Communication Systems
Wi-Fi (IEEE 802.11 WLAN) Part 1

WS 2025/2026@THI

Max Riegel
<max.riegel@ieee.org>

WS 2025/2026 Wi-Fi Lecture Topics

Part 1 (Tue, 2025-11-25):

- Introduction
- Wi-Fi Architecture
- Wi-Fi Specifications
- Wi-Fi Spectrum
- Wireless Channel
- Wi-Fi PHY Evolution

Part 2 (Fri, 2025-11-28):

- Wi-Fi PHY Layer
- Wi-Fi PHY Q&A

Part 3 (Tue, 2025-12-02):

- Wi-Fi MAC Layer

Part 4 (Fri, 2025-12-05):

- Wi-Fi QoS
- Wi-Fi Security
- Wi-Fi MAC Q&A

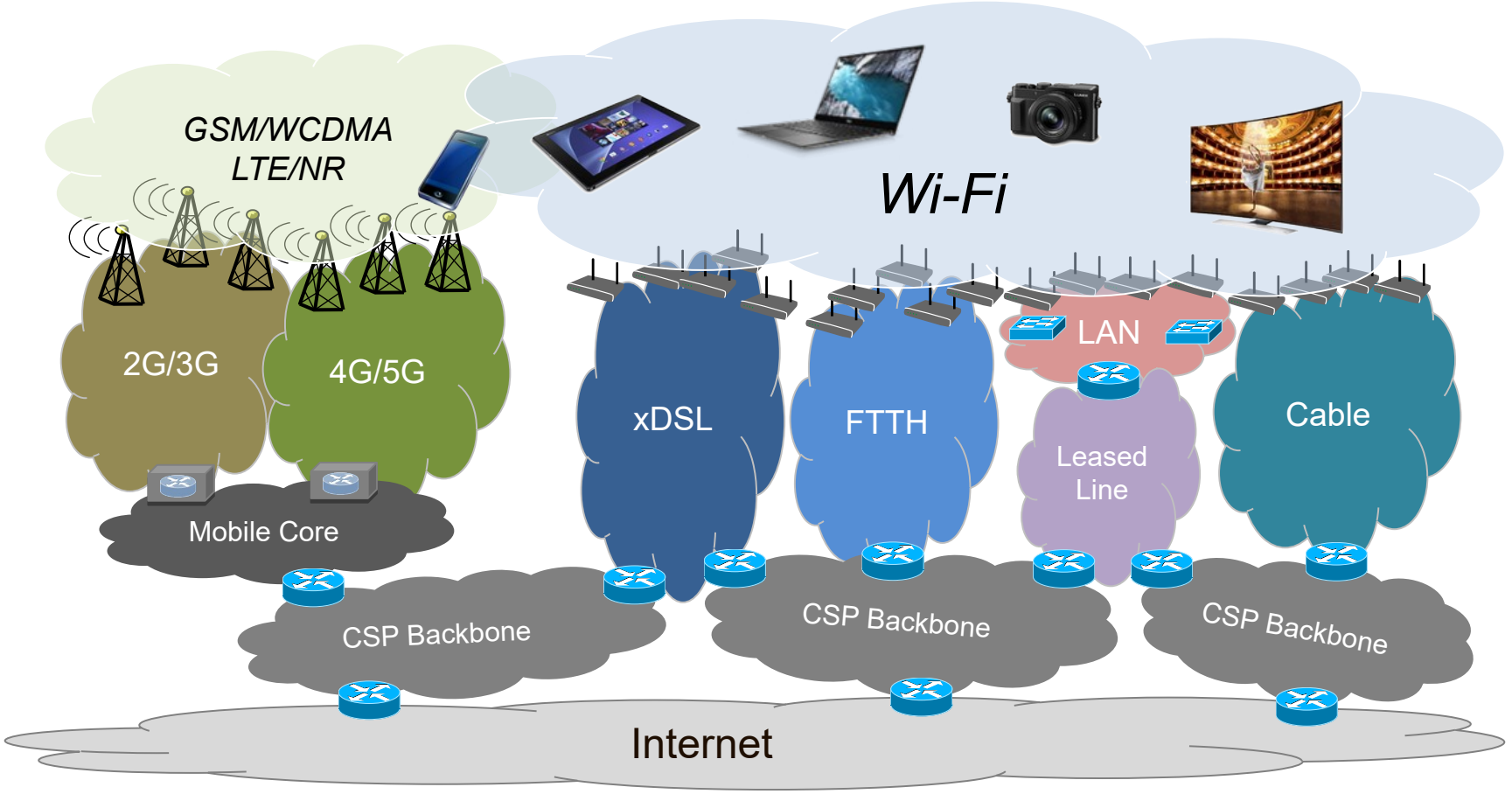
About my person

Max Riegel
<max.riegel@ieee.org>
IEEE & Wi-Fi Standardization Expert

- Job positions
  - prior to 1998: HW and SW development at Philips Kommunikations Industrie and TPS
  - 1998 – 2007: IETF and IEEE Standardization at Siemens Communications
  - 2007 – 2023: IEEE related standardization at NSN/Nokia Networks/Nokia
  - since 2024: Consultancy and 802.11 standardization
- Participation in IEEE 802.11 Standardization since 2000
- IEEE member since 1984; Voting member of IEEE 802.11 working group
- Formerly, participation in Wi-Fi Alliance and in Wireless Broadband Alliance
- Wi-Fi research and product designs in the CSP and Enterprise Wi-Fi domain

INTRODUCTION

Wi-Fi is the wireless interface to fixed broadband services



CSP: Communication Service Provider

Diversity of Wi-Fi terminals and access infrastructure

Wi-Fi is predominantly deployed in homes and indoors

~90%*

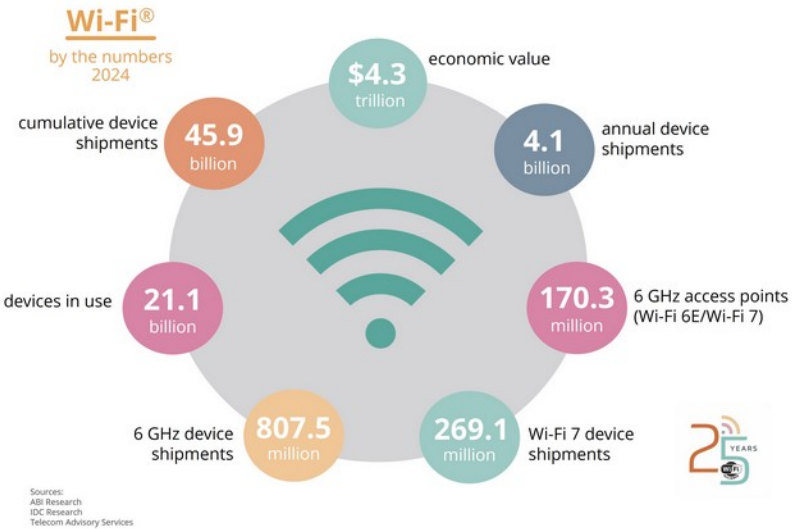
- Mostly managed by millions of 'hobby' operators
- Increasingly offered by CSPs as managed service together with fiber connectivity
- Most heavy growth of Wi-Fi devices and data traffic

~10%*

- Managed by corporate IT departments
- Mission critical service with strict security policies in place
- Public access overlays for guest access and allowing employees to bring their own devices

<1%*

- Usually managed by CSPs or WISPs
- Cumbersome security and usability due to open Wi-Fi and portals
- Mostly offered as amenity to attract customers

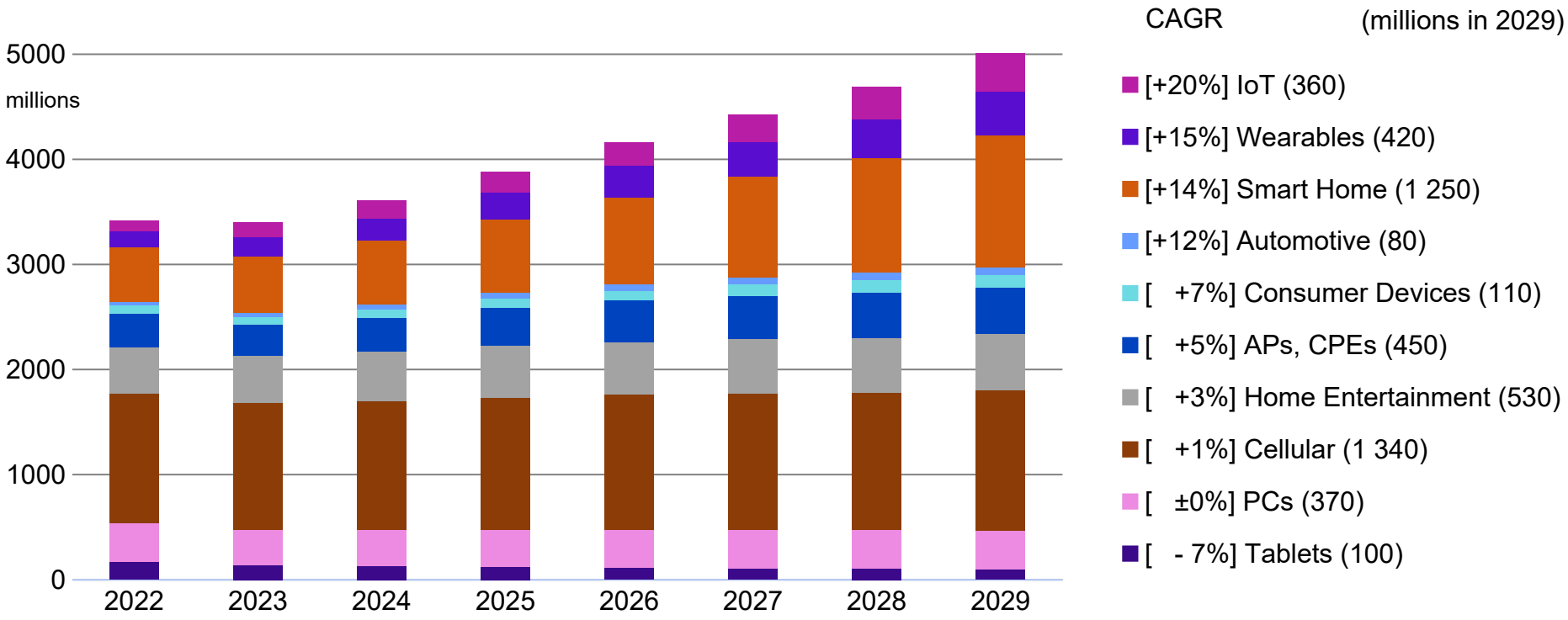


* Percentage of total APs; Source: ABIresearch 2010, Femtocells, Operator, Access Point and Chipset Market Analysis

WISP: Wireless Internet Service Provider

Wi-Fi defines a heavily growing eco-system

Yearly Wi-Fi devices shipments, world market

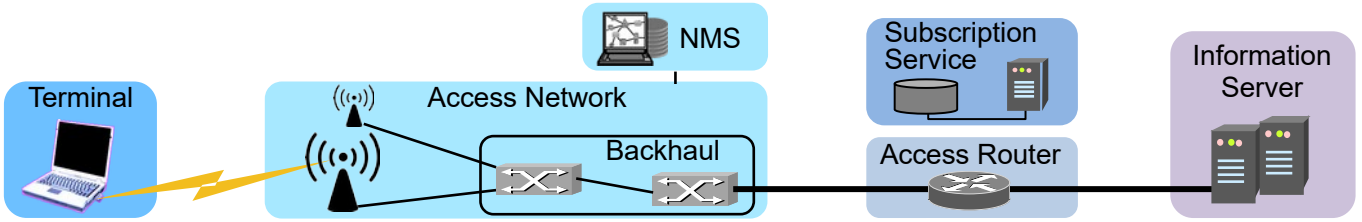


Source: ABIresearch Q3/2024

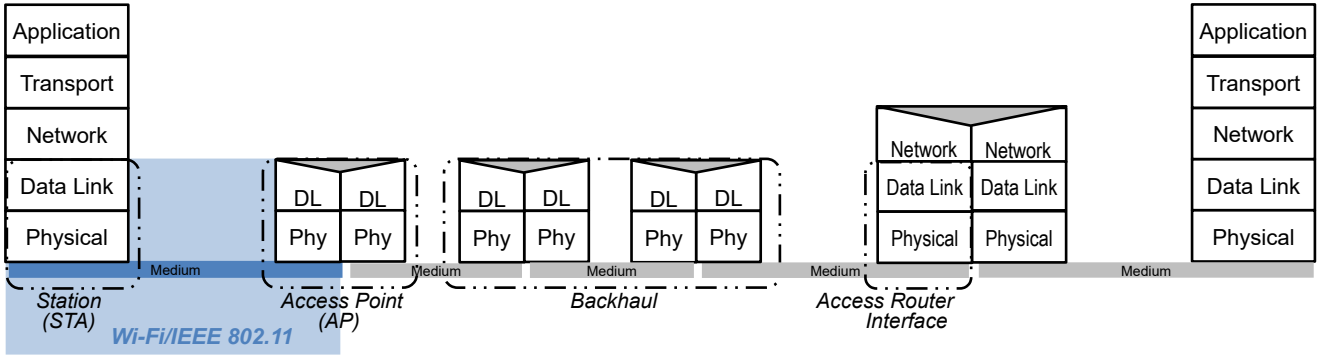
WI-FI ARCHITECTURE

Generic Wi-Fi Network Reference Model

- Functional architecture

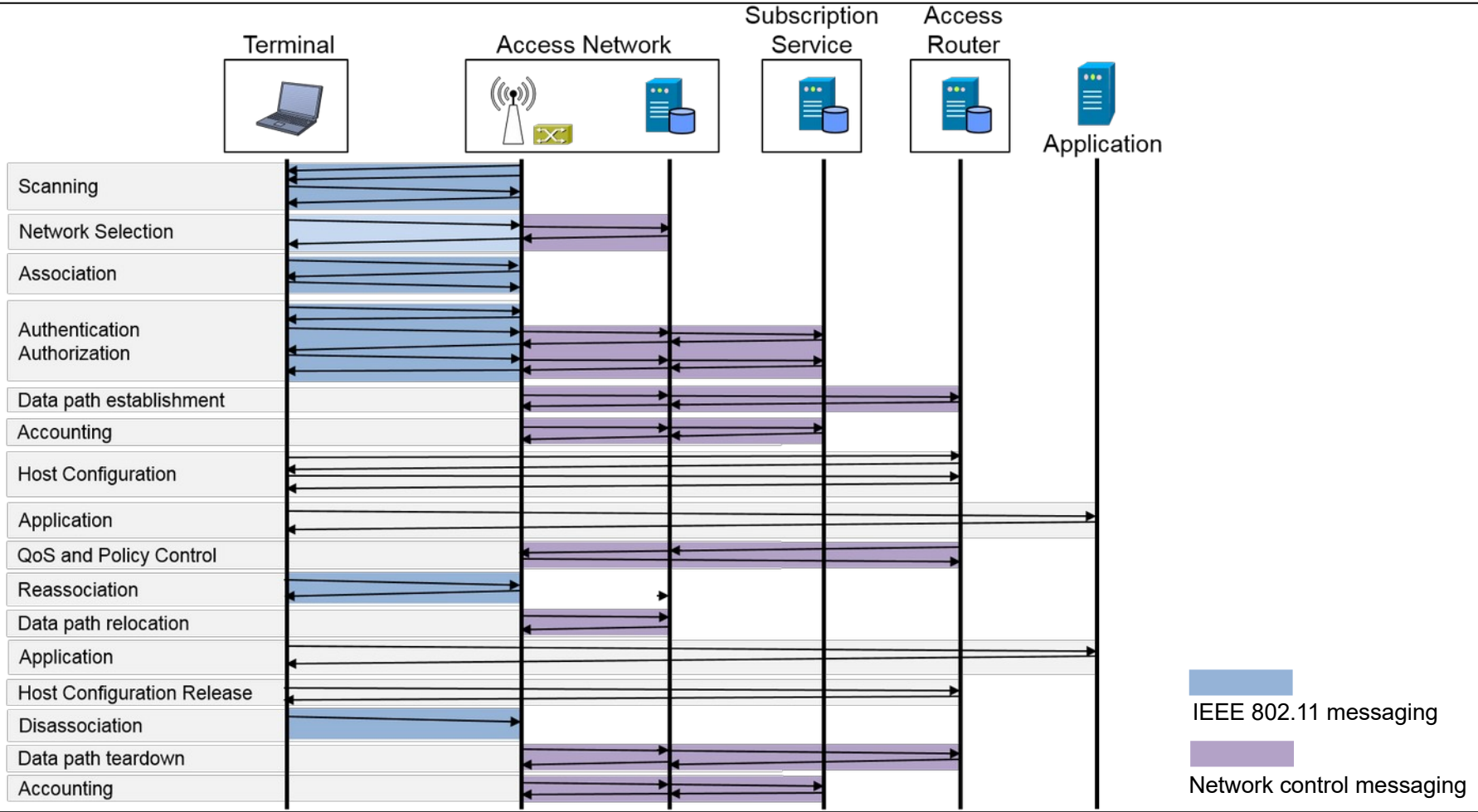


- Protocol architecture



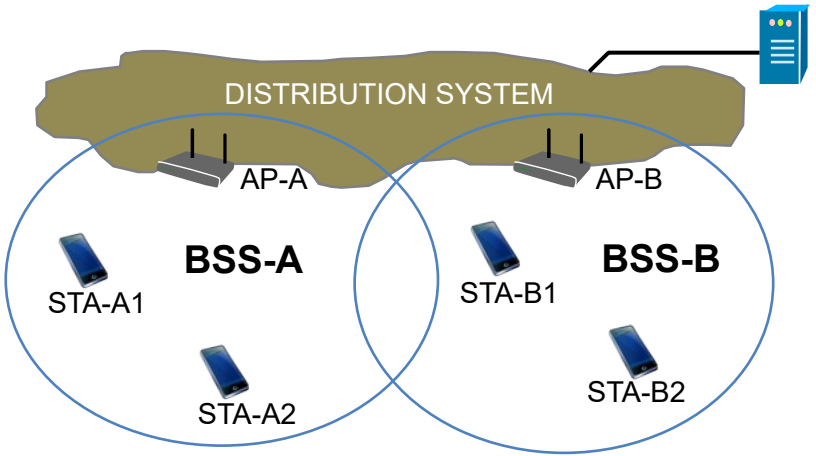
- Wi-Fi covers the radio interface between terminal and access network.
  (FYI: More details can be found in IEEE 802.1CF-2019)

The life-cycle of an Wi-Fi session

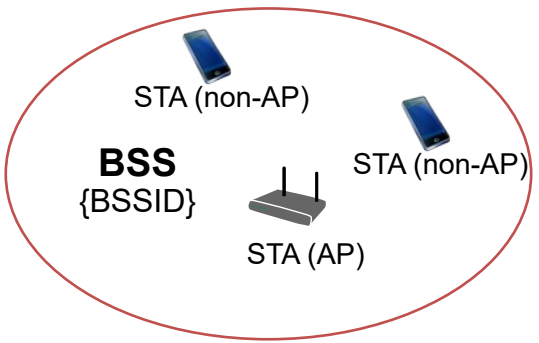


IEEE 802.11 basic configuration and terminology

- Infrastructure
  - Distribution System interconnects multiple BSSs to form a single ESS (Extended Service Set) with SSID.
  - Extends wireless coverage area
  - Establishes Wi-Fi access network



- Basic Service Set (BSS)
  - Single Wi-Fi ‘cell’, limited coverage area
  - Direct communication between STAs
  - Established through an ‘AP’ function
  - BSSID: MAC address of AP
  - Other BSSs may overlap in same radio coverage area (OBSS, "Overlapping BSS")



WI-FI SPECIFICATIONS

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

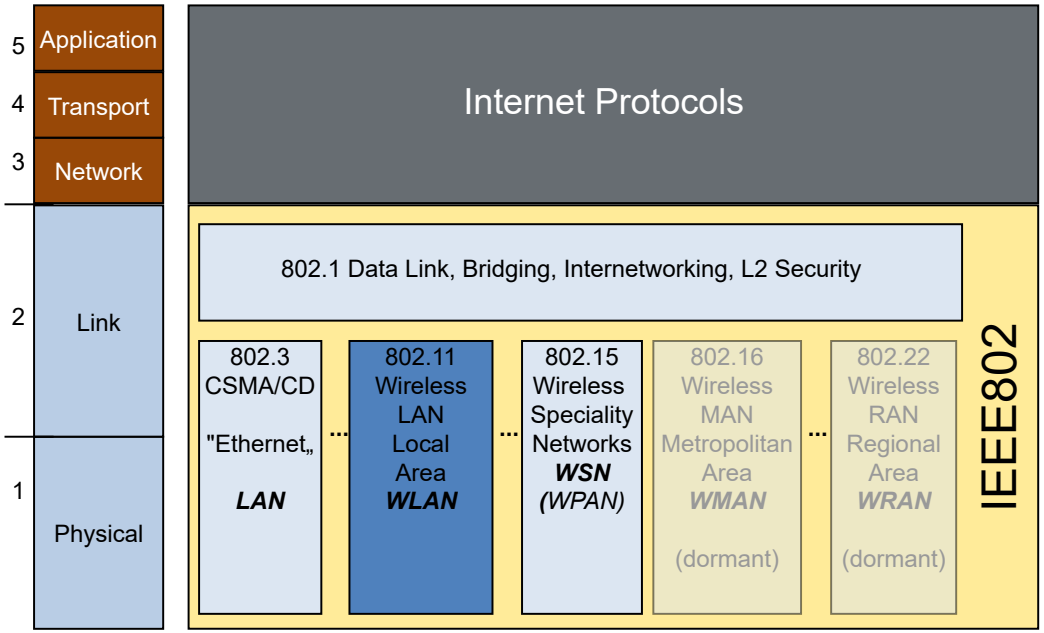
Wi-Fi - Specifications

IEEE 802.11 STANDARDIZATION

IEEE at a Glance

IEEE 802 LAN/MAN Standardization Committee

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

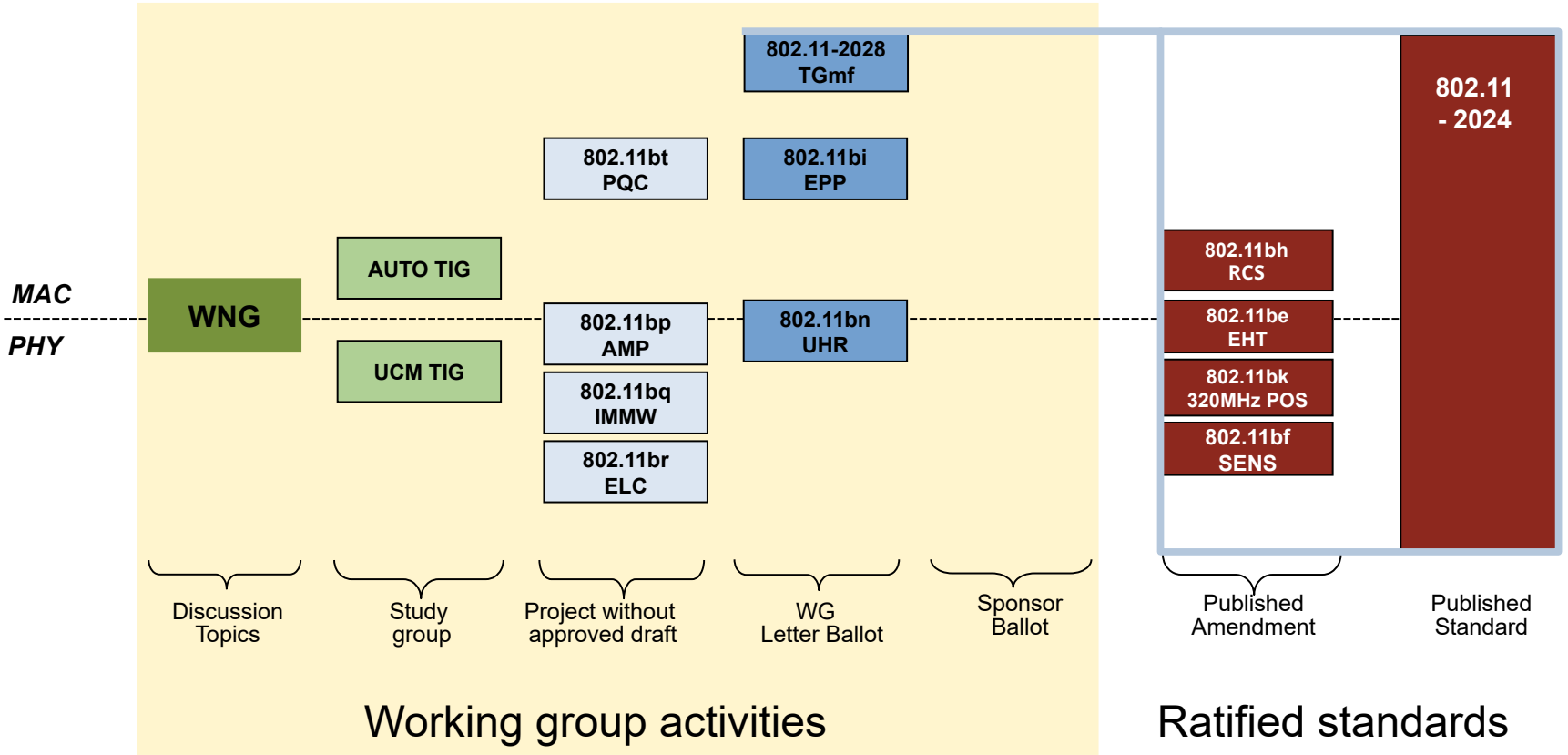


Specifies only Physical and Link Layer.
Complete set of standards for carrying IP

- Start of IEEE Computer Society Project 802 in February 1980.
- Later renamed to “LMSC”: LAN/MAN Standardization Committee
  - Initial work on “Ethernet”
  - Initially with 1 to 20 Mbps!
  - Now IEEE 802.3 with up to 1.6 Tbps
- 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 standards development (Status 11/2025)

The working group concurrently operates in different standardization phases



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
IEEE 802.11-2024	**Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) spec**	**09/2024**
IEEE 802.11be	Extremely High Throughput (EHT)	09/2024
IEEE 802.11bh	Operation with Randomized and Changing MAC Addresses	09/2024
IEEE 802.11bf	WLAN Sensing	05/2025
IEEE 802.11bk	320 MHz Positioning	05/2025
P802.11bi	Enhanced Service with Data Privacy Protection	~ 07/2026
P802.11mf	**Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) spec**	~ 03/2028
P802.11bn	Enhancements for Ultra High Reliability (UHR)	~ 05/2028

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}x 8.6 // 8.3/18.2/28.1/37.9 Gbps	8	SC // OFDM	line of sight	line of sight
be	Sep 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 Standard Reference for the Lecture

- *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 802.11-2020
  - 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 802.11bd-2022
  - *i.e.:* a, b, d, e, g, h, I, j, k, n, p, r, s, u, v, w, y, z, aa, ac, ad, ae, af, ah, ai, aj, ak, aq, ax, ay, az, ba, bb, bc, bd

Amendment standard IEEE Std 802.11be-2024

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

Wi-Fi Specifications

WI-FI ALLIANCE CERTIFICATION

The Wi-Fi Alliance

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

Wi Fi® CERTIFIED

- 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 Wi-Fi 6, Wi-Fi radio technologies were identified through the project acronym of the related IEEE 802.11 standardization project.
  - i.e. 802.11b, 802.11a, 802.11g, 802.11n, 802.11ac
  - Ambiguous communication to end users leading to slow adoption of new Wi-Fi radio technologies.

- Similar to 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 new notation was introduced with 802.11ax denoting it as ‘Wi-Fi 6’.
  - Wi-Fi certified products are identified through ‘Wi-Fi CERTIFIED™ 6’
  - Wi-Fi 6E denotes an enhanced Wi-Fi 6 version also operating in the new 6 GHz band.

Wi-Fi Alliance certification programs - overview

Connectivity	Security	Access	Optimization
Wi-Fi CERTIFIED 7™	Protected Management Frames	Passpoint®	Wi-Fi CERTIFIED Agile Multiband™
Wi-Fi CERTIFIED 6®	Wi-Fi CERTIFIED WPA3™	Wi-Fi Easy Connect™	Wi-Fi Data Elements™
Wi-Fi CERTIFIED ac	Wi-Fi Enhanced Open™	Wi-Fi Protected Setup™	Wi-Fi EasyMesh™
Wi-Fi CERTIFIED n			Wi-Fi Optimized Connectivity™
Wi-Fi CERTIFIED HaLow™	**Applications**	**Additional**	Wi-Fi QoS Management™
Wi-Fi CERTIFIED WiGig™	Miracast™	Power saving features	Wi-Fi Vantage™
Wi-Fi Direct®	Voice-Enterprise	Wi-Fi Home Design™	WMM® (Wi-Fi Multimedia™)
RF Coexistance	Wi-Fi Aware™		WMM-Admission Control
CWG-RF	Wi-Fi Location™		WMM-Power Save

Further details: https://www.wi-fi.org/certification/programs

Wi-Fi CERTIFIED Certificate, e.g. Samsung Galaxy S24 Ultra

Complete certificate: https://api.cert.wi-fi.org/api/certificate/download/public?variantId=129396

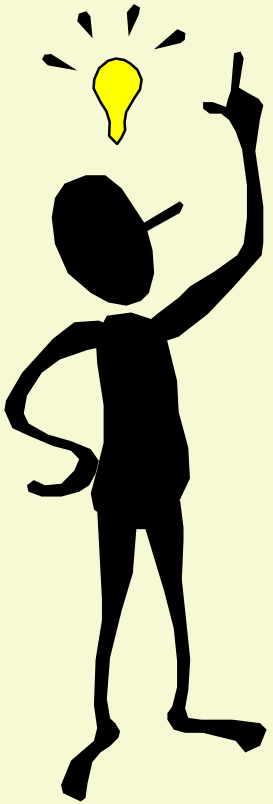
Summary of Certifications for Variant #1

CLASSIFICATION	PROGRAM
Security	Protected Management Frames
	WPA2™-Enterprise
	WPA2™-Personal
	WPA3™-Enterprise
	WPA3™-Personal
Spectrum & Regulatory Features	Spectrum & Regulatory
Optimization	Wi-Fi Agile Multiband™
	Wi-Fi Optimized Connectivity™
	WMM®
	WMM®-Power Save
	WMM®-Admission Control
	Wi-Fi QoS Management™
Connectivity	Wi-Fi CERTIFIED 6®
	Wi-Fi CERTIFIED™ ac
	Wi-Fi CERTIFIED™ n
	Wi-Fi Enhanced Open™
	Wi-Fi Direct®
	Wi-Fi CERTIFIED™ a
	Wi-Fi CERTIFIED™ b
	Wi-Fi CERTIFIED™ g
	2.4 GHz Spectrum Capabilities
	5 GHz Spectrum Capabilities
	6 GHz Spectrum Capabilities
	Wi-Fi CERTIFIED 7™
Applications & Services	Wi-Fi Aware™
	Voice-Enterprise

The certificates of Wi-Fi certified products can be retrieved through:

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

Questions and answers



Standards Environment questions…

1. Where does IEEE 802.11 stem from?
2. Which layers of the ISO-OSI model are addressed in IEEE 802.11 specifications?
3. What is the meaning of BSS in IEEE 802.11?
4. By which means are multiple BSSs connected to an ESS?
5. Which organization introduced the term ‘Wi-Fi?
6. What is the purpose of the Wi-Fi Alliance?
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?

WI-FI SPECTRUM

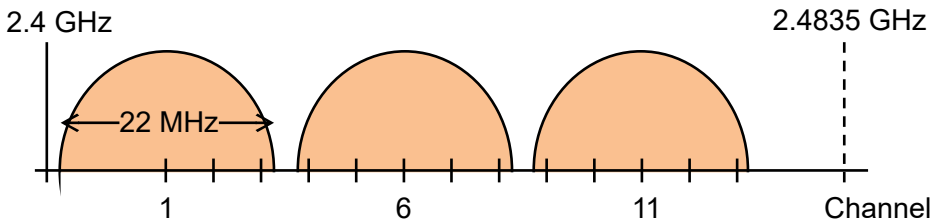
Wi-Fi operates in license-exempt spectrum

- License-exempt
  - Anybody can use the spectrum without acquiring first a formal authorization
  - Can be on secondary base, i.e. usage restricted to cases where primary user is not using it, or is not impacted through secondary use
  - To enable high reuse and minimize interference, radiation power is limited
    - TX power defined as EIRP (Effective Isotropic Radiated Power)
- Common frequency bands allowing license-exempt usage:
  - 2.4 GHz ISM (Industrial Scientific Medical) band – primary assignment
    - Usage regulated in Europe through ETSI EN 300 328
  - 5 GHz band – license-exempt use on secondary base
    - Usage regulated in Europe through ETSI EN 301 893 (5150 – 5725 MHz)
      - ETSI EN 300 440 for 5725 – 5875 MHz
  - 6 GHz band – license-exempt use on secondary base
    - Usage regulated in Europe through ETSI EN 303 687

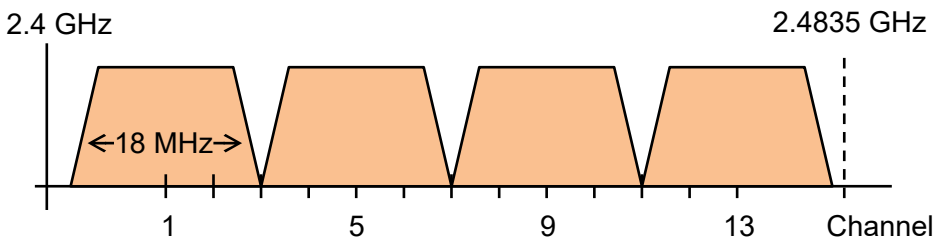
Wi-Fi in the 2.4 GHz ISM band

- Most of Wi-Fi today operates in the 2.4 GHz ISM band
  - In the US, only channels 1 – 11 usable
  - IEEE 802.11b set the legacy rule to deploy Wi-Fi systems on channels 1 – 6 – 11
  - IEEE 802.11 OFDM systems (802.11g/n/ax/be) do 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:
  - Use of spread spectrum coding
  - max TX power: 100 mW EIRP

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

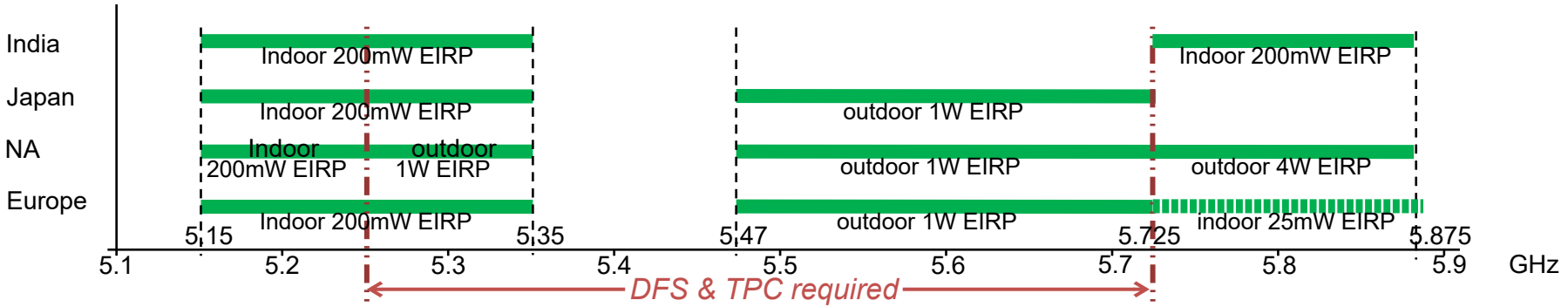


OFDM (802.11g/n/ax/be) fits into 20 MHz channels

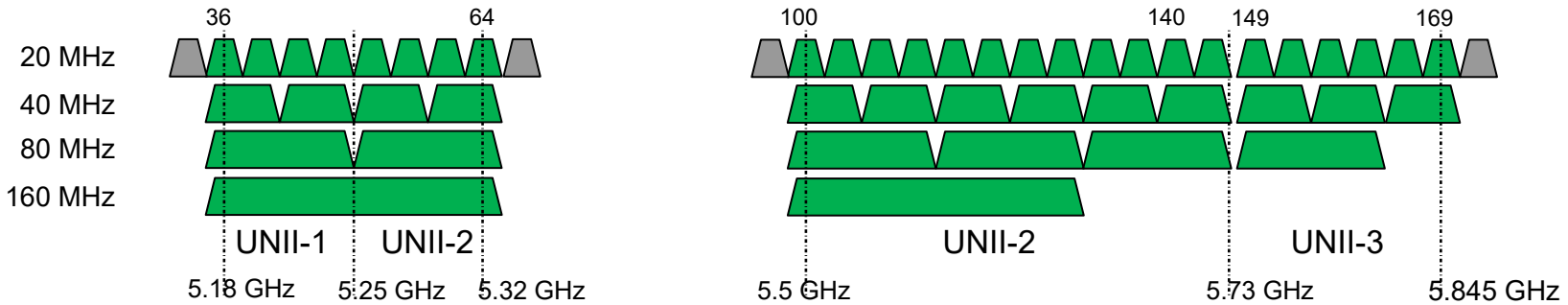


License-exempt operation in the 5 GHz band

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

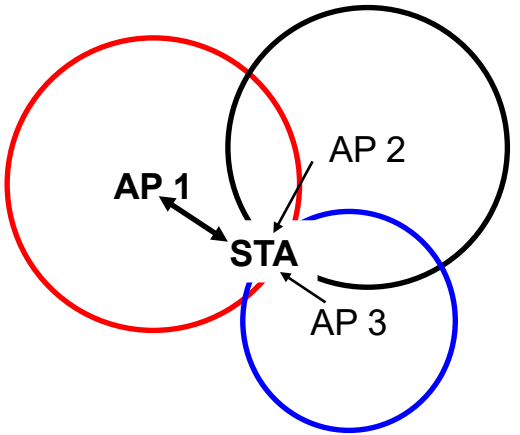


- Channelization:



Spectrum management for the 5 GHz band

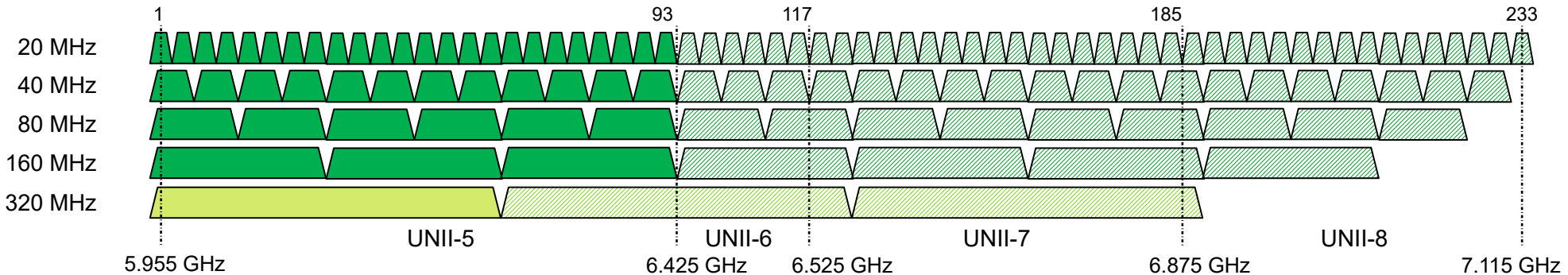
- Dynamic Frequency Selection (DFS) and Transmission Power Control (TPC) are required for most of the 5 GHz spectrum to protect primary users (e.g. weather radars)
- DFS (Dynamic Frequency Selection)
  - APs dynamically select their operating channel after scanning for other users (e.g. weather radars)
  - 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)
  - 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 operation in the 6 GHz band (new)

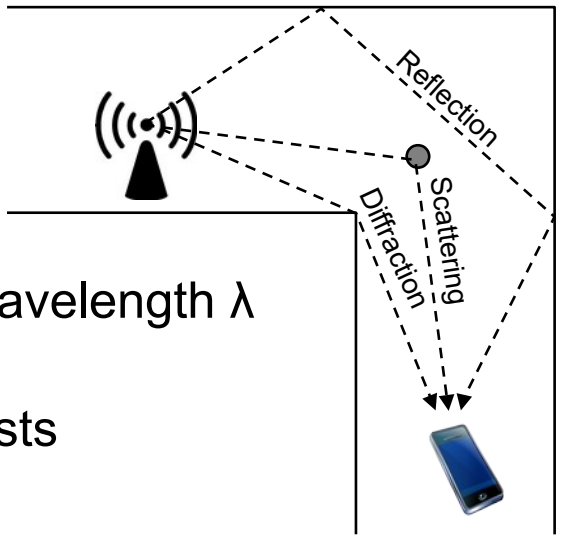
- Wi-Fi operation in the 6 GHz band (5925 – 6425 – 7125 MHz)
  - Full 1.2 GHz band enabled by FCC, many other countries around the world following
  - Europe enabled 5925 – 6425 MHz for license-exempt secondary usage
  - (up to) 3 device categories
    - Very Low Power, VLP (~ 25 mW EIRP) allowed also for outdoor,
    - Low Power Indoor, LPI (~ 200 mW EIRP) only indoor;
    - Potentially, higher power (up to 4W EIRP) with AFC (automatic frequency control)
  - 6 GHz allows for legacy-free Wi-Fi operation (only Wi-Fi 6E and Wi-Fi 7) and wider channels (320 MHz, Wi-Fi 7)



WIRELESS CHANNEL CHARACTERISTICS

Radio signal propagation issues

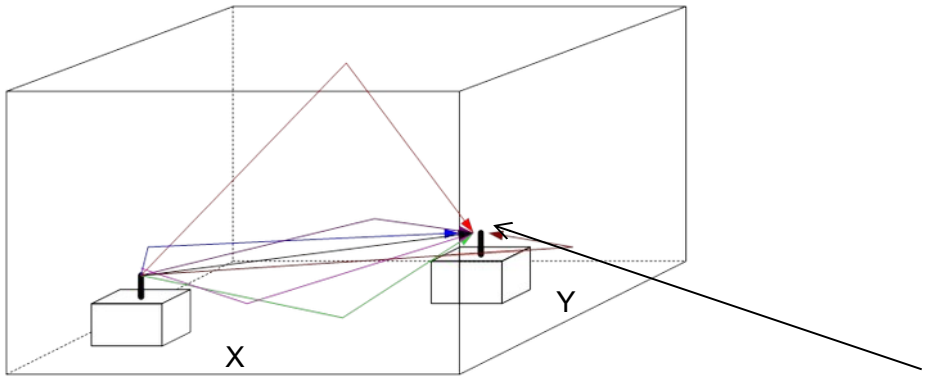
- Path loss
  - Attenuation due to distance and frequency
- Reflection
  - Surface large relative to wavelength λ of signal
- Diffraction
  - Edge of impenetrable body that is large relative to wavelength λ
- Scattering
  - Obstacle size in order of wavelength λ, e.g. lamp posts

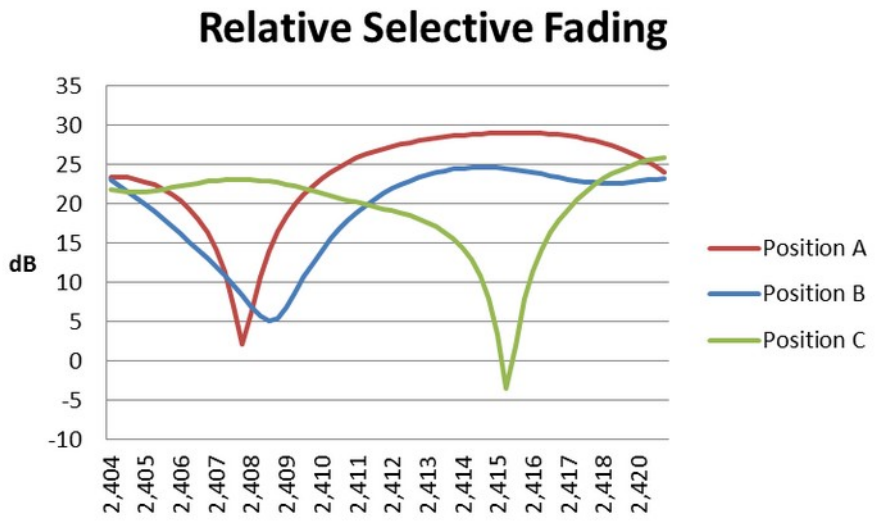


Main propagation issues:

- 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

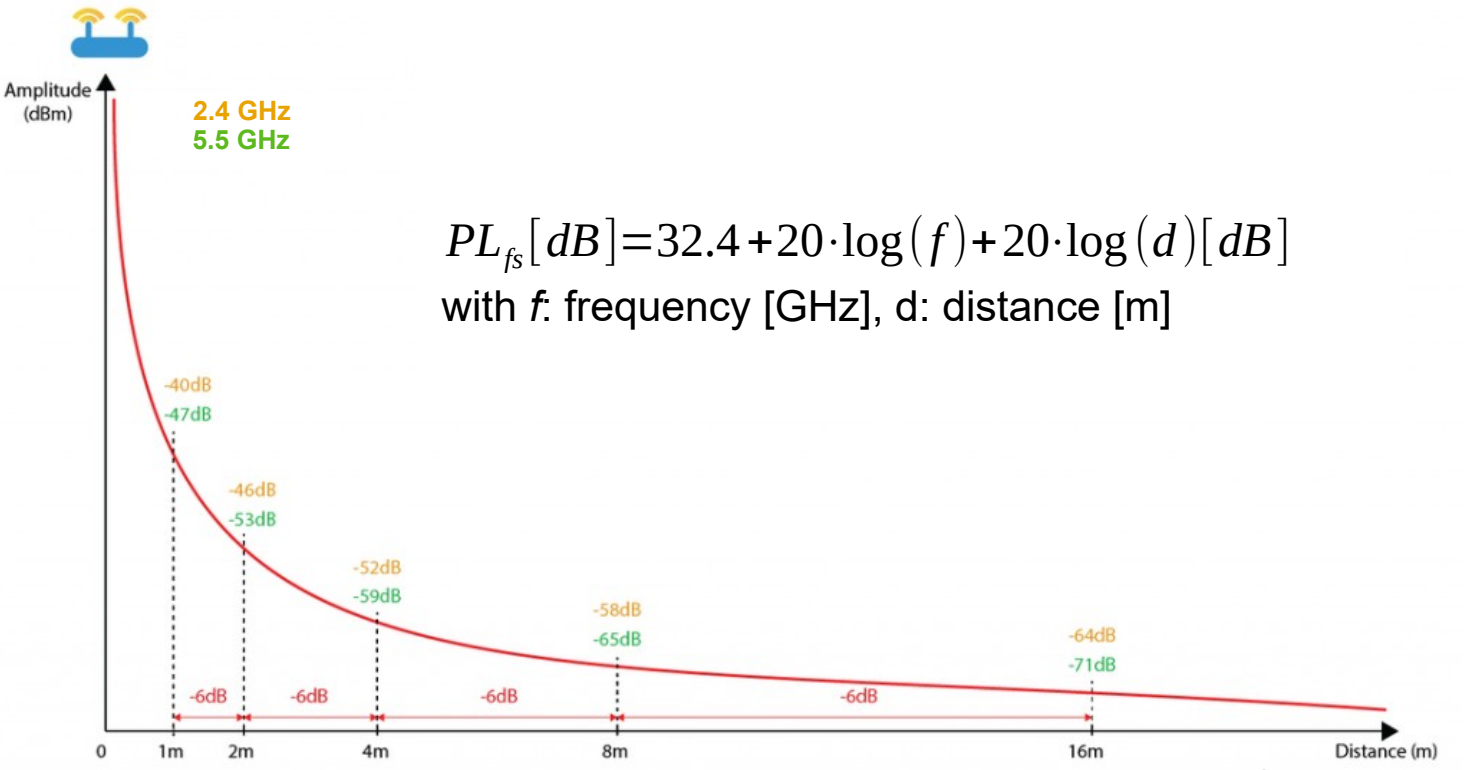
Transmission characteristics taken for

- 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!

Path loss model for Wi-Fi

- For a variety of dense Wi-Fi deployments, the free space path-loss model is a reasonable representation.



$$PL_{fs}[dB] = 32.4 + 20 \cdot \log(f) + 20 \cdot \log(d)[dB]$$

with *f*: frequency [GHz], d: distance [m]

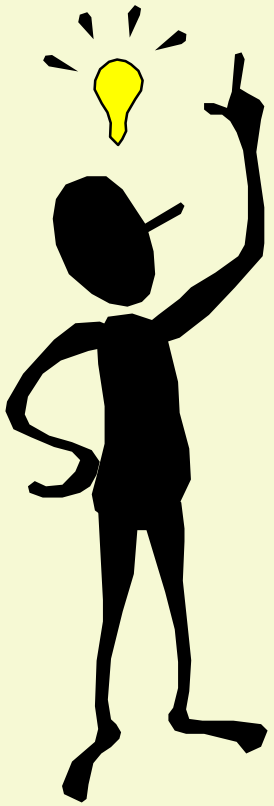
Picture source: https://semfionetworks.com/blog/free-space-path-loss-diagrams/

Generic path-loss:

$$PL = \left(\frac{4 \cdot \pi \cdot d \cdot f}{c}\right)^{\eta}$$

Free space: η = 2
Indoors measured:
Wide variation of η:
- LOS: η = 1.2 .. 2.2
- NLOS: η = 2.4 .. 3

Questions and answers



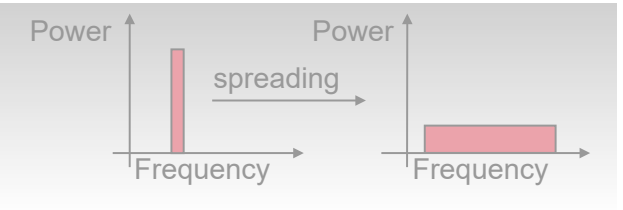
Wi-Fi spectrum questions...

1) What does EIRP mean?
2) Why often the channel arrangement 1 – 6 – 11 is used in the 2.4 GHz band?
3) What is the purpose of DFS and TPC in the 5 GHz band?
4) How many non-overlapping 80 MHz channels can fit in the 5 GHz range in Europe?
5) What is the 6 GHz band?
6) How much spectrum is available in the 6 GHz band in Europe and in the US?
7) Which device categories exist in the 6 GHz band?
8) What are the main propagation issues in case of line-of-sight transmissions?
9) Can you briefly explain the issue of selective fading?
10) By which amount is the signal strength attenuated in free space when doubling the distance to the transmitter?

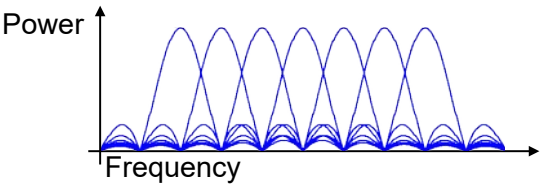
WI-FI PHY EVOLUTION

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

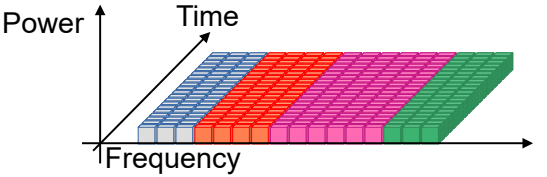
- 2.4 GHz Direct Sequence Spread Spectrum (1997)
  - DBPSK/DQPSK providing 1/2 Mbps
  - Channel bandwidth: 22 MHz
- 2.4 GHz High Rate DSSS **(1999: 802.11b – Wi-Fi 1)**
  - CCK/DQPSK providing 5.5/11 Mbps
  - Channel bandwidth: 22 MHz



- 5 GHz Orthogonal Frequency Division Multiplex **(1999: 802.11a – Wi-Fi 2)**
  - OFDM providing 6/9/12/18/24/36/48/54 Mbps
  - Channel bandwidth: 20 MHz
- 2.4 GHz Extended Rate **(2003: 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



- 2.4 GHz & 5 GHz High Throughput **(2009: 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 **(2013: 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 **(2021: 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



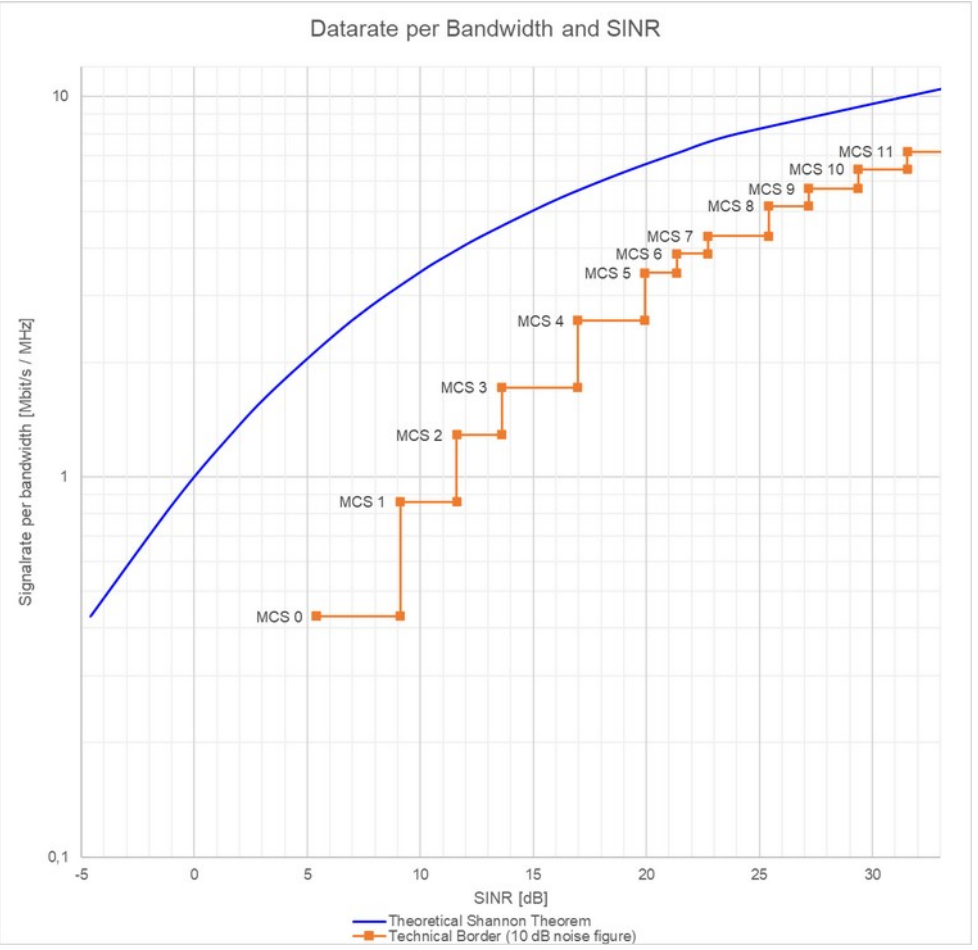
- 1 – 7.25 GHz Extremely High Throughput **(2024: 802.11be – Wi-Fi 7)**
  - OFDM/OFDMA with up to 8x8 MU-MIMO providing up to 23 000 Mbps
  - Channel bandwidth: 20 MHz, 40 MHz, 80 MHz, 160 MHz, 320 MHz

OFDM Modulation and Coding Schemes

- OFDM spreads data transmission across a frequency band
- Depending on Signal-Noise-Ratio, each tone can carry a varying amount of information
- Limit is set through Shannon-Hartley theorem

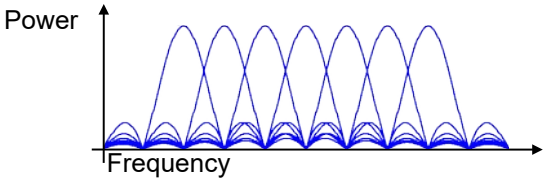
$$C = B \cdot \log_2\left(1 + \frac{S}{N}\right)$$

  - C: channel capacity [bps]
  - B: bandwidth [Hz]
  - S/N: signal-noise-ratio
- Real systems have noise figures of 6..10 dB

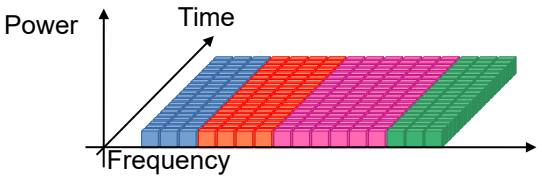


IEEE802.11 PHY layer solutions for 2.4 GHz, 5 GHz, 6 GHz

Step-wise evolution of features and performance



- 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**



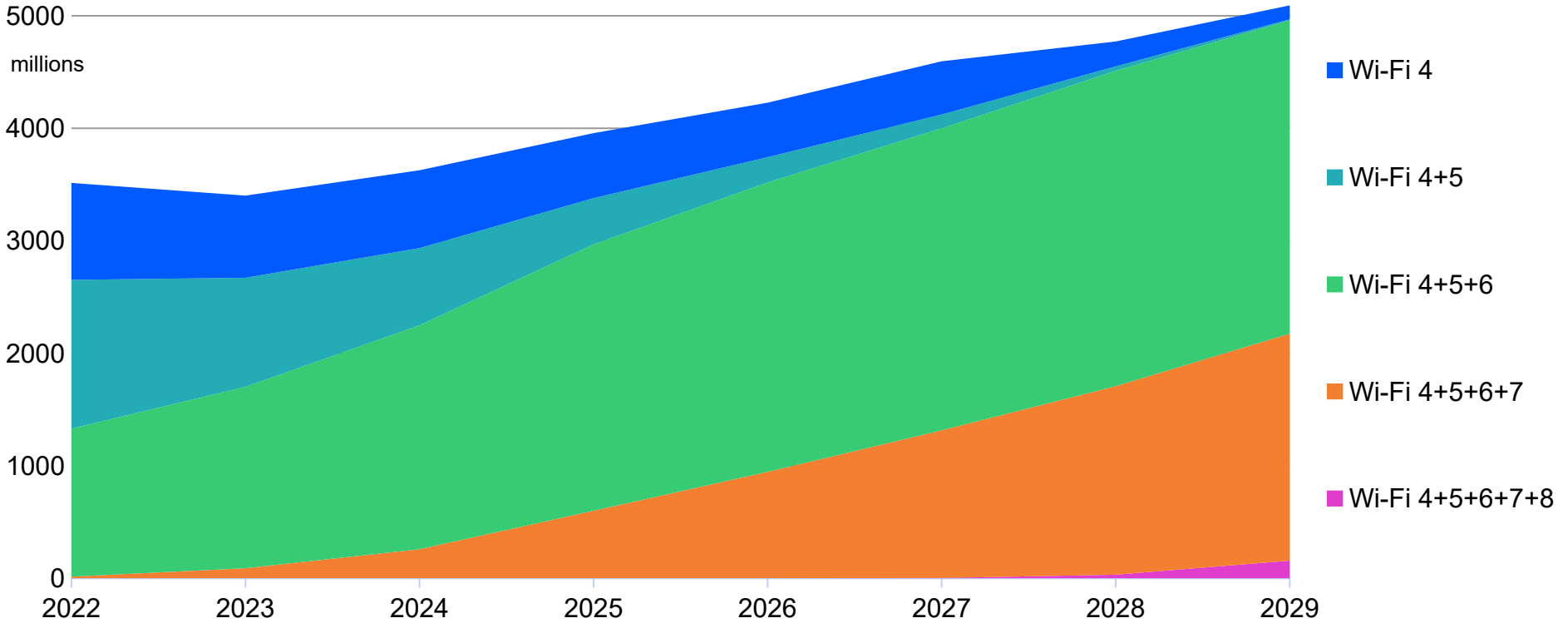
- 1 – 7.25 GHz High Efficiency (***802.11ax – Wi-Fi 6***)
  - OFDM/**OFDMA** with up to **8x8 MU-MIMO** providing up to 9600 Mbps
  - Channel bandwidth: 20 MHz, 40 MHz, 80 MHz, 160 MHz
- 1 – 7.25 GHz Extremely High Throughput (***802.11be – Wi-Fi 7***)
  - OFDM/OFDMA with up to 8x8 MU-MIMO providing up to 23 000 Mbps
  - Channel bandwidth: 20 MHz, 40 MHz, 80 MHz, 160 MHz, **320 MHz**

Wi-Fi Improvements from Wi-Fi 4 to Wi-Fi 7

Parameter	Wi-Fi 4	Wi-Fi 5	Wi-Fi 6	Wi-Fi 7	Benefits of Wi-Fi 7
Bands	2.4 GHz 5 GHz	5 GHz	2.4 GHz 5 GHz 6 GHz	2.4 GHz 5 GHz 6 GHz	Designed for 6 GHz from the ground up, including 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 160 MHz	20 MHz 40 MHz 80 MHz 160 MHz 320MHz	Doubles the size of the widest Wi-Fi 6 channel and makes 160 MHz mandatory to support high-speed use cases
Highest Modulation	64-QAM	256-QAM	1024-QAM	4096-QAM	20% higher transmission rate than Wi-Fi 6
Multi-Link Operation (MLO)	N	N	N	Y	Increased throughput, lower latency, reduced interference, reduced intra-AP roaming time
Max Data Rate	600 Mbps	3.5 Gbps	9.6 Gbps	23 Gbps 36 Gbps (w/MLO)	More than three times higher throughput than Wi-Fi 6
Max Spatial Streams	4	4	8	8	Max streams per STA
Uplink Channel Access	EDCA	EDCA	EDCA Triggered access	EDCA Optimized triggered access	More predictable latency with lower overheads

Wi-Fi growth is driven by backward compatible generations

Yearly Wi-Fi chipset shipments, world market



Source: ABIresearch Q3/2024

End of part 1

Questions and remarks