Advanced Mobile Networks
Wi-Fi (IEEE 802.11 WLAN) Part 1

WS 2024/2025 Lecture

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WS 2024/2025 Wi-Fi Lecture topics overview

Part 0:

- Introduction and overview

Part 1:

- Wi-Fi Deployments
- Wi-Fi Network architecture
- Wi-Fi Stds & Certification
- Wi-Fi Spectrum
- Wireless Channel

Part 2:

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

+ PHY Exercises

Part 3:

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

+ MAC Exercises

Part 4:

- Wi-Fi Security
- Wi-Fi Mobility
- Wi-Fi Security Q&A

AMN – Wi-Fi Lecture dates and content (tentative)

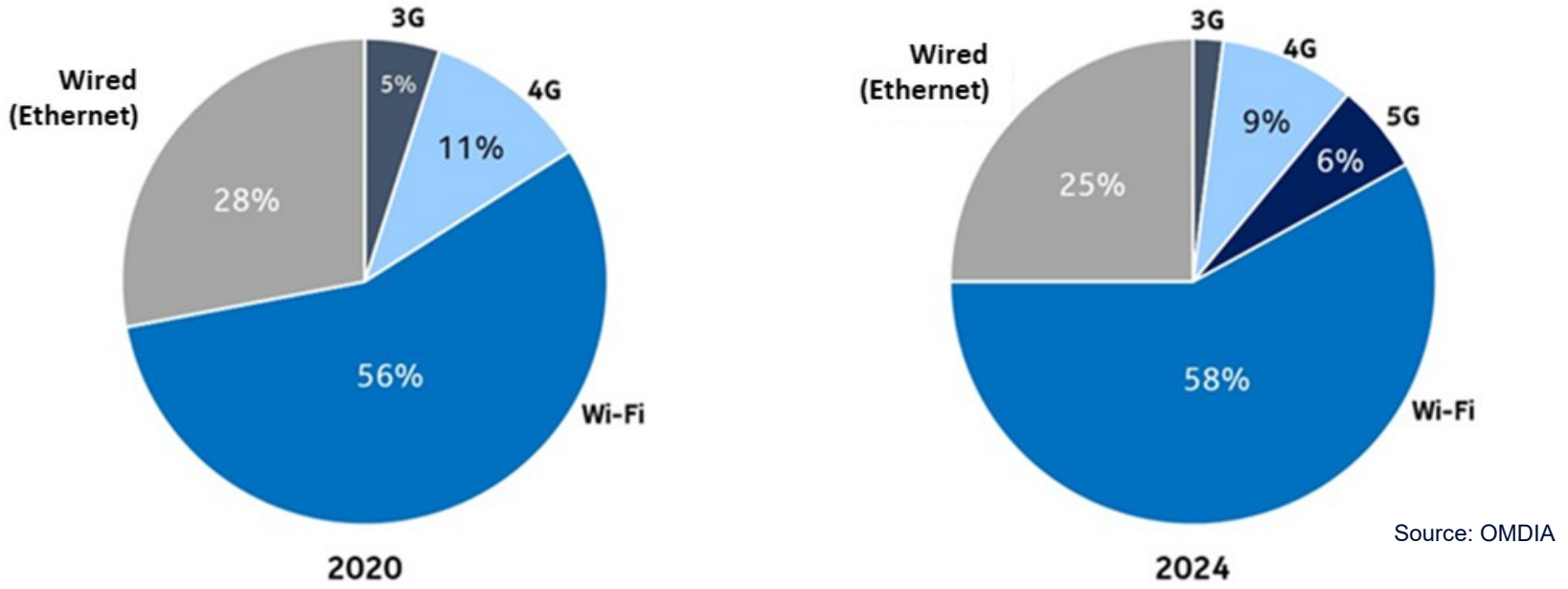
Thu, Nov. 28	Part 0	Thu, Jan 17th	Part 3
Tue, Dec. 10th	Part 1	Tue, Jan 21st	||
Thu, Dec 12th	||	Thu, Jan 23rd	||
Thu, Dec 19th	Part 2	Thu, Jan 30th	||
Tue, Jan 7th	||	Tue, Feb 4th	Part 4
Thu, Jan 9th	||	Thu, Feb 6th	||(partial)

Advanced Mobile Networks – Wi-Fi

WI-FI DEPLOYMENTS

Wi-Fi is the dominant broadband access technology

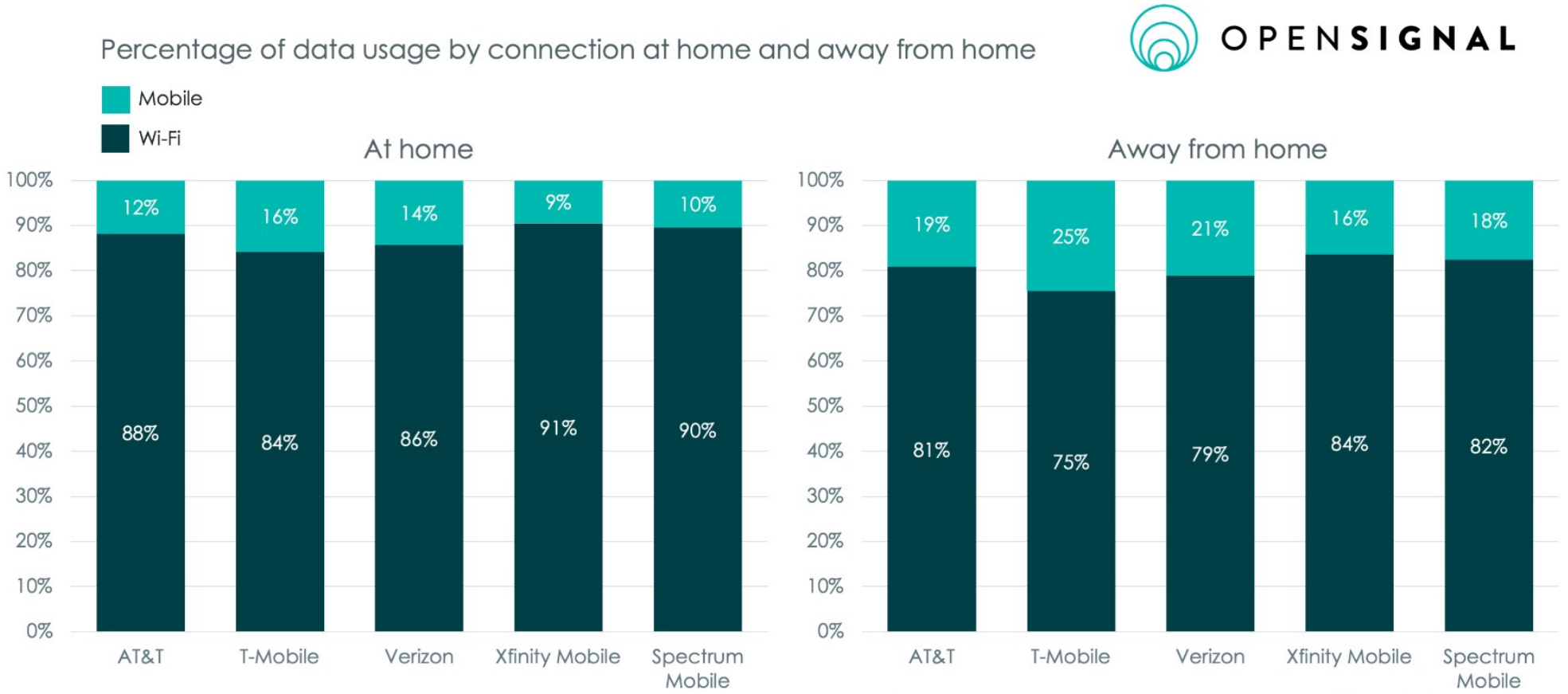
More than half of worldwide network traffic is going over Wi-Fi



Source: OMDIA

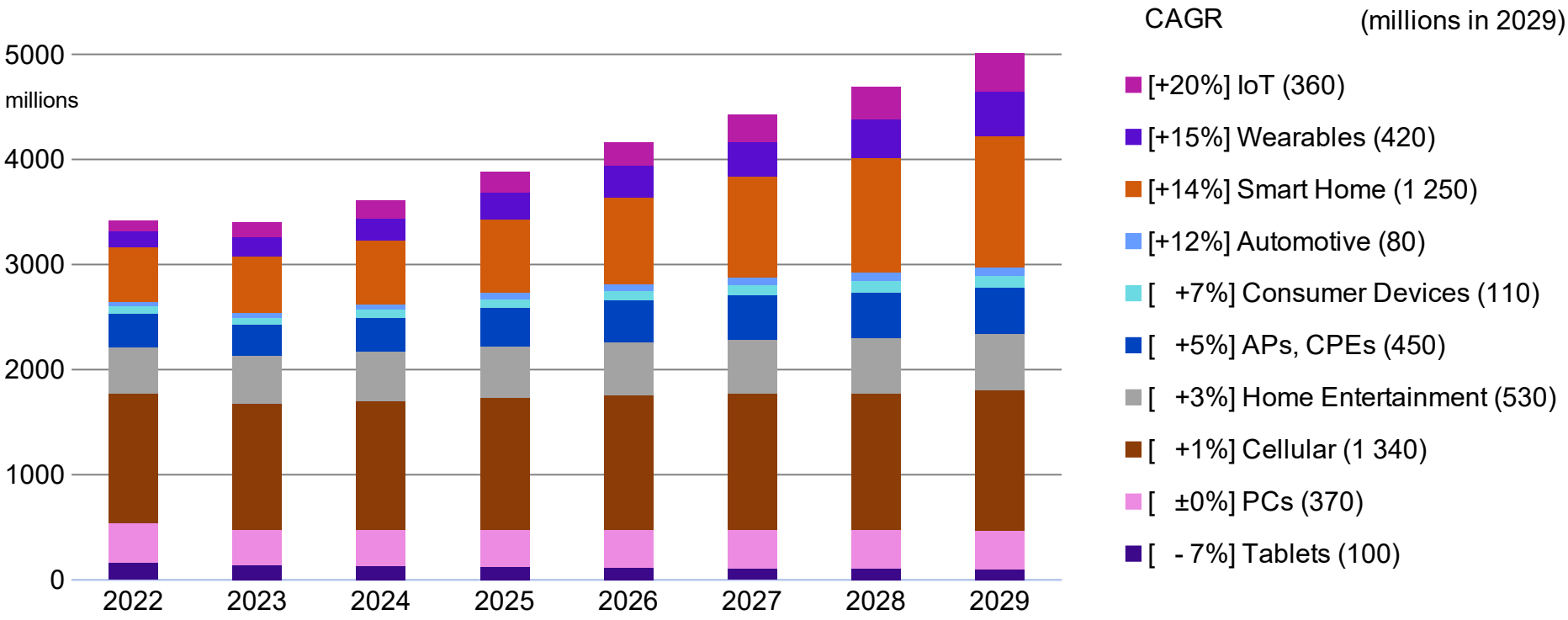
- Wi-Fi is carrying an increasing portion of worldwide IP traffic.
- No signs that Wi-Fi would be replaced by cellular technologies.

Mobile phones prefer Wi-Fi



Wi-Fi defines a heavily growing eco-system

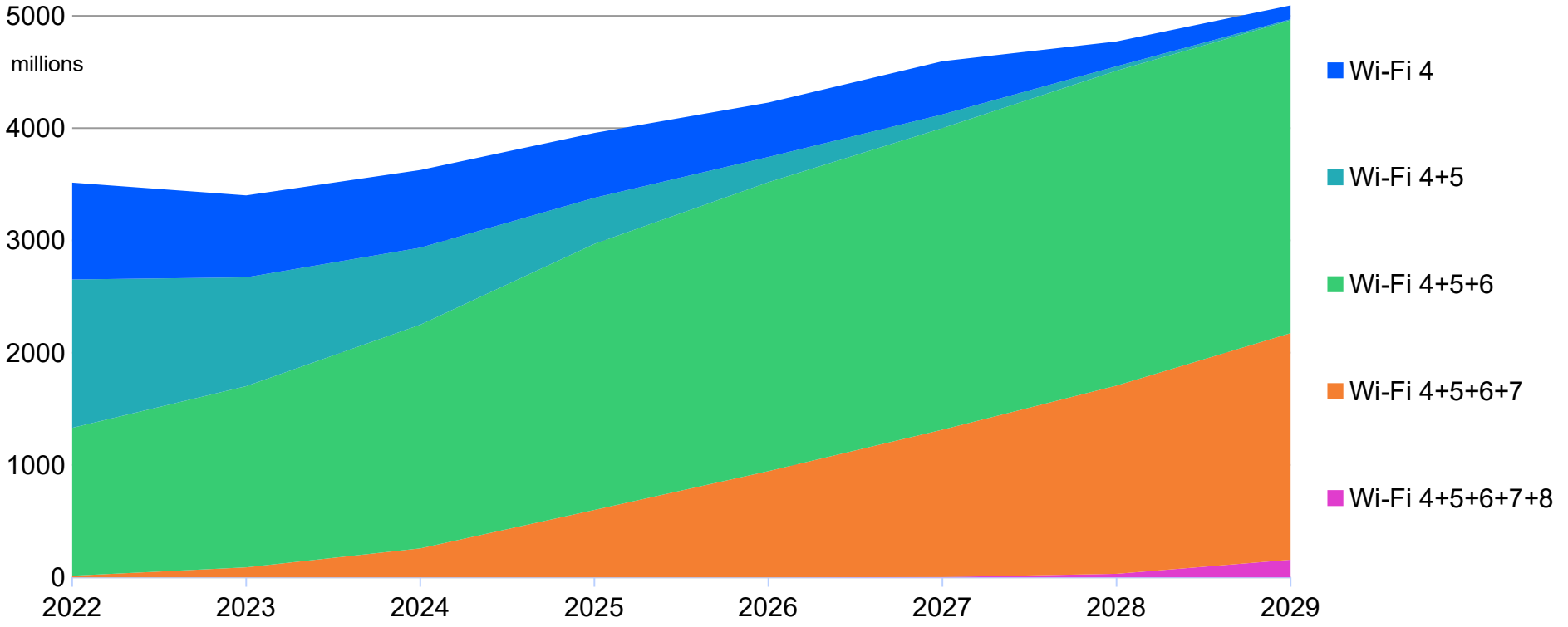
Yearly Wi-Fi devices shipments, world market



Source: ABIresearch Q3/2024

Wi-Fi growth is driven by backward compatible generations

Yearly Wi-Fi chipset shipments, world market

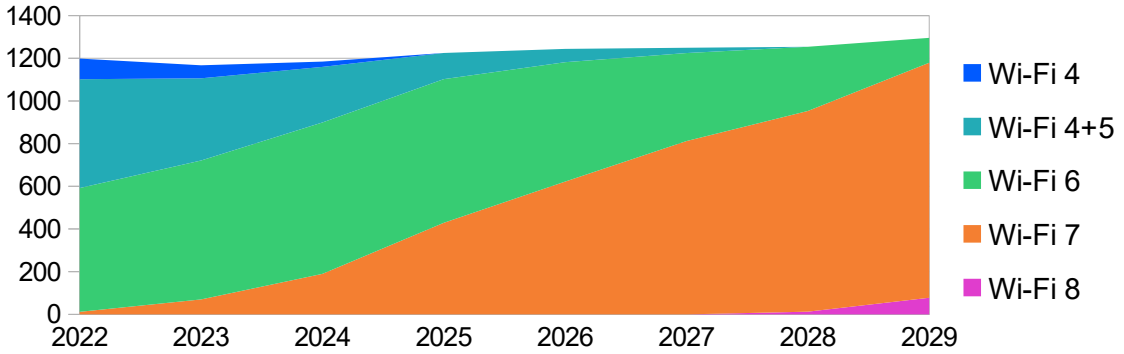


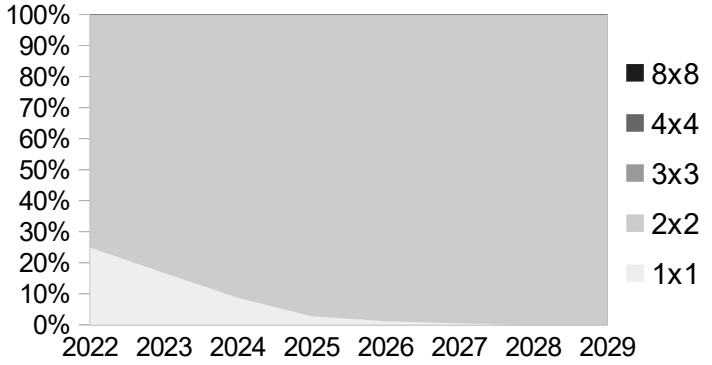
Source: ABIresearch Q3/2024

Smartphones and Wi-Fi infrastructure are early adopters …

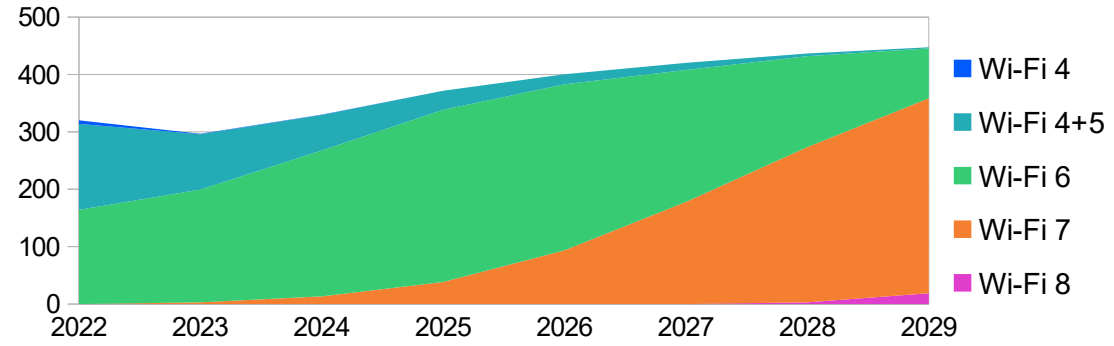
Market needs (Phones) and deployment needs (CPE/AP) will early adopt Wi-Fi 8.

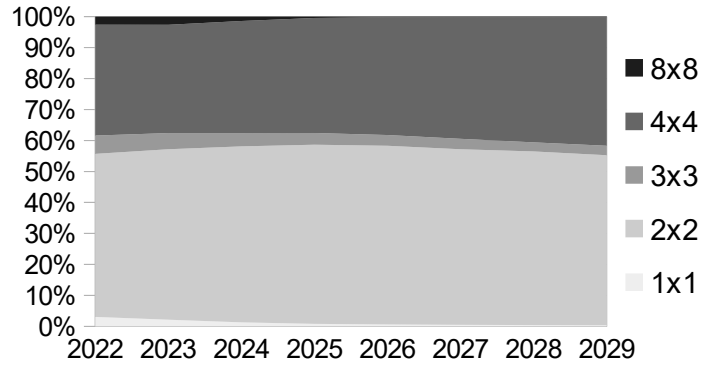
Smartphone Chipsets





AP/CPE Chipsets

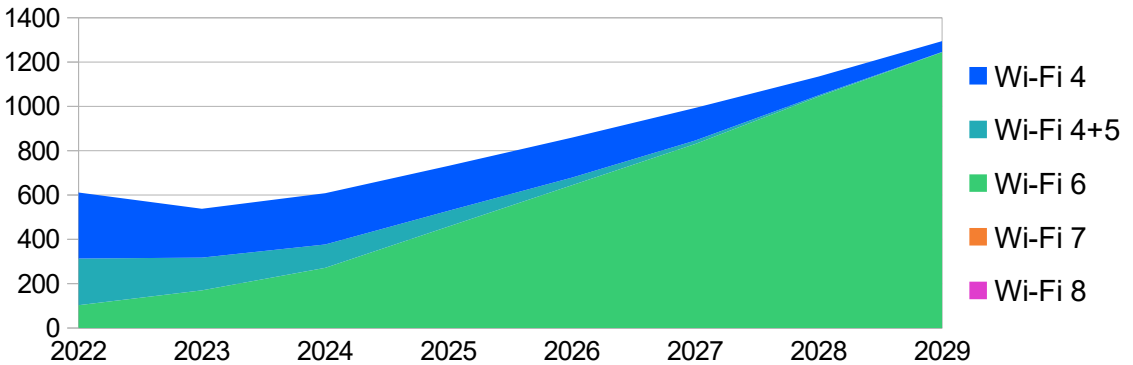


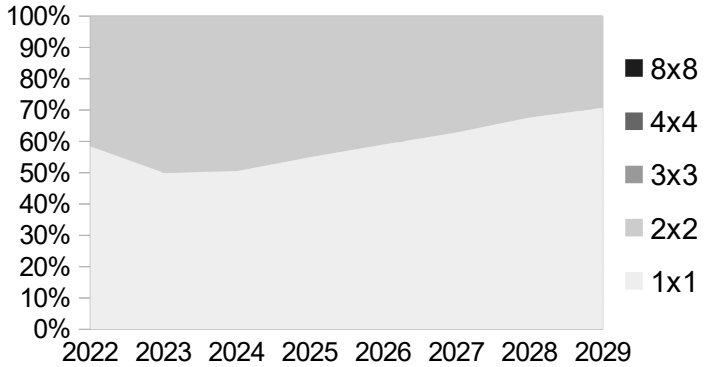


… while growing IoT/M2M leverage cost benefits of legacy.

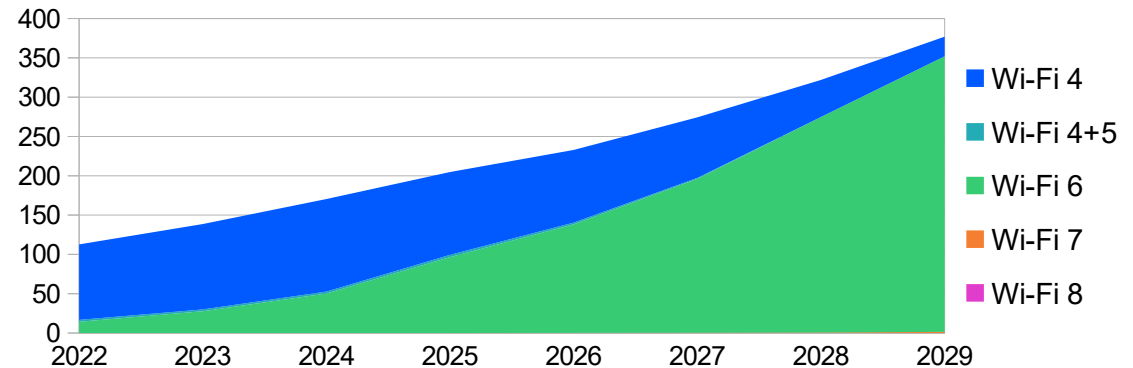
“There is nothing wrong with connecting your dish washer through Wi-Fi 4/Wi-Fi 6.”

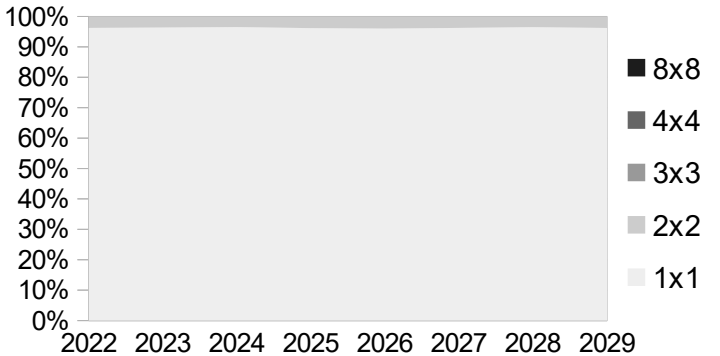
Smart Home Chipsets





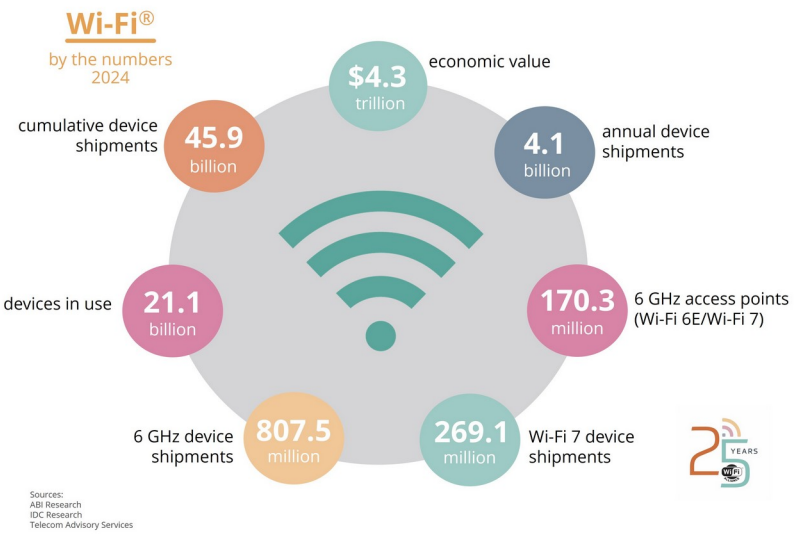
IoT Chipsets





Diversity of Wi-Fi terminals and access infrastructure

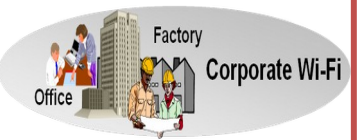
Wi-Fi is predominantly deployed in homes and indoors



~90%*

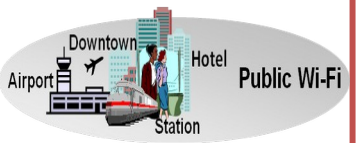
- Currently managed by millions of 'hobby' operators
- Most heavy growth of Wi-Fi devices and data traffic
- Public co-use feasible but requires strict separation from privately operated part.

~10%*



- 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

<1%*



- 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

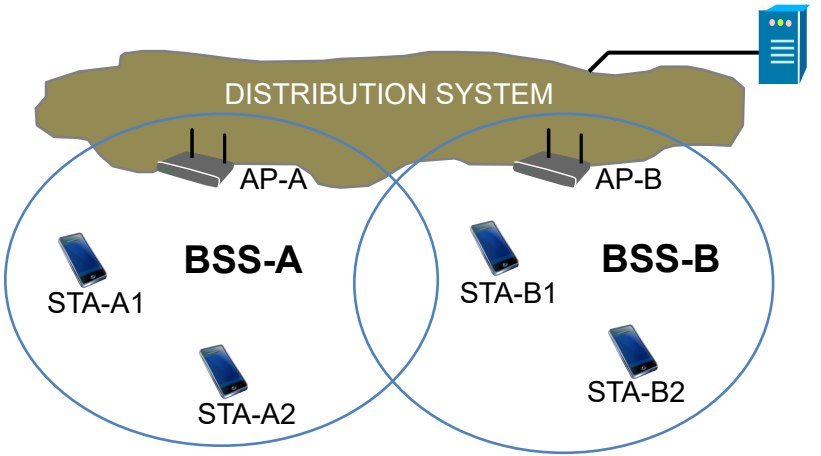
* Percentage of total APs; Source: ABIresearch 2010, Femtocells, Operator, Access Point and Chipset Market Analysis

Advanced Mobile Networks – Wi-Fi

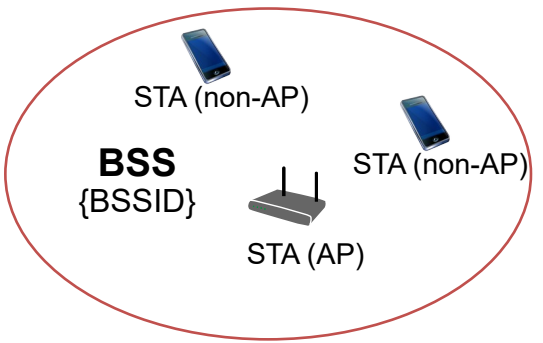
WI-FI NETWORK ARCHITECTURE

Wi-Fi basic configuration and terminology

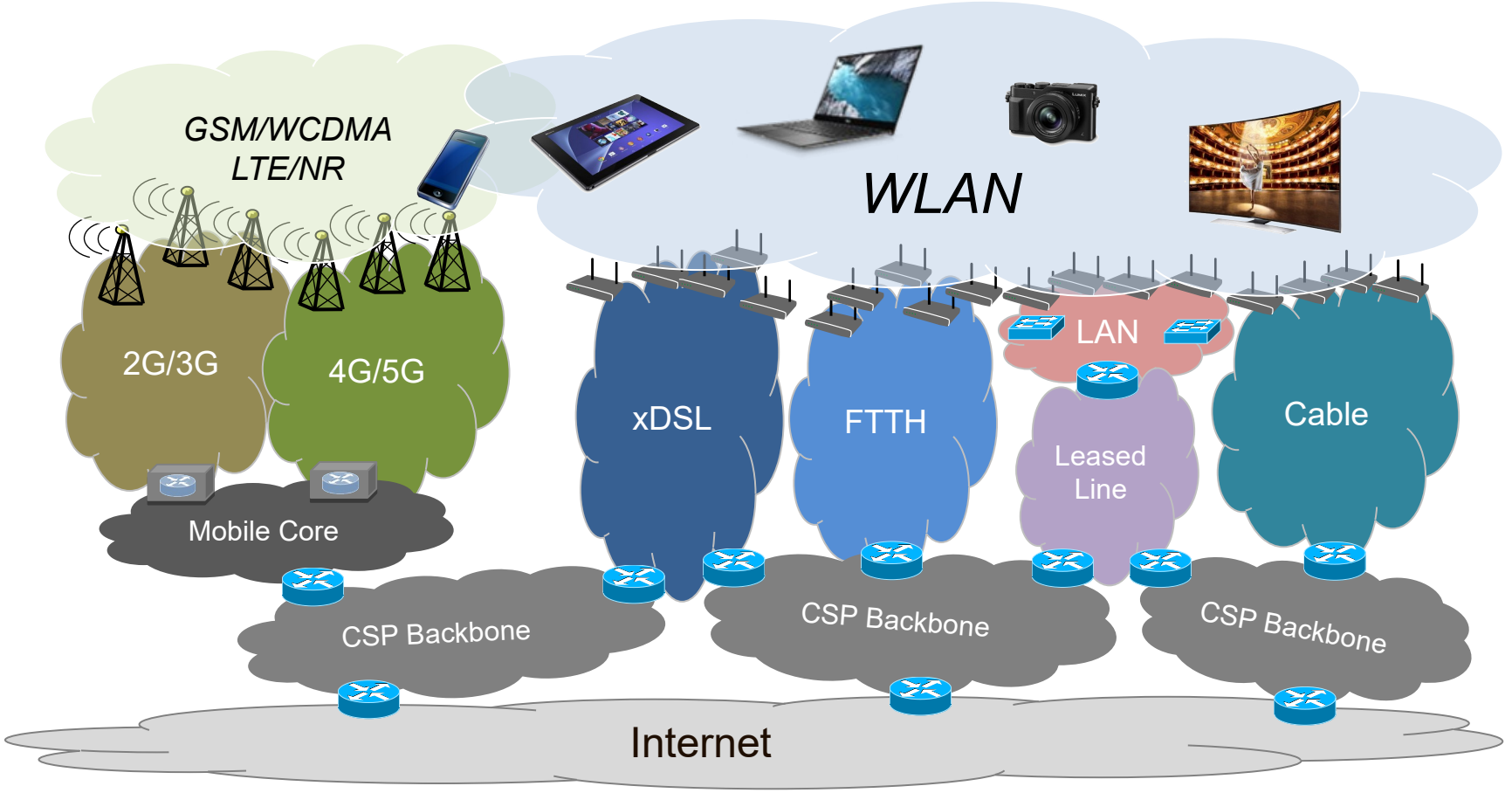
- Infrastructure
  - **Distribution System** interconnects multiple BSSs to form a single **ESS (Extended Service Set)** with a **SSID (Service Set IDentifier)**.
  - Extends wireless coverage area
  - Establishes Wi-Fi access network



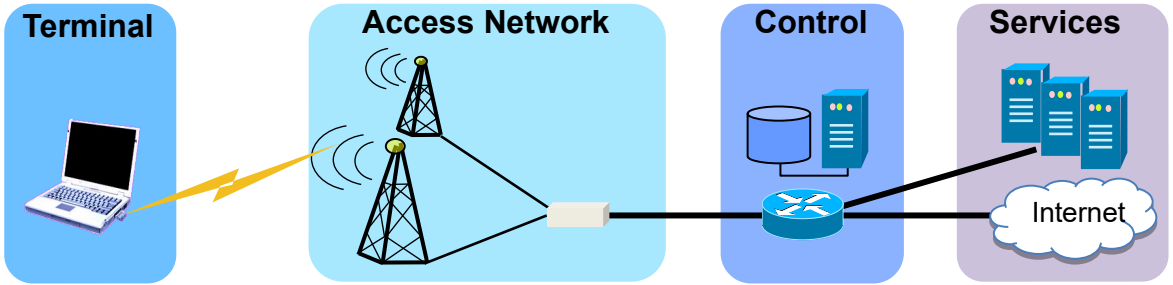
- **Basic Service Set (BSS)**
  - Single Wi-Fi ‘cell’, limited coverage area
  - Direct communication between STAs
  - Established through an ‘AP’ function
  - **BSSID: MAC address of AP**
  - Other BSSs may overlap in same radio coverage area (OBSS, "Overlapping BSS")



Wi-Fi is the wireless interface to fixed broadband services



Wireless communication network structure



Communication networks supporting wireless terminals are usually structured into

- Terminal
  - Communication endpoint towards the consumer and subscriber of communication services
- Access Network
  - Distributed infrastructure for aggregation of multiple network access interfaces into a common interface
- Control and IP connectivity
  - Infrastructure for control and management of network access and end-to-end IP connectivity
- Services
  - Infrastructure for providing services over IP connectivity

Functional decomposition of wireless network access

Access Network

- Network advertisement
- Pre-association signaling
- Authentication, authorization and accounting client
- L2 session establishment w/ QoS and Policy Enforcement
- L2 mobility management inside access networks
- Traffic forwarding to core based on L2 addresses

Control and IP connectivity

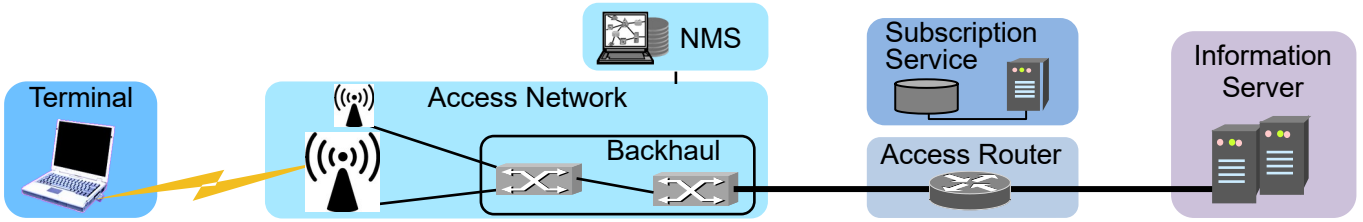
- Subscription management
- Terminal provisioning
- Authentication, authorization and accounting server
- IP address management
- IP connectivity establishment to Internet and services
- Policy & QoS management server (policy decision)
- Mobility Anchor
- Roaming support to other cores

Advanced Mobile Networks – Wi-Fi - Wi-Fi Network Architecture

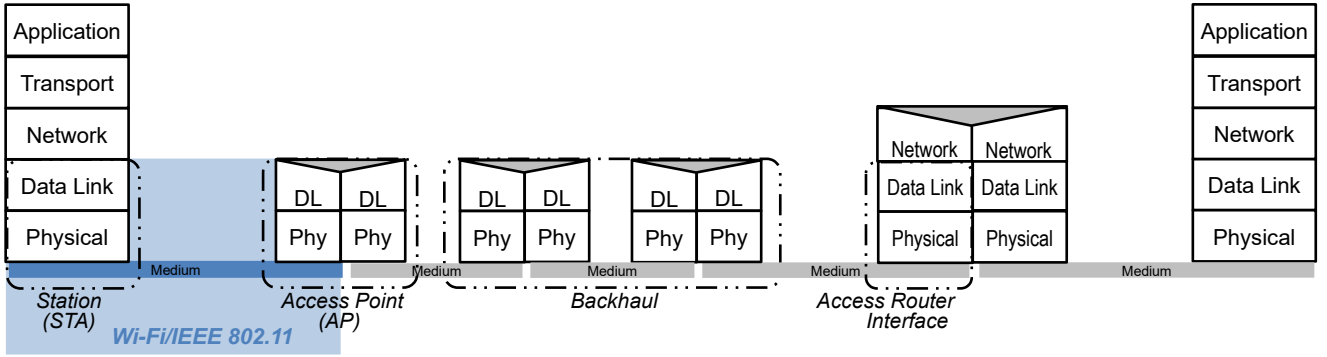
NETWORK REFERENCE MODEL FOR WI-FI

Generic Wi-Fi Network Reference Model

- Functional architecture



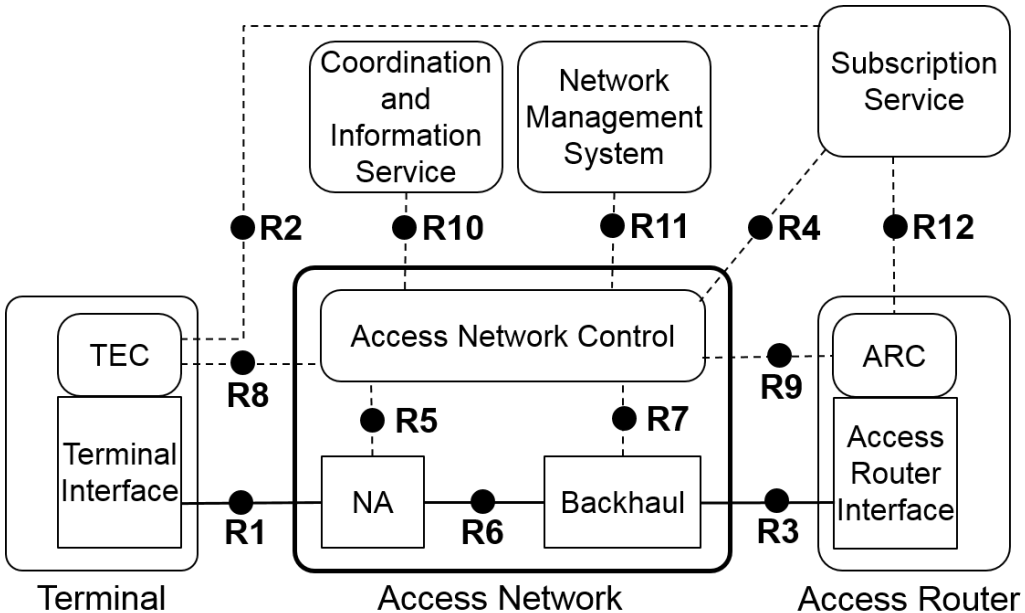
- Protocol architecture



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

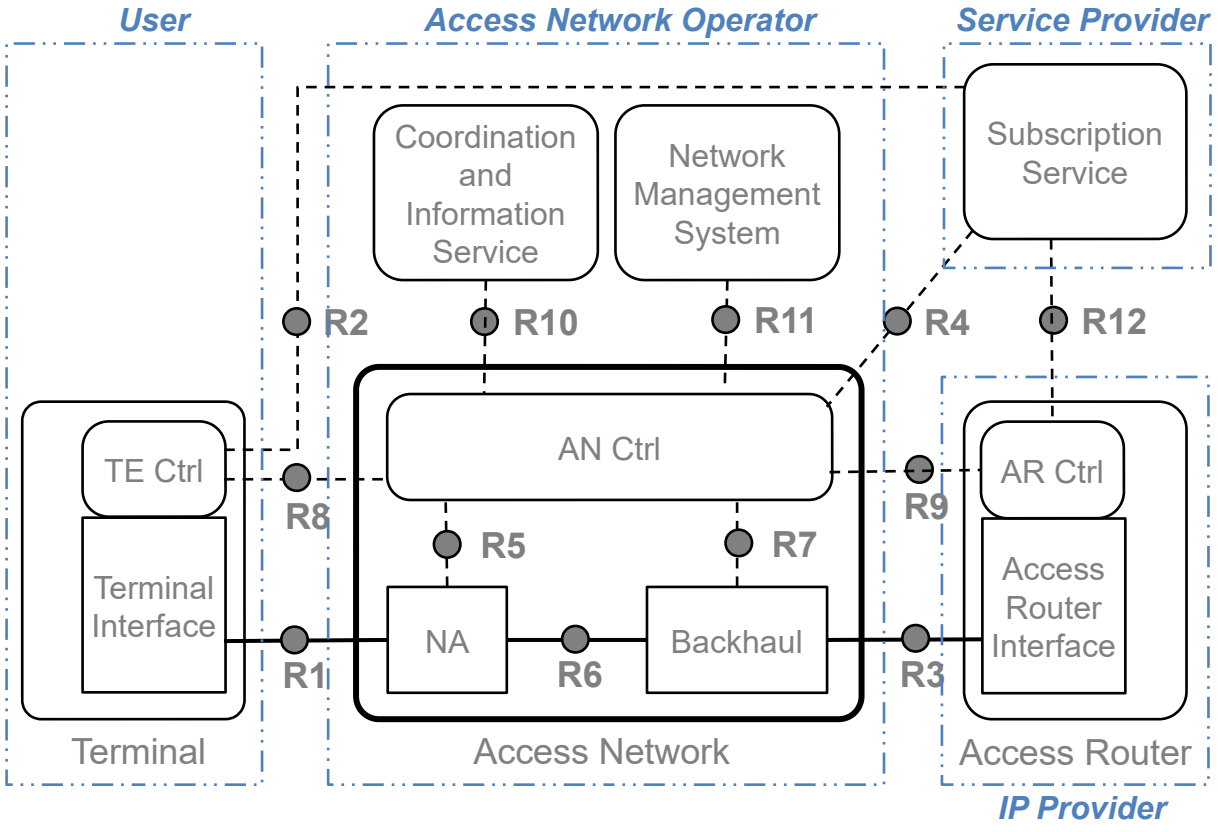
IEEE 802.1CF Access Network Reference Model

- Comprehensive NRM shows highest level of details



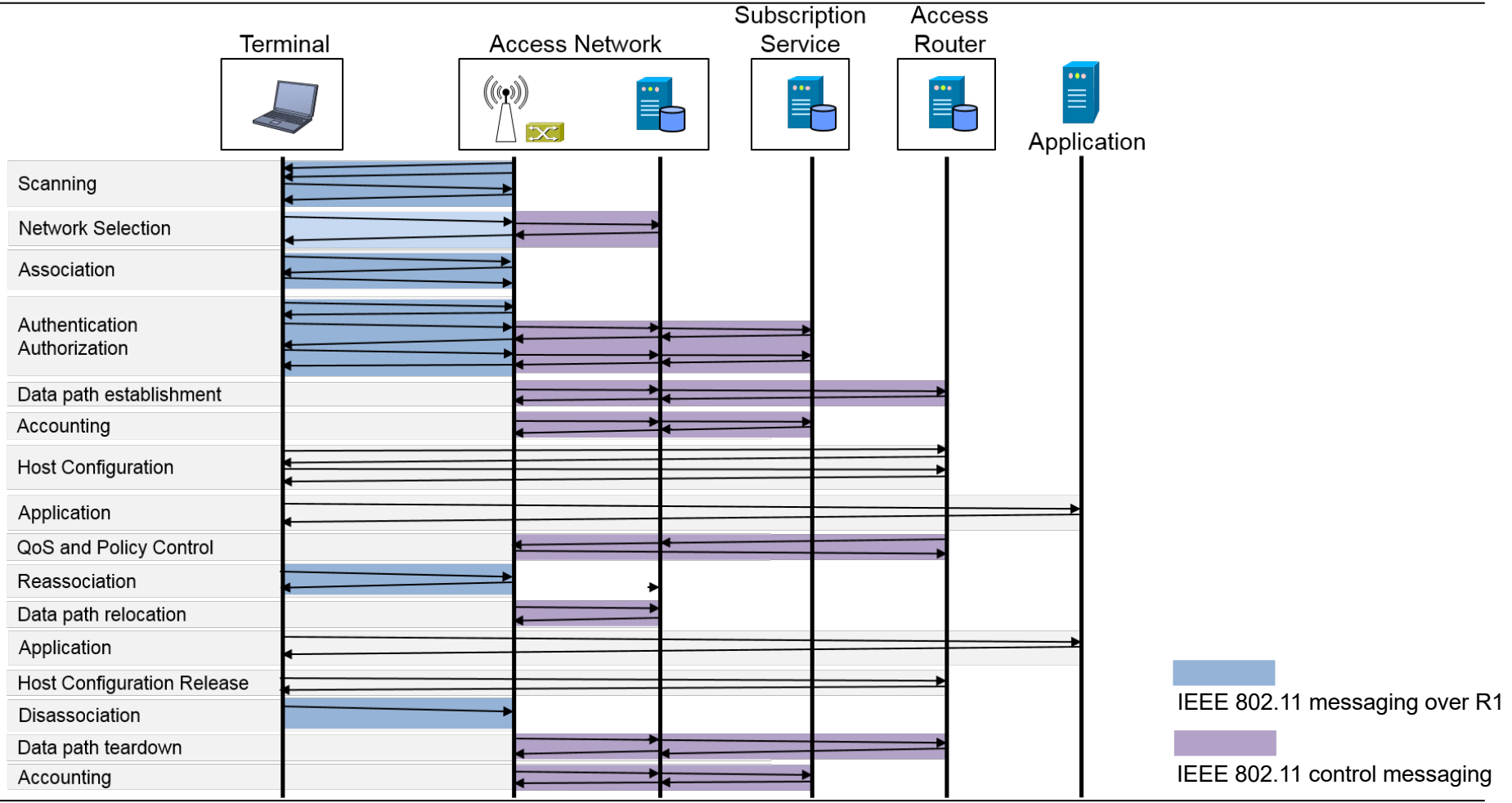
- NRM represents an abstract view on an access network
  - For the purpose to define interfaces
- Control interfaces cover only attributes related to IEEE 802
  - Protocol details on control interfaces are out of scope

Generic operational roles of IEEE 802 access network



- Operational roles define independent security and privacy domains

The life-cycle of an Wi-Fi session



Advanced Mobile Networks – Wi-Fi

WI-FI STANDARDIZATION

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

Advanced Mobile Networks – Wi-Fi - Wi-Fi Standardization

IEEE 802.11 STANDARDIZATION

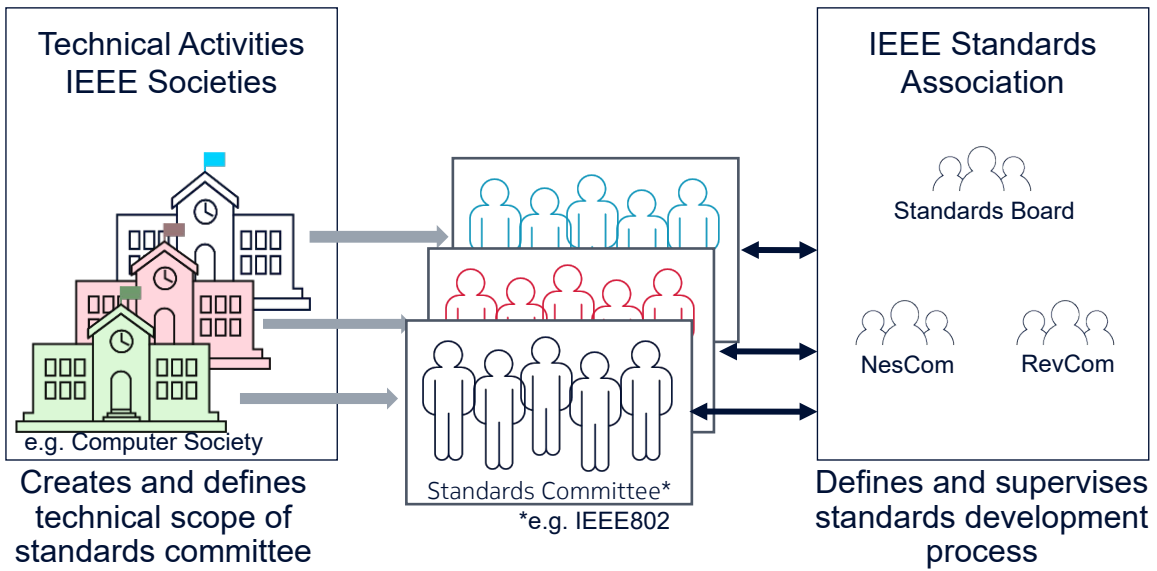
IEEE at a Glance

Advancing Technology for Humanity

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

Standardization within IEEE

IEEE Societies set scope, IEEE Standards Association defines procedural aspects.

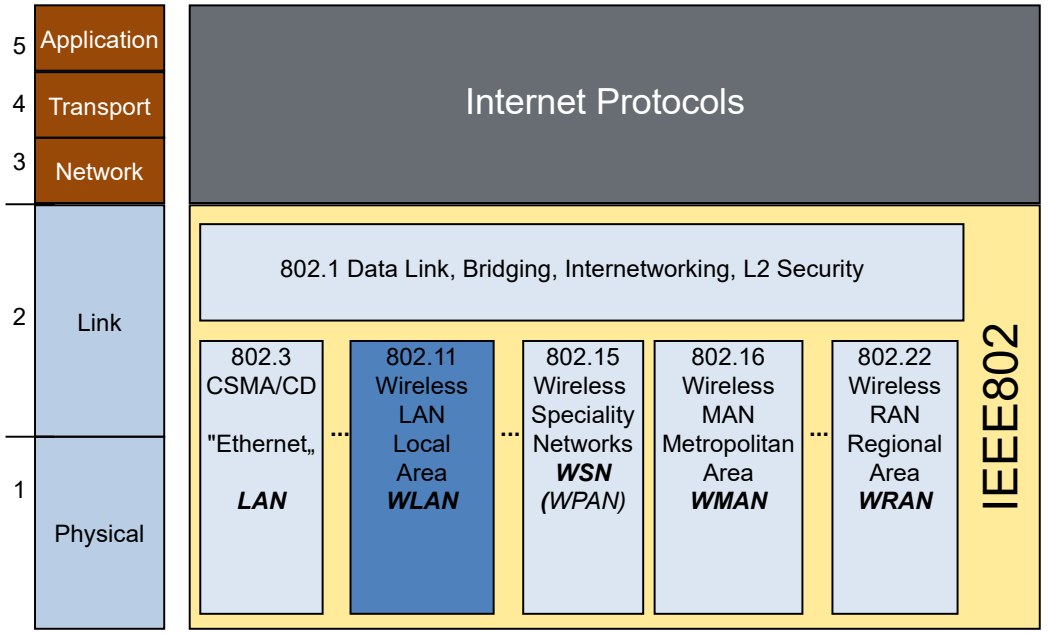


IEEE standardization process

- 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 => IEEE 802.1D	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 => Withdrawn February 2006	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) => Cancelled	
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
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
P802.11bf	WLAN Sensing	~ 06/2025
P802.11bi	Enhanced Service with Data Privacy Protection	~ 07/2026
P802.11bk	320 MHz Positioning	~ 09/2025
P802.11bn	Enhancements for Ultra High Reliability (UHR)	~ 05/2028
P802.11bp	Ambient Power Communication	~ 05/2028

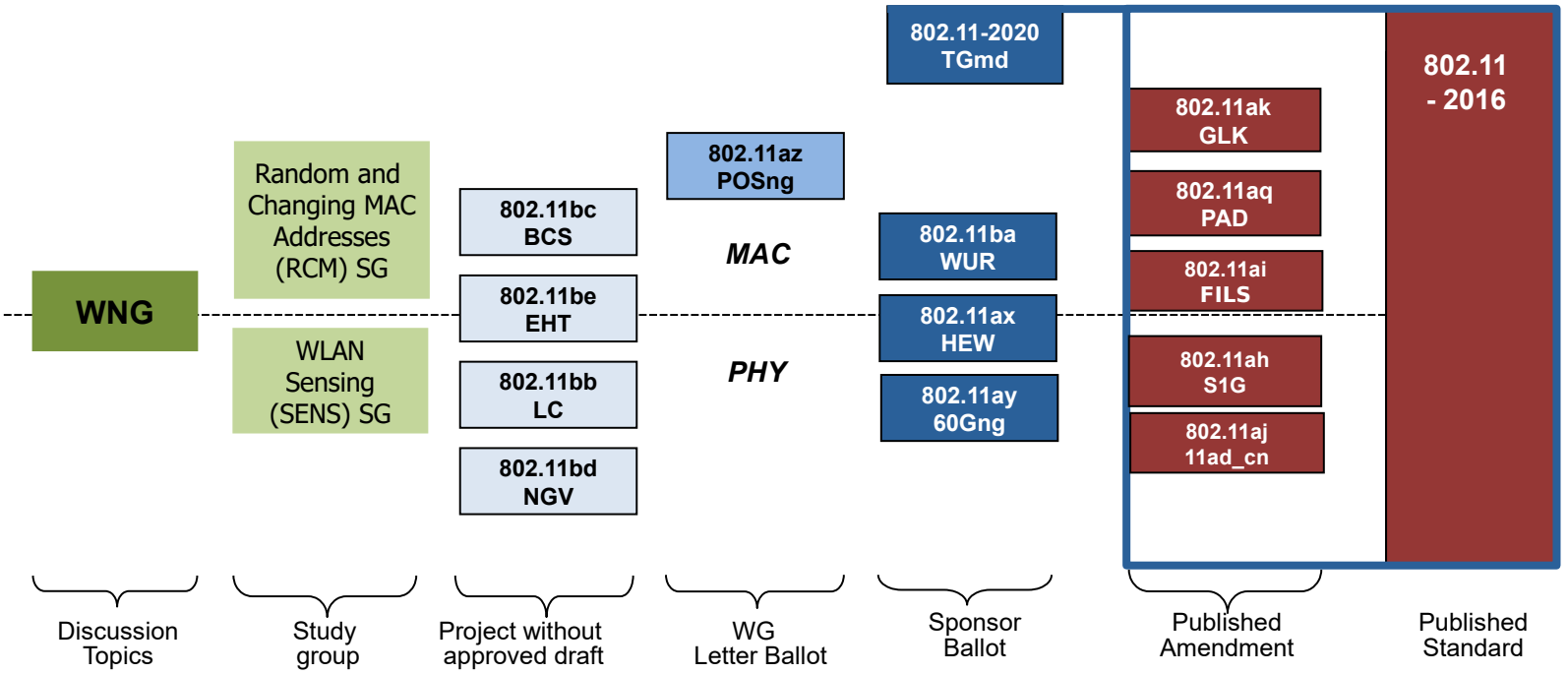
IEEE 802.11 radio standards evolution

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 standards development (Status 06/2020)

The working group concurrently operates in different standardization phases



IEEE 802.11 standards development (Status 11/2023)

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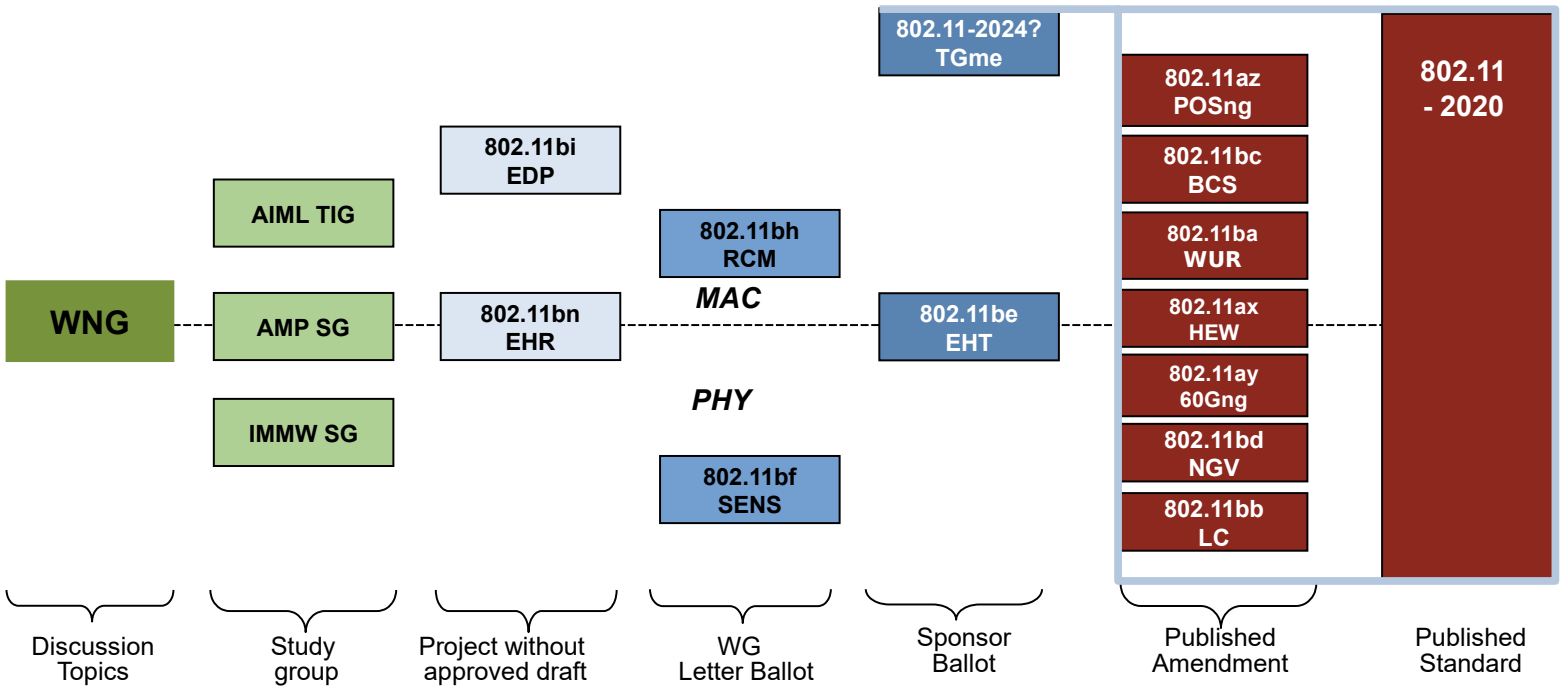
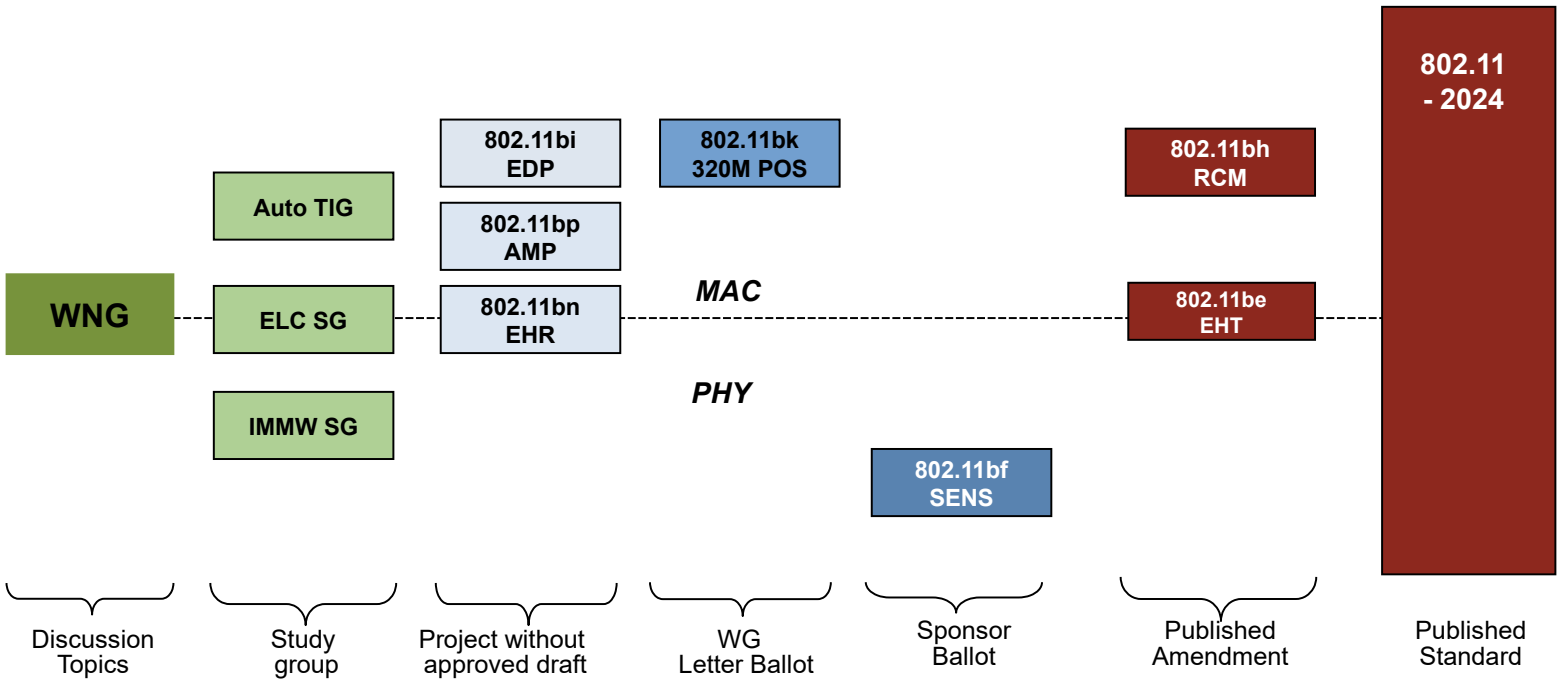


IEEE 802.11 standards development (Status 10/2024)

The working group concurrently operates in different standardization phases



Advanced Mobile Networks – Wi-Fi - Wi-Fi Standardization

IEEE 802.11 STANDARD REFERENCE FOR THE LECTURE

IEEE Std 802.11™-2024 + amendment 802.11be™-2024

- *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)

Advanced Mobile Networks – Wi-Fi - Wi-Fi Standardization

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.

Not widely adopted: 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	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 organization introduced the term ‘Wi-Fi?
3. What is the purpose of the Wi-Fi Alliance?
4. To which IEEE standardization committee belongs IEEE 802.11?
5. Which IEEE 802.11 standards and amendments are comprised in IEEE Std 802.11-2024?
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?

Advanced Mobile Networks – Wi-Fi

WI-FI SPECTRUM

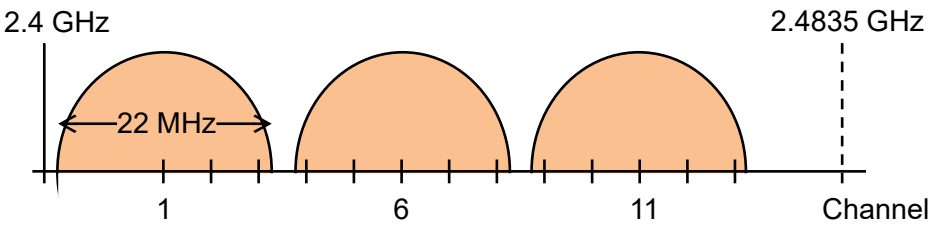
Wi-Fi operates in license-exempt spectrum

- 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

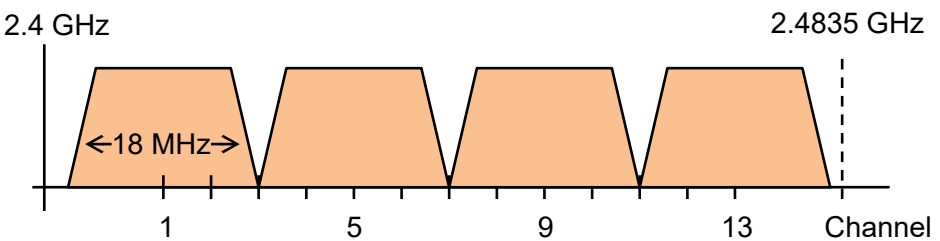
Wi-Fi in the 2.4 GHz ISM band

- 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 (802.11n/ax/be) 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:
  - Use of spread spectrum coding
  - max TX power: 100 mW EIRP

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

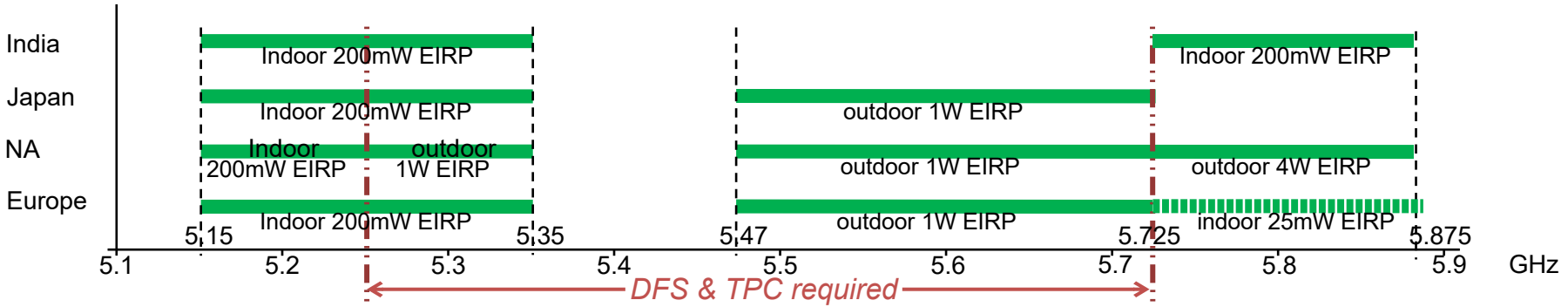


OFDM (802.11g/n/ax) fits into 20 MHz channels

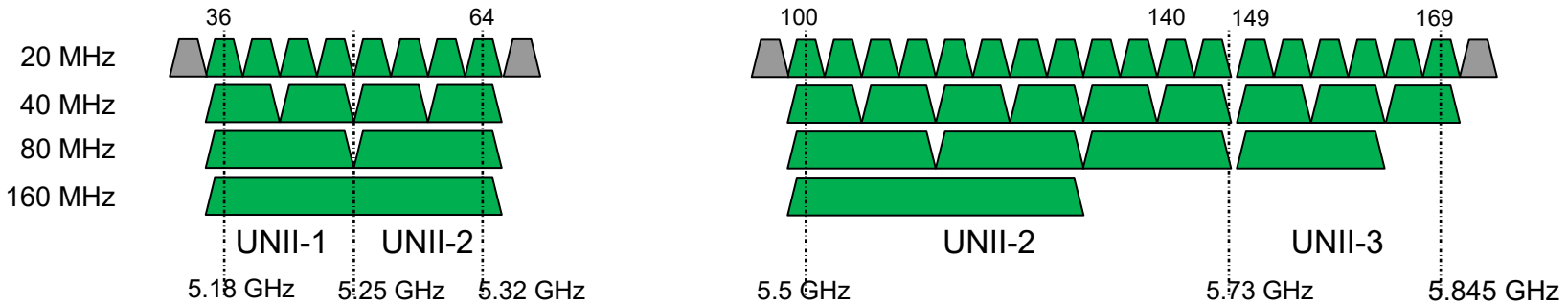


License-exempt operation in the 5 GHz band

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

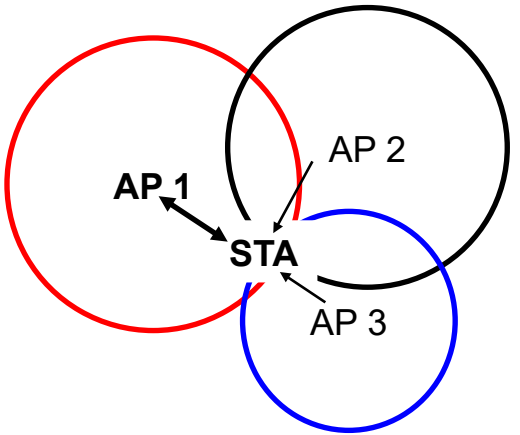


- Channelization:



Spectrum management for the 5 GHz band

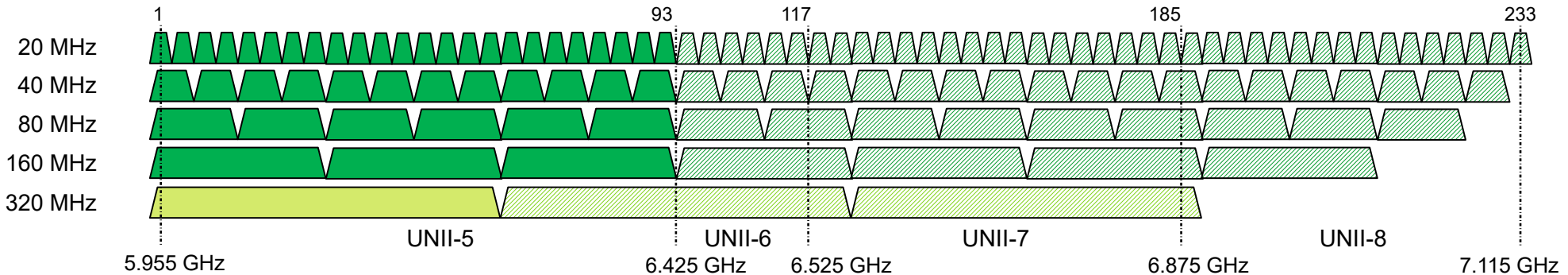
- Dynamic Frequency Selection (DFS) and Transmission Power Control (TPC) are required for most of the 5 GHz spectrum to protect primary users (e.g. weather radars)
- DFS (Dynamic Frequency Selection)
  - APs dynamically select their operating channel after scanning for other users (e.g. weather radars)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



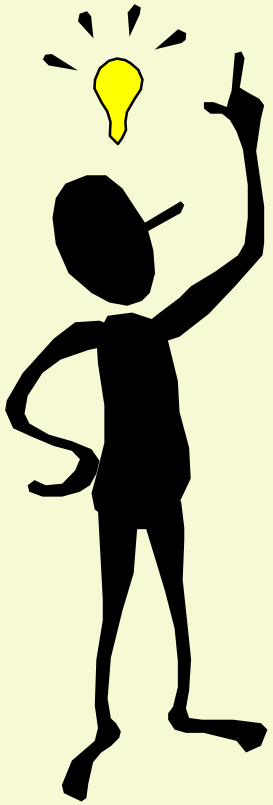
- TPC (Transmission Power Control)
  - APs define and communicate regulatory and local transmit power constraints.
  - Stations select transmit powers for each frame according to local and regulatory constraints.

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)



Questions and answers



Wi-Fi spectrum questions...

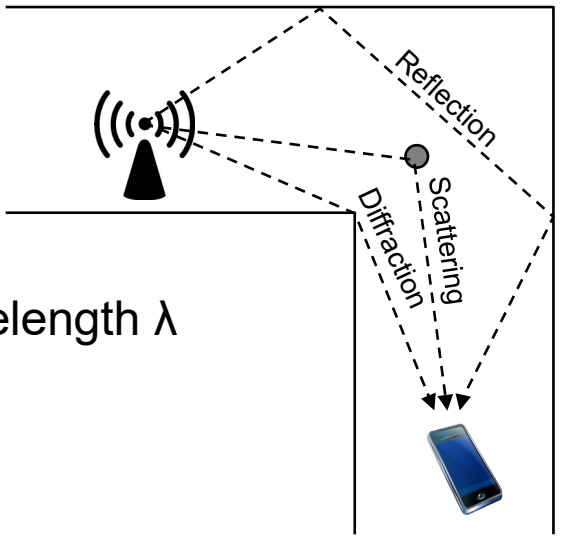
1) What does EIRP mean?
2) Why often the channel arrangement 1 – 6 – 11 is used in the 2.4 GHz band?
3) What would be the optimal channel arrangement for an OFDM-only system in Europe?
4) What is the purpose of DFS and TPC in the 5 GHz band?
5) For which frequencies is the support of DFS and TPC mandatory in Europe?
6) How many non-overlapping 80 MHz 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?
9) Which device categories exist in the 6 GHz band?

Advanced Mobile Networks – Wi-Fi

WIRELESS CHANNEL CHARACTERISTICS

Radio signal propagation issues

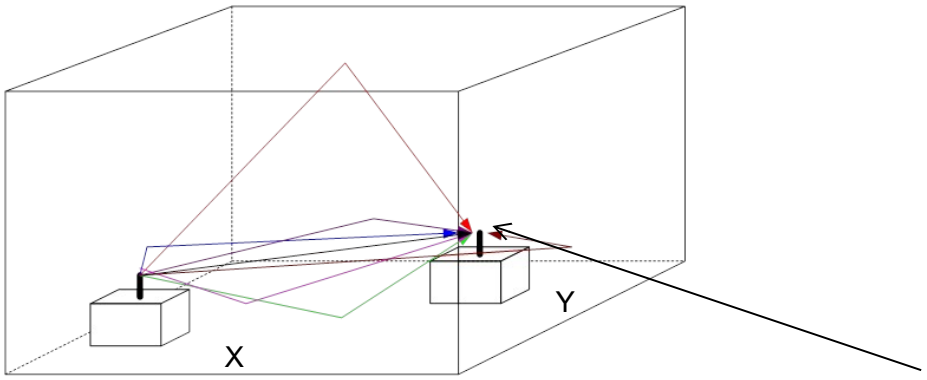
- Path loss
  - Attenuation due to distance and frequency
- Reflection
  - Surface large relative to wavelength λ of signal
- Diffraction
  - Edge of impenetrable body that is large relative to wavelength λ
- Scattering
  - Obstacle size in order of wavelength λ, e.g. lamp posts

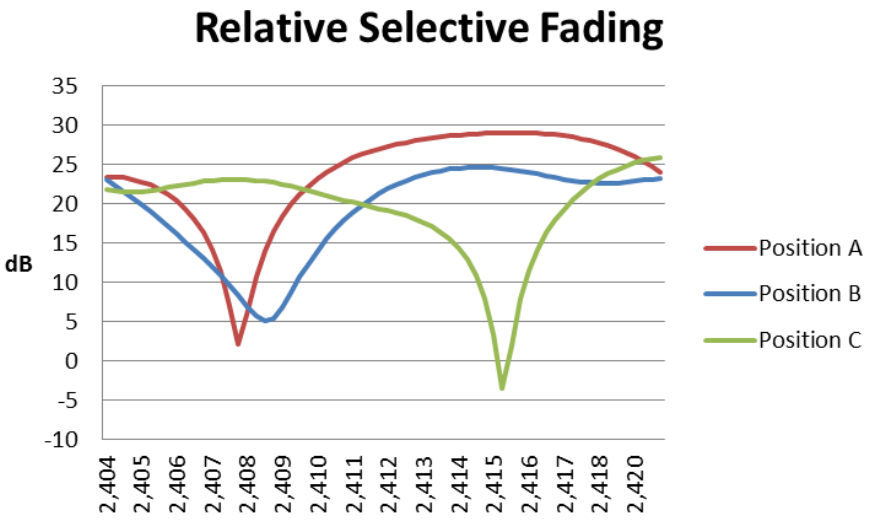


Main issues:

- 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

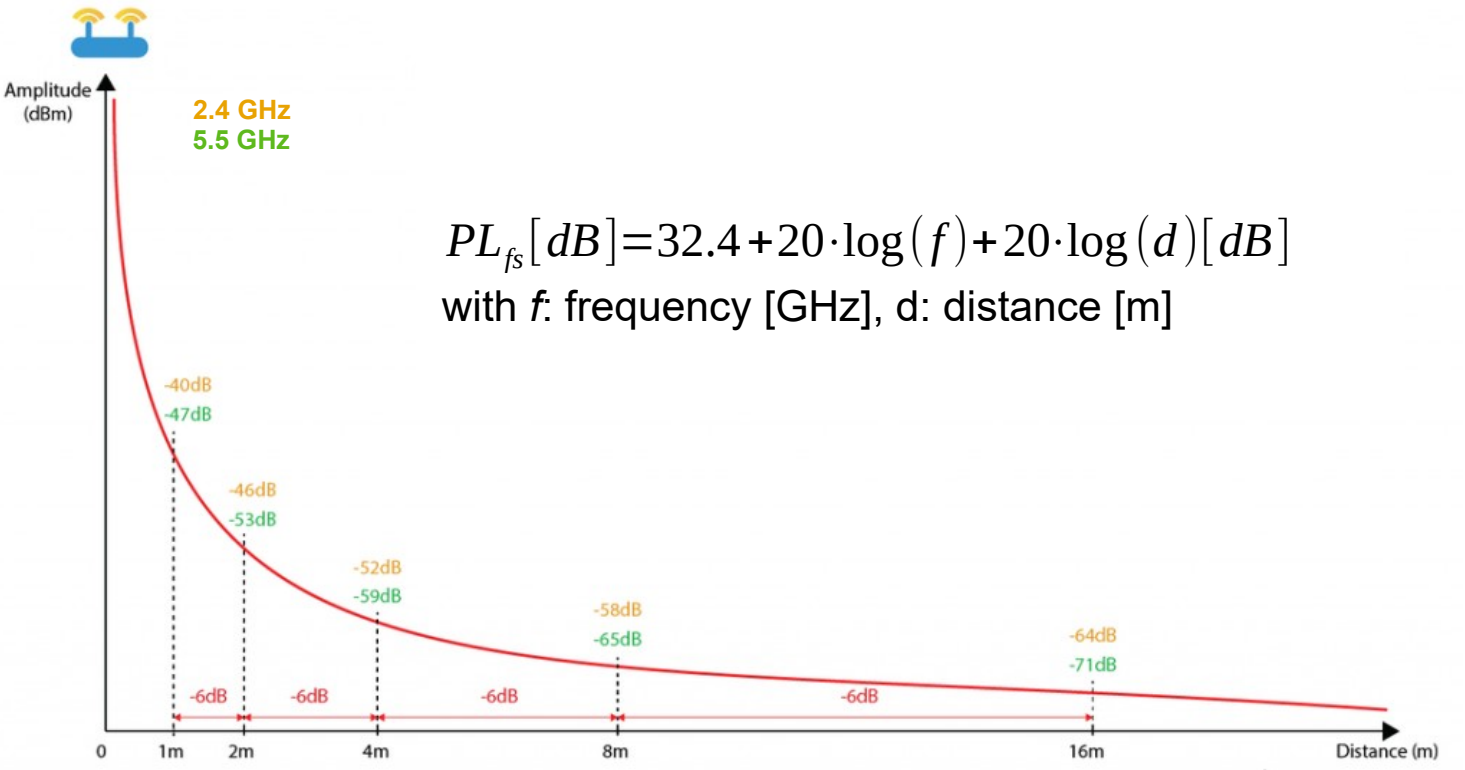
Transmission characteristics taken for

- 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

End of Part 1

Questions and remarks ?