Module 5 Assignment Answers

Wi-Fi Training Program

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Q1. What are the key features of Wi-Fi 6, 6E and 7 and how do they differ from previous standards like Wi-Fi 5 (802.11ac)?

Wi-Fi 6 (802.11ax):

- Frequency Bands: 2.4 GHz and 5 GHz (dual-band)
- OFDMA (Orthogonal Frequency Division Multiple Access): Splits channels into smaller subcarriers for better simultaneous transmission to multiple users. The OFDMA sub carriers are divided into many small subcarriers called Resource Units (RUs). So, this supports multi user, where each user gets a set of RUs for data transfer.
- MU-MIMO Enhancements: Supports uplink and downlink MU-MIMO and it supports up to 8 simultaneous
- users.
- 1024-QAM (Quadrature Amplitude Modulation): Enables 25% more data throughput than 256-QAM in Wi-Fi 5
- BSS colouring: Marks overlapping networks with different colours to reduce co-channel interference
- Target Wake Time (TWT): Schedules device wake/sleep times for improved battery life in IoT devices
- Max Channel Width: 20,40,80 and 160 MHz
- Max Theoretical Speed: ~9.6 Gbps
- Backward Compatibility: With Wi-Fi 5 and earlier

Wi-Fi 6E:

- In Wi-Fi 6E has everything mentioned in Wi-Fi 6 and the following are the additional features are introduced to improve the Wi-Fi capability.
- New Frequency Band: 6 GHz added (in addition to 2.4 GHz and 5 GHz)
- More Spectrum: Up to 1200 MHz of additional spectrum in the 6 GHz band (dependent on region)
- Enables up to 7 additional 160 MHz channels
- Less Congestion: 6 GHz band is exclusive to Wi-Fi 6E and above no interference from older devices
- Performance: Improved throughput and reduced latency due to wider, cleaner channels

Wi-Fi 7 (802.11be):

- In Wi-Fi 7 has everything mentioned in Wi-Fi 6E and the following are the additional features are introduced to improve the Wi-Fi capability.
- Frequency Bands: 2.4 GHz, 5 GHz, and 6 GHz (tri-band)
- Higher Modulation: Up to 4096-QAM: 20% higher throughput than Wi-Fi 6's 1024-QAM
- Wider Channels: Up to 320 MHz, which is double the maximum of Wi-Fi 6/6E
- Multi-Link Operation (MLO): Uses multiple bands (e.g., 5 GHz + 6 GHz) simultaneously which helps greatly in improves speed and reliability with seamless switching
- Puncturing: Enables use of partial bandwidth even in congested environments
- Enhanced OFDMA and MU-MIMO: More flexible, efficient resource allocation across users.
- Max Theoretical Speed: Up to 46 Gbps
- Backward Compatibility: With Wi-Fi 6/6E and earlier

Differences of Wi-Fi 6, 6E, and 7 over Wi-Fi 5 (802.11ac):

- Spectrum Expansion and Frequency Bands: Wi-Fi 5 uses only the 5 GHz band. Wi-Fi 6 adds 2.4 GHz support for better coverage. Wi-Fi 6E introduces a cleaner, faster 6 GHz band. Wi-Fi 7 combines all three bands for faster, more stable connections.
- Increased Speed and Data Rates: Wi-Fi 5 offers speeds up to ~3.5 Gbps. Wi-Fi 6 increases this to ~9.6 Gbps with 1024-QAM. Wi-Fi 7 boosts speeds further to 46 Gbps using 4096-QAM and 320 MHz channels, ideal for high-demand applications like AR/VR and cloud gaming.
- Better Efficiency in Crowded Environments: Wi-Fi 5 struggles in crowded places like offices or stadiums. Wi-Fi 6 and newer use OFDMA and enhanced MU-MIMO to handle many devices at once, improving efficiency in dense environments.
- Wider Channels and More Bandwidth: Wi-Fi 5 supports up to 80 MHz channels (160 MHz optional). Wi-Fi 6/6E standardize 160 MHz, Wi-Fi 7 doubles this with 320 MHz channels for much higher data rates in less time.
- Improved Device Power Efficiency: Wi-Fi 6 and later bring Target Wake Time (TWT), which schedules when devices wake up to send/receive data this extends battery life for IoT and mobile devices, a feature not present in Wi-Fi 5.

FEATURE	Wi-Fi 5	Wi-Fi 6	Wi-Fi 6E	Wi-Fi 7
Frequency Bands	5 GHz	2.5/5 GHz	2.5/5/6 GHz	2.5/5/6 GHz
Max speed	~3.5 Gbps	~9.6 Gbps	~9.6 Gbps	>46Gbps
Channel width	80 MHz	160 MHz	160 MHz	320 MHz
Modulation	256-QAM	1024-QAM	1024-QAM	4096-QAM
OFDMA	No	Yes	Yes	Yes (improved)
MU-MIMO	Downlink	Downlink + Uplink	Downlink + Uplink	Downlink + Uplink (improved)
TARGET WAKE TIME	No	Yes	Yes	Yes
MULTTI-LINK OPERATION	No	No	No	Yes

Q2. Explain the role of OFDMA in Wi-Fi 6 and how it improves network efficiency.

OFDMA (Orthogonal Frequency-Division Multiple Access) allows a Wi-Fi channel to be split into smaller sub-channels so that multiple devices can transmit at the same time, instead of waiting their turn.

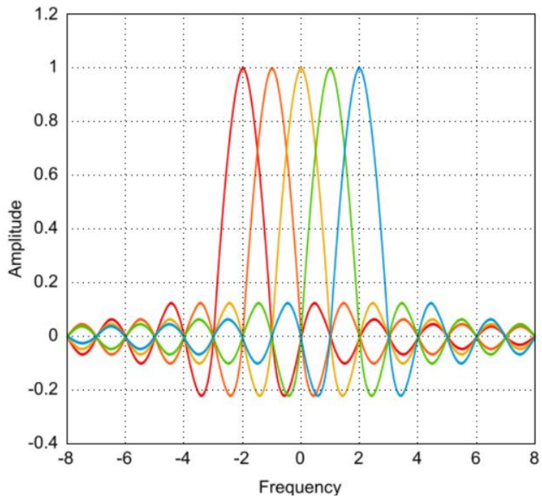

Fig: In the above chart even if the multiple carriers are overlapping each other, we can see that when one carrier is at its maximum amplitude at a specific frequency while the other carriers are either minimum or zero.

Higher Efficiency: The channels are always kept busy carrying data instead of sitting idle.
Lower Latency: Devices don't have to wait long to send small packets.
Supports More Devices: It is deal for homes, offices, airports, loT-heavy environments.
Better Battery Life: The devices wake up, quickly send/receive data, and go back to sleep faster (with Target Wake Time too).

Q3. Discuss the benefits of Target Wake Time (TWT) in Wi-Fi 6 for IoT devices.

Target Wake Time (TWT) is a power-saving feature introduced in Wi-Fi 6 that allows devices-especially low-power and IoT devices-to schedule when they wake up to transmit or receive data, rather than constantly staying active or checking the channel.

<u>Target Wake Time works as follows:</u>

Negotiation Phase:
- The Access Point (AP) and client device (like an IoT sensor) agree on a specific wake-up schedule during the association process.
- The schedule includes details like how often the device should wake up and how long it should stay awake.

Sleep Mode:
- The device enters deep sleep mode to save power when it is not scheduled to transmit or receive data.

Scheduled Wake-Up:
- At the negotiated time, the device wakes up, exchanges data with the AP, and goes back to sleep until the next scheduled interval.

Benefits of TWT for IoT Devices:
- Significant Power Savings: IoT devices like smart sensors or wearables can spend most of their time in sleep mode, conserving battery and extending their operational life.
- Reduced Channel Contention: Because devices are waking up at scheduled intervals rather than randomly, there's less competition for the channel. This reduces collisions and increases overall efficiency.
- Scalability in Dense Networks: TWT allows better scheduling in networks with many devices (like smart homes or industrial setups), preventing them from interfering with each other.

Q4. Explain the significance of the 6 GHz frequency band in Wi-Fi 6E.

Massive New Spectrum Availability:
The 6 GHz band adds up to 1200 MHz of new spectrum (from 5.925 GHz to 7.125 GHz). This is more than double the total spectrum previously available for Wi-Fi, enabling much more room for high-speed connections.

Wider Channels for Higher Speeds:
It allows for more and larger channels, including up to seven 160 MHz channels, or four 320 MHz channels in Wi-Fi 7. This means higher throughput and faster data rates for bandwidth-heavy applications like 4K/8K streaming, AR/VR, and cloud gaming.

Less Congestion and Interference:
Unlike 2.4 GHz which is used by Bluetooth, Zigbee, microwave ovens and other communication protocols and devices which can interfere with Wi-Fi. The 6 GHz band is dedicated exclusively to Wi-Fi 6E and above which means that No interference from older Wi-Fi generations (which only use 2.4/5 GHz). Cleaner and more stable signals, especially in crowded environments like apartments or offices.

Lower Latency and More Reliable Connections: With more available spectrum and cleaner channels, devices can avoid delays caused by congestion. This leads to lower latency and more predictable performance, ideal for real-time applications like video conferencing, online gaming and other multimedia.

Future-Proofing Wi-Fi Networks: The 6 GHz band prepares networks for the growing number of connected devices and data demands in homes, businesses, and smart cities. It supports technologies like Wi-Fi 7 more effectively, ensuring long-term performance improvements.

Effective Aperture of Antenna: When we deal with higher frequencies, the size of the antennas 4π with reduce significantly so this will help in reducing the space usage and the material cost for making and setting up the antenna, and the number of antennas also increase with improve the connectivity.

Q5. Compare and contrast Wi-Fi 6 and Wi-Fi 6E in terms of range, bandwidth, and Interference.

PARAMETER	**Wi-Fi 6 (802.11ax)**	**Wi-Fi 6E (802.11 Extended)**
Release Year	2019	2021
Frequency Band	2.4 and 5 GHz	2.4, 5 and 6 GHz
Range	Longer range on 2.4 GHz	Slightly short
Maximum speed	~9.6 Gbps theoretically	~9.6 Gbps (but more wide channels are available)
Channel Width	Up to 160 MHz	Up to 160 MHz
Available Spectrum	Limited in the 2.4 and 5 GHz	Very large spectrum which are 1200 MHz in some regions
Interference Level	Medium to high in crowded bands	Very low where 6 GHz is clean
Latency	Low	Very low due to less congestion
No. of channels	Limited wide channels	It has more channels especially the 160 MHz channels
Device compatibility	Works with many existing devices	Needs new Wi-Fi 6E compatible devices
Security protocol	WPA3 recommended	WPA3 mandatory
Use cases	General home/office networks, IoT, smartphones	VR/AR, cloud gaming, 8K video streaming, very dense environments
Wall Penetration	Good (2.4 GHz penetrates best)	Weaker (6 GHz is easily absorbed by walls)
Power efficiency	Improved with Target Wake Time (TWT)	Same as Wi-Fi 6 (with TWT)

Q6. What are the major innovations introduced in Wi-Fi 7 (802.11be)?

Improved wide channel bandwidth:
Wi-Fi 7 can use super-wide 320 MHz channels (double Wi-Fi 6/6E's 160 MHz) which allows much more data to move at once.

Higher Modulation:
Higher-level modulation packs more bits per transmission compared to Wi-Fi 6's 1024-QAM wich is about 20% higher throughput as 4096-QAM.

Multi-Link Operation (MLO):
Devices can connect to multiple bands (2.4/5/6 GHz) at once, combining them for faster speed, lower latency, and better reliability.

Preamble Puncturing:
Instead of discarding a channel with interference, Wi-Fi 7 can "puncture" (skip) the noisy part and use the rest while maximizing usable bandwidth.

16 Spatial Streams:
Wi-Fi 7 supports up to 16 streams (compared to 8 in Wi-Fi 6) which means it can handle even more simultaneous connections at high speeds.

Enhanced MU-MIMO and OFDMA:
MU-MIMO and OFDMA are upgraded in Wi-Fi 7 and can serve more users (16) simultaneously with higher efficiency.

Time-Sensitive Networking (TSN):
It was introduced for ultra-low latency and can be use for critical for applications like AR/VR, industrial automation, gaming, and real-time remote surgery.

Multi-AP Coordination:
Access points can coordinate and work together better which reduces interference and boosts performance across a network.

Deterministic Latency and Jitter Control:
Wi-Fi 7 aims for consistent, predictable performance, fast, but stable and reliable even under heavy load.

Backward Compatibility:
Wi-Fi 7 is backward compatible with Wi-Fi 6 and earlier standards, ensuring smooth integration with existing devices while providing performance upgrades.

Q7. Explain the concept of Multi-Link Operation (MLO) and its impact on throughput and latency.

Multi-Link Operation (MLO) is a key feature in Wi-Fi 7 (802.11be) that boosts performance by letting devices connect to multiple frequency bands (2.4 GHz, 5 GHz, and 6 GHz) simultaneously. This significantly enhances both throughput and latency.

<u>**Working of MLO:**</u>
Simultaneous Usage of Multiple Bands: Devices can send and receive data over multiple bands at once (e.g., 5 GHz + 6 GHz), improving speed and stability.
Dynamic Load Balancing: Devices shift traffic between bands based on network conditions, avoiding congestion.
Channel Bonding: Combines channels across bands to create a wider data path, increasing throughput.

<u>**Impact on Throughput:**</u>
Higher Data Rates: MLO expands total bandwidth by using multiple bands, enabling faster data transfers.
Better Spectrum Utilization: Access to cleaner frequencies (especially 6 GHz) ensures efficient use and reduces interference.

<u>**Impact on Latency:**</u>
Reduced Latency: Distributes data across bands to avoid bottlenecks, lowering delays.

Faster Response Times: Simultaneous multi-band connections allow quicker communication, ideal for gaming and real-time apps.
Improved Reliability: If one band faces issues, MLO switches to another, ensuring stable and consistent performance.

Q8. What is the purpose of 802.11k and v, and how does it aid in roaming?

- 802.11k and v are Wi-Fi standards designed to make roaming between access points within the same wireless network faster, smarter, and more seamless especially.
- It is best suited for enterprises and large networks like offices, malls and airports.

<u>802.11k – Neighbour Report (Fast Decision Making):</u>
Purpose: Helps a device quickly find the best nearby access point (AP) to roam to.

Working:
- When roaming might be needed, the current AP sends a list of neighbouring APs (with details like signal strength, channels, etc.).
- Instead of scanning manually, the device already knows where the good options are.

Impact:
- Faster roaming
- Takes less time for scanning which results in less disruption in voice calls, video streaming and gaming.

<u>802.11v – Network Assisted Roaming (smart Steering):</u>
Purpose: It helps the network "nudge" or suggest to a device when and where to roam and connect to the AP with stronger signal.

Working:
- The current AP tells the device to move to an AP with stronger signal.
- This is BSS Transition Management Frame.

Impact:
- The devices move proactively instead of waiting for connection issues
- It provides better load balancing (avoiding overloading a single AP)
- It gives smoother roaming experience

Q9. Explain the concept of Fast BSS Transition (802.11r) and its benefit in mobile environments.

- Fast BSS Transition (FT), defined in the 802.11r amendment to the Wi-Fi standard, is a feature that speeds up the handoff process when a device moves between different access points (APs) in the same wireless network (BSS = Basic Service Set).
- Purpose of 802.11r is designed to make roaming between access points (APs) faster by streamlining the authentication process.

<u>WORKING:</u>
It introduces Fast Transition (FT) by allowing devices to pre-authenticate with nearby APs before actually moving to them.

Handover is seamless: It reduces the time spent on security handshakes (like 4-way handshake) when switching APs, enabling near-instant transitions and improves the user experience.

Ideal for Mobility: It is especially beneficial in mobile environments like VoIP, video calls, or gaming on the move where delay during roaming can cause lags or dropouts.

Faster Roaming: Reduces roaming delay from hundreds of milliseconds to a few milliseconds.

Benefit: Significantly reduces roaming latency (to less than 50ms), ensuring continuous connectivity during movement across a wireless network.

Q10. How do 802.11k/v/r work together to provide seamless roaming in enterprise networks?

802.11k:

- It helps the client identify nearby access points (APs) by providing a neighbour report, so it scans only relevant channels speeding up roaming decisions.
- 802.11k helps in scanning.

802.11v:

- It allows the current AP to suggest better APs based on signal strength, congestion, or load. It also assists with load balancing and power saving.
- 802.11v helps in choosing the best AP.

802.11r:

- It enables quick and secure handoffs by letting clients pre-authenticate with target APs, drastically reducing handover time (ideal for voice/video calls).