
Self Organizing Networks

WLAN IEEE 802.11 aka Wi-Fi

SS 2023 Lecture – Part 1: PHY layer

Max Riegel

About my person



Max Riegel

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Senior Standards Specialist

Nokia Standards – IEEE & Wi-Fi Standardization

- Job positions
 - prior to 1998
 - Various positions regarding HW and SW development at Philips Kommunikations Industrie and TPS
 - 1998 - 2007
 - Responsible for IETF and IEEE Standardization at Siemens Communications
 - since 2007
 - Responsible for IEEE related standardization at NSN/Nokia Networks/Nokia
- Participation in IEEE 802.11 Standardization since 2000
- Currently voting member of IEEE 802.1 and IEEE 802.11
- Engagement in Wi-Fi Alliance and Head of Nokia delegation in Wireless Broadband Alliance
- Various Wi-Fi research and product designs in the Carrier/Enterprise Wi-Fi domain

SS2023 Lectures overview

- **June 8th**
 - Wi-Fi Applications and markets
 - Wi-Fi Standardization environment
 - Wi-Fi Spectrum
- **June 15th**
 - Wireless channel characteristics
 - Direct Sequence Spread Spectrum (initial Wi-Fi radio)
 - Orthogonal Frequency Division Multiplex
 - Wi-Fi 2 .. Wi-Fi 7 radios
- **June 22nd - *electronic***
 - IEEE 802.11 architecture
 - Medium access functions
 - System management
- **June 29th**
 - MAC layer management
 - MAC layer frame formats
 - Quality of Service
- **July 6th**
 - Wi-Fi security
 - Mobility enhancements

Overview Part 1 – PHY layer

- **June 8th /June 15th**
 - Wi-Fi applications and markets
 - Wi-Fi Standardization environment
 - IEEE 802.11 Standardization
 - Wi-Fi Alliance Certification
 - Wi-Fi Spectrum
 - Wireless Channel Characteristics
 - Direct Sequence Spread Spectrum (initial Wi-Fi radio)
 - Orthogonal Frequency Division Multiplex
 - Wi-Fi 2 (OFDM)
 - Wi-Fi 3 (High Rate)
 - Wi-Fi 4 (High Throughput)
 - Wi-Fi 5 (Very High Throughput)
 - Wi-Fi 6 (High Efficiency)
 - Wi-Fi 5 vs. Wi-Fi 6
 - Looking ahead: Wi-Fi 7 (Extremely High Throughput)

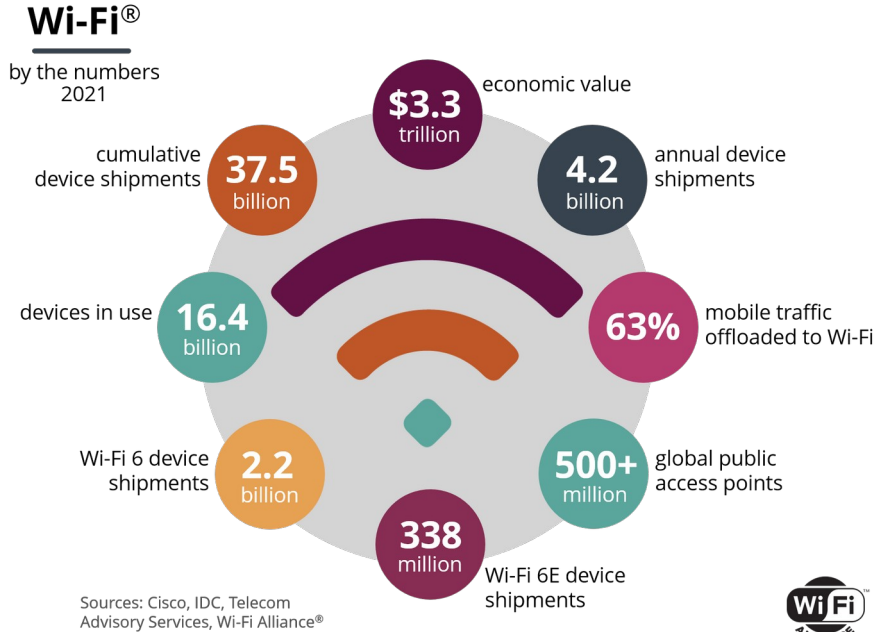





WLAN IEEE 802.11 aka Wi-Fi

WI-FI APPLICATIONS AND MARKETS

Diversity of Wi-Fi terminals and access infrastructure

Wi-Fi is predominantly deployed in homes and indoors



~90%*	~10%*	<1%*
 <p>Residential Wi-Fi</p>	 <p>Corporate Wi-Fi</p>	 <p>Public Wi-Fi</p>
<ul style="list-style-type: none"> Currently managed by millions of 'hobby' operators Most heavy growth of Wi-Fi devices and data traffic Public co-use feasible but requires strict separation from privately operated part. 	<ul style="list-style-type: none"> Managed by corporate IT departments Mission critical service with strict security policies in place Public access overlays for allowing employees to bring their own devices 	<ul style="list-style-type: none"> Managed by public communication service providers or WISPs Cumbersome security and usability due to open Wi-Fi and portals Very good business potential in dense deployments

* Percentage of total APs; Source: ABIresearch 2010, Femtocells, Operator, Access Point and Chipset Market Analysis

Segmenting the Wi-Fi device ecosystem

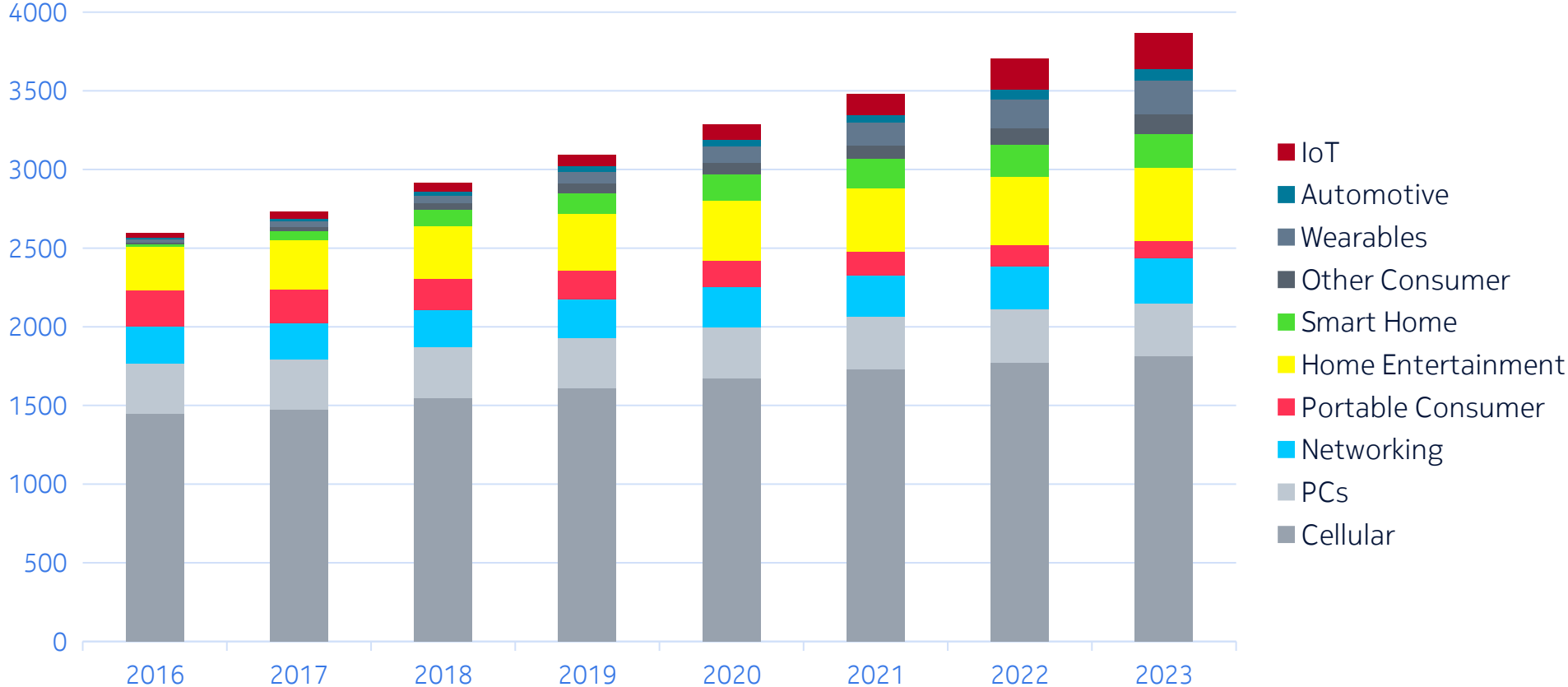
Source: ABI research 'Wireless Connectivity ICs' 2018

- Cellular (**1474**)
 - Smartphones
 - Feature Phones
- PCs (**313**)
 - Desktop PCs
 - Compute Sticks
 - Traditional Notebooks
 - Ultrabooks
 - Chromebooks
 - PC Accessories
 - Printers
- Networking (**235**)
 - Consumer APs
 - Consumer External Adapters
 - Enterprise APs
 - Carrier Wi-Fi APs
 - Mobile Hotspot Routers
 - Residential Wi-Fi Mesh Systems
- Portable Consumer (**214**)
 - Media Tablets
 - White Box Tablets
 - Handheld Gaming
 - Portable Media Players
 - Digital Cameras/Camcorders
 - eBook Readers
- Home Entertainment (**313**)
 - Flat Panel TVs
 - DVD/Blu-Ray Players
 - UHD Blu-Ray Players
 - Set-Top Boxes
 - Media Streaming Adapters
 - OEM Remote Controls
 - Gaming Consoles
 - Speakers
 - Digital Photo Frames
- Other Consumer (**25**)
 - Consumer Robotics
 - Other Consumer Electronics Devices
- Smart Home (**59**)
 - Home Automation Control
 - Home Automation Devices
 - Residential Smart Lighting
 - Smart Appliances
 - Voice-Control Front Ends
- Wearables (**33**)
 - Smartwatches
 - Smart Glasses
 - Sports, Fitness, and Wellness Trackers
 - Virtual Reality
 - Wearable Cameras
 - Wearable Scanners
- Automotive (**19**)
 - In-Car Infotainment
- IoT (**43**)
 - Smart Cities
 - Healthcare
 - Energy Management
 - Asset Management
 - Video Surveillance
 - Location/Tracking
 - Monitoring/Status
 - Other Value-Added Applications

(Figures) reflect millions shipped Wi-Fi connectivity ICs in 2017

Yearly Wi-Fi device shipments

Source: ABI research 'Wireless Connectivity ICs' 2018



Mobile and Wi-Fi offload traffic from mobile devices

Wi-Fi increasingly carries the majority of traffic in mobile communications

Mobile Data Traffic and Offload Traffic,
2022

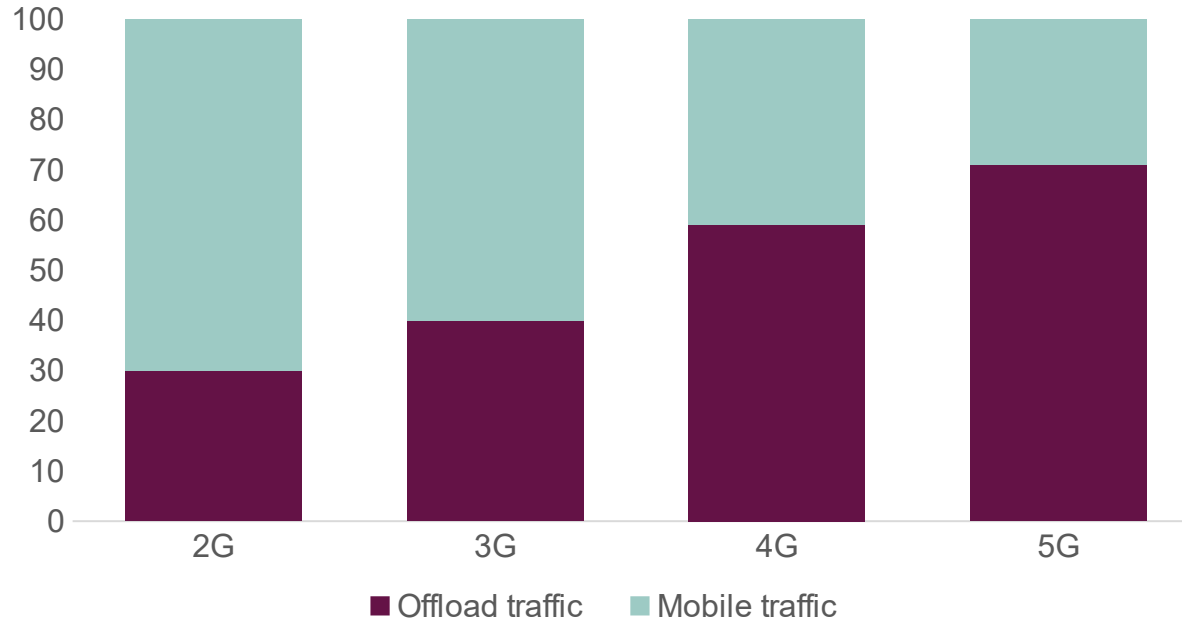


Chart source: Cisco VNI Mobile, 2019

Wi-Fi Standardization Environment

STANDARDS REFERENCE

IEEE Std 802.11™-2020 + amendment 802.11ax™-2021



- Can be downloaded at no charge through the IEEE Get Program
 - <https://ieeexplore.ieee.org/browse/standards/get-program/page/series?id=68>
- No all the features specified in the standard are available in real Wi-Fi products
- This lecture presents behavior of real Wi-Fi products as specified by Wi-Fi Alliance in its certification programs
 - <https://www.wi-fi.org/discover-wi-fi/specifications>

IEEE Standard for Information technology

Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications

- Revision of IEEE Std 802.11-2016
 - Revision of IEEE Std 802.11-2012
 - Revision of IEEE Std 802.11-2007
 - Revision of IEEE Std 802.11-1999
 - First IEEE 802.11 standard release in 1997
- Comprises initial IEEE Std 802.11-1999 and all amendments IEEE 802.11a-1999 ... IEEE 802.11aq-2018
 - i.e.: a, b, d, e, g, h, l, j, k, n, p, r, s, u, v, w, y, z, aa, ac, ad, ae, af, ah, ai, aj, ak, aq

Amendment standard IEEE Std 802.11ax-2021

- Amendment 1: Enhancements for High-Efficiency WLAN

Amendment draft standard IEEE P802.11be/D3.0

- *Amendment 8: Enhancements for extremely high throughput (EHT)*

IEEE 802.11 radio standards evolution

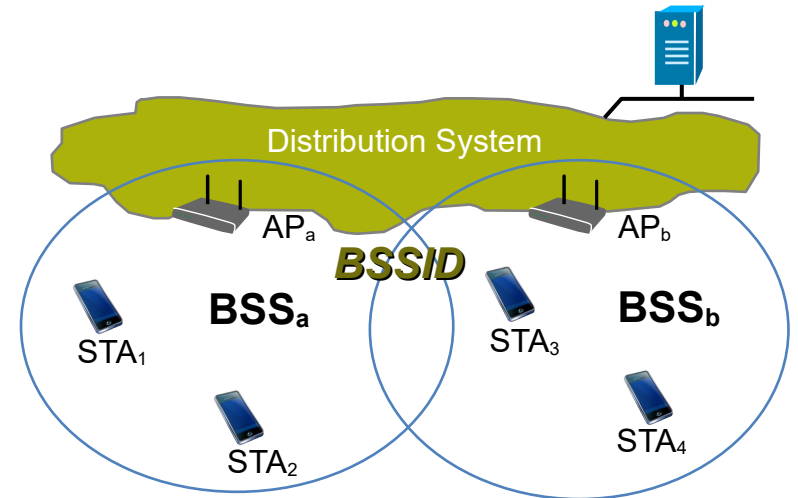
Std	Release	Freq. (GHz)	Bandwidth (MHz)	Data rate per stream (Mbit/s)	Allowable MIMO streams	Modulation	Approximate indoor range (m)	Approximate outdoor range (m)
	Jun 1997	2.4	20	1, 2	1	DSSS	40	150
a	Sep 1999	5	20**	6, 9, 12, 18, 24, 36, 48, 54	1	OFDM	40	150
b	Sep 1999	2.4	20	5.5, 11	1	DSSS	40	150
g	Jun 2003	2.4	20	6, 9, 12, 18, 24, 36, 48, 54	1	OFDM (DSSS)	40	150
n	Oct 2009	2.4 5	20/40	up to 72.2/150	4	OFDM	60 40	200 150
y	Nov 2008	3.7	5/10/20	up to 13.5/27/54	1	OFDM	-	5 000
ac	Dec 2013	5	20/40/80/160	up to 87/200/433/867	8	OFDM	40	150
ad	Oct 2012	60	2160	up to 6 700	1	SC // OFDM	line of sight	line of sight
af	Dec 2013	TV WS	1,2,4x 6/7/8	up to 1,2,4x 26.7/26.7/35.5	4	OFDM	100	1000
ah	Dec 2016	< 1	1/2/4/8/16	0.15 ... up to 4.4/9/20/43/87	4	OFDM	100	1000
ax	Feb 2021	1...7.2	[2]/[4]/[8]/20/ 40/80/160	up to [15]/[30]/[63]/143/287/600/1201	8	OFDMA	80	300
ay	Mar 2021	60	1.4 x 2160	$N_{cb} \times 8.6 // 8.3/18.2/28.1/37.9$ Gbps	8	SC // OFDM	line of sight	line of sight
be _{ibd}	~Dec 2024	1...7.2	[2]/[4]/[8]/20/ 40/80/160/320	up to [18]/[36]/[75]/172/344/720/1441/2882	8	OFDMA	80	300

* Preliminary information; specifications still in early phases of development.

** Half-clocked and quarter clocked variants available for 10 MHz and 5 MHz channel bandwidth, as used by IEEE 802.11p
IEEE 802.11y-2008 is only licensed in the United States by the FCC; licensed spectrum allows for higher TX power

IEEE 802.11 basic terminology and architecture

- **Access Point (AP)**
 - Creates unique coverage area/access zone called Basic Service Set (BSS)
 - BSS identified through 48bit MAC address of AP
- **Station (STA)**
 - IEEE 802.11 terminal
 - Uniquely identified through its MAC address
 - Connected (associated) at a given time to a single BSS
- **Basic Service Set Identifier (BSSID)**
 - Human readable text string to allow for easy identification of IEEE 802.11 access service
 - Multiple BSSs can have the same BSSID
- **Distribution System (DS)**
 - Interconnection system to create a single wireless access network comprising multiple APs to extend the wireless coverage area serving the same BSSID



WLAN IEEE 802.11 aka Wi-Fi

WI-FI STANDARDIZATION ENVIRONMENT

IEEE 802.11 and Wi-Fi Alliance



The IEEE 802.11 provides comprehensive technical specifications

Standards
Framework



The Wi-Fi Alliance defines profiles for deployments and certification of products

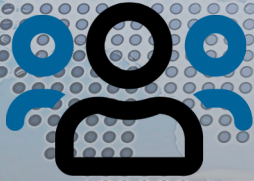
Compatibility
Conformance

Wi-Fi Standardization Environment

IEEE 802.11 STANDARDIZATION

Advancing Technology for Humanity

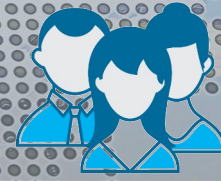
IEEE and its members inspire a global community through highly-cited publications, conferences, technology standards, and professional and educational activities.



419 000+ members



39 Technical Societies
7 Councils



20 000+ standards
developers



1 900+ conferences annually



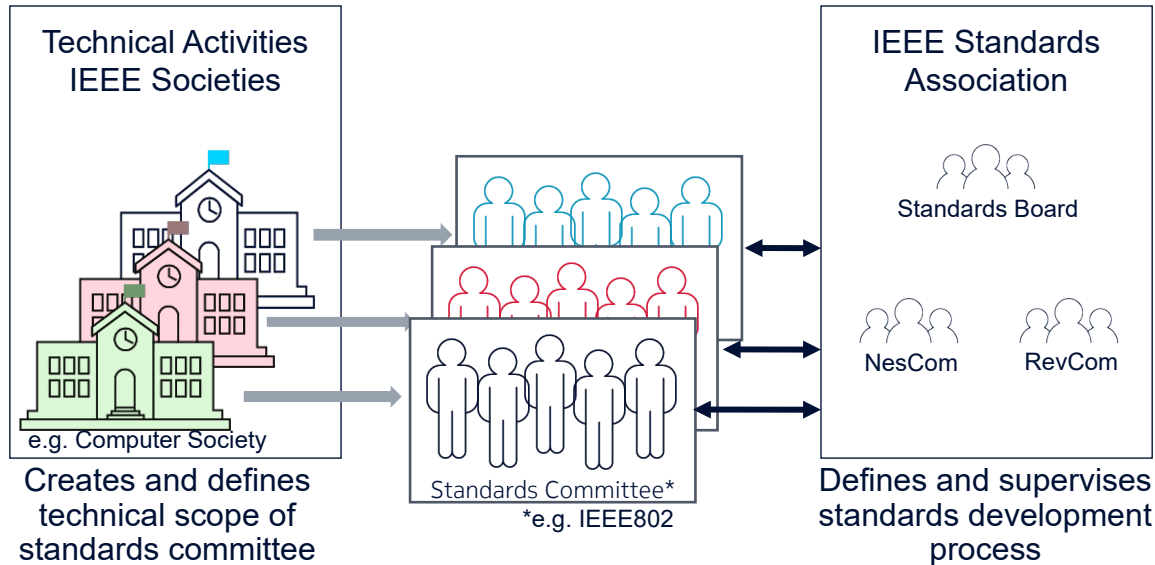
5+ million technical articles
1200+ standards



600+ standards
under development

Standardization within IEEE

IEEE Societies set scope, IEEE Standards Association defines procedural aspects

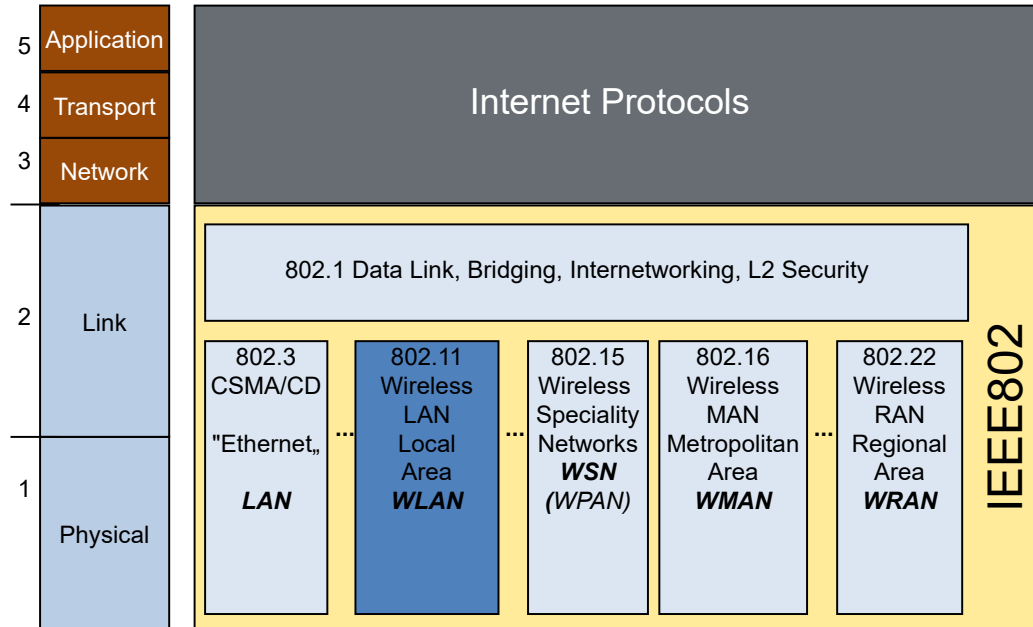


IEEE standardization process

- Mainly addressing **functional components**, very rarely system architectures
- Usually based on **individual membership**, i.e. voting rights belong to individuals
- Open access: **anybody can participate** without need for membership or payments
- **Technical decisions** through comprehensive **voting**

IEEE 802 LAN/MAN Standardization Committee

Wireless LAN became topic in IEEE 802 LMSC ten years after its foundation.



Specifies only Physical and Link Layer.
Complete set of standards for carrying IP

- Start of IEEE Computer Society Project 802 in February 1980.
 - Later renamed to “LMSC”: LAN/MAN Standardization Committee
- Initial work on “Ethernet”
 - With 1 to 20 Mbps!
- IEEE 802.11 started in 1990
 - Initially aimed for cash registers!
 - Challenging regulatory!
- Further MAC and PHY groups added, e.g. 802.15, 802.16
- Unifying themes
 - common upper interface to the Data Link Control
 - common data framing

IEEE 802.11 Specifications

IEEE 802.11-1997	Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) specifications	Jul 1997
IEEE 802.11	Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications	Sep 1999
IEEE 802.11a	High-speed Physical Layer in the 5 GHz Band (54 Mbps in 5GHz)	Sep 1999
IEEE 802.11b	Higher-Speed Physical Layer Extension in the 2.4 GHz Band (11 Mbps in 2.4 GHz)	Sep 1999
IEEE 802.11c	Support of the Internal Sublayer Service to cover bridge operations with 802.11 MAC => <u>IEEE 802.1D</u>	Oct 1998
IEEE 802.11d	Specification for operation in additional regulatory domains	Jun 2001
IEEE 802.11e	Medium Access Control (MAC) Quality of Service Enhancements	Nov 2005
IEEE 802.11F	Inter-Access Point Protocol => <u>Withdrawn February 2006</u>	Jul 2003
IEEE 802.11g	Further Higher Data Rate Extension in the 2.4 GHz Band (54 Mbps in 2.4 Ghz)	Jun 2003
IEEE 802.11h	Spectrum and Transmit Power Management Extensions in the 5 GHz band in Europe	Oct 2003
IEEE 802.11i	Medium Access Control (MAC) Security Enhancements	Jul 2004
IEEE 802.11j	4.9 GHz–5 GHz Operation in Japan	Oct 2004
IEEE 802.11-2007	Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications	Jun 2007

IEEE 802.11 Specifications, continuation

IEEE 802.11-2007	Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) spec	Jun 2007
IEEE 802.11k	Radio Resource Measurement of Wireless LANs	Jun 2008
IEEE 802.11n	Enhancements for Higher Throughput (4x 150 Mbps in 2.4/5GHz)	Oct 2009
IEEE 802.11p	WAVE—Wireless Access for the Vehicular Environment	Jul 2010
IEEE 802.11r	Fast Basic Service Set (BSS) Transition	Jul 2008
IEEE 802.11s	Mesh Networking	Sep 2011
IEEE 802.11T	Wireless Performance Prediction (WPP) => <u>Cancelled</u>	
IEEE 802.11u	Interworking with External Networks	Feb 2011
IEEE 802.11v	IEEE 802.11 Wireless Network Management	Feb 2011
IEEE 802.11w	Protected Management Frames	Sep 2009
IEEE 802.11y	3650–3700 MHz Operation in USA	Nov 2008
IEEE 802.11z	Extensions to Direct Link Set-up (DLS)	Oct 2010
IEEE 802.11-2012	Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications	Mar 2012

IEEE 802.11 Specifications, continuation

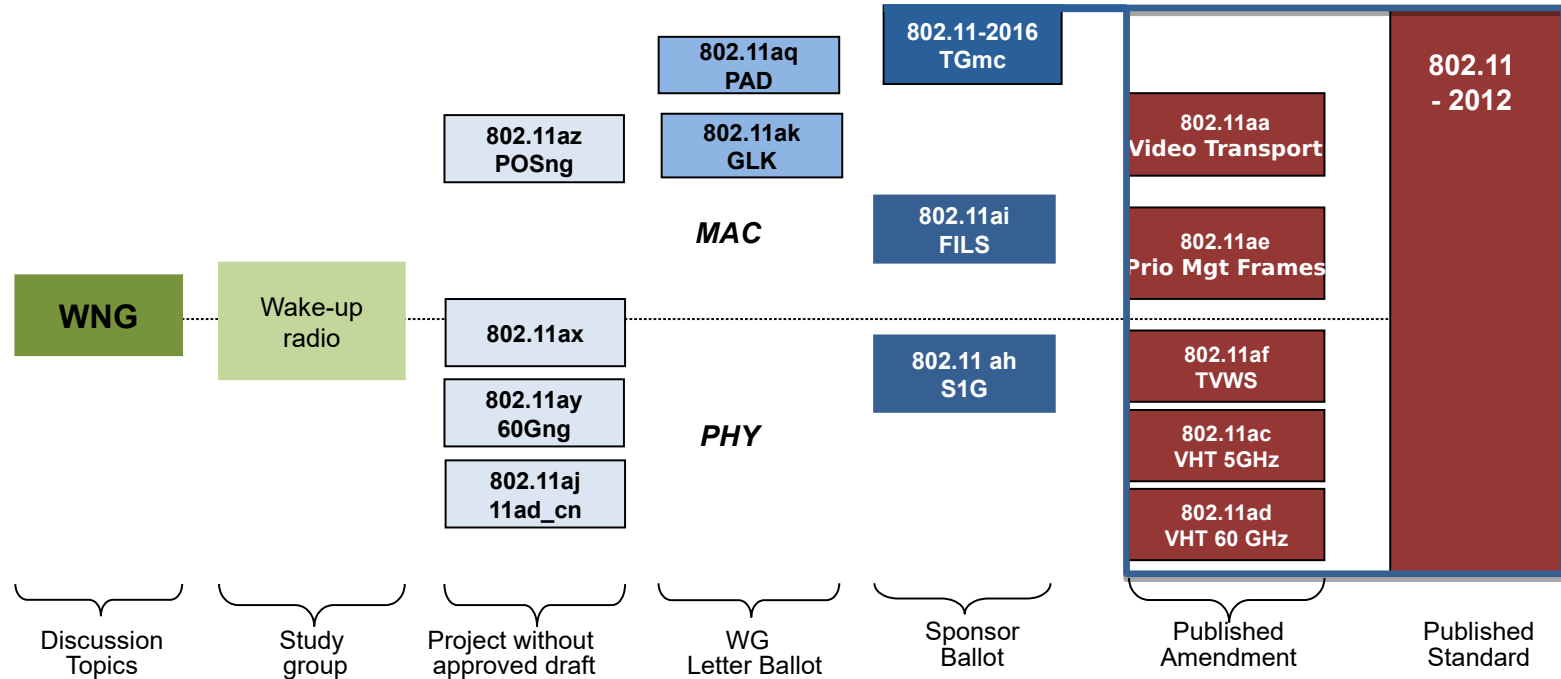
IEEE 802.11-2012	Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) spec	Mar 2012
IEEE 802.11aa	MAC Enhancements for Robust Audio Video Streaming	May 2012
IEEE 802.11ad	Enhancements for Very High Throughput in the 60 GHz Band	Dec 2012
IEEE 802.11ae	Prioritization of Management Frames	Apr 2012
IEEE 802.11ac	Enhancements for Very High Throughput for Operation in Bands below 6 GHz	Dec 2013
IEEE 802.11af	TV White Spaces Operation	Dec 2013
IEEE 802.11-2016	Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) spec	Dec 2016
IEEE 802.11ah	Sub 1 GHz license-exempt operation	Dec 2016
IEEE 802.11ai	Fast Initial Link Set-up	Dec 2016
IEEE 802.11aj	China Milli-Meter Wave (CMMW)	Feb 2018
IEEE 802.11ak	Enhancements For Transit Links Within Bridged Networks	Jun 2018
IEEE 802.11aq	Pre-Association Discovery (PAD)	Sep 2018
IEEE 802.11-2020	Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) spec	12/2020

IEEE 802.11 ongoing standardization projects

IEEE 802.11-2020	Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) spec	12/2020
IEEE 802.11ax	High Efficiency WLAN	02/2021
IEEE 802.11ay	Enhanced Throughput for Operation in License-Exempt Bands above 45 GHz	03/2021
IEEE 802.11az	Next Generation Positioning	12/2022
IEEE 802.11ba	Wake Up Radio (WUR)	03/2021
IEEE 802.11bb	Light Communication (LC)	06/2023
IEEE 802.11bc	Enhanced Broadcast Service	06/2023
IEEE 802.11bd	Enhancements for Next Generation V2X	12/2022
P802.11be	Extremely High Throughput	~ 12/2024
P802.11bf	WLAN Sensing	~ 03/2025
P802.11bh	Operation with Randomized and Changing MAC Addresses	~ 09/2024
P802.11bi	Enhanced Service with Data Privacy Protection	~ 03/2026
P802.11REVme	Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) spec	~ 09/2024

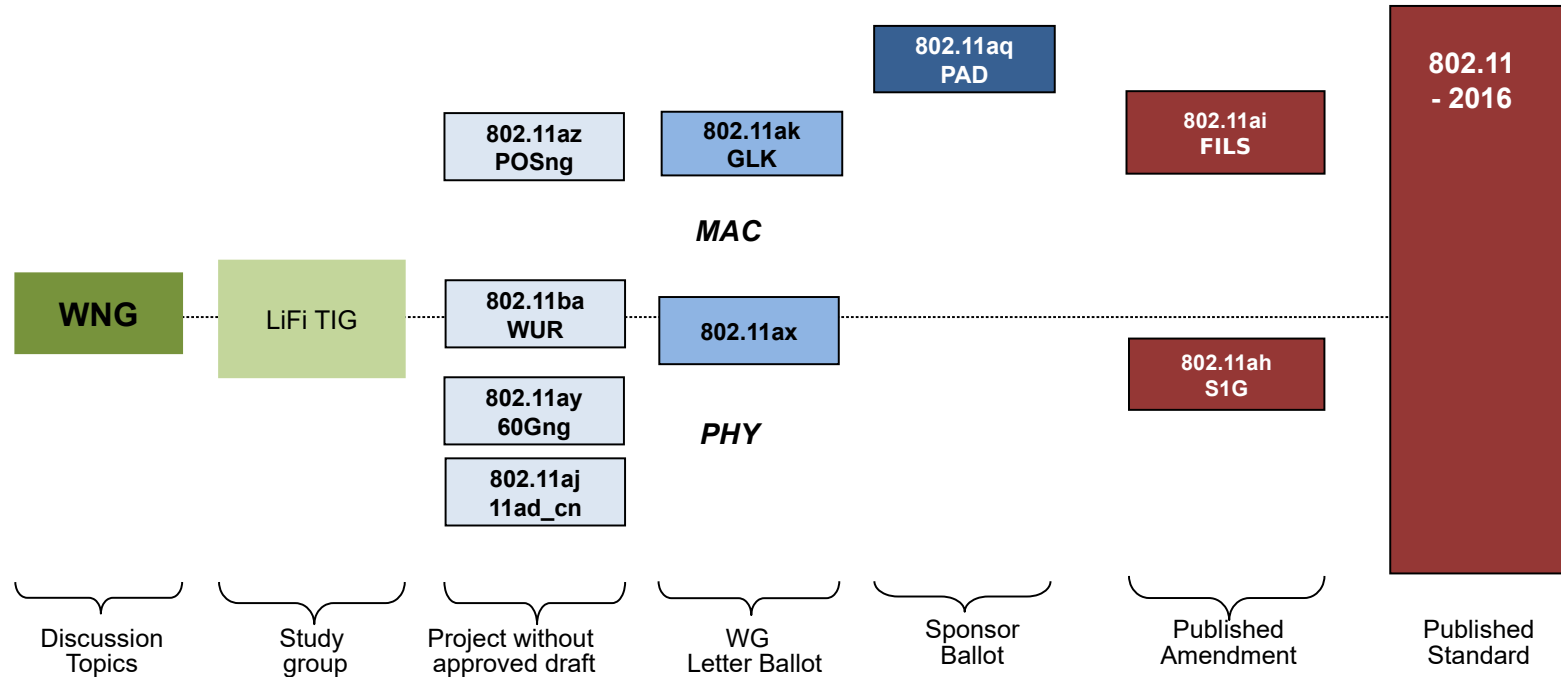
IEEE 802.11 standards development (Status 06/2016)

The working group concurrently operates in different standardization phases



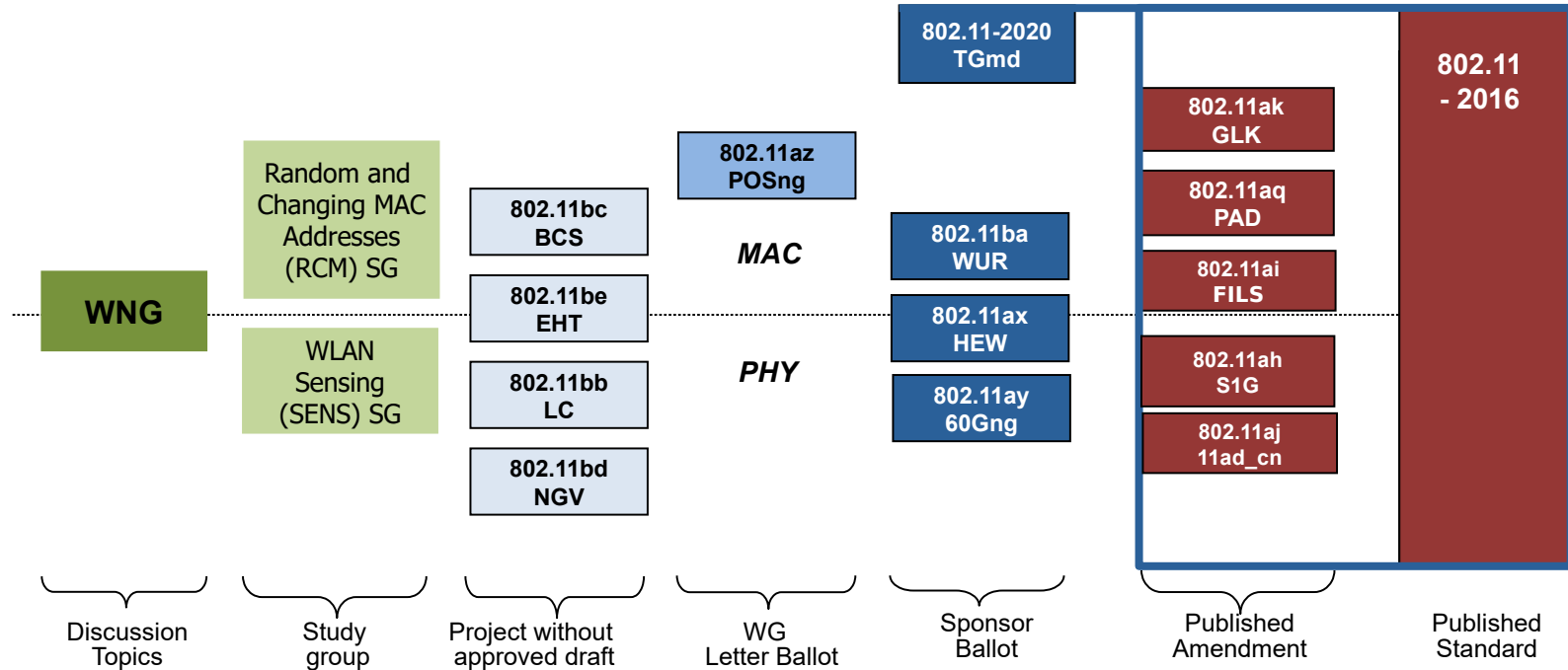
IEEE 802.11 standards development (Status 06/2017)

The working group concurrently operates in different standardization phases



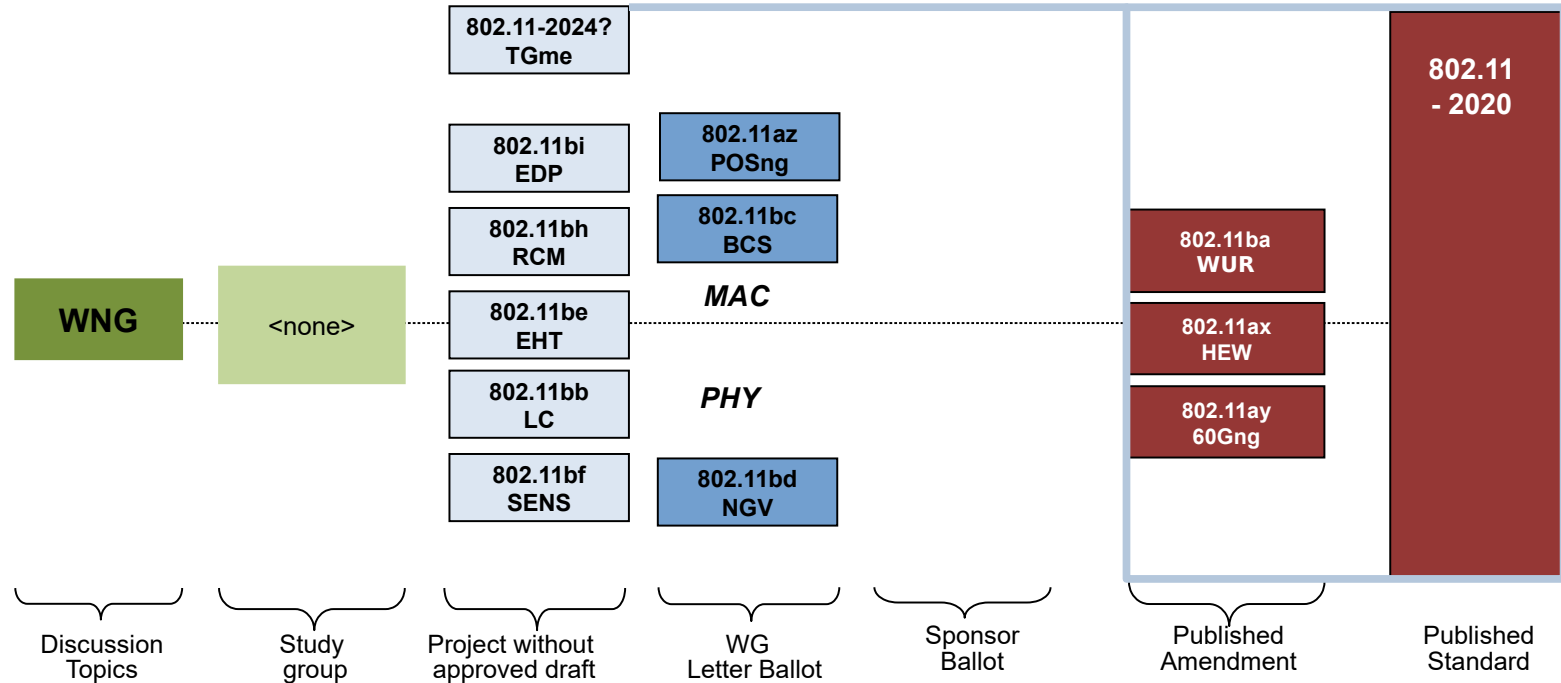
IEEE 802.11 standards development (Status 06/2020)

The working group concurrently operates in different standardization phases



IEEE 802.11 standards development (Status 06/2021)

The working group concurrently operates in different standardization phases



Wi-Fi Standardization Environment

WI-FI ALLIANCE CERTIFICATION

The Wi-Fi Alliance



Wi-Fi CERTIFIED™ makes it Wi-Fi.

To overcome interoperability issues experienced with early IEEE 802.11 products, the Wireless Ethernet Compatibility Alliance (WECA) was founded in 1999 with the completion of IEEE 802.11b.

'Wi-Fi' was introduced as brand-name for interoperable IEEE 802.11 WLAN.

In 2001, WECA became the

Wi-Fi Alliance



- Internationally recognized seal of approval for devices meeting industry-agreed standards for interoperability, security, and application specific protocols
- Interoperable with billions of installed devices
- Proven performance and security that provide positive user experiences
- ISO 17025 certification process of development and testing; testing conducted at independent test organizations around the world

The Wi-Fi Alliance Approach to Certification

Wi-Fi CERTIFIED products have to demonstrate that they can perform well in networks with other Wi-Fi CERTIFIED products, running common applications, in situations similar to those encountered in everyday use.

Interoperability

Rigorous test cases are used to ensure that products from different equipment vendors can interoperate in a wide variety of configurations.

Backward Compatibility

Backward compatibility protects investments in legacy Wi-Fi products and enables users to gradually upgrade and expand their networks.

Innovation

Timely introduction of new certification programs as the latest technology and specifications come into the marketplace. Equipment vendor can differentiate in areas that are not covered by certification testing.

Generational Wi-Fi technology notation

- Up to 802.11ax, Wi-Fi radio technologies were identified through the project acronym of the related IEEE 802.11 standardization project.
 - 802.11a, 802.11b, 802.11g, 802.11n, 802.11ac
- It led to ambiguous communication and slow adoption of new Wi-Fi radio technologies through the market.
- Aligned to the much better perceived notation of radio technologies in the cellular market, Wi-Fi Alliance moved forward and introduced a similar notation for Wi-Fi radio technologies.
 - E.g. cellular communications: 1G -> 2G -> 3G -> 4G -> 5G
- The next Wi-Fi radio technology based on IEEE 802.11ax will be denoted 'Wi-Fi 6'.
 - Wi-Fi certified products are identified through 'Wi-Fi CERTIFIED™ 6'
 - Wi-Fi 6E denotes the Wi-Fi 6 version able to operate also in the new 6 GHz band.



Visualization of Wi-Fi generations

- Identification and visualization of various Wi-Fi radio technologies:

If the most advanced technology a device supports is ...	Then it shall be identified as generation
802.11ax	Wi-Fi 6
802.11ac	Wi-Fi 5
802.11n	Wi-Fi 4



- A simple and clear identification allows the user to distinct the radio technology supported by the equipment and used for a connection.
 - The main intention is the faster market adoption of new Wi-Fi technologies by creating more evident demand of users and operators.

Wi-Fi Alliance certification programs - overview

Connectivity	Security	Access	Additional
Wi-Fi CERTIFIED 6™	Wi-Fi CERTIFIED WPA3™	Wi-Fi CERTIFIED Passpoint®	Power saving features
Wi-Fi CERTIFIED™ n	Wi-Fi CERTIFIED Enhanced Open™	Wi-Fi CERTIFIED Easy Connect™	Wi-Fi CERTIFIED Home Design™
Wi-Fi CERTIFIED™ ac	Protected Management Frames	Wi-Fi CERTIFIED Wi-Fi Protected Setup™	
Wi-Fi CERTIFIED WiGig™			
Wi-Fi CERTIFIED Wi-Fi Direct™			
Optimization		Applications	Coexistence
Wi-Fi CERTIFIED EasyMesh™	Wi-Fi CERTIFIED Vantage™	Wi-Fi CERTIFIED Miracast™	CWG-RF
Wi-Fi CERTIFIED Data Elements™	Wi-Fi CERTIFIED WMM® (Wi-Fi Multimedia™)	Wi-Fi CERTIFIED Voice-Enterprise	
Wi-Fi CERTIFIED Agile Multiband™	Wi-Fi CERTIFIED WMM-Admission Control	Wi-Fi CERTIFIED Wi-Fi Aware™	
Wi-Fi CERTIFIED Optimized Connectivity™	Wi-Fi CERTIFIED WMM-Power Save	Wi-Fi CERTIFIED Location™	

Connectivity certification programs

Program	Description	Remarks
Wi-Fi CERTIFIED n	Based on the IEEE 802.11n ratified standard. Includes Wi-Fi radio standards - 802.11a, 802.11b, 802.11g in single, dual mode as required for backward compatibility. Also denoted as Wi-Fi 4.	Includes also Wi-Fi Multimedia (WMM) testing
Wi-Fi CERTIFIED ac	Based on IEEE 802.11ac standard and associated with the fifth Wi-Fi generation, Wi-Fi CERTIFIED ac operates in 5 GHz and is capable of gigabit data rates. Also denoted as Wi-Fi 5	Requires devices to pass all CERTIFIED n tests
Wi-Fi CERTIFIED 6	Based on the IEEE 802.11ax standard, Wi-Fi CERTIFIED 6 is the newest generation of Wi-Fi technology operating in 2.4, 5, and 6 GHz. Wi-Fi CERTIFIED 6 provides greater capacity, multi-gigabit data rates, better power efficiency, and high performance even in densely populated environments. Wi-Fi 6E introduces the advancements of Wi-Fi 6 into the 6 GHz spectrum.	Requires devices to pass all CERTIFIED ac tests
Wi-Fi CERTIFIED WiGig	Utilizes the 60 GHz frequency band to enable extremely high performance, multi-gigabit connectivity and low latency for a range of applications, including wireless docking, augmented reality/virtual reality (AR/VR), high-definition multimedia streaming, gaming, and networking.	
Wi-Fi Direct	Allows Wi-Fi client devices to connect directly to one another without use of an access point.	

Security certification programs

Program	Description	Remarks
Wi-Fi CERTIFIED WPA3™ (Wi-Fi Protected Access 3)	Most advanced security capabilities for personal and enterprise Wi-Fi networks; simplifies Wi-Fi security configuration and enhances network security protections.	
Wi-Fi Enhanced Open™	Brings data protection to users in open networks without the need for user intervention	
Protected Management Frames	Extends security protections to unicast and multicast management action frames, maintaining the resiliency of mission-critical networks	

Optimization certification programs

Program	Description	Remarks
TDLS (Tunneled Direct Link Setup)	Allows network-connected devices to create a secure, direct link to transfer data more efficiently	
WMM® (Wi-Fi Multimedia™)	Support for multimedia content over Wi-Fi networks enabling Wi-Fi networks to prioritize traffic generated by different applications using Quality of Service (QoS) mechanisms.	“WMM Technical Specification”
WMM-Admission Control	Enhanced bandwidth management tools to optimize the delivery of voice and other traffic in Wi-Fi® networks.	“WMM Technical Specification”
WMM-Power Save	Power savings for multimedia content over Wi-Fi networks - helps conserve battery life while using voice and multimedia applications by managing the time the device spends in sleep mode	
Wi-Fi QoS Management™:	Enables devices, applications, and network managers to prioritize traffic flows, providing consistent end-to-end Quality of Service treatment, and quality experiences with real-time applications.	
Wi-Fi Agile Multiband™:	Enables client devices and access points (APs) to exchange information so the Wi-Fi network can guide devices to the best bands, channels, and APs to maximize system efficiency and provide the best user experience.	

Optimization certification programs, cont

Program	Description	Remarks
Wi-Fi Optimized Connectivity™:	Optimizes roaming and network selection in managed network environments through improved scanning, link quality metric assessment, faster initial authentication, and more efficient transmissions	
Wi-Fi Vantage™:	Provides an ongoing evolution of advanced features to elevate the user experience in managed Wi-Fi networks	
Wi-Fi EasyMesh™:	Brings a standards-based approach to residential and small office Wi-Fi networks that utilize multiple access points. Wi-Fi EasyMesh delivers scalable, smart Wi-Fi networks that are easy to set up and manage.	
Wi-Fi Data Elements™:	Establishes a standardized set of key performance indicators for ensuring the health of Wi-Fi networks, enabling service providers to deliver better Wi-Fi service, potentially reduce customer support calls, and increase customer satisfaction; also provides a necessary foundation for Wi-Fi EasyMesh networks.	

Wi-Fi CERTIFIED Certificate, e.g. Samsung Galaxy S20

Summary of Certifications – Samsung SM-G980

CLASSIFICATION	CERTIFICATION
Applications & Services	Voice-Enterprise Wi-Fi Aware™ Wi-Fi Direct®
Connectivity	2.4 GHz Spectrum Capabilities 5 GHz Spectrum Capabilities Wi-Fi CERTIFIED 6™ Wi-Fi CERTIFIED™ a Wi-Fi CERTIFIED™ ac Wi-Fi CERTIFIED™ b Wi-Fi CERTIFIED™ g Wi-Fi CERTIFIED™ n Wi-Fi Enhanced Open™ 2018-04
Optimization	WMM® WMM®-Admission Control WMM®-Power Save Wi-Fi Agile Multiband™ Wi-Fi Optimized Connectivity™ 2018
Security	Protected Management Frames WPA3™-Enterprise 2018-04 WPA3™-Personal 2019-08

<https://www.wi-fi.org/product-finder>

Questions and answers



Standards Environment questions...

- 1) Where does IEEE 802.11 stem from?
- 2) Which organization introduced the term 'Wi-Fi'?
- 3) What is the purpose of the Wi-Fi Alliance?
- 4) To which IEEE standardization organization belongs IEEE 802.11?
- 5) Which IEEE 802.11 standards and amendments are comprised in IEEE Std 802.11-2020?
- 6) Which layers of the ISO-OSI model are addressed in IEEE 802.11 specifications?
- 7) What aspects are covered through the Wi-Fi Alliance certification process?
- 8) On which IEEE radio standards are Wi-Fi 5 and Wi-Fi 6 based on?

WLAN IEEE 802.11 aka Wi-Fi

WI-FI SPECTRUM

Wi-Fi in the 2.4 GHz ISM band

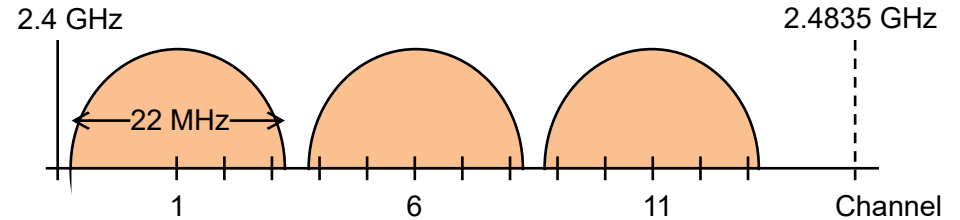
- Most of Wi-Fi today operates in the 2.4 GHz ISM band (13 channels)

- In the US, only channels 1 – 11 are allowed.
- IEEE 802.11b set the legacy rule to deploy Wi-Fi systems on channels 1 – 6 – 11
- Plain IEEE 802.11 OFDM systems (802.11g/n/ax) would not interfere when operating on channels 1 – 5 – 9 – 13
- Hint: Follow established usage patterns to avoid collisions with multiple channels (stay in the lane)

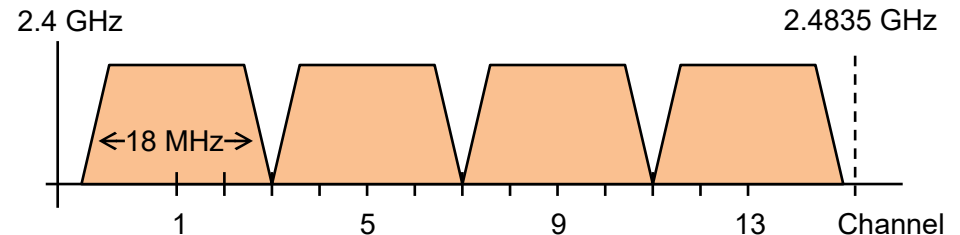
- European regulatory requirements:

- max TX power: 100 mW EIRP
- Use of spread spectrum coding
- Specification: ETSI EN 300 328

Legacy Wi-Fi (802.11b) requires 22 MHz channels

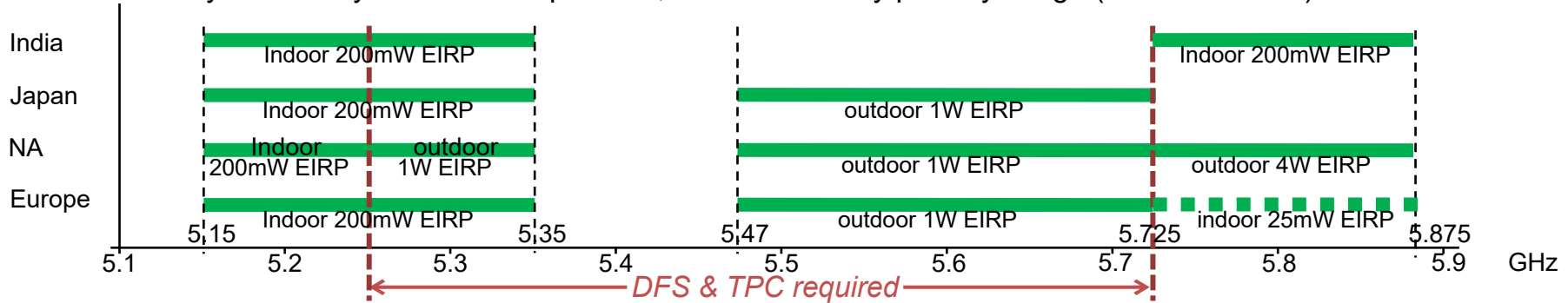


OFDM (802.11g/n/ax) fits into 20 MHz channels

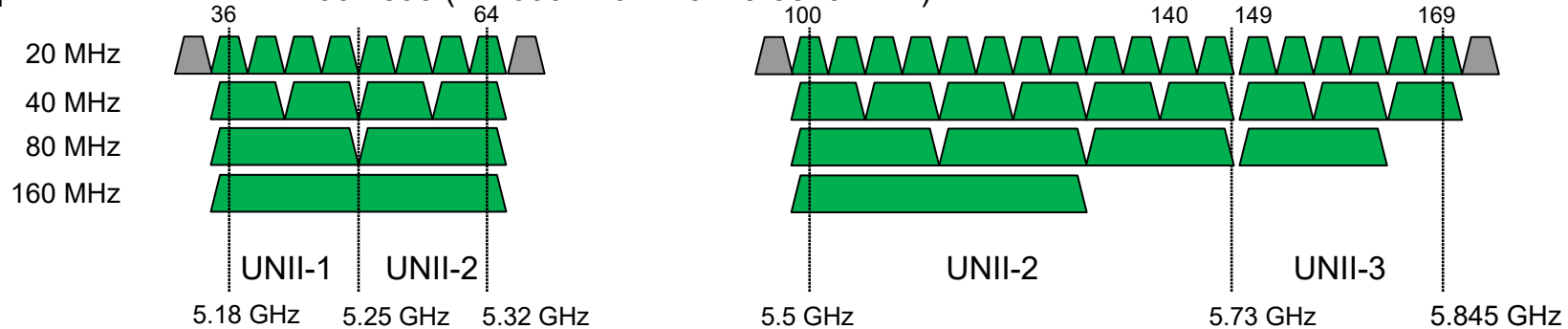


License-exempt operation in the 5 GHz band

- 455 MHz of licensed-exempt spectrum available mostly worldwide
 - Wi-Fi is usually secondary user of that spectrum, and has to obey primary usage (weather radars).



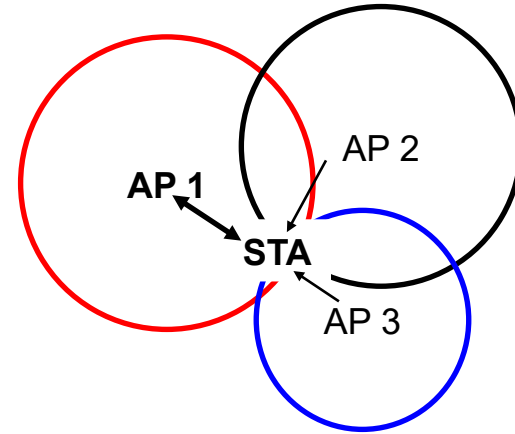
- Dynamic Frequency Selection (DFS) and Transmission Power Control (TPC) are required for most of the 5 GHz spectrum to protect primary users (e.g. weather radars)
 - Specification: ETSI EN 301 893 (EN 300 440 for 5725-5875 MHz)



Spectrum management for the 5 GHz band

- DFS (Dynamic Frequency Selection)

- APs dynamically select their operating channel after scanning for other users (e.g. weather radars)
- STAs provide to APs detailed reports about spectrum usage at their locations.
- In the case of detection of other spectrum users, APs stop operation and move to other (free) channels.

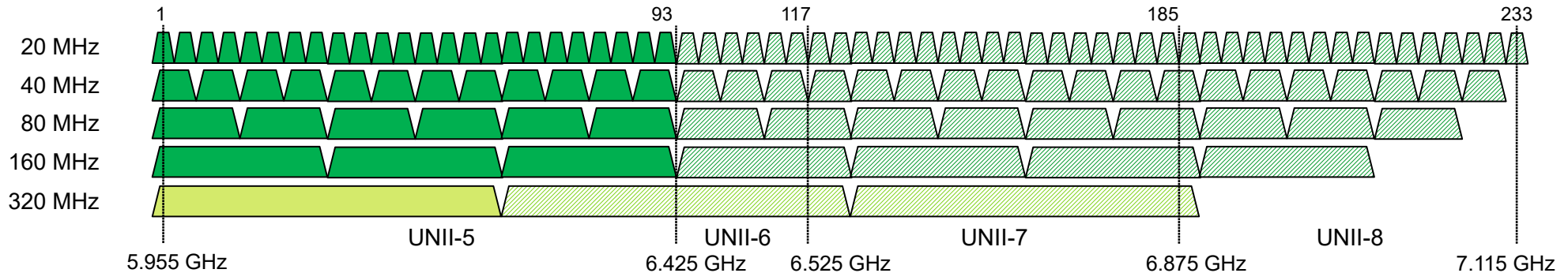


- TPC (Transmission Power Control)

- Supports interference minimization, power consumption reduction, range control and link robustness.
- APs define and communicate regulatory and local transmit power constraints.
- Stations select transmit powers for each frame according to local and regulatory constraints.

License-exempt extension into 6 GHz band

- New Wi-Fi spectrum in the 6 GHz band (5925 – 6425 – 7125 MHz)
 - Full 1.2 GHz band enabled by FCC, many other countries around the world following
 - Europe enables 5925 – 6425 MHz for license-exempt secondary usage
 - (up to) 3 device categories
 - Very Low Power (~ 25 mW EIRP) allowed also for outdoor,
 - Low Power (~ 200 mW EIRP) only indoor;
 - Potentially, higher power (up to 4W EIRP) with AFC (automatic frequency control)
- 6 GHz allows for wider channels (320 MHz) and legacy-free Wi-Fi operation (only Wi-Fi 6E)



Questions and answers



Wi-Fi spectrum questions...

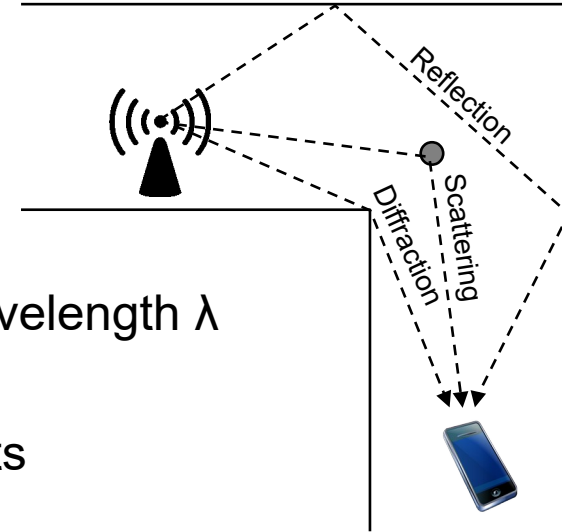
- 1) What would be the optimal channel arrangement for a 802.11g/n-only system in Europe?
- 2) Why often the channel arrangement 1 – 6 – 11 is used?
- 3) Which channel bandwidth does IEEE 802.11b occupy?
- 4) What is the purpose of DFS and TPC in the 5 GHz band?
- 5) For which frequencies is the support of DFS and TPC mandatory in Europe?
- 6) How many non-overlapping 80MHz channels can fit in the 5 GHz range in Europe?
- 7) What is the 6 GHz band?
- 8) How much spectrum is available in the 6 GHz band in Europe and in the US?

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WIRELESS CHANNEL CHARACTERISTICS

Radio signal propagation issues

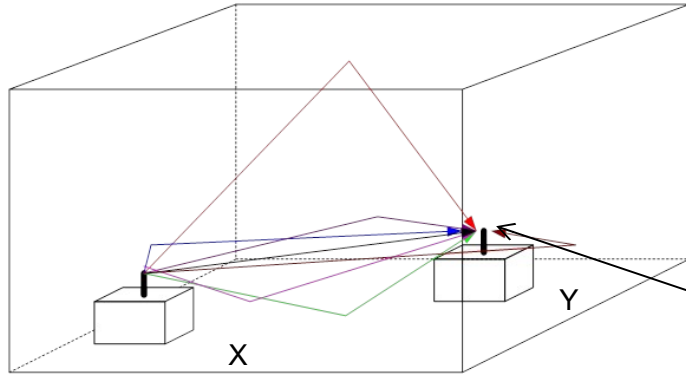
- Path loss
 - Attenuation due to distance and frequency
- Reflection
 - Surface large relative to wavelength λ of signal
- Diffraction
 - Edge of impenetrable body that is large relative to wavelength λ
- Scattering
 - Obstacle size in order of wavelength λ , e.g. lamp posts



Main issues:

- Line-Of-Sight:
 - Reflected signals may cause major impact on signal
- non-Line-Of-Sight:
 - Diffraction and scattering are primary means of reception

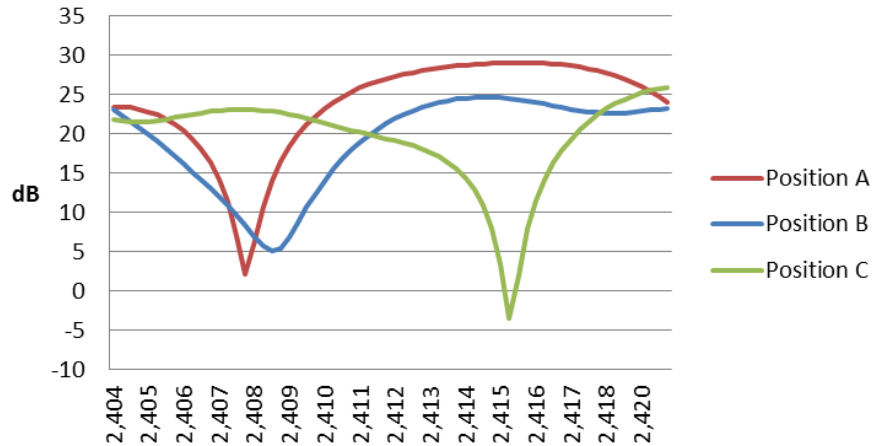
WLAN channels with selective fading



Example of selective fading

- Reference doc.: IEEE 802.11-13/0416r5
- Use of ray tracing to estimate delays
- Scenario
 - Room 100 ft by 70 ft (x, y)
 - Ceiling 20 ft
 - RX position (65, 44 w/ 3ft off ground)
 - 10dB obstruction to direct and floor rays

Relative Selective Fading



Transmission characteristics taken for

- Position A (21, 45) (delays 23 - 100 ns)
- Position B (30, 45) (delays 27 - 102 ns)
- Position C (13, 45) (delays 21 - 99 ns)

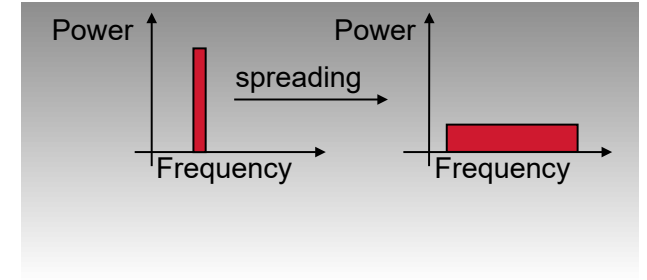
Fades up to 25 dB!

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DIRECT SEQUENCE SPREAD SPECTRUM (DSSS)

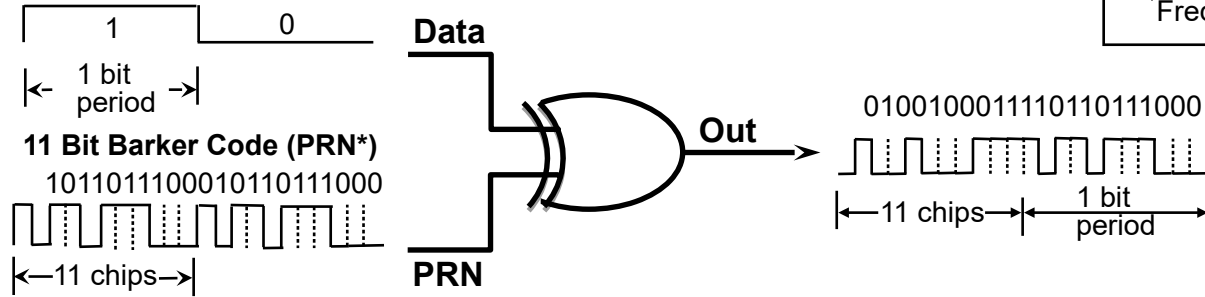
Legacy IEEE802.11 PHY layer solutions for 2.4 GHz

- 2.4 GHz Direct Sequence Spread Spectrum
 - DBPSK/DQPSK providing 1/2 Mbps
 - Channel bandwidth: 22 MHz
- 2.4 GHz High Rate DSSS (**802.11b – Wi-Fi 1**)
 - CCK/DQPSK providing 5.5/11 Mbps
 - Channel bandwidth: 22 MHz

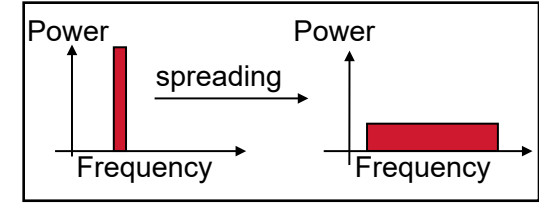


Direct Sequence Spread Spectrum

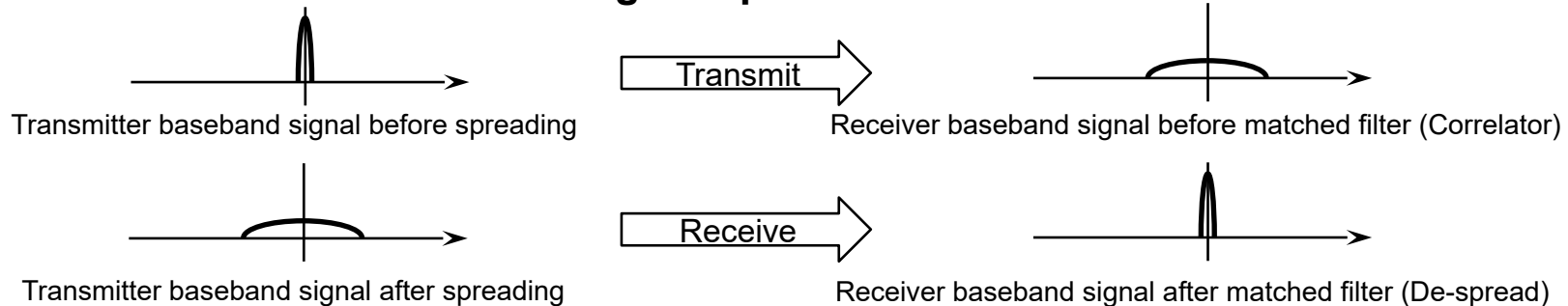
RF energy is spread by XOR of data with PRN sequence



* PRN: Pseudorandom Number



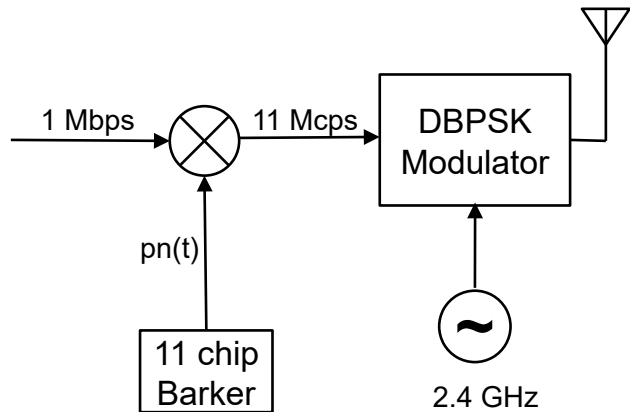
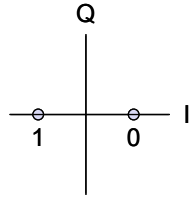
Signal Spectrum



Modulation of spreaded signal to carrier

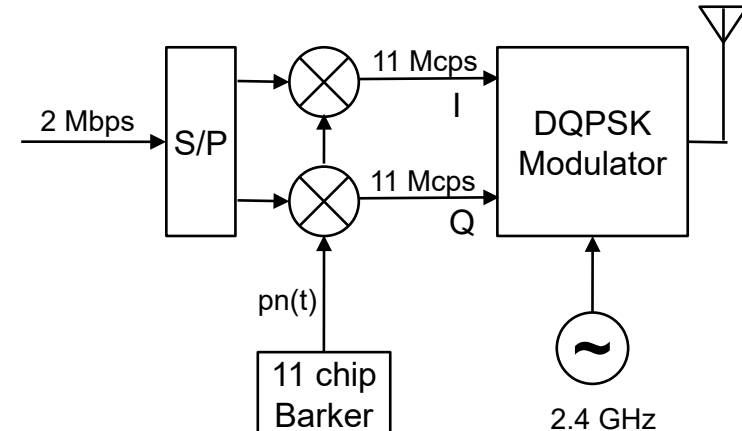
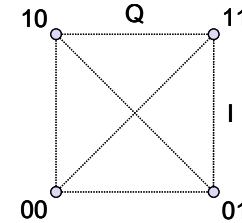
1 Mbps by DBPSK

- Differential Binary Phase Shift Keying
 - $0 = 0$
 - $1 = \pi$



2 Mbps by DQPSK

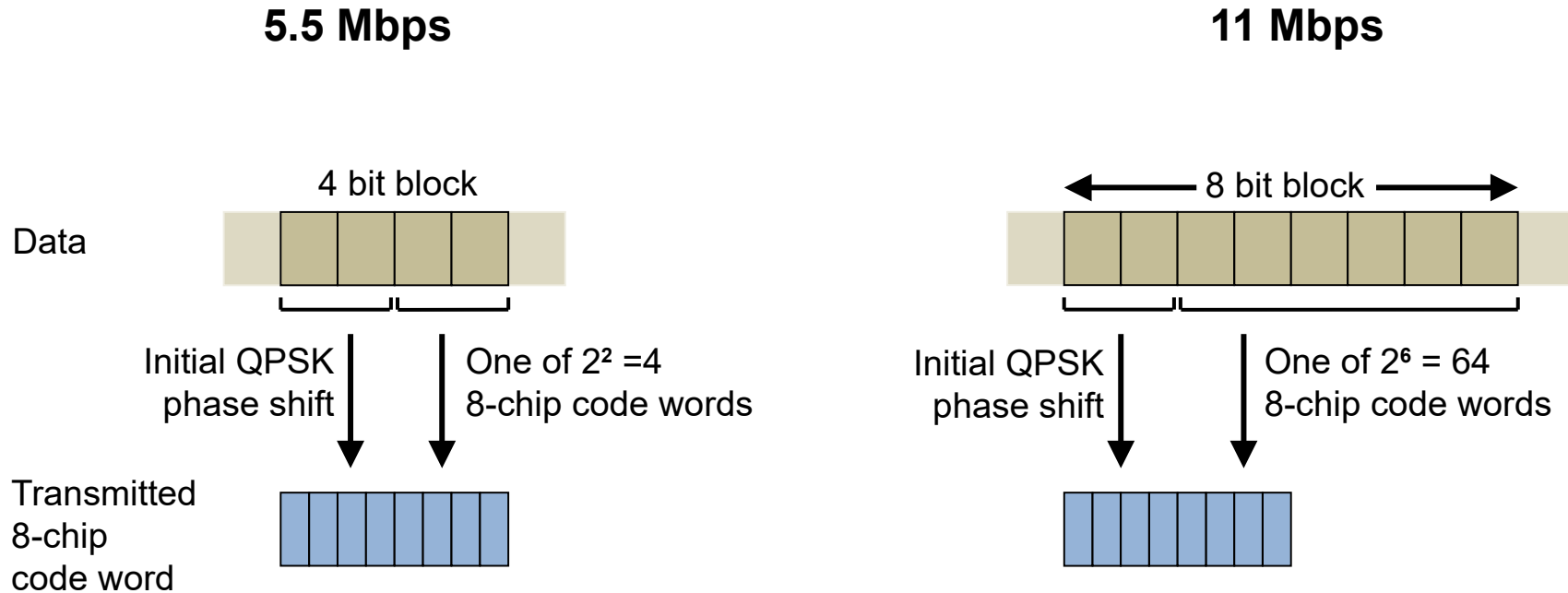
- Differential Quadrature Phase Shift Keying
 - $00 = 0$
 - $01 = \pi/2$
 - $10 = -\pi/2$
 - $11 = \pi$



High Rate DSSS (IEEE 802.11b) overview

- Efficient coding scheme using the same spectrum allocation of a 802.11 DSSS system
 - Introduced by IEEE 802.11b
- Basic idea:
 - Instead of transmitting a spreaded signal with a particular code sequence, different complex code sequences are used for spreading the transmitted signal
 - Each 8-bit word of the original signal is encoded with a complex chip word consisting of 8 symbols; the chip rate is 11 Mchip/s.
 - Complementary Code Keying (CCK)
 - Leads to practically the same spectrum allocation as a DSSS system

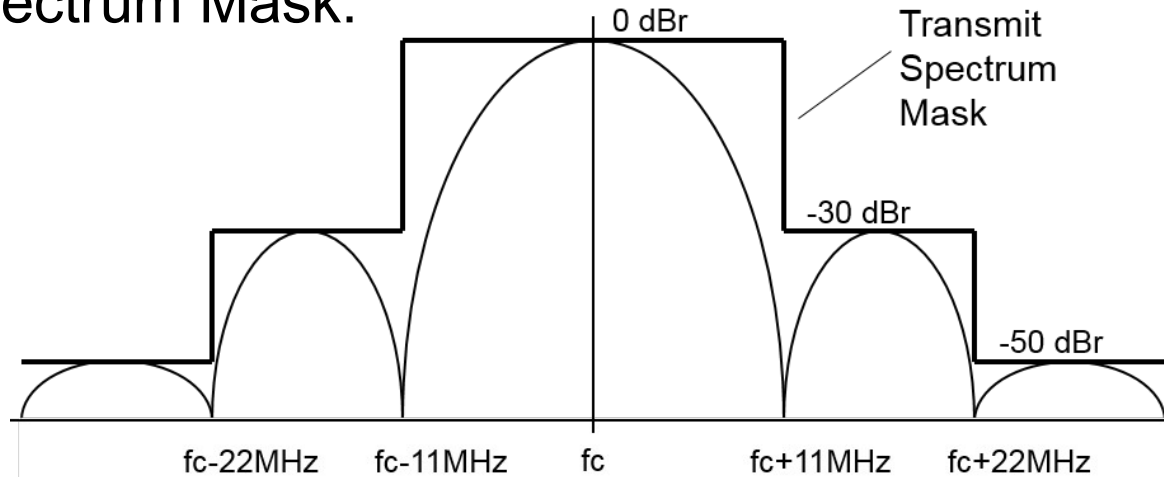
Complementary Code Keying (CCK)



Code word repetition rate = 1.375 Mwords/s

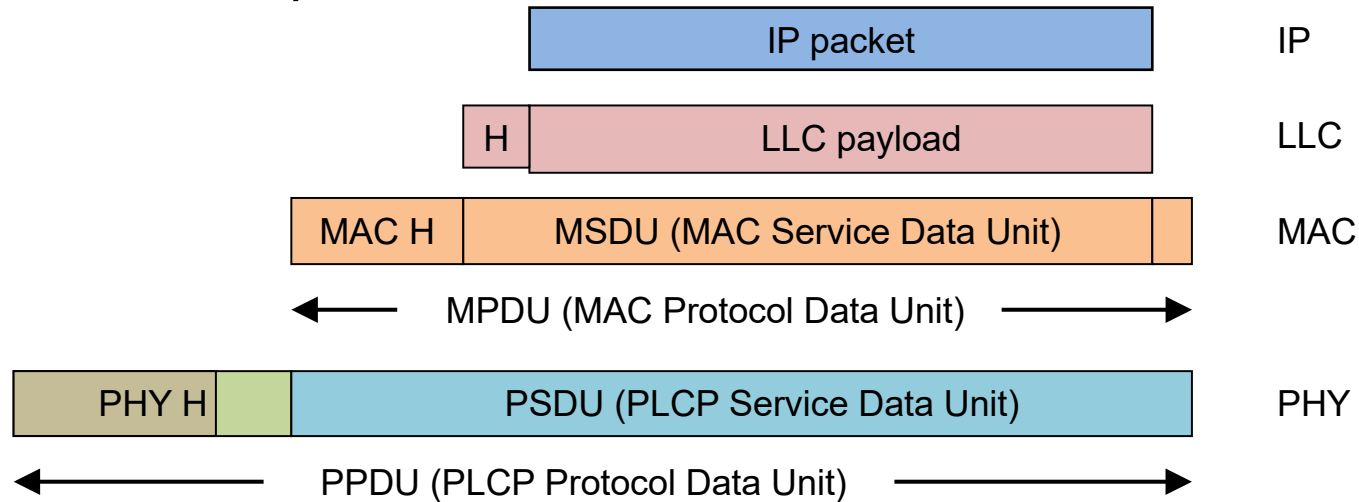
HR/DSSS Summary and Spectrum

- Maximum data rate: 11 Mbps
 - intermediate steps: 1, 2, 5.5, 11 Mbps
- Modulation: BPSK, DQPSK, CCK
 - CCK = Complementary Code Keying
 - High data rate DSSS coding with inherent spreading
- Channel bandwidth: 22 MHz
- HR/DSSS Spectrum Mask:



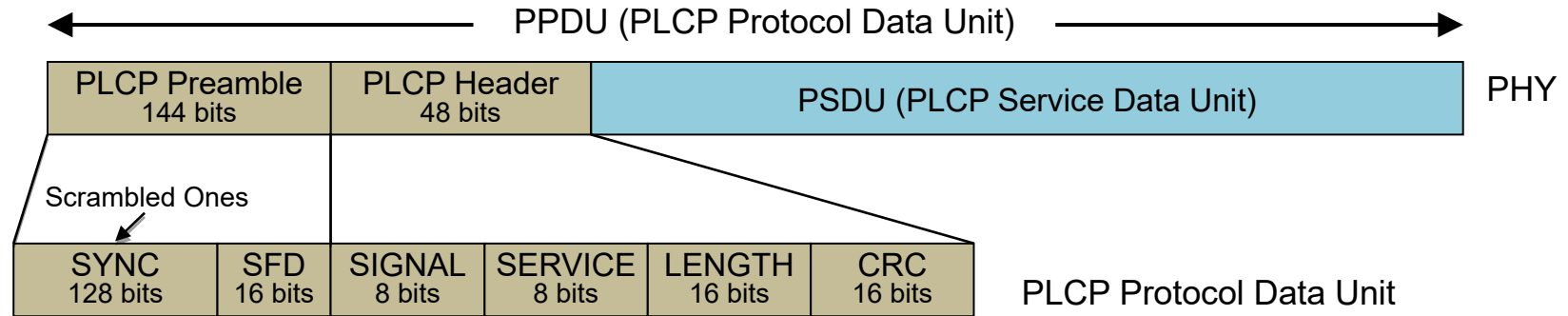
IEEE 802.11 Frame structure overview

- Each protocol layer deploys its own header for conveying the protocol information between peers



- IEEE 802.11 PHY header carries the information for setting up the reception of radio frames
- Physical Layer Convergence Protocol (PLCP) provides a PHY independent Service Access Point (SAP) for higher layers

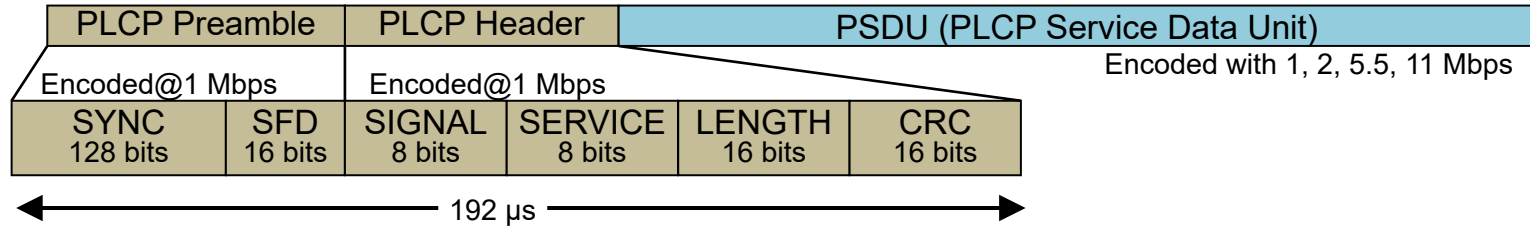
DSSS Physical Layer Convergence Protocol (PLCP)



- SYNC - gain setting, energy detection, antenna selection, frequency offset compensation
- SFD - Start Frame Delimiter “0000 1100 1011 1101”, bit synchronization
- SIGNAL - rate indication; (1, 2, 5.5, 11 Mbps)
- SERVICE – used to distinguish the coding schemes
- LENGTH - length of the PSDU part in μs
- CRC - CCITT CRC-16, protects signal, service, and length field
- Coding:
 - PLCP preamble is sent with minimum data rate (1 Mbps)
 - PLCP header is either sent with 1 Mbps (long preamble) or with 2 Mbps (short preamble)

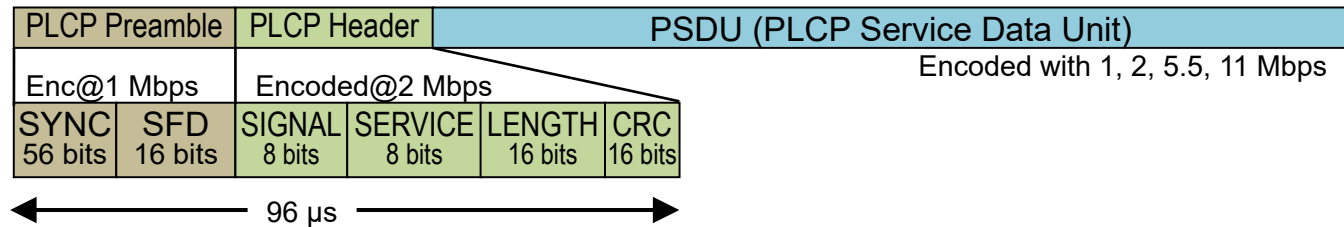
IEEE 802.11 DSSS Preambles

- The Preamble allows the receiver to acquire the wireless signal and synchronize itself with the transmitter.
- **Long Preamble:**



- Compatible with legacy IEEE 802.11 systems operating at 1 and 2 Mbps (Megabits per second)
- PLCP with long preamble is transmitted at 1 Mbps regardless of transmit rate of data frames
- Total Long Preamble transfer time is a constant at 192 μs

- **Short Preamble:**



- Not compatible with legacy IEEE 802.11 systems operating at 1 and 2 Mbps
- PLCP with short preamble: Preamble is transmitted at 1 Mbps and header at 2 Mbps
- Total Long Preamble transfer time is a constant at 96 μs

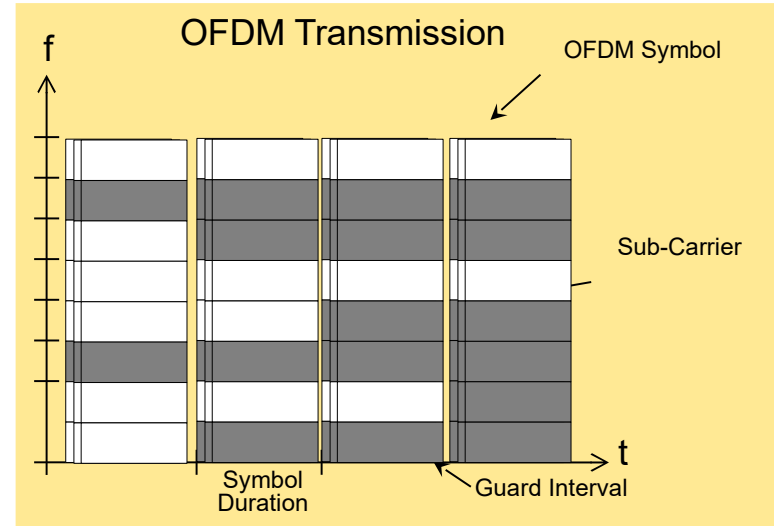
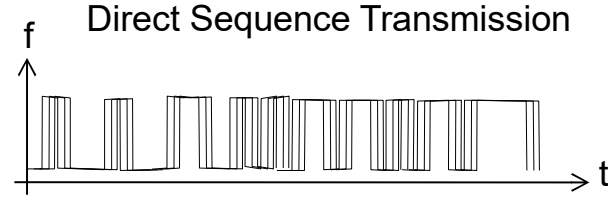
WLAN IEEE 802.11 aka Wi-Fi

ORTHOGONAL FREQUENCY DIVISION MULTIPLEX (OFDM)

Mitigating Delay Spread Channels

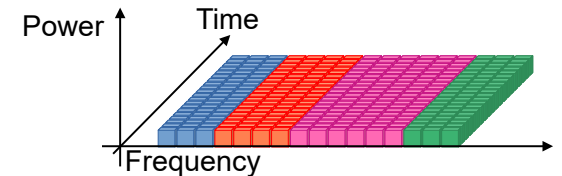
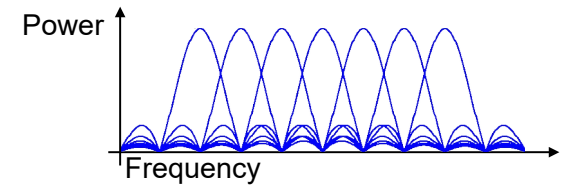
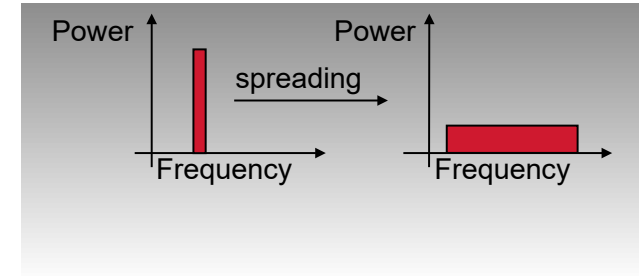
- More robust transmission by transformation of high speed bit sequences into a slower sequence of complex symbols

	D	e	m	o
ASCII	68	101	109	111
128	0	0	0	0
64	1	1	1	1
32	0	1	1	1
16	0	0	0	0
8	0	0	1	1
4	1	1	1	1
2	0	0	0	1
1	0	1	1	1



IEEE802.11 PHY layer solutions for 2.4 GHz, 5 GHz, 6 GHz

- 2.4 GHz Direct Sequence Spread Spectrum
 - DBPSK/DQPSK providing 1/2 Mbps
 - Channel bandwidth: 22 MHz
- 2.4 GHz High Rate DSSS (**802.11b – Wi-Fi 1**)
 - CCK/DQPSK providing 5.5/11 Mbps
 - Channel bandwidth: 22 MHz
- 2.4 GHz Extended Rate (**802.11g – Wi-Fi 3**)
 - DSSS providing 1/2/5.5/11 Mbps
 - OFDM providing 6/9/12/18/24/36/48/54 Mbps
 - Channel bandwidth: 22/20 MHz
- 5 GHz Orthogonal Frequency Division Multiplex (**802.11a – Wi-Fi 2**)
 - OFDM providing 6/9/12/18/24/36/48/54 Mbps
 - Channel bandwidth: 20 MHz
- 2.4 GHz & 5 GHz High Throughput (**802.11n – Wi-Fi 4**)
 - OFDM with up to 4x4 MIMO providing up to 600 Mbps
 - Channel bandwidth: 20 MHz & 40 MHz
- 5 GHz Very High Throughput (**802.11ac – Wi-Fi 5**)
 - OFDM with up to 8x8 DL MU-MIMO providing up to 6900 Mbps (3460 Mbps to single STA)
 - Channel bandwidth: 20 MHz, 40 MHz, 80 MHz, 160 MHz
- 1 – 7.25 GHz High Efficiency (**802.11ax – Wi-Fi 6**)
 - OFDM/OFDMA with up to 8x8 MU-MIMO providing up to 9600 Mbps
 - Channel bandwidth: 20 MHz, 40 MHz, 80 MHz, 160 MHz
- 1 – 7.25 GHz Extremely High Throughput (**802.11be – Wi-Fi 7**)
 - OFDM/OFDMA with up to 8x8 MU-MIMO providing up to 23 000 Mbps
 - Channel bandwidth: 20 MHz, 40 MHz, 80 MHz, 160 MHz, 320 MHz

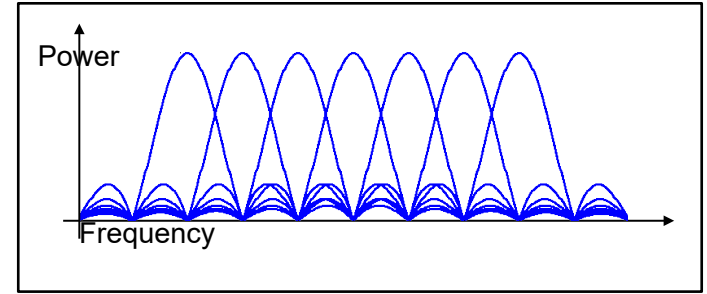


WLAN IEEE 802.11 aka Wi-Fi

WI-FI 2 (OFDM)

Orthogonal Frequency Division Multiplex (OFDM)

- Initially introduced through 802.11a-1999
 - Cooperation with ETSI
- Transforms data into a set of orthogonal signals
 - Each signal is build by a combination of 'tones'
 - Generation/separation by FFT-64
 - IFFT/FFT used for coding/decoding
 - 52 sub-carriers out of the 64 samples used
 - 48 data sub-carriers and 4 pilot sub-carriers
 - 312.5 kHz sub-carrier spacing,
 - Total bandwidth: 16.25 MHz
- One OFDM symbol of a duration of $3.2 \mu\text{s}$ is sent every $4 \mu\text{s}$ (250 kSymbols/s)
 - Guard interval between symbols enable orthogonality of subsequent symbols despite delay spread
- Robust against reflections and multipath propagation



OFDM Throughput calculations

$$\text{Maximum physical data rate} = \frac{N_{SD} \cdot N_{CBPS} \cdot R \cdot N_{SS}}{T_{SYM}}$$

With:

- N_{SD} : Number of data subcarriers
- N_{CBPS} : Number of coded bits per OFDM symbol
- R : Code rate of forward error correction (1/2, 2/3, 3/4, 5/6)
- N_{SS} : Number of spatial streams
- T_{SYM} : OFDM symbol duration including guard time

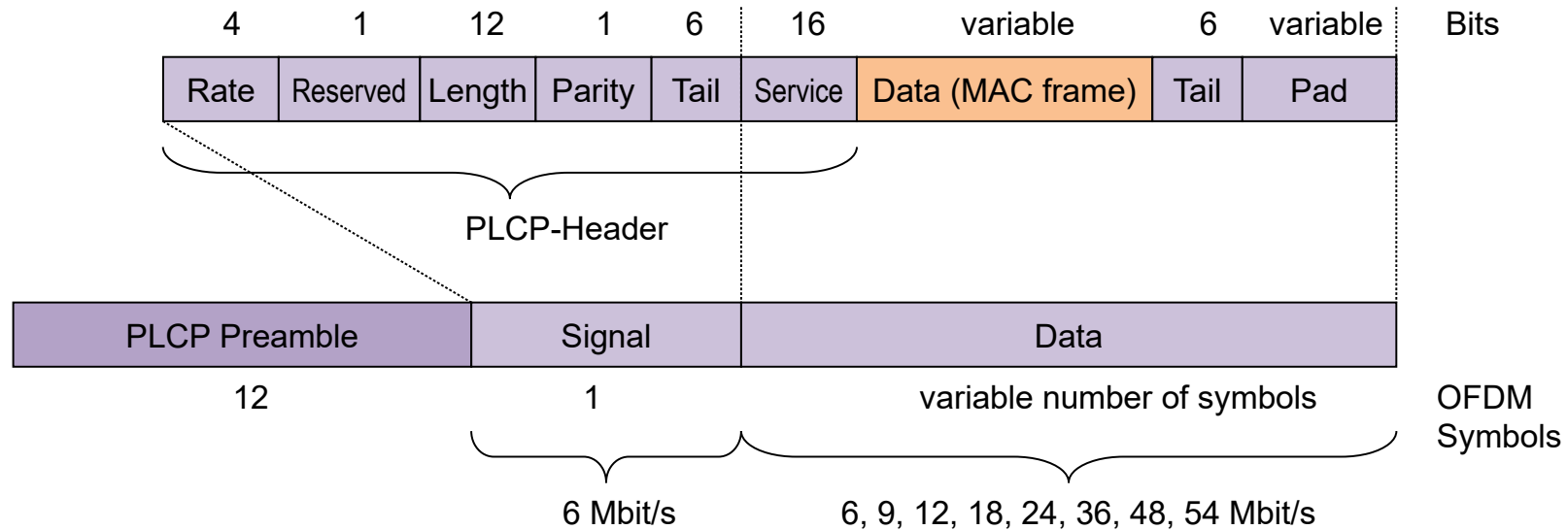
	BPSK	QPSK	16QAM	64QAM	256QAM	1024QAM	4096QAM
N_{CBPS}	1 bit	2 bit	4 bit	6 bit	8 bit	10 bit	12 bit

OFDM - Coding and Modulation (802.11a/802.11g)

- 48 Data sub-carriers
- Sub-carrier modulation:
 - BPSK, QPSK, 16QAM, 64QAM
- Bit interleaved convolutional FEC coding
 - R=1/2, 2/3, 3/4
- Data rates:
 - 6, 9, 12, 18, 24, 36, 48, 54 Mbps

Data Rate (Mbps)	Modulation	Coding Rate	Coded bits per subcarrier	Coded bits per OFDM symbol	Data bits per OFDM symbol	Receive sensitivity
6	BPSK	1/2	1	48	24	- 82 dBm
9	BPSK	3/4	1	48	36	- 81 dBm
12	QPSK	1/2	2	96	48	- 79 dBm
18	QPSK	3/4	2	96	72	- 77 dBm
24	16-QAM	1/2	4	192	96	- 74 dBm
36	16-QAM	3/4	4	192	144	- 70 dBm
48	64-QAM	2/3	6	288	192	- 66 dBm
54	64-QAM	3/4	6	288	216	- 65 dBm

OFDM - PHY Frame Format



- OFDM PHY Preamble with 12 symbols takes 16 μ s
 - 10 short training symbols without guard periods
 - Timing synchronization, antenna selection and locking to the signal
 - 2 long training symbols with guard periods for fine tuning
- Signal is one OFDM symbol with 24 data bits which takes 4 μ s

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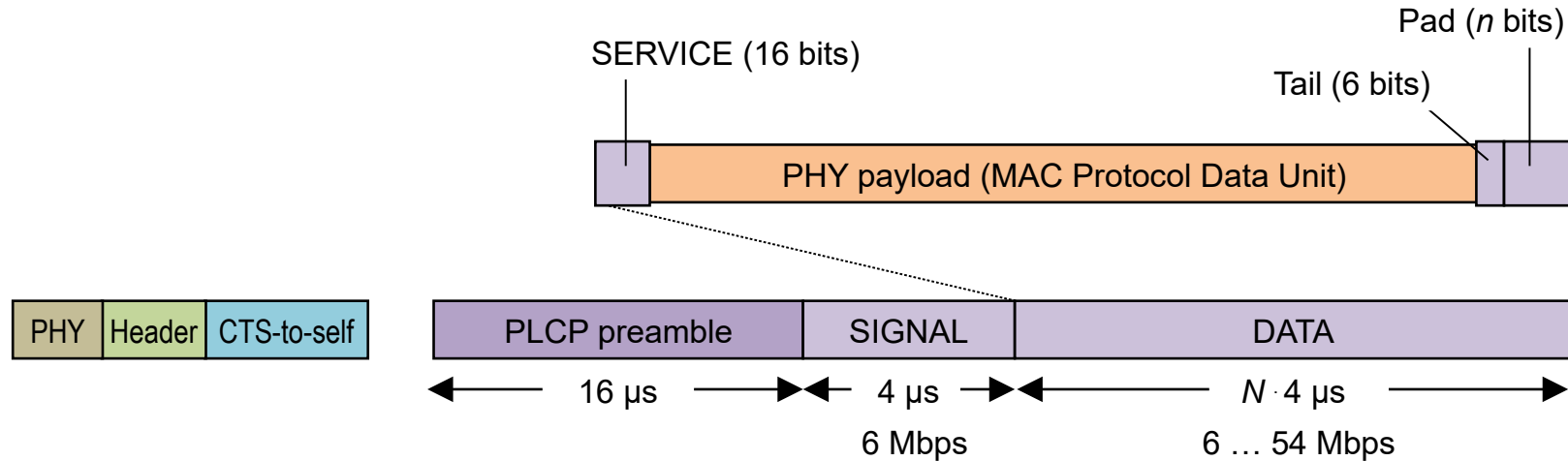
WI-FI 3 (HIGH RATE)

Extended Rate PHY (802.11g)

- Introduced by 802.11g
 - Uses OFDM according to 802.11a in the 2.4 GHz band
 - Backward compatibility with HR/DSSS added
- Support of data rates above 11 Mbps
 - Data rates like 802.11a: 6 Mbps up to 54 Mbps
- Advantages of OFDM in the 2.4 GHz band:
 - worldwide harmonized license-free frequency band
 - lower attenuation than in the 5GHz band
 - less transmission power required
- MAC layer extensions with backward compatibility to HR/DSSS
- Can use same transmission channels as HR/DSSS
 - 18 MHz OFDM fits easily in 22 MHz HR/DSSS channel

ERP PHY frame (OFDM native)

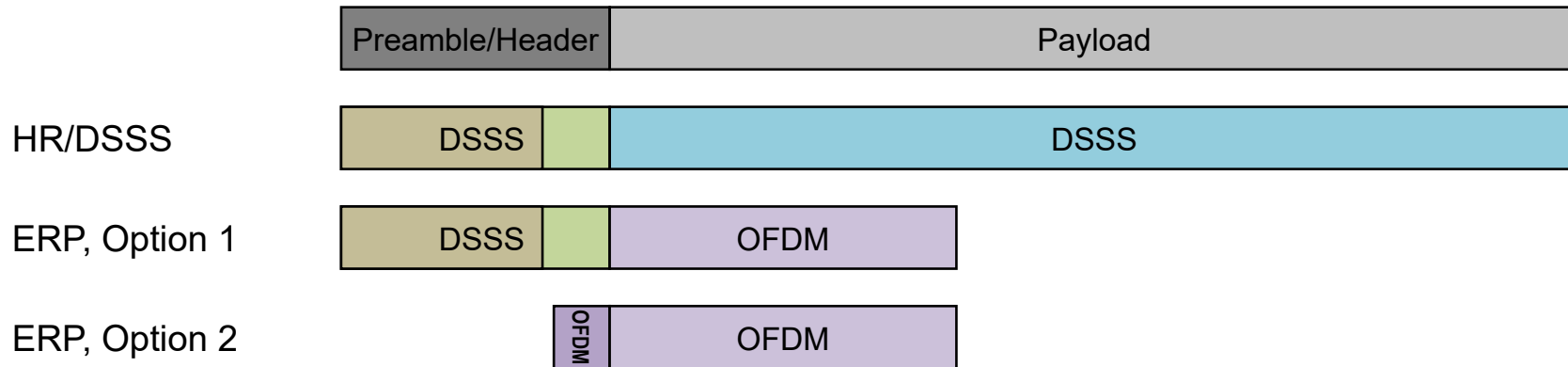
- Without backward compatibility, ERP deploys the same PHY frame as OFDM (802.11a)



- HR/DSSS systems are not able to decode OFDM PHY frames
 - For coexistence an additional protection methods like CTS-to-self or RTS/CTS may be required

ERP – HR/DSSS Interworking

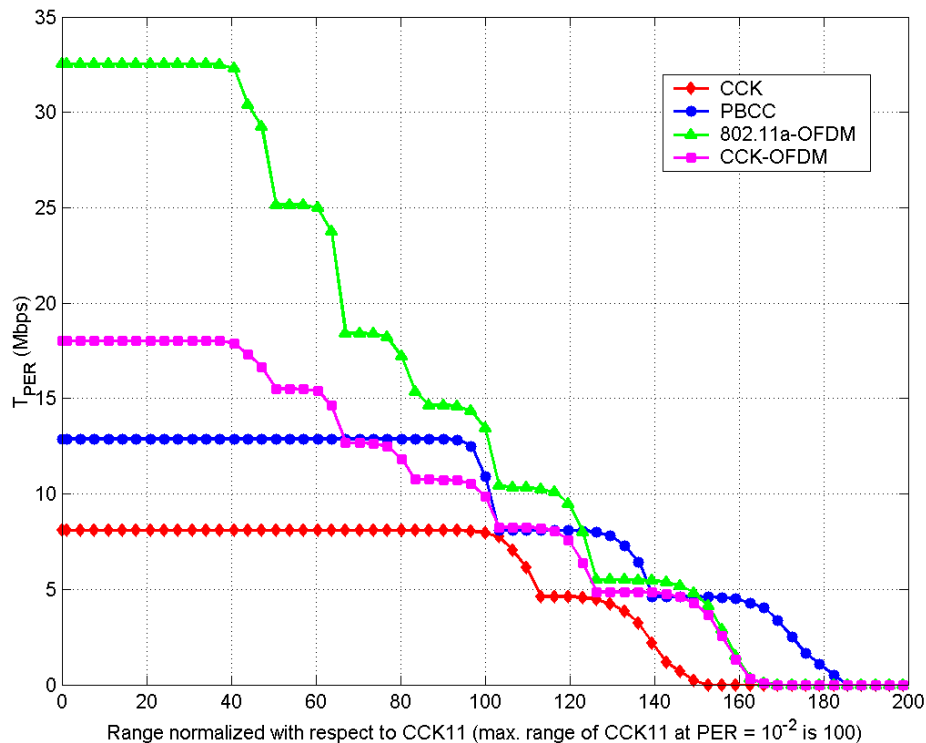
- ERP (802.11g) and HR/DSSS (802.11b) interworking is based on two alternatives regarding the ERP PHY frame structure:



- Option 1 enables HR/DSSS stations to decode the PHY header and keep off the medium according to the Length information
- Option 2 requires additional methods like CTS-to-self or RTS/CTS to provide information to HR/DSSS about other transmissions blocking the medium.

IEEE 802.11 a/b/g – performance and efficiency values

Range vs. Rate



Batra, Shoemake; Texas Instruments;
(Doc: IEEE 802.11-01-286r2)

Efficiency

Mode	Mod.	Coding	Mbps	Mbps	%
OFDM	64-QAM	3/4	54	26.12	48%
OFDM	64-QAM	2/3	48	23.25	48%
OFDM	16-QAM	3/4	36	18.31	51%
OFDM	16-QAM	1/2	24	14.18	59%
OFDM	QPSK	3/4	18	11.50	64%
OFDM	QPSK	1/2	12	8.31	69%
OFDM	BPSK	3/4	9	6.55	73%
OFDM	BPSK	1/2	6	4.64	77%
HR	CCK		11	7.18	65%
HR	CCK		5.5	4.07	74%
DSSS	QPSK		2	1.58	79%
DSSS	BPSK		1	0.81	81%

Huawei Quidway WA1006E Wireless Access Point
(http://www.sersat.com/descarga/quidway_wa1006e.pdf)

WLAN IEEE 802.11 aka Wi-Fi

WI-FI 4 (HIGH THROUGHPUT)

High Throughput (IEEE 802.11n)

- Enhancement to OFDM (5GHz) and ERP (2.4GHz)
 - Up to 600 Mbps in either band
- Main techniques deployed for increase of bitrate:
 - Enhancements to OFDM modulation scheme and timing
 - Channel bonding of two adjacent channels to 40 MHz
 - Up to 4 parallel streams using MIMO (Multiple Input Multiple Output) technique
 - MAC frame aggregation
 - A-MPDU as well as A-MSDU
 - Block acknowledgements

Wi-Fi 4 (802.11n) High Throughput (HT) PHY improvements

- OFDM (54 -> 58.5 Mbps)
 - 52 data sub-carriers instead of 48
- Forward Error Correction (58.5 -> 65 Mbps)
 - 5/6 coding rate in addition to 3/4
- Short Guard Interval (65 -> 72.2 Mbps)
 - 0.4 μ s down from 0.8 μ s
- Channel Bonding (72.2 -> 150 Mbps)
 - 40 MHz by combining two 20 MHz (108 data sub-carrier)
- MIMO (150 -> 600 Mbps)
 - Up to 4 parallel streams

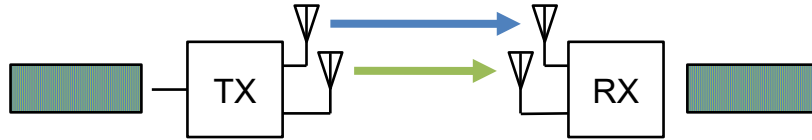
HT (IEEE 802.11n) MCS Options for single stream

MCS Index	Spatial Streams	Modulation type	Coding rate	Data Rate [Mbps]			
				20MHz		40 MHz	
				0.8 μ s GI	0.4 μ s GI	0.8 μ s GI	0.4 μ s GI
0	1	BPSK	1/2	6.5	7.2	13.5	15.0
1	1	QPSK	1/2	13.0	14.4	27.0	30.0
2	1	QPSK	3/4	19.5	21.7	40.5	45.0
3	1	16-QAM	1/2	26.0	28.9	54.0	60.0
4	1	16-QAM	3/4	39.0	43.3	81.0	90.0
5	1	64-QAM	2/3	52.0	57.8	108.0	120.0
6	1	64-QAM	3/4	58.5	65.0	121.5	135.0
7	1	64-QAM	5/6	65.0	72.2	135.0	150.0

- For multiple streams multiply numbers in table by number of streams.

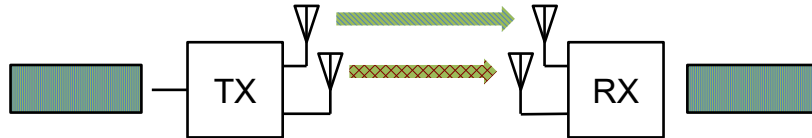
HT MIMO (Multiple Input Multiple Output) versions

- Spatial Multiplexing (SM)



- Subdivides an outgoing signal stream into multiple pieces, transmitted through different antennas.
- When individual streams are received with sufficiently distinct spatial signatures, an SM enabled receiver can reassemble the multiple pieces back into one stream
- Maximizes data rate.

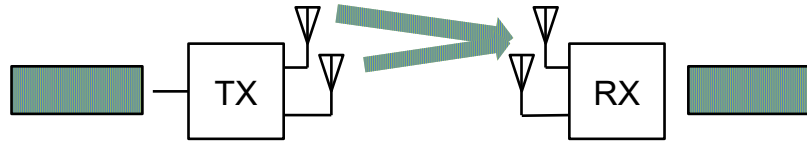
- Space-Time Block Coding (STBC)



- Sends an outgoing signal stream redundantly, using different coding for each of the transmit antennas
- Receiver has a better chance of accurately decoding the original signal stream in the presence of RF interference and distortion.
- STBC improves reliability by reducing the error rate and may be combined with SM.

HT MIMO versions, cont.

- Transmit Beamforming (TxBF)



- Steers signal stream towards the intended receiver by concentrating transmitted RF energy in a given direction.
 - Leverages signal reflection and multipath to improve received signal strength and sustain higher data rates.
 - Required channel knowledge can be obtained implicitly or explicitly by obtaining feedback from the receiver
-
- Availability in HT products:
 - Only Spatial Multiplexing is part of Wi-Fi certification for HT out of the three different MIMO techniques specified in the standard IEEE 802.11n.

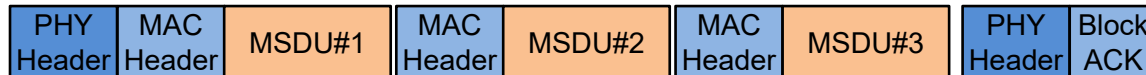
HT MAC Protocol Data Unit Aggregation

- MAC efficiency suffers when transferring sequence of smaller frames



- Frame aggregation increases the payload that can be carried within a single 802.11 physical layer frame

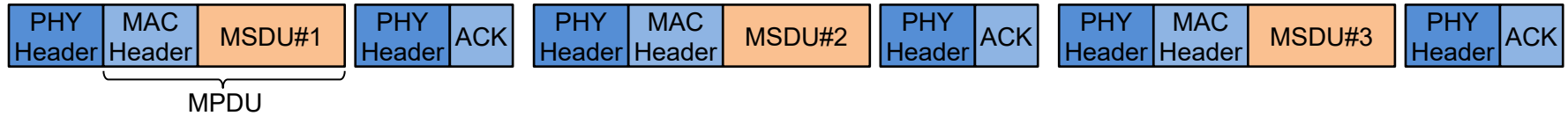
- MAC Protocol Data Unit Aggregation (A-MPDU) groups multiple MPDU sub-frames each with its own MAC header into one PSDU with up to 65535 bytes.



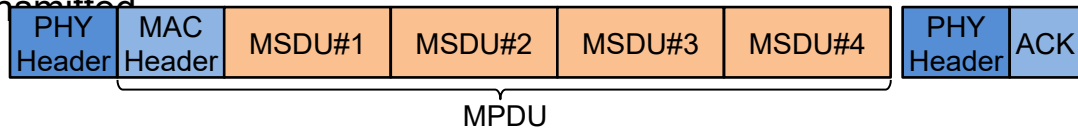
- Reduced Interframe Space (RIFS) of $2\mu\text{s}$ used as delimiter between MPDUs
- Block Acknowledgement for reduction of ACKs to one per multiple MPDU transmission
- Selective retransmission of a single MPDU possible in the case that one of the aggregated MPDUs gets impacted.

HT MAC Service Data Unit Aggregation

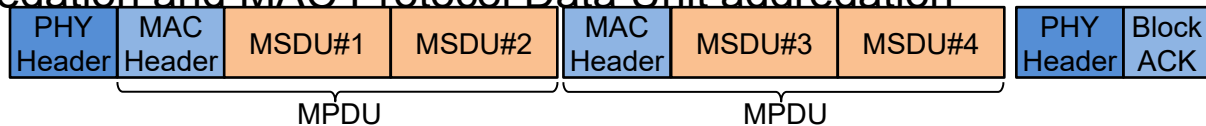
- MAC efficiency suffers when transferring sequence of smaller frames



- MAC Service Data Unit Aggregation (A-MSDU) groups multiple MSDUs into a single PSDU with a MAC header and up to 7935 data bytes.
 - All MSDUs with the same SA, DA and 802.11e QoS profile
 - High sensitivity against transmission errors; in the case of a single bit error the whole A-MSDU has to be re-transmitted



- Higher resilience against transmission errors by a combination of MAC Service Data Unit aggregation and MAC Protocol Data Unit aggregation



– Only erroneous MPDU has to be retransmitted.

WLAN IEEE 802.11 aka Wi-Fi

WI-FI 5 (VERY HIGH THROUGHPUT)

Wi-Fi 5 (IEEE 802.11ac) Very High Throughput (VHT)

Extension to High Throughput (802.11n) in 5GHz with:

- Wider channel bandwidths
 - 80 MHz and 160 MHz channels in addition to 40 MHz and 20 MHz
- More MIMO spatial streams
 - Support for up to 8 spatial streams
- Multi-user MIMO (MU-MIMO)
 - Multiple STAs, each with one or more antennas, transmit or receive independent data streams simultaneously
 - Max. 4 streams to a single STA
- New MCS 8, 9
 - 256-QAM, rate 3/4 and 5/6, added as optional modes in addition to modes available in HT
- Single sounding and feedback format for beamforming
 - Instead of multiple methods in HT – to make certification happen.
- Coexistence mechanisms for 20/40/80/160 MHz channels
 - Dynamic spectrum allocation among 11ac and 11a/n devices
- Minor MAC modifications (mostly to support above changes)

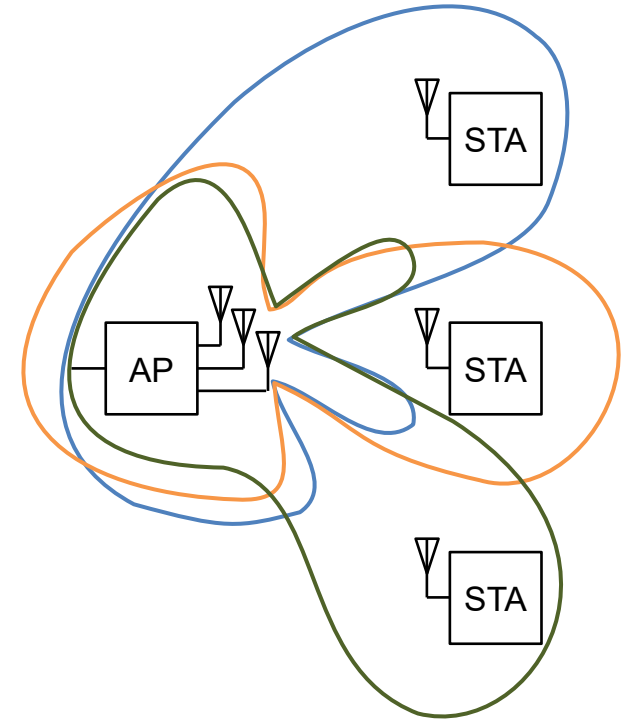
VHT (IEEE 802.11ac) MCS Options for single stream

MCS index	Spatial Streams	Modulation type	Coding rate	Data rate [Mbps]							
				20 MHz		40 MHz		80 MHz		160 MHz	
				0.8 μ s GI	0.4 μ s GI	0.8 μ s GI	0.4 μ s GI	0.8 μ s GI	0.4 μ s GI	0.8 μ s GI	0.4 μ s GI
0	1	BPSK	1/2	6.5	7.2	13.5	15.0	29.3	32.5	58.5	65.0
1	1	QPSK	1/2	13.0	14.4	27.0	30.0	58.5	65.0	117.0	130.0
2	1	QPSK	3/4	19.5	21.7	40.5	45.0	87.8	97.5	175.5	195.0
3	1	16-QAM	1/2	26.0	28.9	54.0	60.0	117.0	130.0	234.0	260.0
4	1	16-QAM	3/4	39.0	43.3	81.0	90.0	175.5	195.0	351.0	390.0
5	1	64-QAM	2/3	52.0	57.8	108.0	120.0	234	260.0	468.0	520.0
6	1	64-QAM	3/4	58.5	65.0	121.5	135.0	263.3	292.5	526.5	585.0
7	1	64-QAM	5/6	65.0	72.2	135.0	150.0	292.5	325.0	585.0	650.0
8	1	256-QAM	3/4	78.0	86.7	162.0	180.0	351.0	390.0	702.0	780.0
9	1	256-QAM	5/6	N/A	N/A	180.0	200.0	390.0	433.3	780.0	866.7

- For multiple streams multiply numbers in table by number of streams.

Multi-User DL MIMO and Beamforming

- An VHT AP is able to use its antenna resources to transmit multiple frames to different clients.
 - all at the same time and over the same frequency spectrum.
- To send data to a particular user, the AP forms a strong beam toward that user
 - Minimizing at the same time the signal strength in the direction of the other users (“null steering”)
 - Each of the users receives a strong signal of the desired data that is only slightly degraded by interference from data for the other users.
- AP has to know about the channel conditions to all connected terminals, detected
 - either detected implicitly out of the received signal, or
 - explicitly by the 802.11ac sounding protocol.
- By serving clients in parallel DL MU-MIMO allows to deliver more data in sum to clients being limited to a single or dual antenna.



MU- MIMO with combination of Beamforming and Null Steering

Wi-Fi 5 - VHT (IEEE 802.11ac) example configurations

Scenario	Typical Client Form Factor	PHY Link Rate	Aggregate Capacity
1-antenna AP, 1-antenna STA, 80 MHz	Handheld	433 Mbps	433 Mbps
2-antenna AP, 2-antenna STA, 80 MHz	Tablet, Laptop	867 Mbps	867 Mbps
1-antenna AP, 1-antenna STA, 160 MHz	Handheld	867 Mbps	867 Mbps
2-antenna AP, 2-antenna STA, 160 MHz	Tablet, Laptop	1.69 Gbps	1.69 Gbps
4-antenna AP, four 1-antenna STAs, 160 MHz (MU-MIMO)	Handheld	867 Mbps to each STA	3.39 Gbps
8-antenna AP, 160 MHz (MU-MIMO) -- one 4-antenna STA -- one 2-antenna STA -- two 1-antenna STAs	Set-top Box, Tablet, Laptop, PC, Handheld	3.39 Gbps to 4x STA 1.69 Gbps to 2x STA 867 Mbps to each 1x STA	6.77 Gbps
8-antenna AP, four 2-antenna STAs, 160 MHz (MU-MIMO)	Digital TV, PC, Tablet, Laptop,	1.69 Gbps to each STA	6.77 Gbps

- *'ac Wave 2'* certification supports MU-MIMO, up to 4x4 MIMO and 160 MHz channel

WLAN IEEE 802.11 aka Wi-Fi

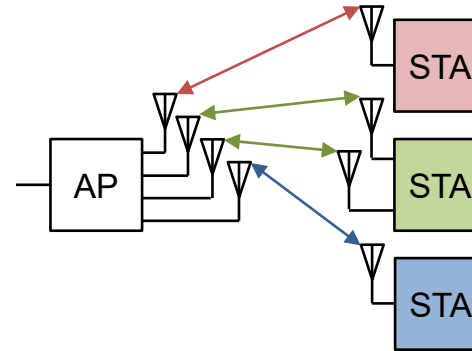
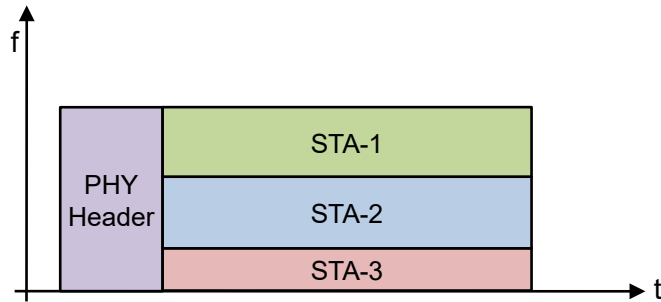
WI-FI 6 (HIGH EFFICIENCY)

Wi-Fi 6 (IEEE 802.11ax) High Efficiency (HE) Wireless LAN

- No aim to increase peak data rates far beyond what is already available by VHT
- Main focus is on increasing performance of 802.11 in uncoordinated high density scenarios
- Three key focus points:
 - (1) To improve efficiency in dense networks with large number of STAs
 - (2) To improve efficiency in dense heterogeneous networks with large number of APs
 - (3) To improve efficiency in outdoor deployments
- The aim is to achieve a substantial increase in the real-world throughput
 - Creating an instantly recognizable improvement in QoE (cell edge behavior)
 - Generating spatial capacity increase (area throughput)

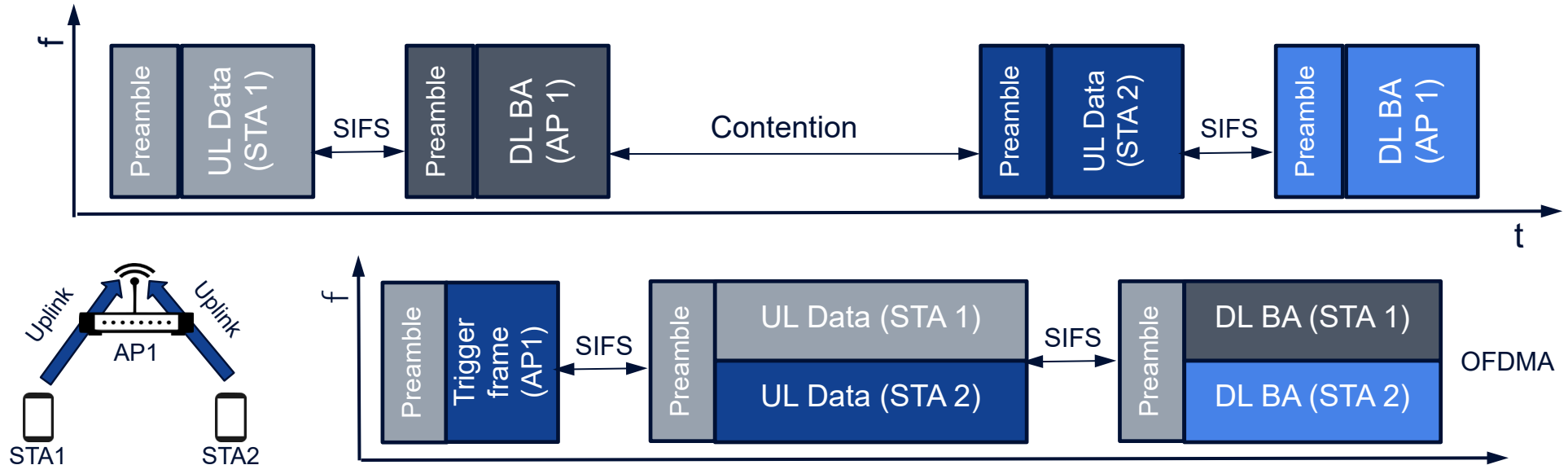
Wi-Fi 6 – High Efficiency (HE) technical highlights

- Increase network efficiency through multiplexing users in both frequency and space
 - Uplink and downlink OFDMA and MU-MIMO
 - OFDMA allows for much more fine-grain radio resource management than MU-MIMO



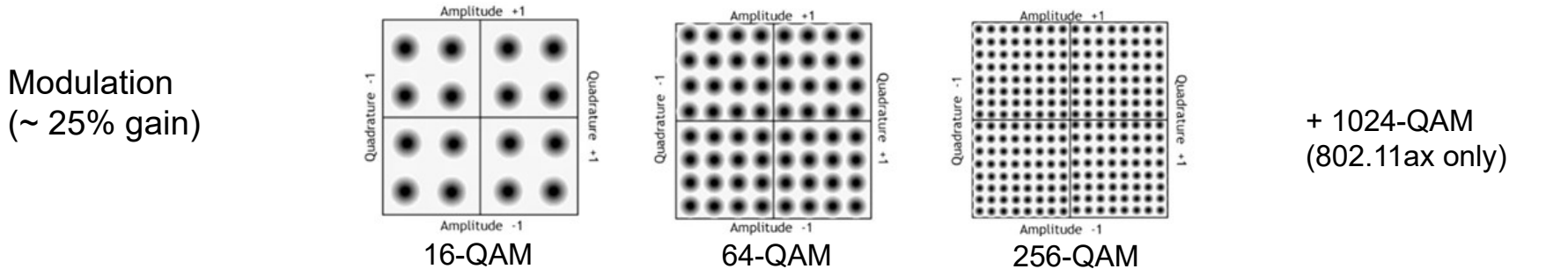
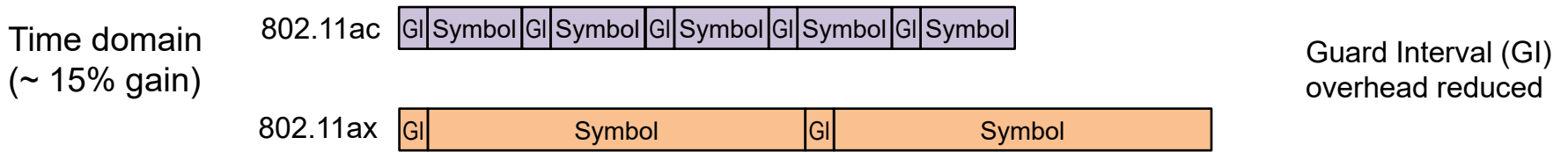
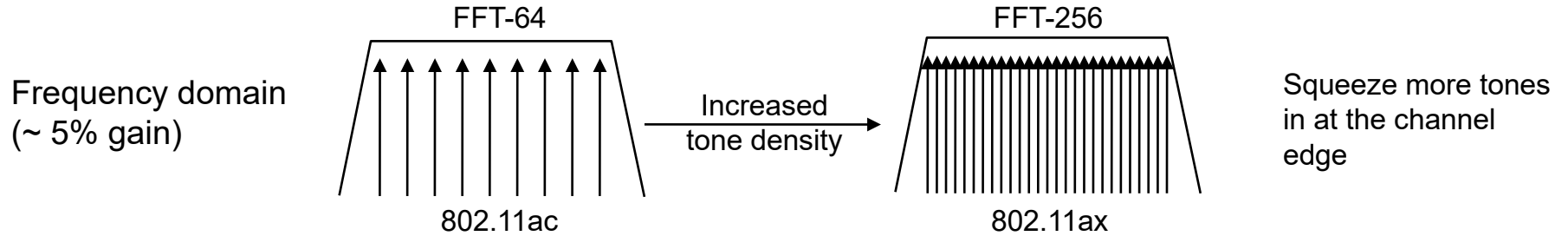
- Increase link efficiency with longer OFDM symbol (256-FFT) and high order modulation (1024-QAM)
- Improved support for outdoor operation (optional longer guard interval)
- Increase spatial reuse through BSS coloring, Spatial Reuse Groups, and dynamic clear channel assessment (CCA)
 - Will be addressed in next section

OFDMA TBT reduces access overhead compared to OFDM



- OFDMA enables APs to further split channel usage to various parallel streams for concurrent access of multiple STAs
- Uplink OFDMA Trigger Based Transmission (TBT) starts with trigger frame directly followed by responses of STAs within their assigned resource units
 - Flexible arrangements of resource units to accommodate high variety of throughput demands
 - Leads to increased efficiency for frequent short data frames, in particular in the uplink
- Overall, OFDMA results in shorter transmission delays and less jitter.

Wi-Fi 6 – IEEE 802.11ax increased link efficiency



Wi-Fi 6 – IEEE 802.11ax MCSs for single spatial stream

MCS index	Modulation type	Coding rate	Data rate (in Mb/s)							
			20 MHz channels		40 MHz channels		80 MHz channels		160 MHz channels	
			1600 ns GI	800 ns GI	1600 ns GI	800 ns GI	1600 ns GI	800 ns GI	1600 ns GI	800 ns GI
0	BPSK	1/2	8	8.6	16	17.2	34	36.0	68	72
1	QPSK	1/2	16	17.2	33	34.4	68	72.1	136	144
2	QPSK	3/4	24	25.8	49	51.6	102	108.1	204	216
3	16-QAM	1/2	33	34.4	65	68.8	136	144.1	272	282
4	16-QAM	3/4	49	51.6	98	103.2	204	216.2	408	432
5	64-QAM	2/3	65	68.8	130	137.6	272	288.2	544	576
6	64-QAM	3/4	73	77.4	146	154.9	306	324.4	613	649
7	64-QAM	5/6	81	86.0	163	172.1	340	360.3	681	721
8	256-QAM	3/4	98	103.2	195	206.5	408	432.4	817	865
9	256-QAM	5/6	108	114.7	217	229.4	453	480.4	907	961
10	1024-QAM	3/4	122	129.0	244	258.1	510	540.4	1021	1081
11	1024-QAM	5/6	135	143.4	271	286.8	567	600.5	1134	1201

WLAN IEEE 802.11 aka Wi-Fi

WI-FI 5 VS. WI-FI 6

IEEE 802.11ax enhancements compared to IEEE 802.11ac

Feature	IEEE 802.11ac	IEEE 802.11ax
OFDMA	Not available	Centrally controlled medium access with dynamic assignment of 26, 52, 106, 242, 484, or 996 tones per station. Each tone consists of a single subcarrier of 78.125 kHz bandwidth. Therefore, bandwidth occupied by a single OFDMA transmission is between 2.03125 MHz and ca. 80 MHz bandwidth.
Multi-user MIMO (MU-MIMO)	Available in downlink direction	Available in downlink and uplink direction
Trigger-based Random Access	Not available	Allows performing UL OFDMA transmissions by stations which are not allocated RUs directly.
Spatial frequency reuse	Not available	Coloring enables devices to differentiate transmissions in their own network from transmissions in neighboring networks. Adaptive Power and Sensitivity Thresholds allows dynamically adjusting transmit power and signal detection threshold to increase spatial reuse.
Target Wait Time (TWT)	Not available	TWT reduces power consumption and medium access contention.
Guard Interval duration	0.4 μ s or 0.8 μ s	0.8 μ s, 1.6 μ s or 3.2 μ s
Symbol duration	3.2 μ s	3.2 μ s, 6.4 μ s, or 12.8 μ s

Real-world throughput comparisons

Wi-Fi 5 vs. Wi-Fi 6 throughput

Results of Wi-Fi 6 access-point throughput tests with both Wi-Fi 5 and Wi-Fi 6 clients in Mbps.

Product	Extreme AP-650		Cisco Catalyst C9115		EnGenius EWS377		Meraki MR55	
	AVG	MAX	AVG	MAX	AVG	MAX	AVG	MAX
TP-Link AC600 USB Adapter (Wi-Fi 5)	196.13	229.19	122.17	187.01	134.28	150.67	194.73	214.04
Galaxy S5 Phone (Wi-Fi 5)	485.45	603.61	231.60	384.64	498.50	578.69	304.49	336.55
Ubiquiti AX200 PCI Adapter (Wi-Fi 6)	370.53	418.86	177.59	226.74	454.69	528.42	420.31	483.28
Apple iPhone 11 (Wi-Fi 6)	535.05	700.13	266.87	310.87	617.58	929.37	296.94	360.26

NETWORK WORLD / IDG

‘Despite being better in theory, today’s Wi-Fi 6 does not always outperform Wi-Fi 5 in reality.’

<https://www.networkworld.com/article/3541759/test-and-review-of-4-wi-fi-6-routers-whos-the-fastest.html>

<https://www.smallnetbuilder.com/wireless/wireless-reviews/33220-wi-fi-6-performance-roundup-five-routers-tested>

<https://www.techspot.com/article/2098-wifi-5-vs-wifi-6/>

<https://www.heise.de/select/ct/2021/3/2030915164965629451>

	NAT-Durchsatz		WLAN-Durchsatz			
	PPPoE	IP/IP	2,4 GHz nah	20 Meter	5 GHz nah	20 Meter
	besser ▶	besser ▶	besser ▶	besser ▶	besser ▶	besser ▶
Asus RT-AX58U	904	950	332	305	737	347
AVM Fritzbox 7530AX	884	950	346	213	706	226
D-Link DIR-X1860	901	950	421	297	695	216
Huawei WiFi AX3 (WS7200)	187	948	382	276	893	283
Linksys MR7350	849	949	322	256	691	309
Telekom Speedport Pro Plus	nicht messbar	nicht unterstützt	403	322	898	371
AVM Fritzbox 7580	882	949	204	189	848	309

alle Werte in MBit/s, NAT-Performance Downstream, WLAN gegen Intel AX200

WLAN IEEE 802.11 aka Wi-Fi

WI-FI 7 (EXTREMELY HIGH THROUGHPUT)

Looking ahead: Wi-Fi 7 aka IEEE P802.11be

- **Extremely High Throughput**
 - Both enhancements to MAC and PHY
 - Maximum MAC throughput of up 36 Gbps/AP through Multi-Link-Operation (MLO) on all three Wi-Fi bands (40 MHz @2.4 GHz, 160 MHz @5 GHz, 320 MHz @6 GHz)
 - Carrier frequencies between 1 and 7.125 GHz
- **Low latency**
 - Improved worst case latency and jitter through MLO and restricted Target Wake Time
- **Compatibility**
 - Backward compatibility and coexistence with legacy 802.11 devices in the 2.4 GHz, 5 GHz and 6 GHz unlicensed bands
- **Timeline**
 - IEEE ratification expected for December 2024, certified products from early 2024
- **Technical features**
 - Wider bandwidth (320 MHz), 4k coding and modulation, better efficiency through puncturing and new header structures. Technical highlight: Multi Link Operation

Comparison of Wi-Fi 7 with previous generations of Wi-Fi

	Wi-Fi 4	Wi-Fi 5	Wi-Fi 6	Wi-Fi 7	Advantages of Wi-Fi 7
Band(s)	2.4 GHz, 5 GHz	5 GHz	2.4 GHz, 5 GHz and 6 GHz	2.4 GHz, 5 GHz and 6 GHz	MLO across two or more bands
Channel Widths	20 MHz, 40 MHz	20 MHz, 40 MHz, 80 MHz, 160 MHz	20 MHz, 40 MHz, 80 MHz, 160MHz	20 MHz, 40 MHz, 80 MHz, 160 MHz 320 MHz	Doubles the size of widest Wi-Fi 6 channel
Multi-Link Operation (MLO)	n/a	n/a	n/a	Triband total speed up to 36 Gbps	Increased throughput, lower latency, reduced interference, reduced intra-AP roaming disruption
Highest modulation	64-QAM	256-QAM	1024-QAM	4096-QAM	Higher peak data rates
Spatial streams	4	4	8	8	
Max data rate	600 Mbps	3.5 Gbps	9.6 Gbps	36 Gbps	> 3x throughput of Wi-Fi 6
Multi-user support	n/a	DLMU-MIMO	UL/DL MU-MIMO + OFDMA	UL/DL MU-MIMO + OFDMA	
Target Wake Time (TWT)	n/a	n/a	Individual TWT Broadcast TWT	Restricted TWT Individual TWT Broadcast TWT	More predictable latency with power saving benefit

Questions and answers



Wi-Fi radio questions...

- 1) Which of the IEEE 802.11 radio standards support operation in 2.4 GHz?
- 2) Which IEEE 802.11 radio standards only support operation in 5 GHz?
- 3) What are the bit-rates supported by a HR/DSSS system (IEEE 802.11b)?
- 4) What is the difference between a PPDU and MPDU data frame?
- 5) What is the purpose of the preamble of the physical layer protocol data unit?
- 6) Through which method is the duration of the short preamble reduced by 50%?
- 7) What does OFDM stand for?
- 8) How many of the 52 sub-carriers of 802.11a OFDM are used for data?
- 9) What is the purpose of guard intervals in OFDM?
- 10) Which symbol rate are is used by OFDM as introduced through 802.11a?
- 11) How long does a OFDM PHY preamble in IEEE 802.11a take?
- 12) What is the benefit when operating the Extended Rate PHY (802.11g) without backward compatibility to HR/DSSS?
- 13) What additional methods are needed for coexistence of Extended Rate PHY without backward compatibility with HR/DSSS?

Wi-Fi radio questions, cont.

- 14) Which modulation is applied for 54 Mbit/s in the 802.11a/802.11g OFDM mode, and how many bits can be encoded in one tone?
- 15) What are the main techniques deployed by the High Throughput PHY (802.11n) to increase the maximum bitrate from 54 Mbit/s to 600 Mbit/s?
- 16) How does the OFDM symbol rate change in 802.11n/802.11ac through shortening the guard interval?
- 17) Which MIMO methods are specified in 802.11n, and which is mandatory for certification?
- 18) What is the benefit of MAC Protocol Data Unit aggregation compared to MAC Service Data Unit aggregation?
- 19) What is the drawback of MAC Protocol Data Unit aggregation compared to MAC Service Data Unit aggregation?
- 20) By which means does Very High Throughput (VHT) PHY (802.11ac) provide higher bitrates compared to High Throughput (HT) PHY (802.11n)?
- 21) What is the difference between explicit beam-forming and implicit beam-forming?
- 22) What is the benefit of deploying a FFT-256 in 802.11ax instead of a FFT-64?

End of part 1

Questions and remarks



BTW: Getting personal insights into IEEE 802.11 working style...

- On July 9th - 14th , 2023, IEEE 802 holds its plenary meeting in Berlin – very rare!
 - IEEE 802.11 working group (~ 250 experts) meets at this plenary meeting.

IEEE 802 Student Outreach Program at Tuesday, July 11th, 2023 in Berlin

- The purpose of the IEEE 802 Student Outreach program is to give students a chance to see firsthand how the Standards process works.
 - Nominal fee of US\$ 25 (instead of US\$ 800 for the whole meeting)
- It is a one-day event at Tuesday, July 11th, 2023:
 - 7:30-9:00 – Sign in and get badge
 - 9:00 – Start with an introduction meeting with a couple of the 802 Leadership members to orient the students to what activities may be of most interest to them that day
 - 10:30 – The students attend actual working meetings and can meet and participate in the discussions.
 - 17:00 – Debrief: A short debrief meeting at the end of the day is provided to answer questions and help provide closure to the experience.

Please send me (maximilian.riegel@nokia.com) an email, if you would like to participate