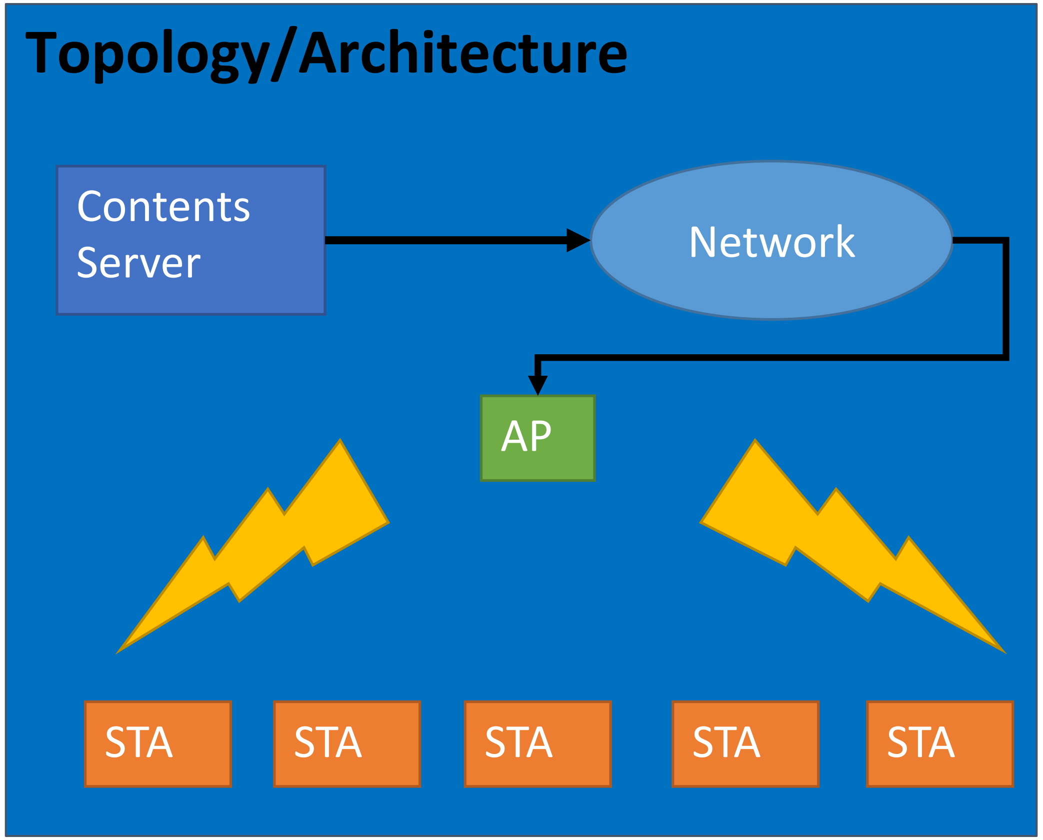
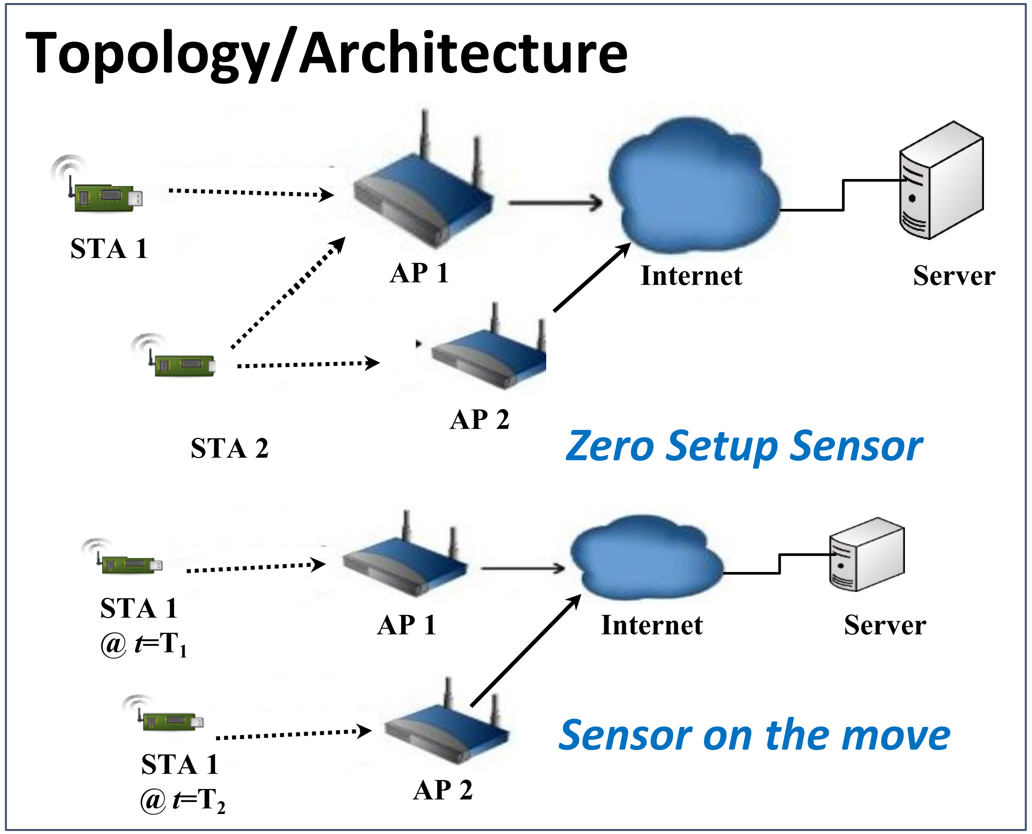
802.11bc use cases description

- **Broadcast Downlink**
  - Provides enhanced Broadcast Services (eBCS) of data (e.g. videos) to a large number of densely located STAs. These STAs may be associated, or un-associated with the AP or may be low-cost STAs that are receive only.
- **Broadcast Uplink**
  - Pre-configured devices (e.g. IoT) automatically connect to the end server through APs with zero setup action required.
  - Alternatively, low power IoT devices that are in motion, report to their servers through APs without scanning and associating

802.11bc use cases: Broadcast Downlink





Broadcast Uplink

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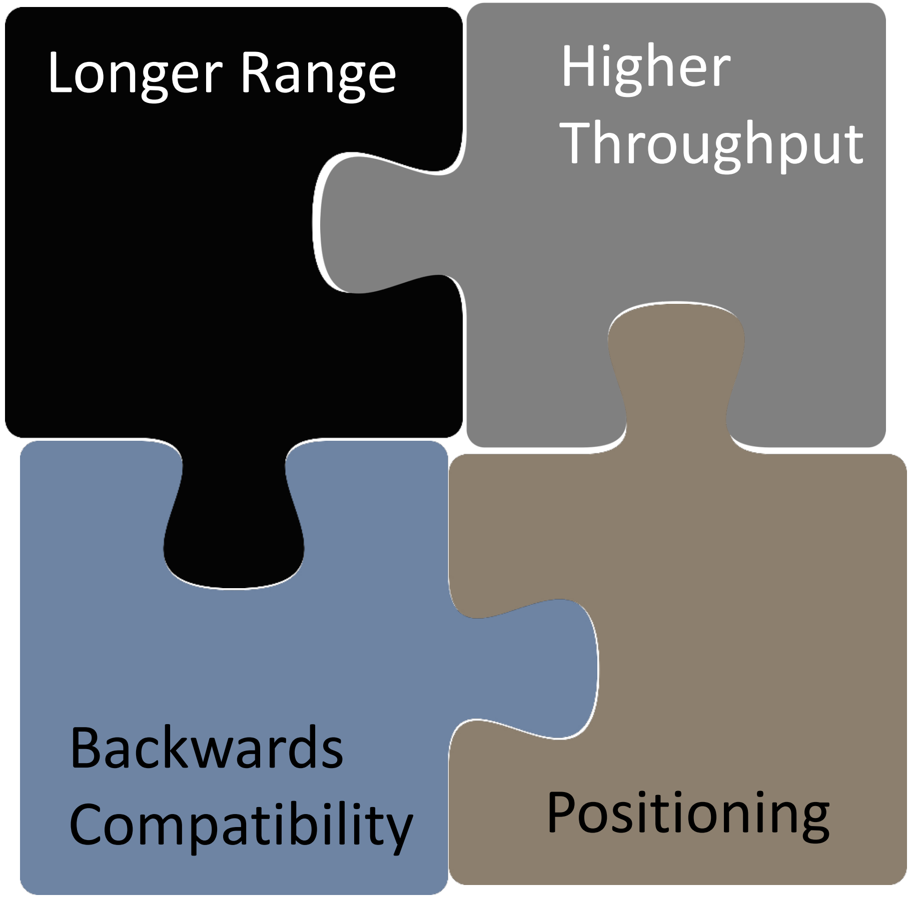
802.11bd defines an evolution of 802.11p for Vehicle to Anything (V2X)

- 802.11p is largely based on 802.11a.
- 802.11bd defines MAC/PHY enhancements from 802.11n, ac, ax, to provide a backwards compatible next generation V2X protocol.
- **Higher Throughput**
  - OFDM frame design
  - Higher MCS, LDPC coding
  - Packet aggregation
- **Longer Range**
  - Mid-amble design
  - Repeated transmission mechanism
  - More robust channel coding
- **Support for Positioning**
- **Backward Compatibility**
  - Backward compatible frame format design, Version indication



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802.11bd: Next Generation V2X Use Cases

5.9 GHz band mainly, and optionally 60 GHz;
Completion in 2022
http://www.ieee802.org/11/Reports/tgbd_update.htm

V2X Use Cases:

- Suport all defined DSRC/802.11p use cases, including Basic safety message (safety, range, backward compatibility, fairness)
- Sensor sharing (throughput)
- Multi-channel operation (safety channel + other channels)
- Infrastructure applications (throughput)
- Vehicular positioning & location (LoS and NLoS positioning accuracy)
- Automated driving assistance (safety, throughput)
- Aerial vehicle IT application (video)
- Train to train (high speed)
- Vehicle to train (high speed, long range)

Key additions :

- Higher throughput (2x) than 802.11p
- Longer range (3dB lower sensitivity level)
- Support for positioning
- Backward compatibility with 11p

802.11be is a new amendment that builds on 802.11ax

Extremely High Throughput (EHT)

- Higher throughout – up to 30 Gbps
- Support for low latency communications
- Operations in 2.4 GHz, 5 GHz, and 6 GHz bands
- Targeted completion in 2023

Use Cases:
- AR/VR
- 4K and 8K video streaming
- Remote office
- Cloud computing
- Video calling and conferencing

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802.11be features under consideration

- 320 MHz bandwidth and more efficient utilization of non-contiguous spectrum
- Multi-band/multi-channel aggregation and operation
- 16 spatial streams and MIMO protocols enhancements
- Multi-AP Coordination (e.g. coordinated and joint transmission)
- Enhanced link adaptation and retransmission protocol (e.g. HARQ)
- Adaptation to regulatory rules specific to 6 GHz spectrum
- Refinements of 802.11ax features

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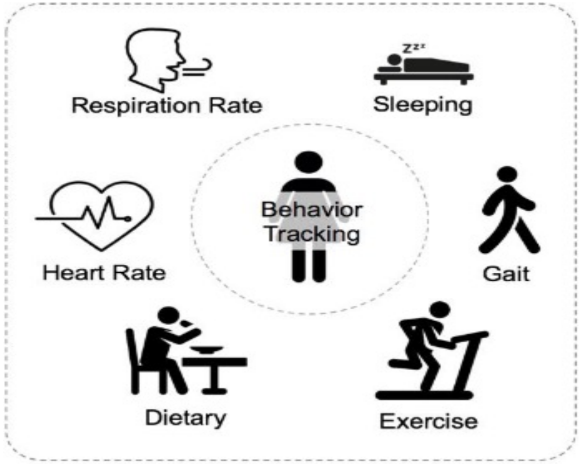
802.11bf WLAN sensing

- **WLAN sensing is the use of received WLAN signals to detect features of an intended target in a given environment.**
  - Measure range, velocity, angular, motion, presence or proximity
  - Detect objects, people, animals
  - Use in room, house, car, enterprise environments

- **Target frequency bands are:**
  - between 1 GHz and 7.125 GHz (MAC/PHY service interface)
  - above 45 GHz (MAC/PHY)

802.11bf use cases



Smart home

Gaming control

Gesture recognition

Presence and proximity detection
(Home/Enterprise/Vehicle)

- Note: The specification of applications that make use of WLAN sensing measurements is beyond the scope of P802.11bf.

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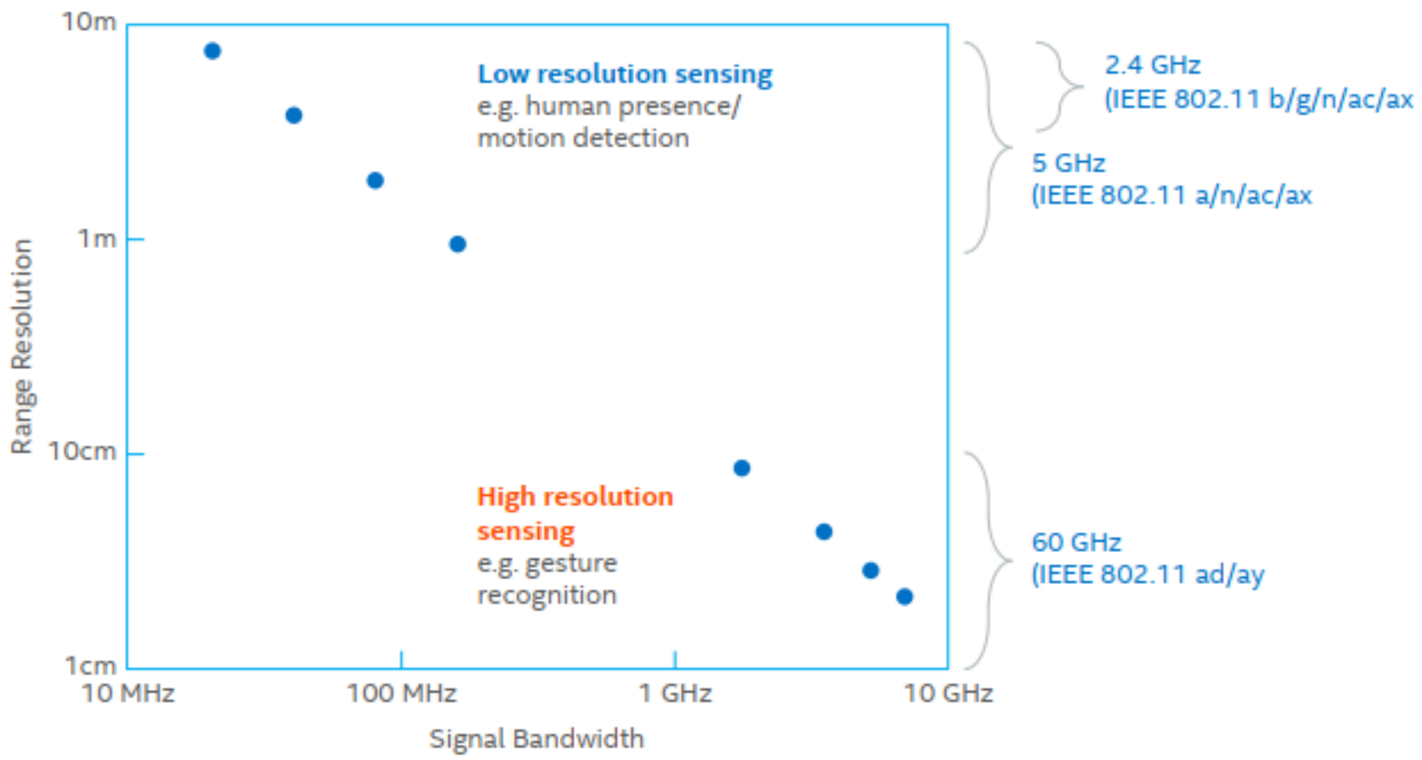
802.11bf WLAN sensing

- **802.11bf enables:**
  - Stations to inform other stations of their WLAN sensing capabilities
  - Request and setup transmissions that enable WLAN sensing measurements to be performed
  - Exchange of WLAN sensing feedback and information

- **Sensing performance metrics include**
  - Accuracy of range, angle and velocity resolution
  - Resolution of range, angle and velocity
  - Coverage range, field of view



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802.11ay, 802.11ad (60GHz) and 802.11ax (2.4GHz, 5(6)GHz) technology can be leveraged to meet 5G requirements

- Today's 4G networks include 802.11 technologies
  - For offload: "More traffic was offloaded from cellular networks (on to Wi-Fi) than remained on cellular networks in 2016" (Cisco VNI)
  - For Wi-Fi calling
- Wi-Fi carries most public & private Internet traffic worldwide
  - Between 50-80% depending on country.
- 5G radio aggregation technologies will natively incorporate Wi-Fi
  - 802.11/Wi-Fi is a Peer Radio Access Technology in the 5G Architecture

802.11ax
8Gb/s (OFDMA, U/L MU-MIMO)
5G Hotspot Mobile Broadband

802.11ay/aj
60GHz
n*20Gb/s (Aggregation+MIMO)
Device connectivity

802.11ah (Sub 1 GHz) + 11ba
900 MHz Indoor IoT PANs
Wearables, sensors, smart home

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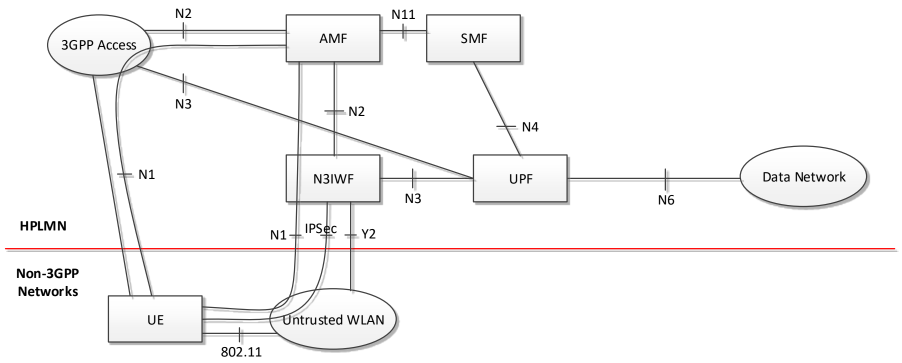
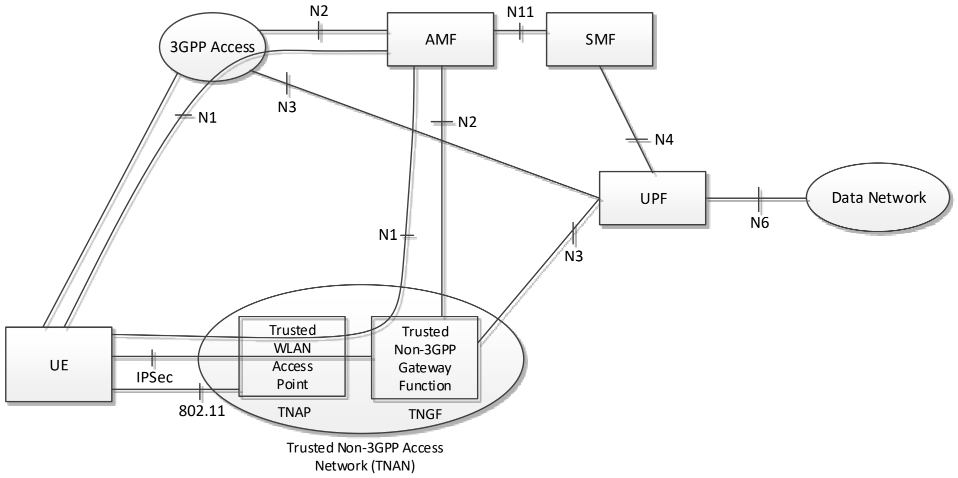
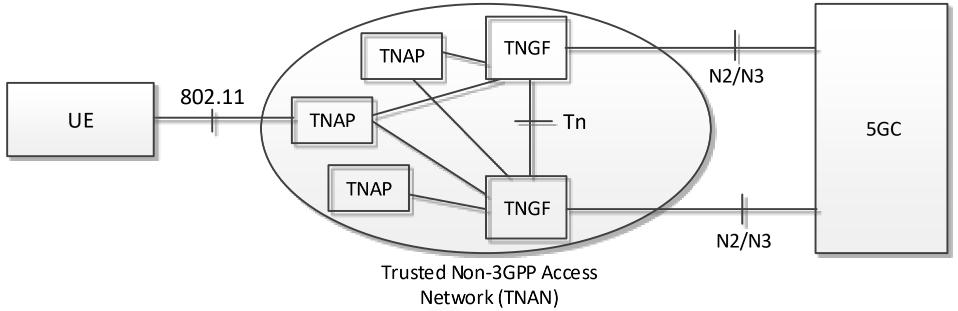
802.11 is a Peer Radio Access Technology in 5G System

Untrusted WLAN Access (3GPP Rel-15 onwards)



Trusted WLAN Access (3GPP Rel- 16 onwards)





- 5G System is Access Agnostic: UE devices can register and access 5G services without the need of licensed based access;
- Unified EAP based authentication mechanism for all accesses;
- Unified transport mechanism over WLAN access for both trusted and untrusted use cases;
- Policies based mechanism for access selection and traffic selection, steering and splitting;
- Unified QoS mechanism for both cellular and WLAN access.

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802.11 and cellular radio technologies are largely complementary in meeting the comprehensive 5G service vision

- WLAN access is integral part of the into the 5G system architecture developed by 3GPP

- 5G architecture is a functional based architecture
  - This provides the flexibility that both core network anchoring and the RAN based anchoring from 4G system are seamlessly supported in 5G system architecture

- 802.11 defined technologies – 2.4/5/6/60GHz and cellular radio technologies are essential – and largely complementary – in meeting the comprehensive 5G service vision

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Networking II

WLANs

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