# Chapter 2

# Wireless Technologies

# RF (Radio Frequency) Bands in Practice

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*A closer look at the wireless spectrum — from SCADA to E-Band*

## Sub-1GHz

*< 1 GHz*

**▶ SCADA · Telemetry · Industrial Sensors**

Long range · Penetrates terrain & buildings · Low data rate · Licensed

*216–450 MHz: 30–80+ km LOS · 900 MHz: 10–30 km*

## Cellular (4G LTE · 5G · WCS)

*600 MHz – 2.1 GHz | WCS: 2.305–2.360 GHz*

**▶ Mobile broadband · IoT · Wide-area coverage**

Scheduled access · Mobility support · Licensed carrier · 3GPP standard · WCS (Wireless Communications Service) — T-Mobile largest US holder

*Low band: coverage & penetration · Mid band: capacity · WCS Band 30: urban LTE*

## WiFi · Bluetooth · Zigbee (802.11 / 802.15 / ISM)

*2.4 GHz · 5 GHz · 6 GHz*

**▶ Local access · Personal area networks · IoT**

Contention-based (CSMA — Carrier Sense Multiple Access) · Shared unlicensed · Degrades under load · Standard Wi-Fi requires careful system design to support critical infrastructure. Purpose-built systems (e.g., managed mesh, controller-based architectures, or Rajant-style MANET) are typically required for mobility and resilience.

*Bluetooth & Zigbee: 2.4 GHz · WiFi: 2.4 / 5 / 6 GHz • ISM (Industrial, Scientific and Medical)*

## CBRS (Citizens Broadband Radio Service)

*3.55 – 3.65 GHz | LTE Band 48 / 5G NR n48*

**▶ Private LTE · Private 5G · Industrial wireless**

SAS (Spectrum Access System) managed · DoD → PAL (Priority Access License) → GAA (General Authorized Access) · No carrier required · Most modern smartphones are CBRS capable

*Factories · Warehouses · Ports · Mines · Stadiums*

## Licensed • Unlicensed Microwave

*6 – 42 GHz*

**▶ Point-to-Point (PtP) backhaul · Network backbone**

Coordinated licensed spectrum · Predictable · SLA (Service Level Agreement) grade · Long links

*11 GHz: 30–50 km · 18 GHz: 15–25 km*

## V-Band 60 GHz (Millimeter Wave or mmWave)

*57 – 71 GHz*

**▶ Short-range high capacity · Campus links**

Oxygen absorption limits range · Unlicensed in most of the world · Multi-gigabit · Beam steering

*PrMP ~ >1km; PtP ~1 km (with RF lens up to ~3km) · Camera aggregation · Campus backhaul*

## E-Band 70/80 GHz (Millimeter Wave or mmWave)

*71 – 86 GHz*

**▶ High-capacity backhaul · Multi-gigabit PtP (Point-to-Point)**

Lightly licensed (U.S.; varies by region) · ~3 km typical · up to ~5 km with E-band stabilization (e.g., Siklu / Ceragon Networks · BATS ) · XPIC doubles capacity (dual-pol)

*256 QAM + XPIC: ~20 Gbps · 1024 QAM: ~40 Gbps at < 1 km*

*▶ Every band has a purpose — the art is knowing which one to use, and when to combine them.*

# How Cellular Was Born — and How It Evolved

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*From a single tower serving a city to a global standard built on frequency reuse*

## The Problem Cellular Was Designed to Solve

Before cellular, radio telephone systems (SMR — Specialized Mobile Radio) used a single powerful tower to cover an entire city.

Each call occupied a channel. When channels were full — no one else could connect. There was no way around it.

## The Solution: Channel Reuse

Divide coverage into many small cells. Each cell reuses the same frequencies as non-adjacent cells. Capacity multiplies — without needing more spectrum.

> 📍*In 1978, Chicago hosted a major AMPS field trial, developed by Bell Labs and commercially deployed in 1983 as the first large-scale cellular system. The system used analog FDMA, although engineers believed a digital FDMA approach was feasible; analog was chosen as the lowest-risk path at the time.*

**1G** — *1980s* — **AMPS — Advanced Mobile Phone System**
Analog voice only. The first commercial cellular networks. Engineers knew digital was possible — analog was chosen for the low technical risk. FDMA – Frequency Division Multiple Access

**2G** — *1990s* — **GSM / CDMA / TDMA — Digital voice + SMS**
First digital generation. Voice quality improved. Text messaging introduced. GSM (Global System for Mobile) became the dominant global standard. Limited mobile data.

**3G** — *2000s* — **UMTS / HSPA — True mobile data begins**
Mobile internet becomes real. Smartphones emerge. Data speeds reach 1–14 Mbps. The foundation for the app economy.

**4G** — *2010s* — **LTE — Long Term Evolution — all-IP network**
Voice over IP replaces circuit switching. Speeds of 50–150 Mbps typical. Enabled streaming, video calls, cloud services. 3GPP (3rd Generation Partnership Project) standard.

**5G** — *2020s* — **NR — New Radio — three very different use cases**
Sub-6 GHz: coverage. mmWave: extreme capacity at short range. Private 5G (CBRS): industrial deployments. Two visions: 3GPP carrier-led vs IEEE Wi-Fi-influenced architectures.

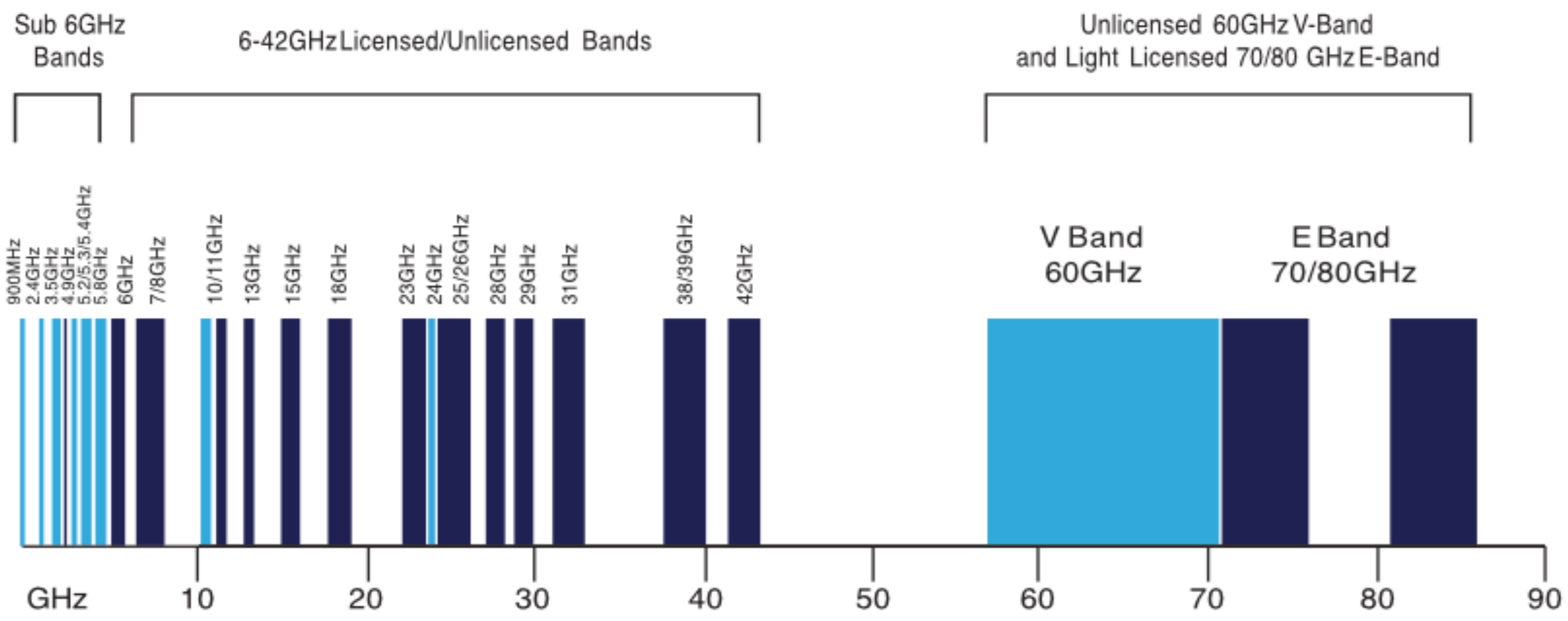
**6G** — *2030s* — **Research phase — Terahertz & AI-native networks**
Still in research. Expected to integrate AI natively into the network. Terahertz frequencies for extreme short-range capacity. No commercial standard yet.

▶ *Each generation solved a capacity problem — more users, more data, more devices. This is a physics problem — frequency reuse makes it possible..*

# Microwave Frequency Bands

## — The Spectrum at a Glance

*Sub-6GHz through E-Band — every band has a purpose*




▶ *Light Blue = unlicensed (shared).* ▶ *Dark Blue = licensed.* (valid for the US and many counties)

*Spectrum utilization reflects the balance of range, capacity, interference, and cost.*

# Signal Quality — What the Numbers Mean

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*How engineers measure whether a wireless link is actually working well*

**Signal strength does not determine performance. Signal quality does. A weaker, but clean signal, often outperforms a stronger yet noisy signal.**

## RSSI

**Received Signal Strength Indicator**

*mmWave systems • WiFi*

An estimate of how strong the received signal is. In WiFi it is useful for basic diagnosis — is anything there? — but not reliable for performance evaluation. In mmWave – the Calculated RSSI vs the actual RSSI is the target in how you determine if the link is aligned. RSSI is expressed in negative dBm values. A value closer to 0 (e.g., -50 dBm) is stronger than a lower value (e.g., -80 dBm).

► *RSSI measures total power (including noise and interference) and is often used alongside RSRP (Reference Signal Received Power) and RSRQ (Reference Signal Received Quality) for more precise handover and mobility management*

## RSL

**Received Signal Level**

*Engineered microwave & licensed links*

A precise measurement of received signal power in dBm (decibels relative to 1 milliwatt). Used in link budgets and performance verification against design targets.

► *RSL is the engineering metric — if the RSL matches the link budget, the link is performing as designed.*

## SINR

**Signal to Interference plus Noise Ratio**

*All wireless systems — the most important metric*

Measures how much stronger the desired signal is compared to the interference and noise around it. Directly determines usable throughput and which modulation the system can support

► *SINR is the number that matters most. Low SINR = low modulation = low throughput, regardless of signal strength.*

## RSRP / RSRQ

**Reference Signal Received Power / Quality**

*Cellular systems — LTE (4G) and 5G NR*

RSRP measures the power of the cellular reference signal. RSRQ accounts for interference from neighboring cells. Together they inform handoff decisions and coverage quality.

► *These are the cellular equivalents of RSL and SINR — used by carriers to manage coverage and capacity.*

► *Know your signal metrics — they tell you whether your link is healthy, not just whether it exists.*

# WiFi Standards — IEEE 802.11 Evolution

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*From 11 Mbps in 1999 to 46 Gbps today — every generation built on the last*

| Standard | Wi-Fi Name | Year | Frequency Band | Max PHY Rate | Key Features |
|---|---|---|---|---|---|
| **802.11b** | Wi-Fi 1 | 1999 | 2.4 GHz | 11 Mbps | First widely adopted consumer Wi-Fi |
| **802.11a** | Wi-Fi 2 | 1999 | 5 GHz | 54 Mbps | Faster than b; shorter range; mainly business |
| **802.11g** | Wi-Fi 3 | 2003 | 2.4 GHz | 54 Mbps | Combined a speed with b range; backward compatible |
| **802.11n** | Wi-Fi 4 | 2009 | 2.4 & 5 GHz | 600 Mbps | Introduced MIMO — multiple antennas for speed & range |
| **802.11ac** | Wi-Fi 5 | 2013 | 5 GHz | 6.9 Gbps | Wider channels (160 MHz), MU-MIMO |
| **802.11ax** | Wi-Fi 6/6E | 2019 | 2.4, 5, 6 GHz | 9.6 Gbps | OFDMA for dense areas; 6E adds the 6 GHz band |
| **802.11be** | Wi-Fi 7 | 2024 | 2.4, 5, 6 GHz | 46 Gbps | EHT: 320 MHz channels, Multi-Link Operation |
| **802.11bn** | Wi-Fi 8 | ~2028 | TBD | TBD | AI-native networks; next-gen capacity in development |
| **802.11ad** | WiGig | 2012 | 60 GHz | 6.7 Gbps | Outdoor ~200m – 300m<br>Short-range mmWave: docking stations, VR/AR, proximity links |
| **802.11ay** | WiGig 2 | 2021 | 60 GHz | 40 Gbps | Extended WiGig; outdoor range ~300 m; MIMO & channel bonding |
| **802.11bq** | WiGig 3 | In dev | 60 GHz+ | >100 Gbps | Next-gen WiGig; sub-THz extensions; ultra high-density venues |

## Key Technical Concepts

**MIMO:** Multiple antennas transmit/receive simultaneously — more data, better range. First used in 802.11n.

**WiGig:** 60 GHz mmWave family (ad/ay/bq). Extreme throughput, short range — ideal for fixed links & aggregation.

**OFDMA:** Serves multiple clients per transmission — reduces lag in dense environments. Introduced in Wi-Fi 6.

**6 GHz:** Wi-Fi 6E and Wi-Fi 7 added the 6 GHz band — wider lanes, far less interference, more total capacity.

► *Wi-Fi is backward compatible — a Wi-Fi 7 router talks to a Wi-Fi 4 phone. Each generation added speed or efficiency without breaking older devices.*

# Wi-Fi vs Cellular — Two Very Different Animals

*Same goal, fundamentally different architecture — and that difference matters enormously under load*

## Wi-Fi (IEEE 802.11)

**Access method:**
Contention-based (CSMA — Carrier Sense Multiple Access)

**How it works:**
Devices listen for a clear channel, then transmit. If two transmit simultaneously — collision. Both retry after a random delay.

**Under load:**
Performance degrades under contention as device count grows, particularly without careful channel planning, airtime management, and system design. 5 devices: good. 20 devices: noticeable degradation. High device density (over 50) requires careful design and capacity planning. • purpose-built systems for high-capacity loads.

**Mobility:**
Poor. Connections drop when moving between access points. Re-association takes seconds.

**Best for:**
Short-range local access, office environments, temporary networks

**Avoid for:**
Critical infrastructure (unless using high grade MANET • Mobile Ad Hoc Network), backbone links, high device count, mobile assets

VS

## Cellular (3GPP — 3rd Generation Partnership Project)

**Access method:**
Scheduled access — the base station controls when each device transmits. No collisions possible.

**How it works:**
The scheduler assigns time slots to each device. Traffic is managed and prioritized. Every device gets its turn.

**Under load:**
Predictable and graceful. More devices means shared throughput — but the system stays organized and functional.

**Mobility:**
Designed for it. Coordinated handoffs between towers keep connections alive as users move.

**Best for:**
Mobile assets, wide-area coverage, backup connectivity, IoT at scale

**Avoid for:**
Deterministic high-capacity point-to-point backhaul • use licensed microwave, or mmWave instead

▶ *Wi-Fi is an access technology. Cellular is a coverage and mobility technology. Neither replaces the other — both have a role.*

# Microwave Link Physics — How Links Are Engineered

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*Understanding the forces that work against every wireless link — and how engineers account for them*

## FSPL
**Free Space Path Loss**

As a signal spreads out from its source, its power diminishes with distance. This is the single largest source of signal loss — typically 130 dB or more. Both distance and frequency increase FSPL — a higher frequency signal at the same distance loses more power than a lower one.

▶ *You cannot eliminate FSPL — you can only budget for it with sufficient transmit power and antenna gain.*

## Fade
**Signal Loss from Atmospheric Conditions**

Rain, fog, and atmospheric turbulence scatter and absorb microwave signals. Rain is the dominant factor — rain fade becomes severe above 11 GHz and critical above 30 GHz. Engineers use rain outage models to predict how much attenuation to expect for a given rainfall rate and frequency.

▶ *Above 11 GHz, increasing power alone is not enough — link length must also be limited. Yet an accurately planned link can account for fade – and is highly stable and reliable.*

## ATPC
**Adaptive Transmit Power Control**

The radio continuously monitors received signal level and dynamically adjusts transmit power to compensate for fading conditions. When the link degrades, ATPC increases power to maintain performance. When conditions improve, it backs off — conserving power and reducing interference to other links.

▶ *ATPC is the primary real-time tool for maintaining link quality through variable atmospheric conditions.*

## BER
**Bit Error Rate — the Digital Performance Standard**

In digital systems, link performance is measured by how many transmitted bits arrive with errors. Carrier-grade systems typically operate at very low BER ($10^{-9}$ or better post-FEC), ensuring negligible impact on user traffic.

▶ *Five-nines availability (99.999%) means the link operates within BER spec for all but ~5 minutes per year.*

▶ *Every microwave link is an exercise in managing loss. The engineer's job is to ensure system gain exceeds all losses — in all conditions — with margin to spare.*