Deep Dive: WiFi in IoT Communications

Why Study WiFi in IoT?

WiFi is one of the most accessible and widely deployed wireless technologies. In IoT, it's commonly used for:

- **High-bandwidth sensors** (e.g., cameras, audio)
- **Gateway devices** (e.g. Raspberry Pi, ESP32, smart hubs)
- **Infrastructure environments** (e.g., office, factory, smart home)

However, it comes with **trade-offs** — including **power consumption**, **interference sensitivity**, and **range limitations**. The goal of this chapter is for you to be more familiar with thinking about wireless protocols overall.

The IEEE 802.11 Standard Family

WiFi is standardized under **IEEE 802.11**, a family of specifications that define the **MAC and PHY layers** for wireless LANs. This is a theme you'll run into again: IEEE laying out the framework for the lower layers of the protocol stack. See why it's so smart knowing about the OSI stack yet?

Name	Year	Max Speed	Frequency Bands	Modulation Techniques
802.11b	1999	11 Mbps	2.4 GHz	DSSS (Direct Sequence Spread Spectrum)
802.11g	2003	54 Mbps	2.4 GHz	OFDM
802.11n	2009	600 Mbps	2.4 & 5 GHz	MIMO, OFDM
802.11ac	2013	~1.3 Gbps	5 GHz	MU-MIMO, wider channels, QAM
802.11ax (WiFi 6)	2019	~9.6 Gbps	2.4 & 5 GHz (also 6 GHz in WiFi 6E)	OFDMA, 1024-QAM, BSS Coloring

This is an overview of the standards and how they have evolved.

Key Evolution Points

- **802.11b**: First mass-market WiFi, slow but robust.
- **802.11g**: Improved speeds but still crowded 2.4 GHz.
- **802.11n**: Introduced **MIMO** (multiple antennas) and **channel bonding**.
- **802.11ac**: Shifted focus to 5 GHz to reduce interference.
- **802.11ax (WiFi 6)**: Designed for dense environments; efficient and low-latency.

Modulation and Spectral Efficiency

WiFi transmits data by **modulating a carrier wave** using **Quadrature Amplitude Modulation (QAM)** and **Orthogonal Frequency Division Multiplexing (OFDM)**.

The important part is to understand that QAM and OFDM are different techniques of separating data channels.

OFDM Basics

OFDM splits the signal across **multiple orthogonal subcarriers**. Wait, what does this mean? Let's break it down a little.

The FDM is fairly easy to understand. Frequency division multiplexing means we divide the frequency into many smaller frequencies, which we call subcarriers. Each subcarrier has a super-narrow range, say 312.5 kHz.

The **orthogonal** aspect is that the frequencies are chosen so that they interfere as little as possible. It's like voices in a choir. If many people sing whatever, it's tricky to hear anything. But when we space out the voices "orthogonally," the different pitches become distinct.

Each subcarrier works independently in **modulating** the data. That means they can choose the best modulation technique for how well that specific frequency is working at the moment.

QAM

QAM is cool. It means that we can modulate the Phase and the Amplitude simultaneously, which means we can send more data simultaneously.

If we only modulate the Amplitude, we have limited options. One option could be:

High amplitude: 1

Low amplitude: 0

Then, we can transmit a lot of 1s and 0s and get some data across. But we can do better! If we also modulate the phase, we can send more data across simultaneously!

	High amplitude	Low amplitude
Late phase	11	10
Early phase	01	00

With the late phase, we delay the radio wave a little. Of course, it's more complicated than this, but that's the general idea.

Of course, we can subdivide this further. But the more we subdivide, the easier it is to mess this up. So, and this is the important part, **the higher the QAM level, the more data we can send across**. But the risk of interference also increases.

QAM Level	Bits per Symbol	Remarks
16-QAM	4	Basic WiFi (e.g. 802.11g)
64-QAM	6	802.11n
256-QAM	8	802.11ac
1024-QAM	10	802.11ax

> Higher QAM levels = more bits per symbol → faster throughput, **but also more sensitive to noise and interference**.

WiFi Limitations and Interference

Overall, radio signals with higher frequencies have a shorter range and a higher risk of interference. The lower frequencies give us longer wavelengths that can sort of "wrap around" stuff that gets in their way (like people, which is so annoying). This is somewhat true, but I hope it gives you a good intuitive sense.

Frequency Bands

- **2.4 GHz**: Longer range, better wall penetration, but **very crowded** (Bluetooth, ZigBee, microwaves).
- **5 GHz**: Less crowded, **shorter range**, more absorption by walls.
- **6 GHz** (WiFi 6E): New and relatively unused, limited device support.

Sources of Interference

Source	Affects Band	Example
Bluetooth	2.4 GHz	BLE devices transmitting nearby
Microwave Ovens	2.4 GHz	Emits EM radiation in GHz range
ZigBee	2.4 GHz	Overlapping channels
Dense WiFi usage	2.4/5 GHz	Collisions, congestion
Physical Barriers	All	Walls, metal, water (high absorption)

Channel Planning

Only three non-overlapping channels exist in 2.4 GHz (1, 6, 11). If you don't plan your Wi-Fi properly, you may encounter interference from adjacent channels.

WiFi in Embedded Systems and IoT

Pros

- **High throughput**: Can handle large sensor payloads (e.g., image uploads).
- **Ubiquitous**: Works in most home and office environments.
- **TCP/IP stack available**: Many IoT chips (e.g., ESP32) have full

support.

Cons

- **High power draw**: WiFi radios consume significant energy, which is bad for the battery.
- **Crowded spectrum**: Especially problematic in smart homes and offices.
- **Relatively complex**: Stack and connection management can be heavier than BLE or LoRa.

Setting the Stage for Other Radios

WiFi's limitations in power and range motivate the use of **other wireless standards** in IoT:

Technology	Range	Power Usage	Speed	Notes
BLE	~10–50 m	Very Low	Low	Great for wearables, sensors
ZigBee	~10–100 m	Low	Low	Mesh networking, 2.4 GHz
LoRa	~2–10 km	Ultra Low	Very Low	Long range, narrowband, slow
WiFi	~20–50 m	High	High	Good for gateways or power-fed

By understanding WiFi in-depth, you can better appreciate why **BLE is better for a door sensor**, but **WiFi is great for a smart speaker**.

Suggested Practice

1. **RF Analysis with WiFi Analyzer**: Scan 2.4 GHz channels at home/school and identify interference.
2. **Compare ESP32 Power Modes**: Measure power draw between deep sleep and WiFi transmission.

3. **Channel Planning Exercise**: Given 3 APs in a floor plan, assign optimal channels to minimize overlap.
4. **Modulation Simulation**: Plot 16-QAM and 64-QAM constellations (bonus for advanced students).

Quiz Questions

1. What modulation technique is used in WiFi 802.11g and beyond?
2. Why does increasing QAM level increase throughput but also require better signal quality?
3. What are the differences in propagation between 2.4 GHz and 5 GHz WiFi?
4. How many non-overlapping channels exist in the 2.4 GHz band?
5. Why is WiFi often unsuitable for battery-powered IoT sensors?
6. What are typical sources of RF interference for WiFi?
7. How does OFDM help in high-multipath environments?
8. Compare the power and range trade-offs of WiFi vs LoRa.
9. What features were introduced in WiFi 6 (802.11ax) to help in crowded environments?
10. When would you prefer BLE over WiFi in an IoT system?