Wireless Technologies

DOMAIN 2

MODULE 10

Wireless Technologies Topics

Wireless Overview

Radio Basics

Modulation

Wi-Fi Standards

Wi-Fi Channels

Antennas

Wi-Fi Service Sets

Wi-Fi Security

Cellular

Wireless Overview

Bounded and Unbounded Networks

Bounded
- Wired
- Uses metallic or fiber optic cables
- You can control its boundaries

Unbounded
- Wireless
- Uses radio waves instead of cables
- You can’t fully control its boundaries

Wireless LAN (WLAN)

LAN based on wireless technologies

Wi-Fi is the most common implementation

Adds security risks because the network is “unbounded”

WiMax

Worldwide Interoperability for Microwave Access

IEEE 802.16

2.3, 2.4, 2.5, 3.5 and 5 GHz

Gigabit speed

Interoperable with 4G/LTE

Good support for time-sensitive applications, QoS and multicasting

Transmitters are higher power than Wi-Fi
- Covers large distances

Still used extensively:
- Wireless Internet in rural areas
- Middle-mile backhaul to connect remote areas to fiber networks
- Supplement LTE networks
- IoT smart metering

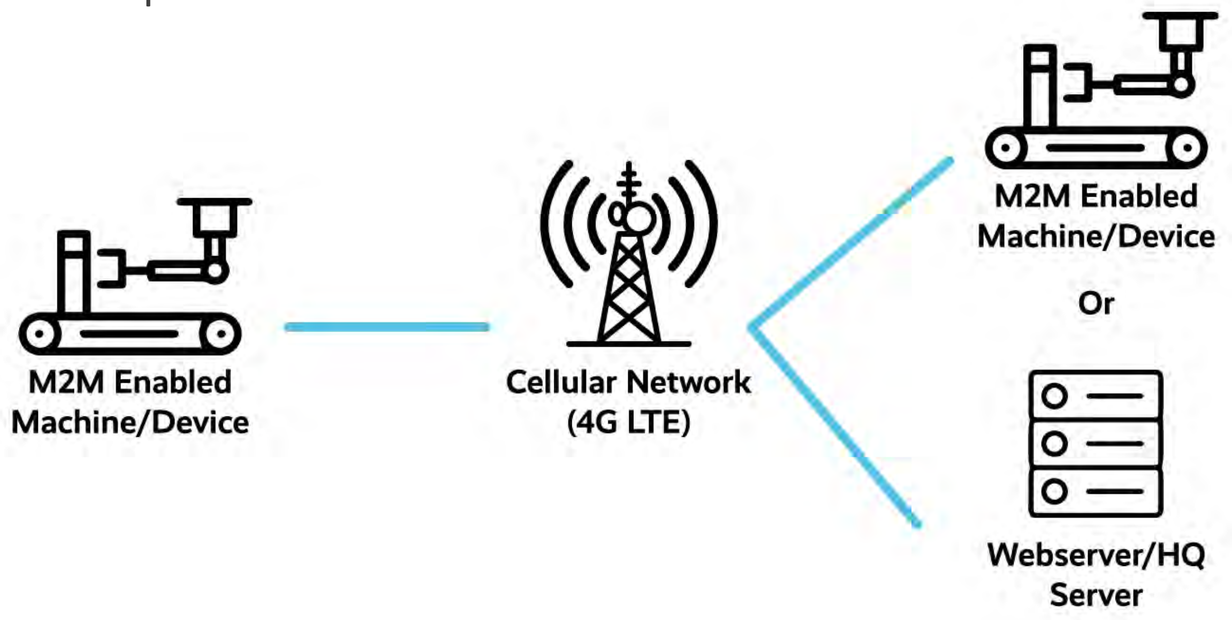
Machine-to-Machine (M2M) Networks

Direct communication between devices using any communications channel

- Information can be exchanged and actions performed without manual assistance from humans

First adopted in industrial settings

- Readings from sensors would be routed to a central hub for analysis, then re-routed to a PC
- M2M eliminates those steps



M2M Applications

Manufacturing

Remote monitoring

Billing

Robotics

Security

Automotive

Logistics/fleet management

Traffic control

Telemedicine

Utilities

Industrial

M2M vs IoT

Similar, but not (yet) the same

M2M	IoT
Simple device-to-device communication Embedded software at the client site	Grand-scale projects
Isolated systems of devices using the same standards	Integrates devices, data, and applications across varying standards
Limited scalability	Inherently more scalable
Wired or cellular network used for connectivity	Devices usually require active Internet connection
Extensive background of historical applications	State-of-the-art approach with roots in M2M

IoT Wireless Options

Technology	Description	Comment
ZigBee	• 802.15.4 • Mesh topology • 300 ft range • AES 128 encryption • 800 – 900 MHz, 2.4 GHz	• Designed for M2M networks • Low latency, low power use • Short – Medium distance • Ideal for Smart Homes
Z-Wave	• 100 ft range • AES 128 encryption • 800-900 MHz	• Lower-cost competitor to ZigBee • Fewer devices
Bluetooth Low Energy (BLE)	2.4 GHz	Fitness trackers, smart watches, headsets/speakers, hands-free calling, wireless keyboards and printers
HaLow (Wi-Fi 5)	• 802.11ah • 1 km range • Native IP support • Sub-1 GHz spectrum • WPA3	• Long battery life • Penetrates walls / other obstacles • Does not need hub (access point) or gateway • Industrial and home automation • Smart cities
HEW (High Efficiency Wi-Fi) (Wi-Fi 6)	• 802.11ax • 1 – 6 GHz	• Designed for IoT in high-density public environments • 6 GHz reserved for new devices
2.4 GHz Wireless	10 meters max range	• Neither Wi-Fi nor Bluetooth; single frequency for a specific device • Requires USB receiver • Keyboard, mouse

Cellular IoT

Cellular IoT is a new development aimed at low-power, long-range applications

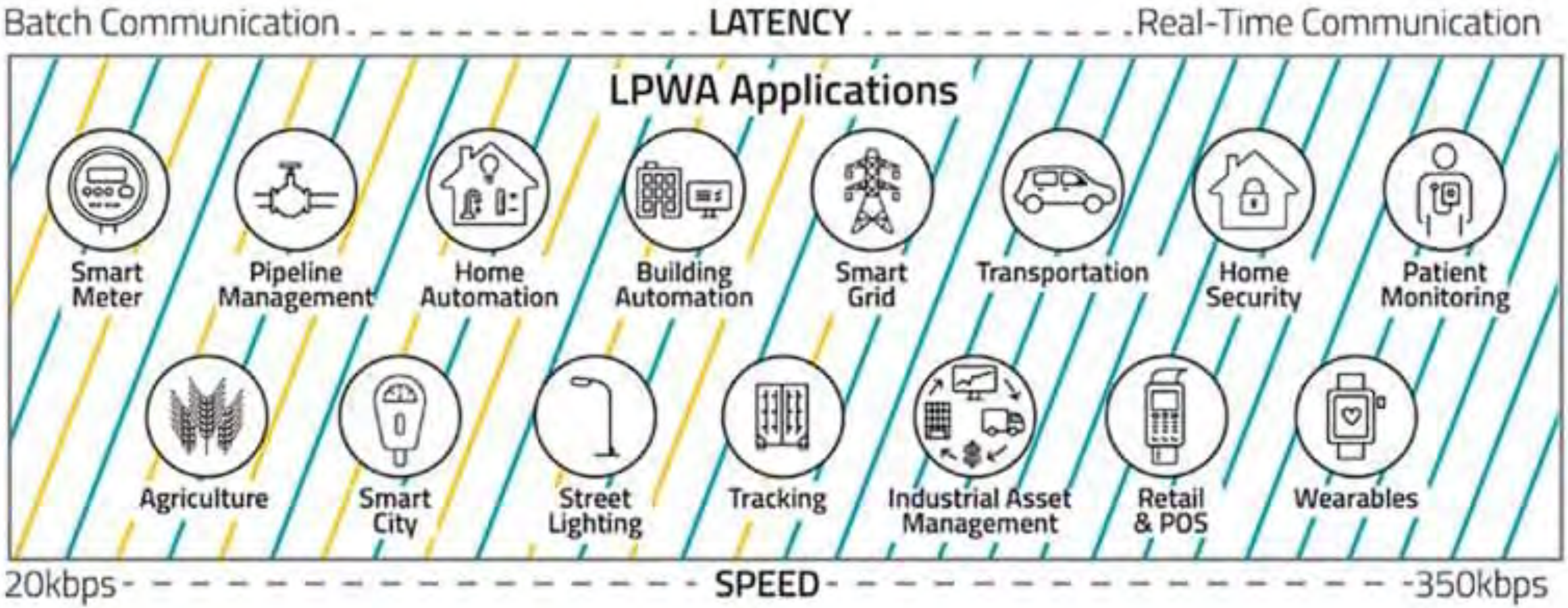
Currently 2 billion IoT devices connected via cellular technology

Traditional cellular options such as 4G and LTE networks consume too much power

- They don't fit well with applications where only a small amount of data is transmitted infrequently

- Many IoT devices require low power and low throughput over a wide area
  - Data transfer is in small intermittent packets (10 – 1000 bytes)
- The goal is for IoT devices to operate reliably for up to 10 years on a single battery charge
- Low Power Wide Area (LPWA) refers to a class of wireless technologies that are well-suited to the specific needs of M2M and IoT
  - LPWAN – WAN that specifically caters to long-distance M2M and IoT

IoT Low Power Wide Area Applications



Radio Basics

How Radio Works

Radio is a very broad spectrum of electromagnetic frequencies that can be used to carry voice, video, data or any other kind of information

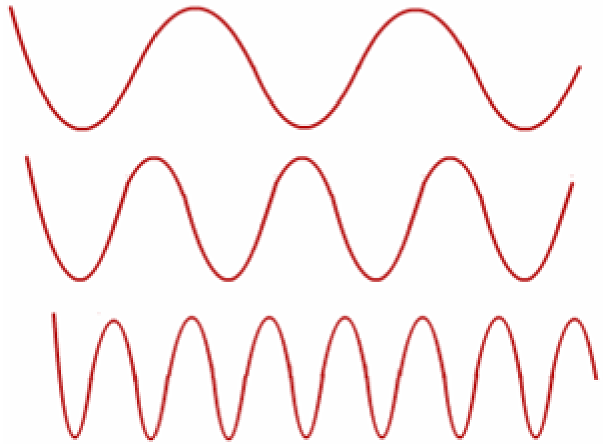
The weak data signal is modulated (piggy-backed) on top of a carrier signal

The carrier can be amplified to be very strong and travel great distances

The radio spectrum ranges between sound and infrared

Features of an Electromagnetic Wave

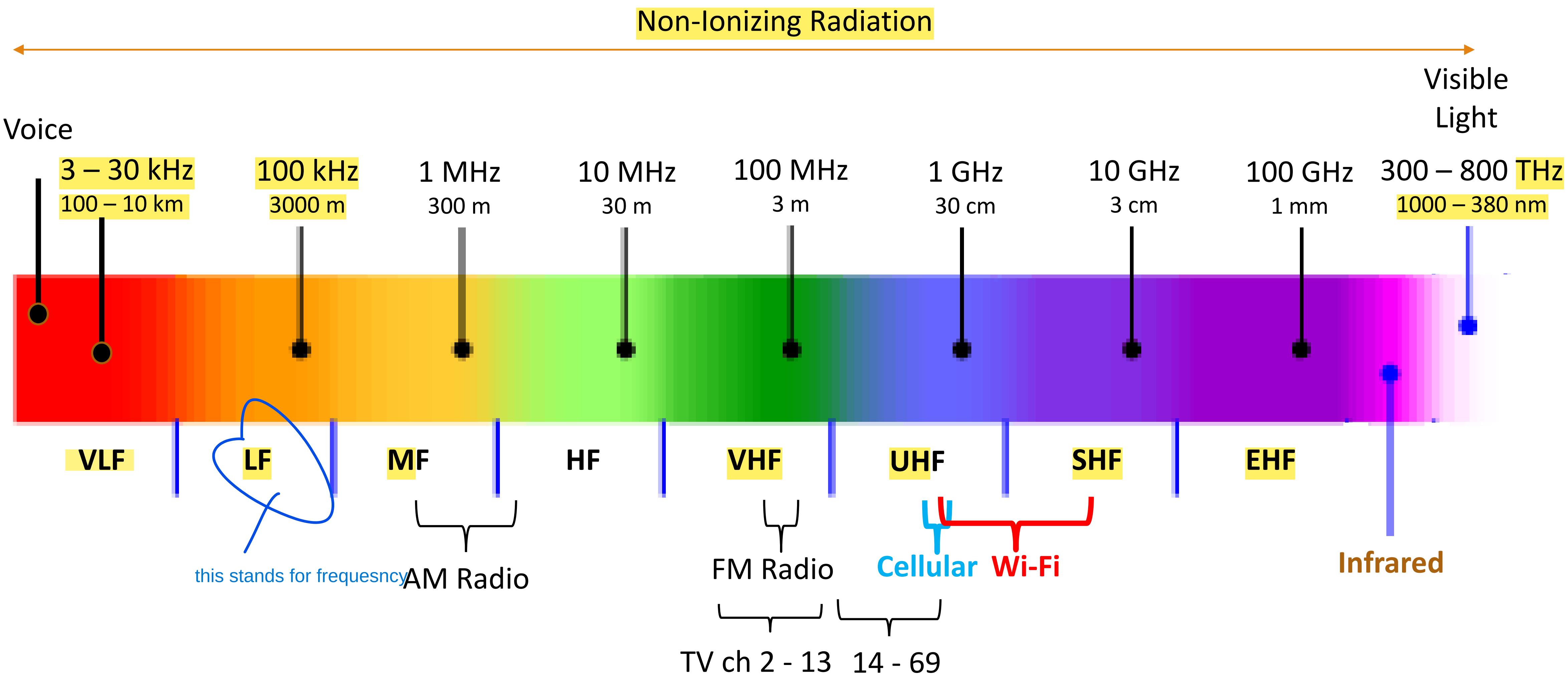
- Wavelength (distance between peaks)
  - measured in meters, millimeters, nanometers
- Frequency (how often the wave repeats)
  - measured in hertz (Hz) or cycles per second
- Amplitude (power level or intensity of the wave)
  - measured in watts, kilowatts (thousands of watts) or milliwatts (thousandths of a watt)



- Wavelength and frequency are directly proportional
  - When one increases, the other decreases
  - Lower frequencies have longer wavelengths
  - Higher frequencies have shorter wavelengths
- Extremely high frequencies are usually

  referred to by wavelength in nanometers (nm)

Radio Spectrum



What Interferes with Radio?

Obstructions that reflect or absorb radio waves:

- steel, concrete, building materials, earth, water, forests, atmospheric conditions

Other electromagnetic transmissions that “confuse” or overwhelm the receiving device:

- other devices transmitting at too close proximity/frequency
- wave reflections that cause phase cancellation of the signal
- solar and electrical storm activity
- bursts of radiant energy from machines, motors, appliances, faulty electrical circuits, power lines
- Earth’s magnetic field

Reflection	A radio wave changes direction as it bounces off a barrier
Refraction	The path of the radio wave is bent (and its speed changes) as it passes from one medium to another
Absorption	When a radio wave hits the surface of some material, its energy is transferred into that material, and the wave stops

Modulation

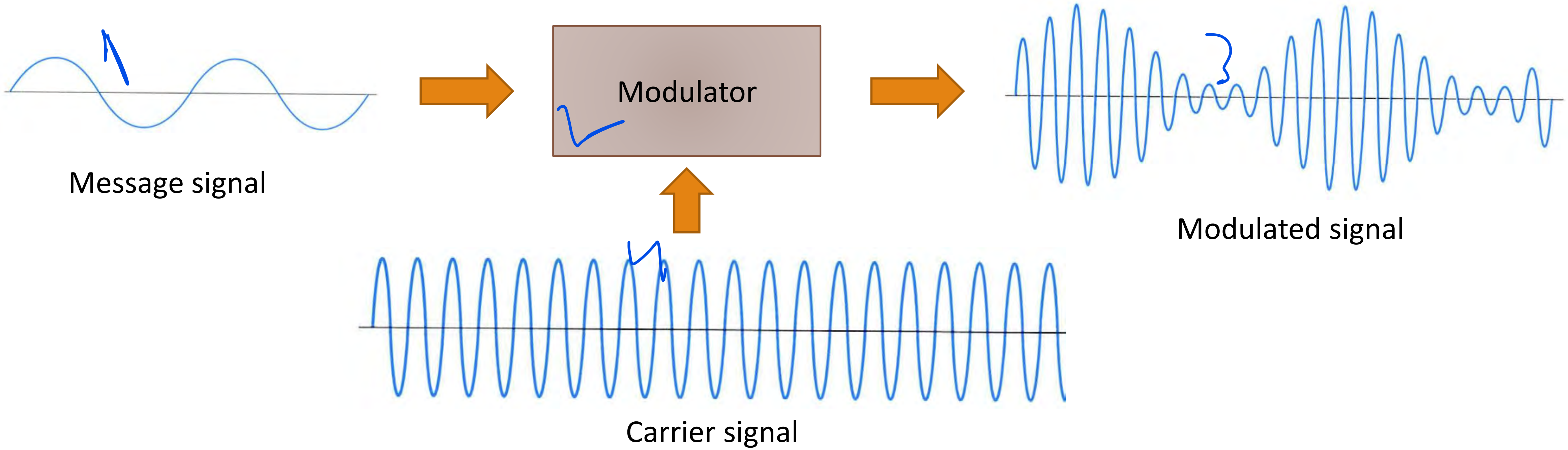
What is Modulation?

A message signal (voice, video, data) is “piggybacked” on top of a carrier signal (radio wave)

The modulated carrier is amplified and then transmitted on the media

The receiver picks up the transmission and strips off the carrier (demodulates)

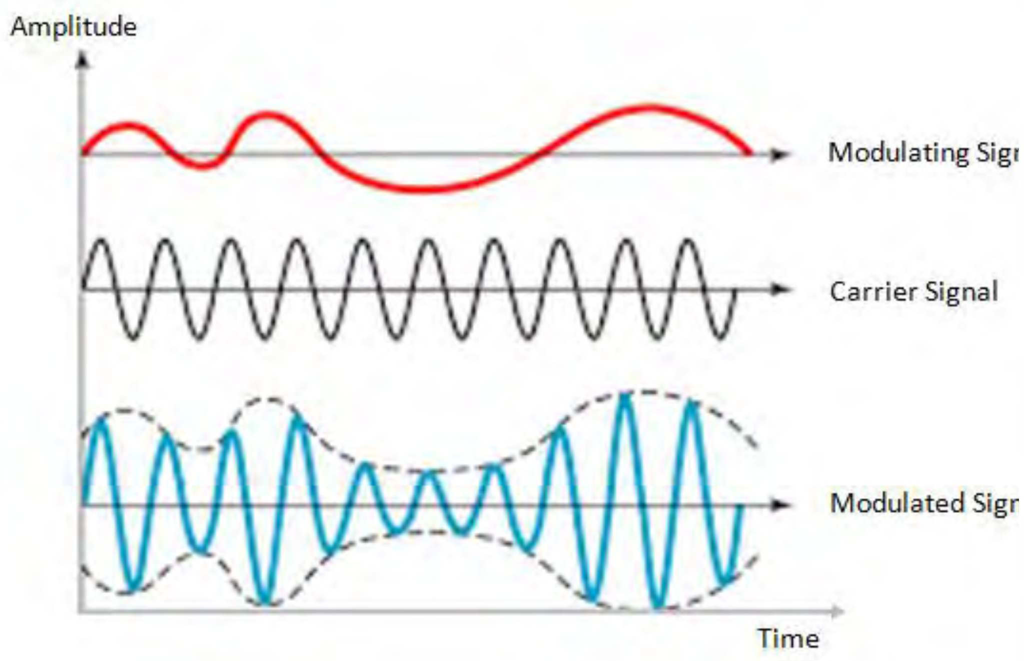
- The remaining data is sent to the application for use

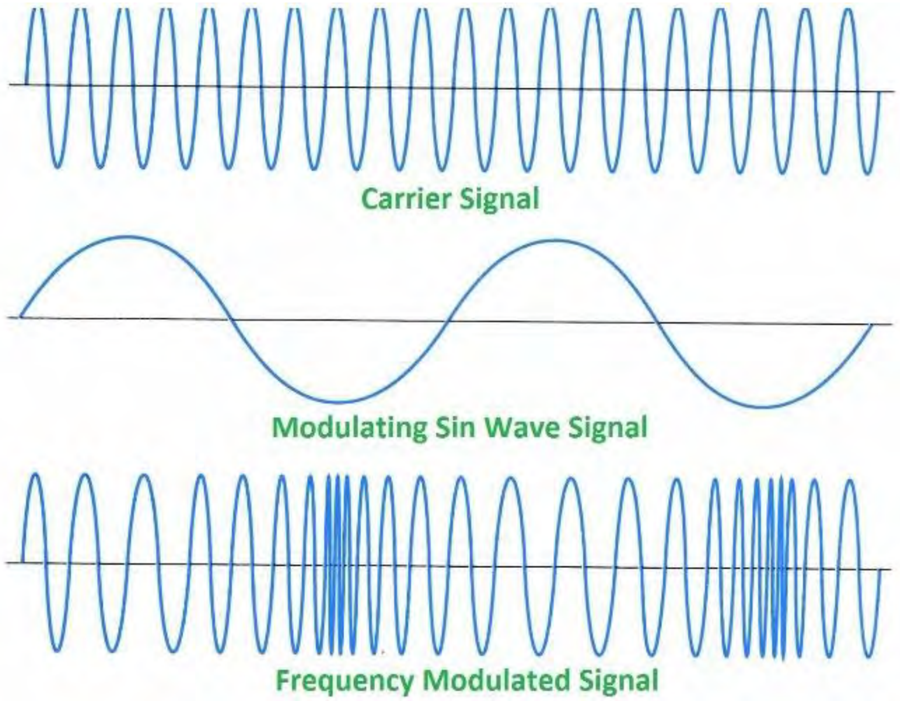


Amplitude and Frequency Modulation

Amplitude Modulation (AM)
Carrier amplitude changes with voice signal
AM Radio, early amateur radio, early TV

Frequency Modulation – FM
Carrier frequency shifts with the voice signal
FM Radio, amateur radio, early TV

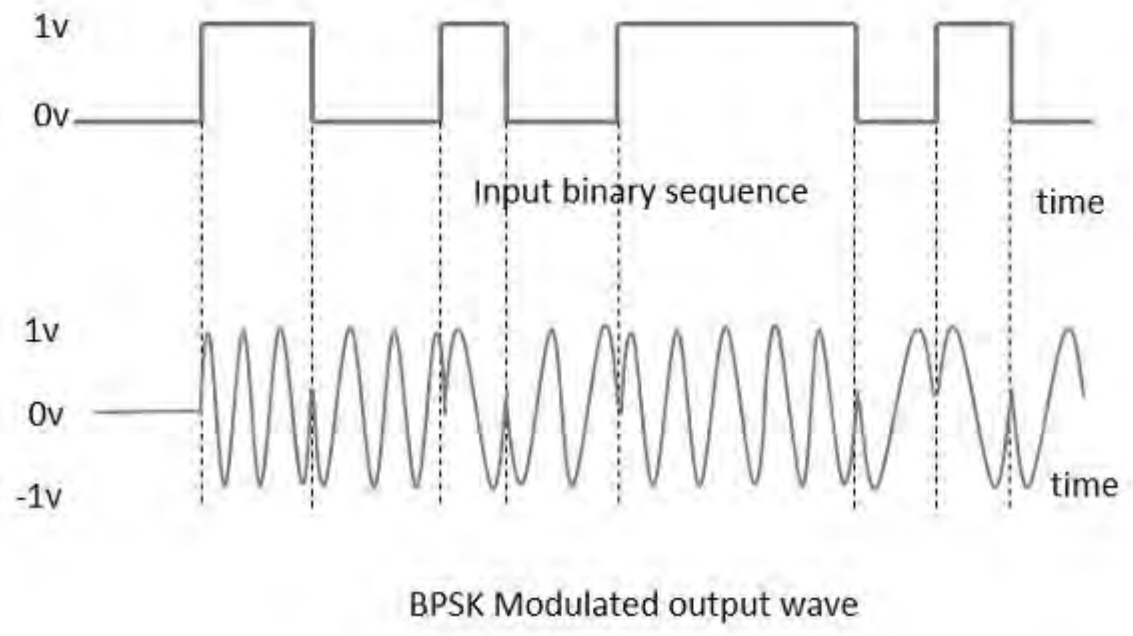


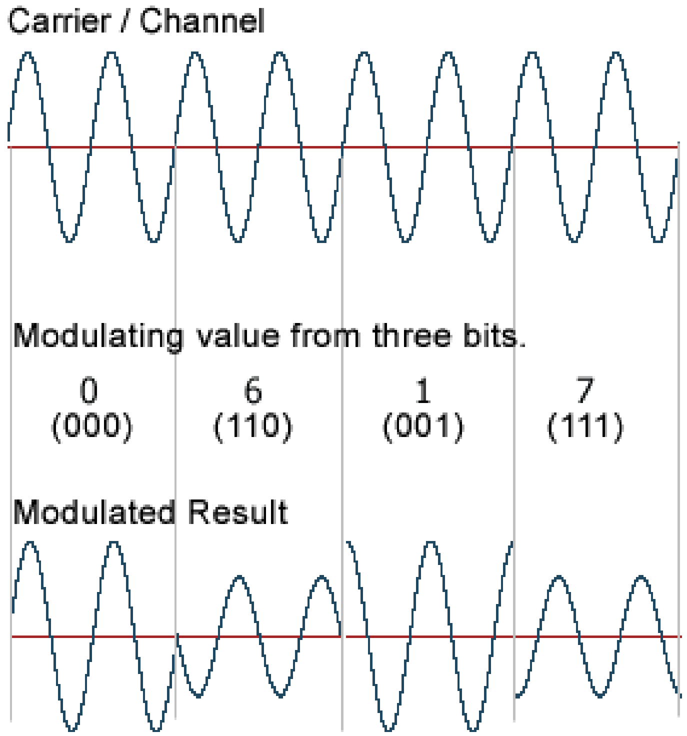


Phase Shift Keying Modulation

Digital signal changes the phase of a carrier

Binary phase (BPSK) and quadrature phase (QPSK) shift keying are commonly used in wireless LANs, RFID, Bluetooth, satellite



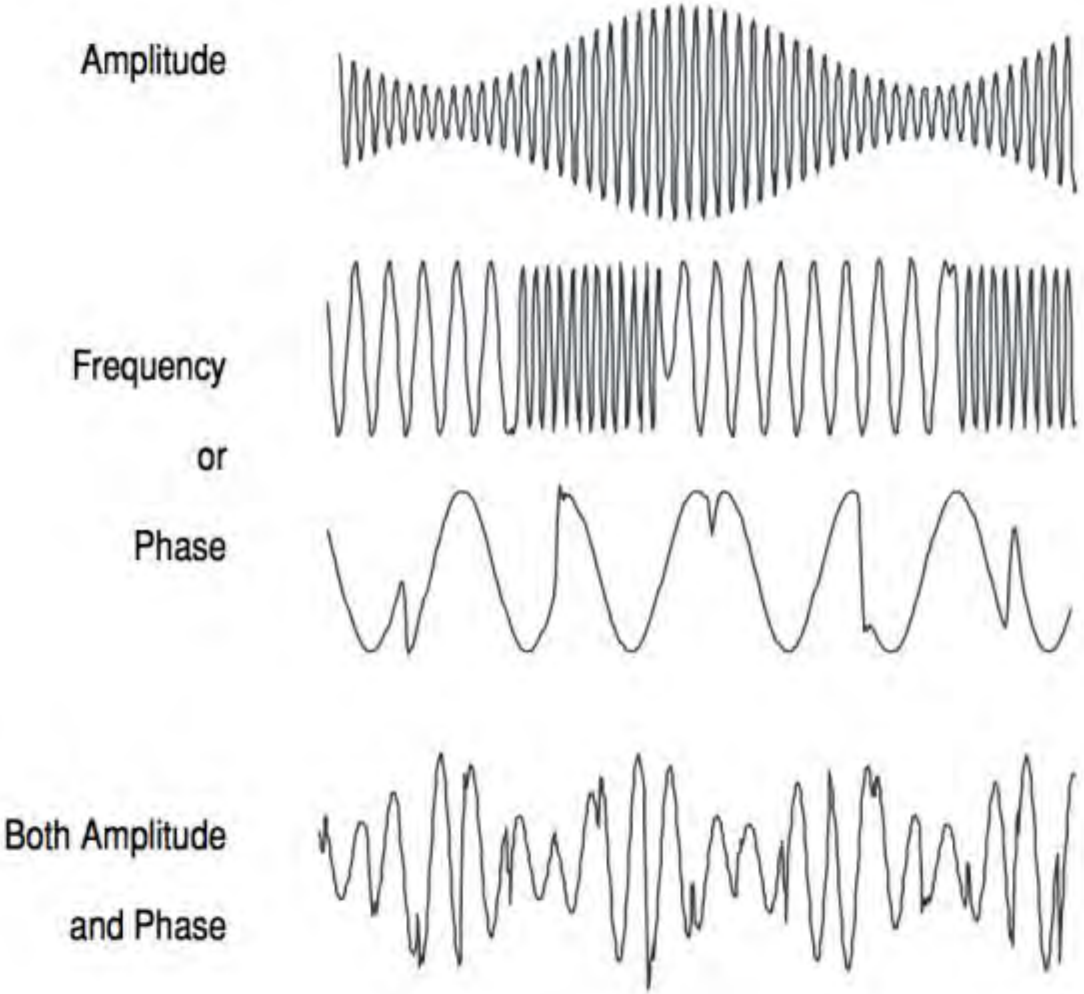


Quadrature Amplitude Modulation (QAM)

Combination of phase and amplitude modulation

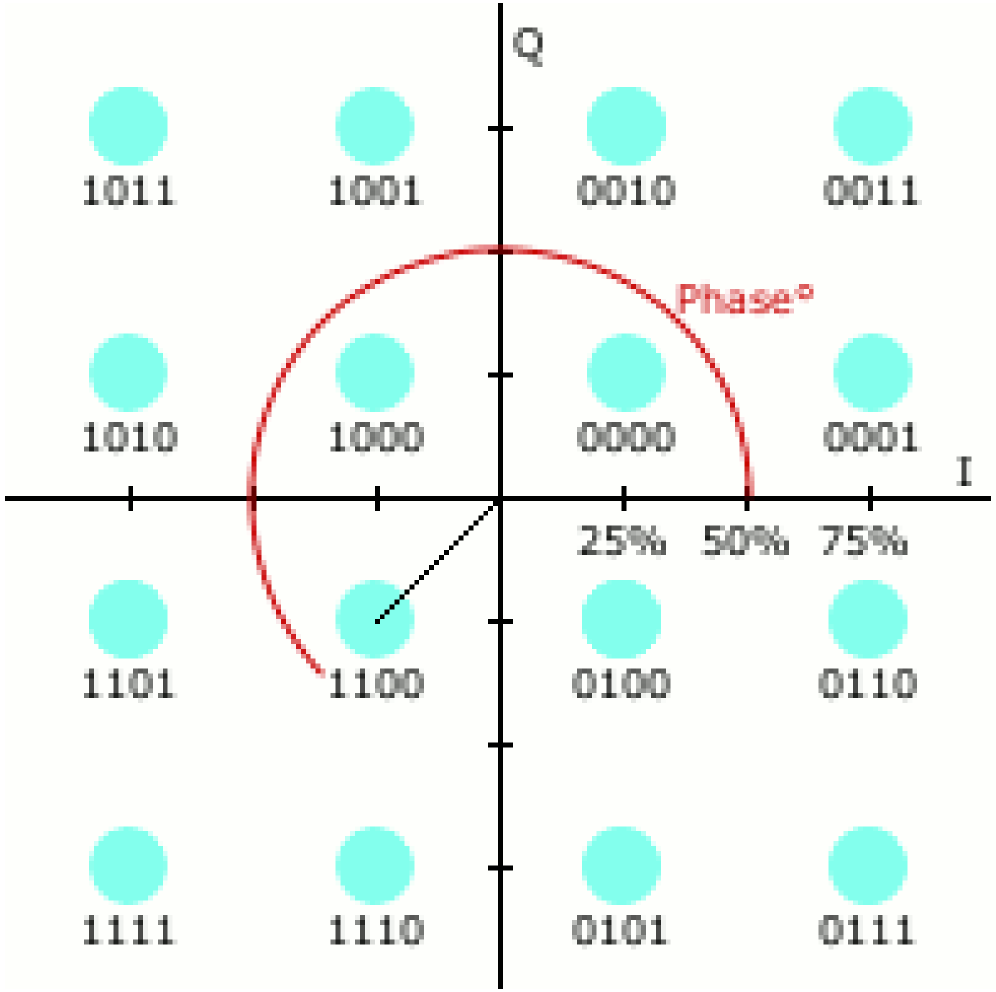
RF carrier is divided into "constellations"

- Sub-signals are out of phase (non-interfering) with each other
- Larger constellations can carry more data per Hz
  - 16 QAM – 4 bits per symbol (constellation point)
  - 32 QAM – 5 bits per symbol
  - 64 QAM – 6 bits per symbol
  - 128 QAM – 7 bits per symbol
  - 256 QAM – 8 bits per symbol
  - 1024 QAM – 10 bits per symbol
- Wi-Fi, digital video, WiMAX, Cable TV



Note: Over-the-air HDTV uses other types of modulation including 8VSB and COFDM

16 QAM Example



Amp	Phase	Data
25%	225°	1100

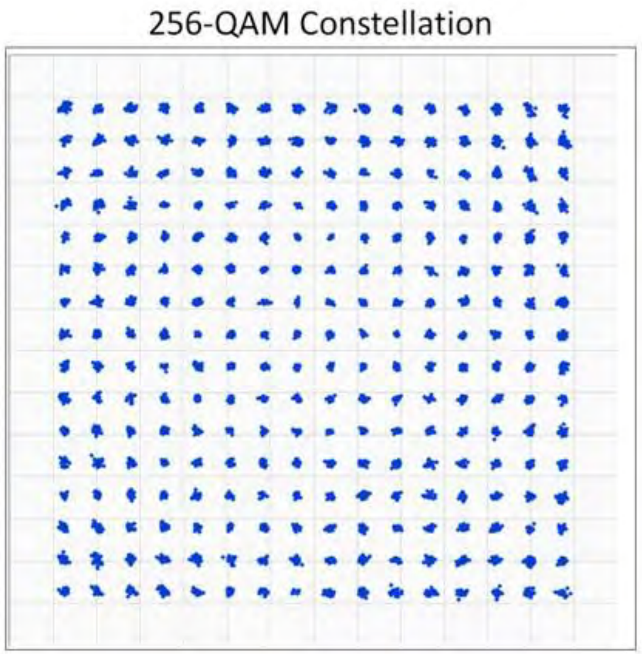
Image: Chris Watts

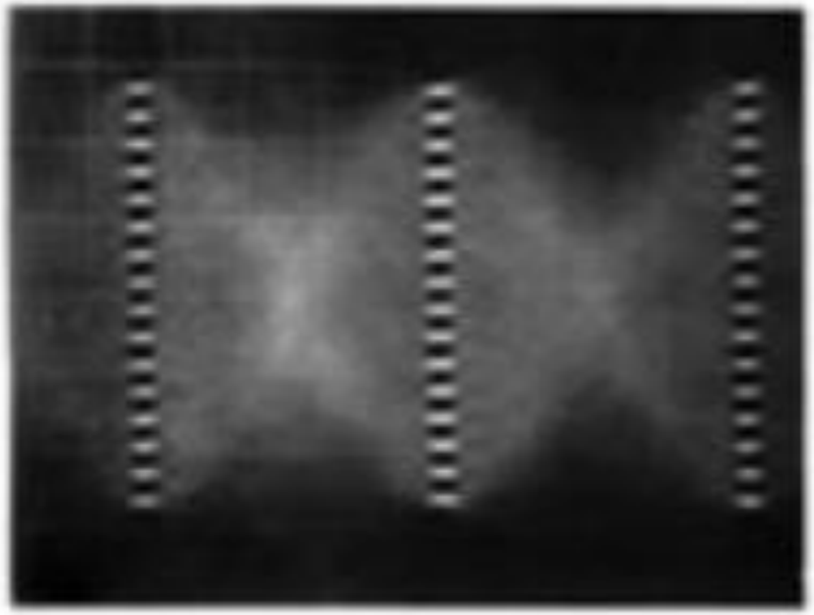
256 QAM

Higher order constellation carries more data
- Sub-signals are out of phase (non-interfering) with each other

Each constellation is modulated with part of the data signal (8 bits per Hz)

5G small cells



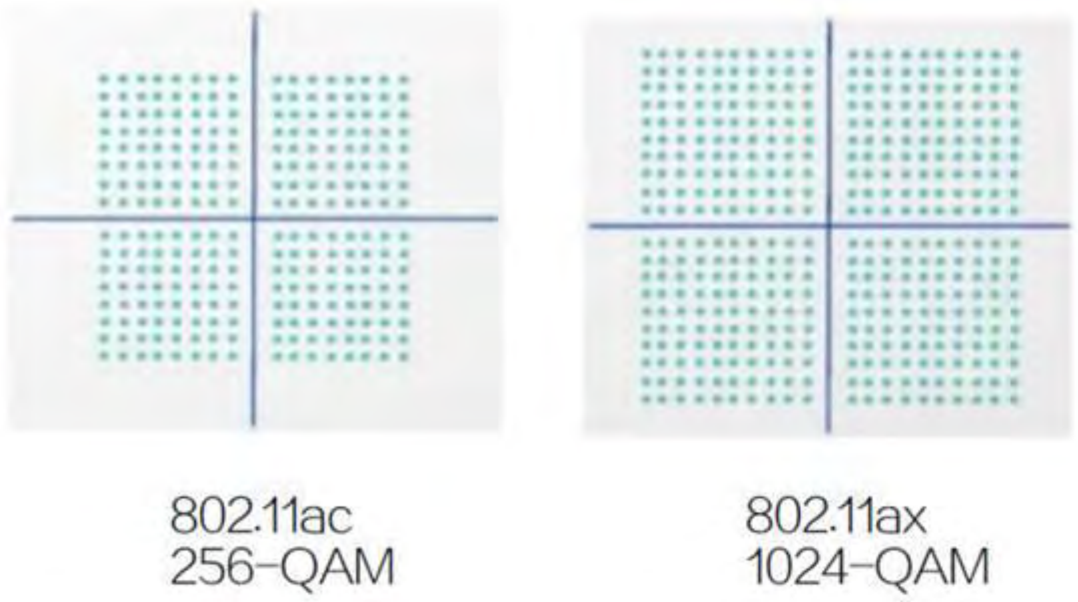


1024 QAM

1024 constellation points

10 bits of data per Hz

802.11ax, 5G



Time Division Multiplexing

Different transmissions have allotted time slots

They take turns, round robin style, transmitting on the same medium

Systems that use TDM:

- Primary rate ISDN* carrying multiple phone conversations on the same link
- DSL broadband

TDM is largely being replaced by other mechanisms

* Also other traditional T1/E1, T3/E3, SDH/SONET links carrying multiple voice conversations

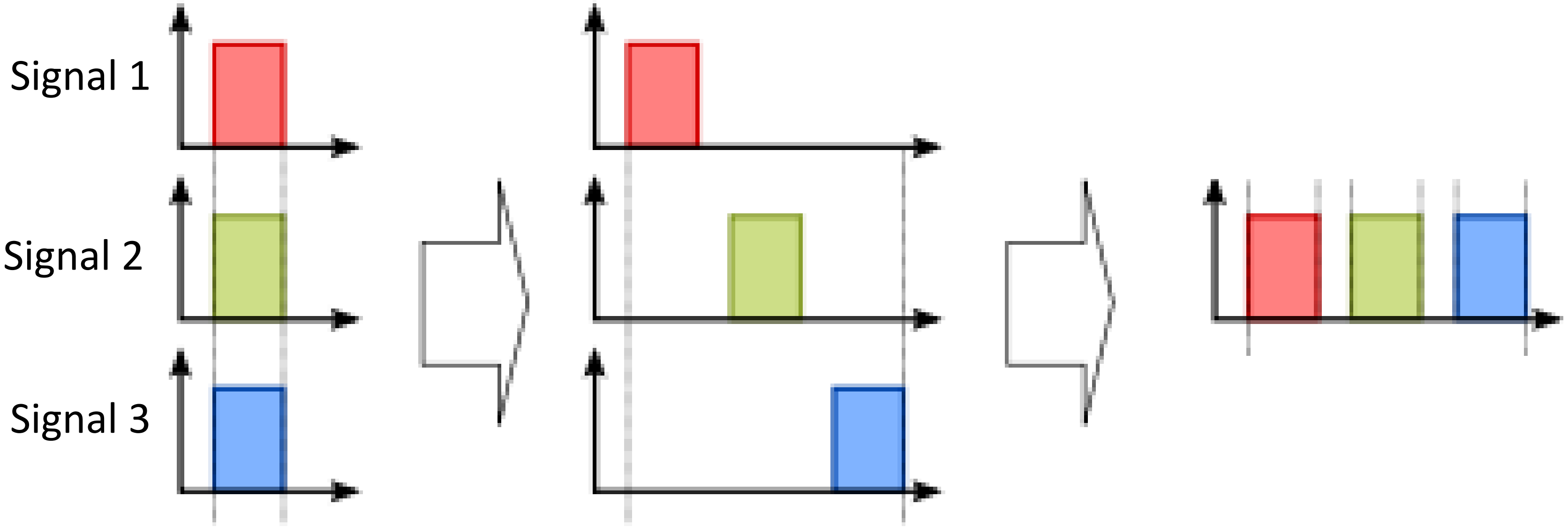
Frequency Division Multiplexing (FDM)

Different modulated carrier frequencies share the same transmission medium

The total available bandwidth is divided into non-overlapping frequency bands

DSL uses FDM (and TDM) to separate voice from data:

- 4 kHz and below is for voice
- Above 4 kHz – 1+ MHz is for data



Orthogonal Frequency Division Multiplexing (OFDM)

Specialized version of FDM

More efficient than DSSS

- Uses BPSK, QPSK, or QAM as the modulation technique

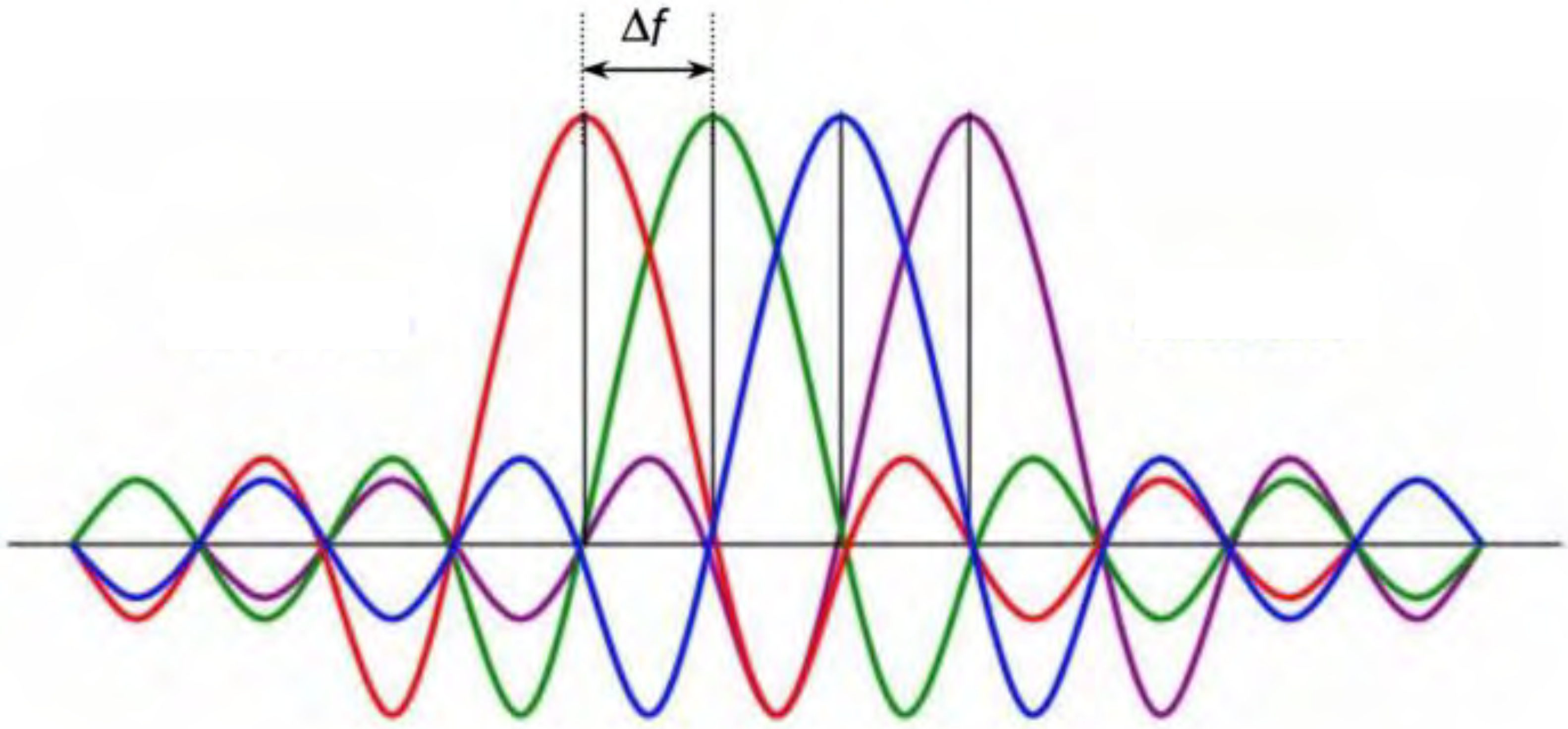
A mechanism for encoding digital data across multiple carrier frequencies

- Divides a given channel into many narrower subcarriers
- Subcarriers are orthogonal (at right angles) to each other
- Subcarriers won’t interfere with one another despite the lack of guard bands (unused frequencies)

Can handle severe channel conditions (attenuation, interference, fading) better than a single channel

802.11a, 802.11g, 802.11n, 802.11ac, 4G, 5G

OFDM Example



Frequency Hopping Spread Spectrum (FHSS)

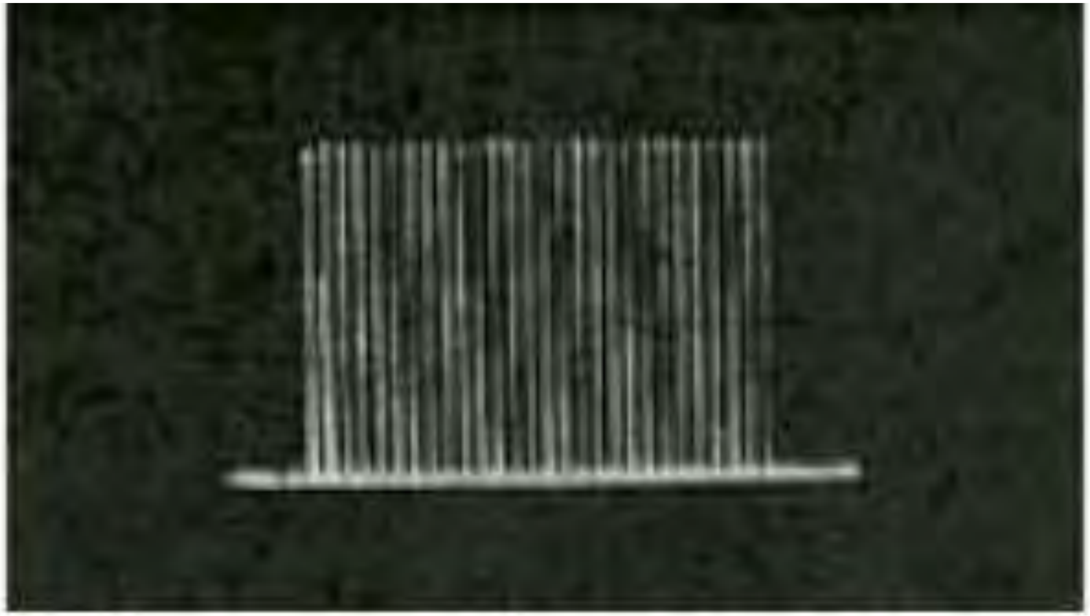
Technique to reduce signal interference

Carrier RF constantly hopping around different frequencies within the channel

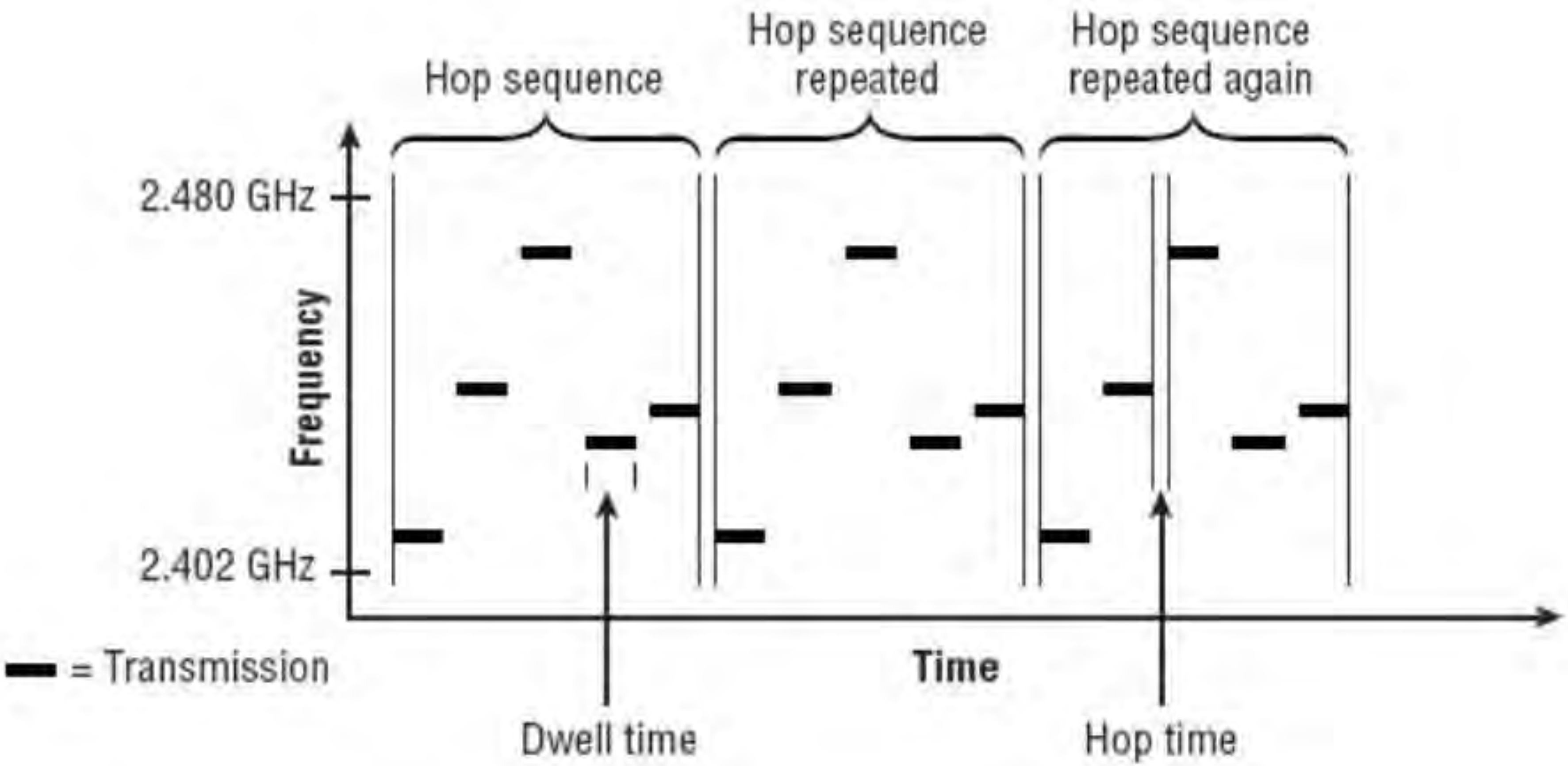
- Signal spread across time
- Meant to make signal harder to intercept or jam
- Better EMI / RFI resistance
  - If the carrier "lands" on a noisy frequency, it will hop off soon

Robust, but can only deliver up to 3 Mb/s

Has been replaced by DSSS



Frequency Hopping Example



Direct Sequence Spread Spectrum (DSSS)

Improved upon FSSS

Uses a pseudo random binary sequence to spread the data bits

- AKA Pseudo Noise (PN)

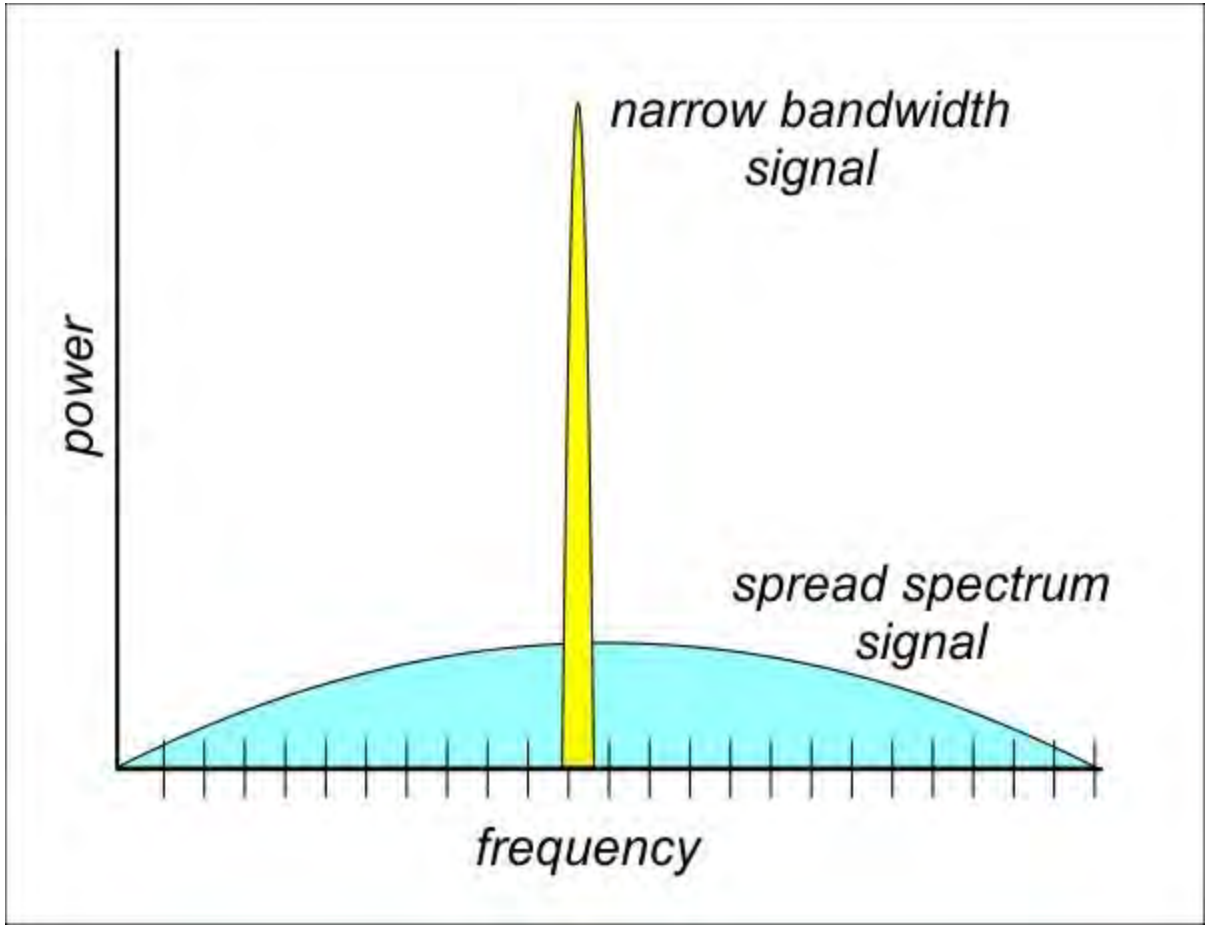
Total signal power is spread over a wide bandwidth

- Transmitted signal bandwidth is wider than original information bandwidth
- The signal appears noise-like
- Hard for attacker to detect or jam
- The receiver knows the PN sequence and uses it to track and recover the actual data

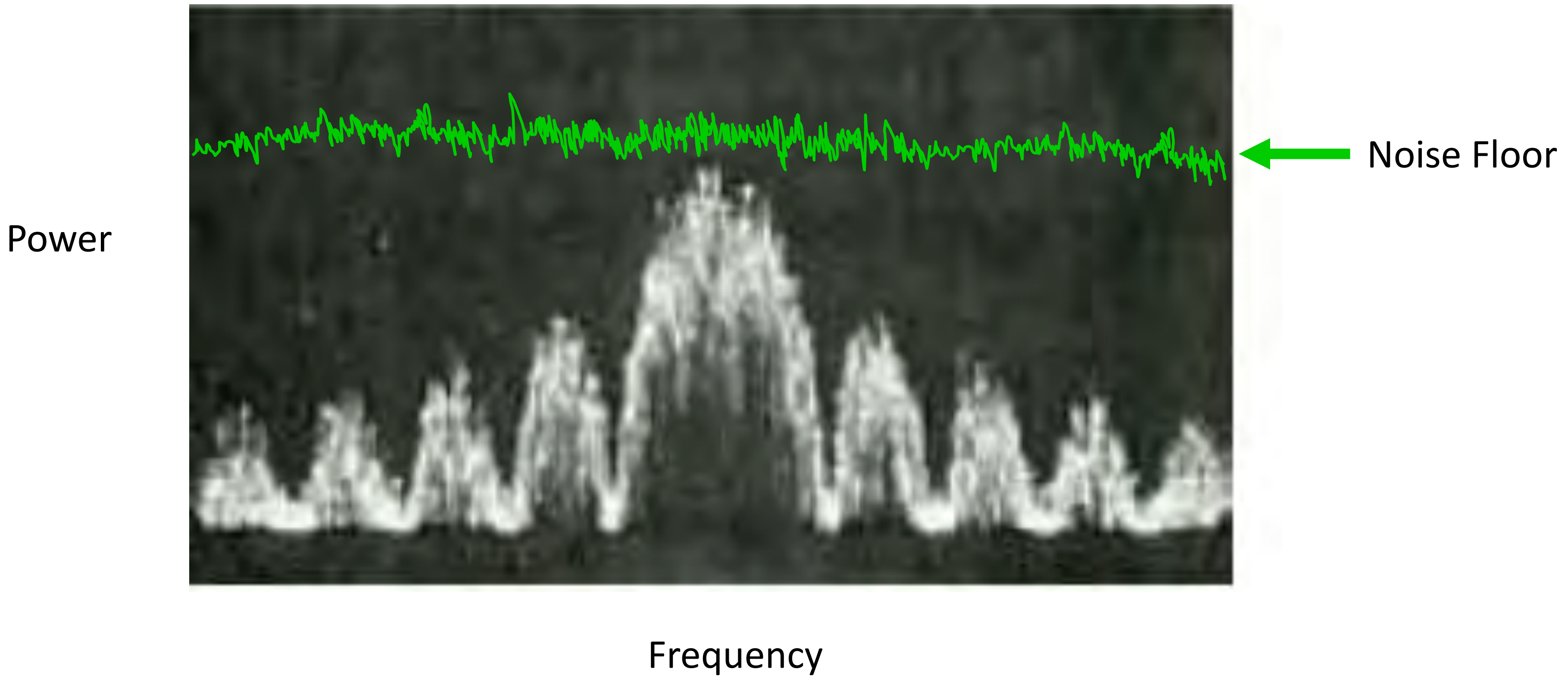
Allows the Wi-Fi signal to be lower than the surrounding “noise” threshold

- You can still receive and decode without loss of quality

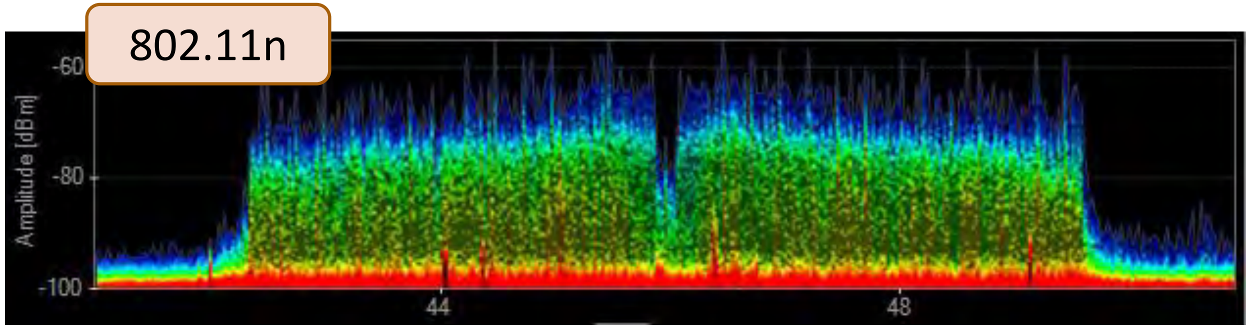
Spread Spectrum Example

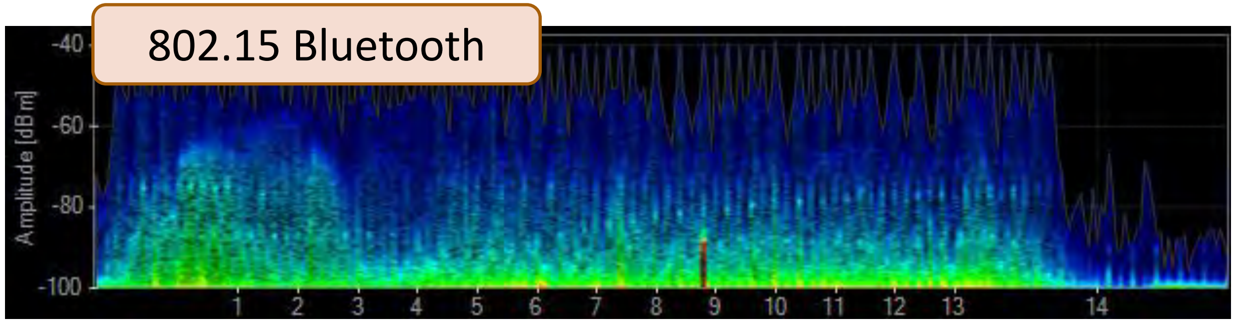


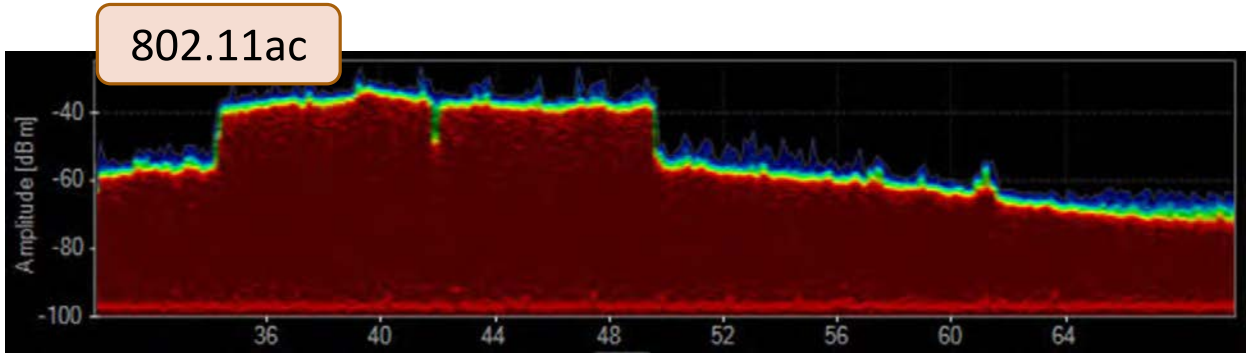
DSSS Example

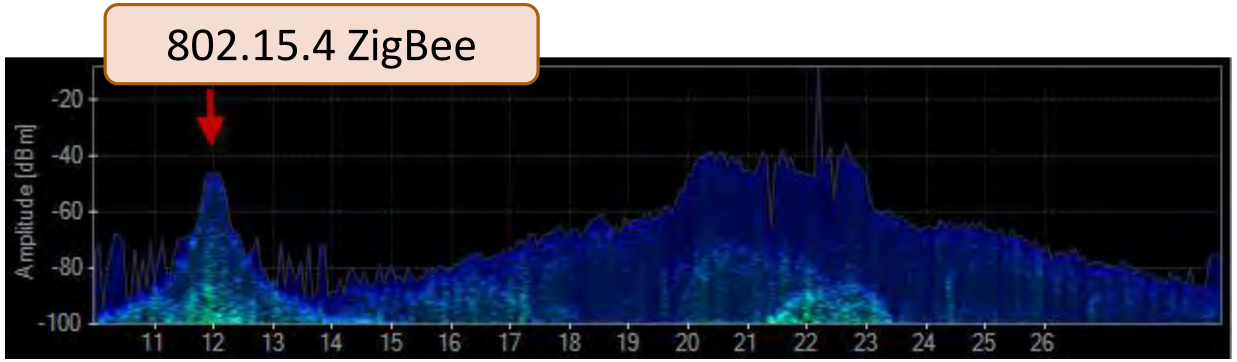


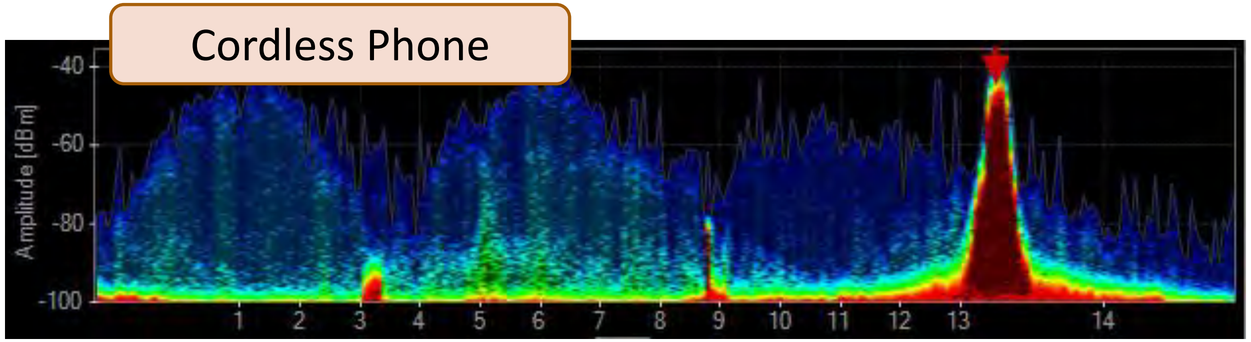
Spectrum Analyzer View of Wireless Signals

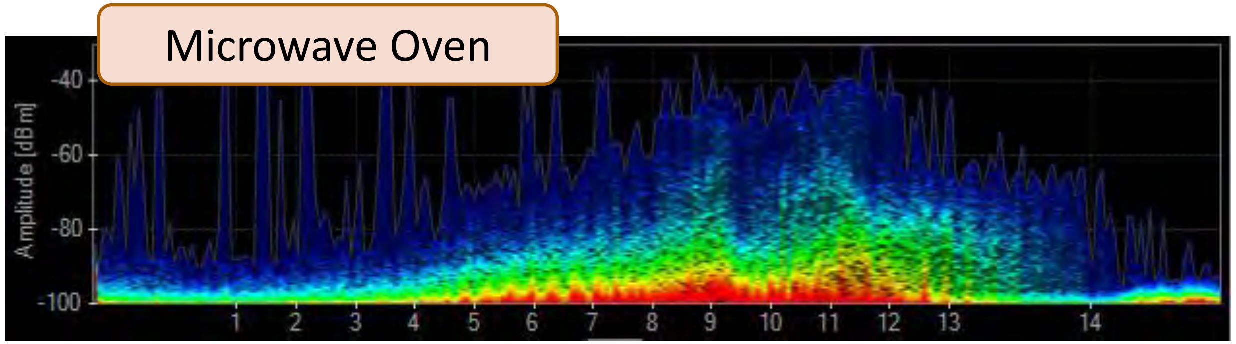






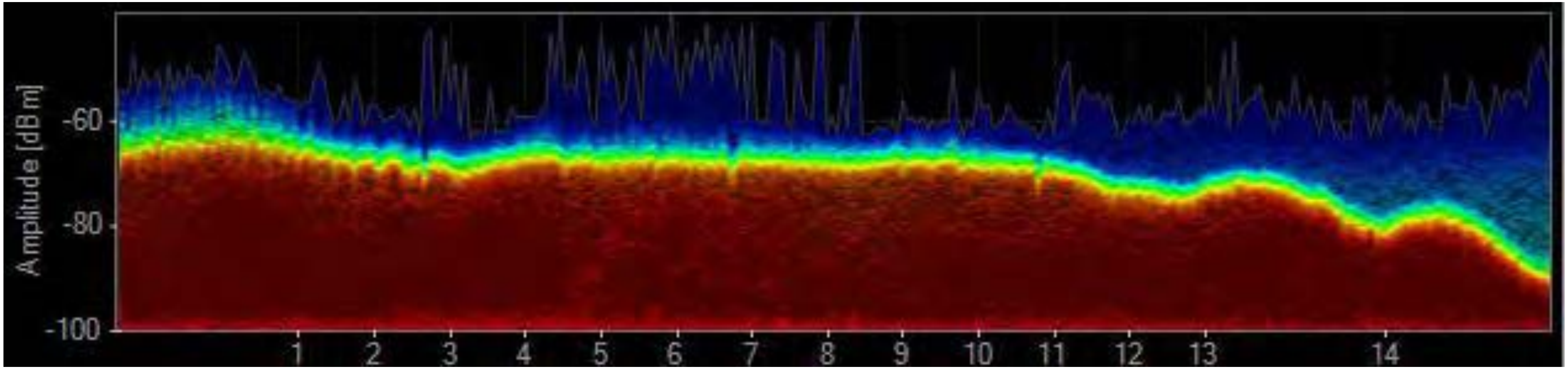






Images courtesy metageek.com

Wi-Fi Jammer!



Wi-Fi Standards

802.11

Original Wi-Fi standard (legacy)

2.4 GHz

1 – 2 Mb/s speed

Used either frequency-hopping or direct-sequence spread spectrum (FHSS, DSSS)

802.11 and the OSI Model

Layer 2 Sub layers:

Logical Link Control LLC
- receive MAC Service Data Unit (all upper layer data)

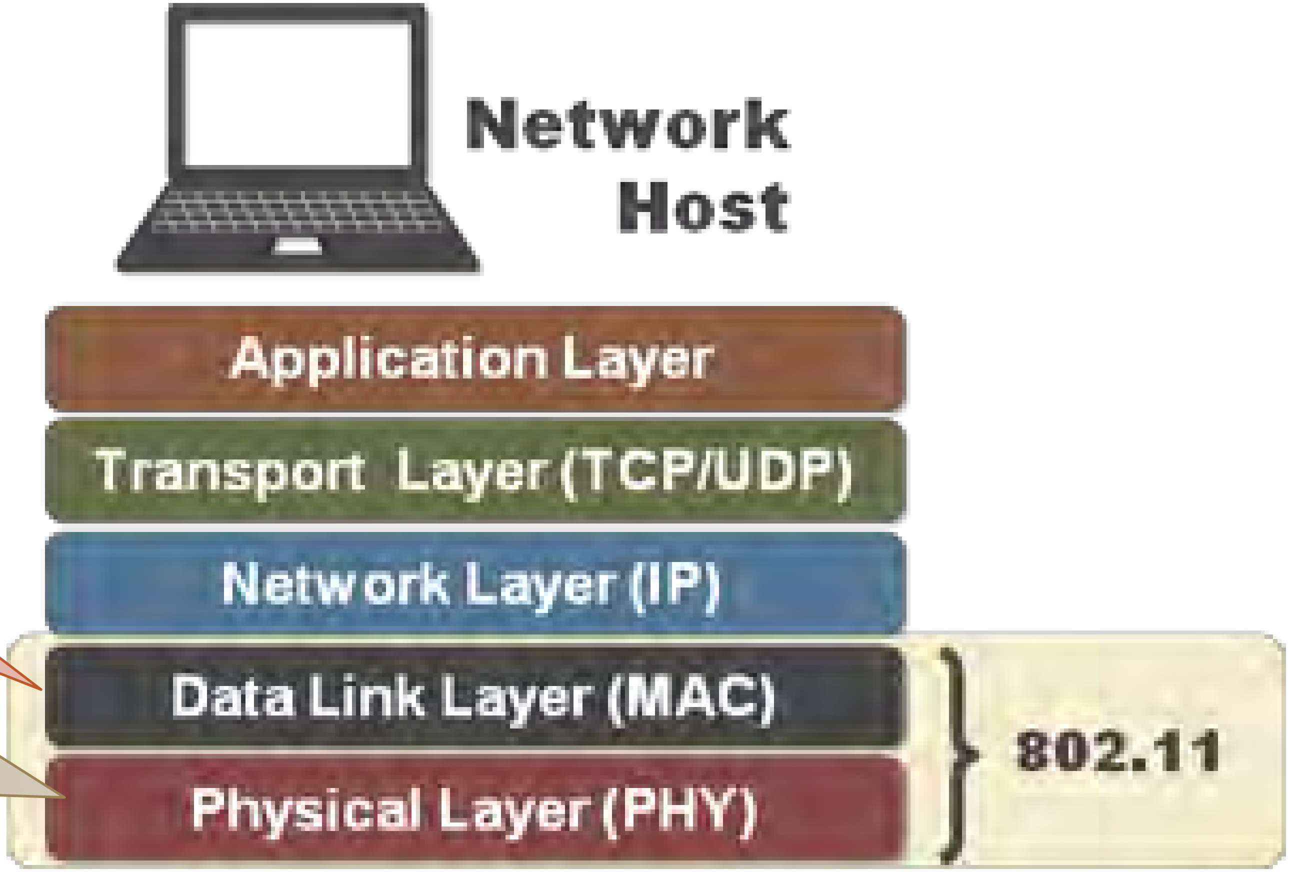
Media Access Control (MAC)
- add source/dest MAC addresses, BSSID

At this layer the frame is called an “MPDU”

Layer 1 Sub layers:

Physical Layer Convergence Procedure (PLCP)
- add preamble and PHY header

Physical Medium Dependent (PMD)
- modulate and convert to bits



802.11a

One of the first Wi-Fi wireless network communication standards

5.0 GHz kept it out of congested 2.4 GHz band

Maximum theoretical bandwidth of 54 Mbps

- 6 Mbps more common

Short distance - up to 75 feet outdoors

OFDM

802.11b

The first wireless LAN standard to be widely adopted

Built into many laptop computers and other forms of equipment

2.4 GHz

- Operated in the congested ISM band
- Competition with garage door openers, cordless phones, baby monitors, etc.

11 Mbps max

Up to 400 feet outdoors

- Could be significantly extended with a directional antenna and more power
- Longer distance made it more popular than 802.11a
- Antenna not compatible with a - you had to have a dual antenna to operate both a and b

Complimentary Code Keying (CCK – a complex variant of QPSK) modulation and DSSS

802.11g

Provided higher speeds of 802.11a while operating at 2.4 GHz

Replaced the 802.11b standard

Maximum raw data throughput of 54 Mbps

- Practical maximum throughput of just over 24 Mbps

150 feet indoors

OFDM and DSSS

802.11n

Wi-Fi 4

Developed to provide much better performance

Raw speed is 600Mbps

2.4 and 5 GHz bands

Backwards compatible with earlier 802.11a/b/g standards

175+ feet indoors

Orthogonal Frequency Division Multiplexing (OFDM) modulation

802.11ac

Wi-Fi 5

Aka “Gigabit Wi-Fi”

5 GHz band

~ 7 Gb/s throughput

256 Quadrature Amplitude Modulation (QAM)

8 x 8 MIMO

802.11ax

Wi-Fi 6

Designed to improve overall spectral efficiency, especially in dense deployment scenarios

2.4 / 5 GHz

OFDMA* + 1024 QAM modulation

9.6 Gb/s

WPA3

MU-MIMO 8 antennas

* Orthogonal Frequency Division Multiple Access

TPLink AX6000 Wi-Fi 6 Router

Wi-Fi 6E and Wi-Fi 7

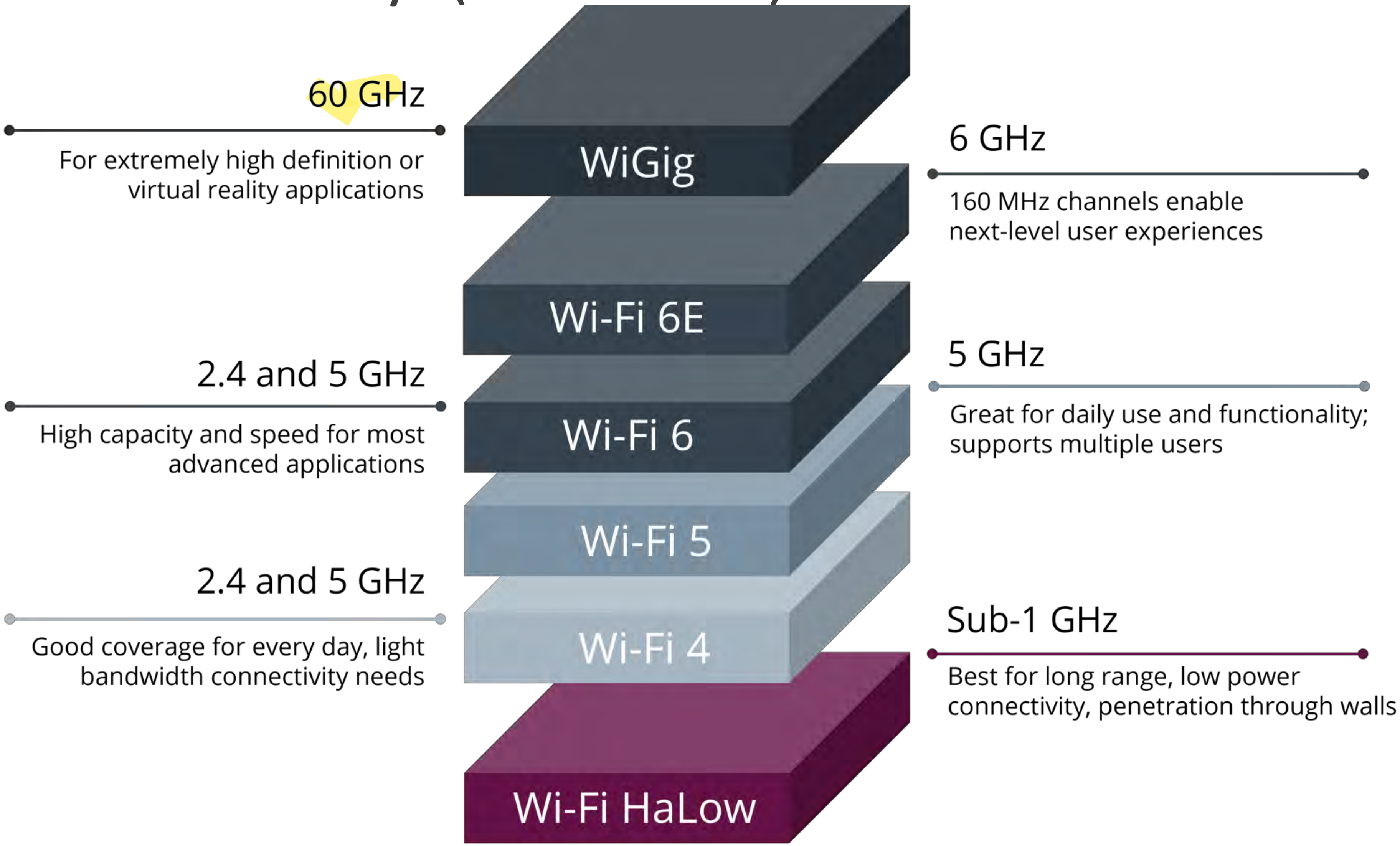
Wi-Fi 6E	**Wi-Fi 7**
Extends Wi-Fi 6	802.11be
2.4, 5, 6 GHz	1 - 7 GHz
9.6 Gb/s	40 Gb/s
8 MU-MIMO Antennas	16 MU-MIMO Antennas
	Multi-link Operation (devices will be able to use multiple channels simultaneously

NETGEAR Nighthawk Wi-Fi 6E Router

Wi-Fi 7 expected release date = 2024

Wi-Fi Channels

Wi-Fi Family (Current)



Wi-Fi Speed and Distance

Speed = throughput in kbps, Mbps, or Gbps

Speed can be negotiated down until the link is stable for both sides

The speed decreases as:

- The distance between the transmitter and receiver increases
- Interference increases

Wi-Fi Distance Fun Fact

The Swedish Space Agency holds the distance record for Wi-Fi transfer at 420km or 260 miles.

The agency used 6W amplifiers to transfer data from the ground to an overhead balloon high up in the stratosphere.

Of course, there were no physical barriers in the way to stop the signal.

2.4 GHz

- Part of the Industrial, Medical, Scientific (ISM) band
  - Unlicensed – anyone can transmit within power limits
- Longer waveform requires an antenna of appropriate length
- Able to reach farther than the 5GHz frequency which means more coverage
- Fewer channel options with only three of them non-overlapping
- Many devices use 2.4 GHz frequencies which cause interference
  - Microwaves, cordless phones, baby monitors

2.4 GHz Channels

A channel is actually a range frequencies

20 MHz wide

Data is spread across the channel range

Channels 1, 6, 11, and 14 are the only non-overlapping channels*

Ch. 12 – 13 also used by Europe

Ch. 12 - 14 also used by Japan

*US only - other countries have different patterns

5 GHz

Also part of the ISM band

Shorter waveform needs shorter antenna length

- 2.4 and 5 GHz antennas are not compatible

Shorter distance than 2.4 GHz

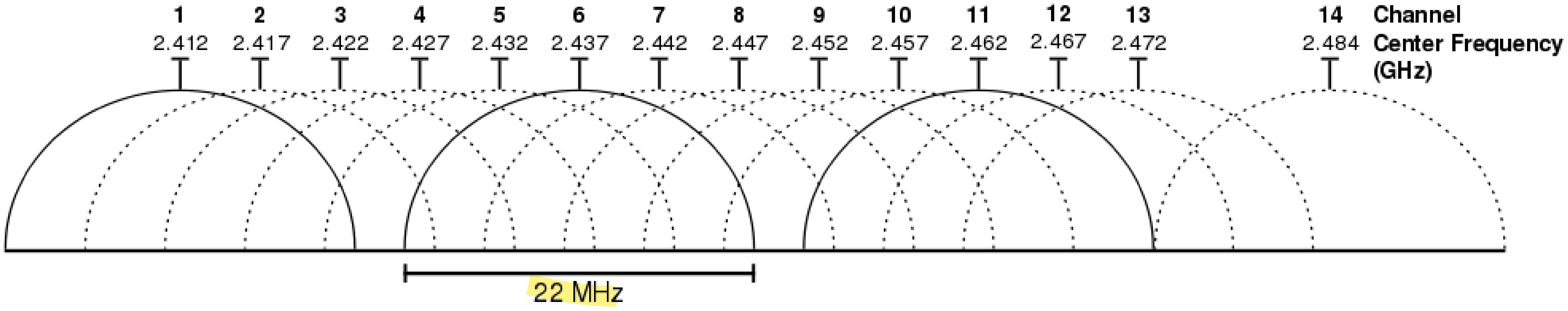
Fewer interference sources than 2.4 GHz

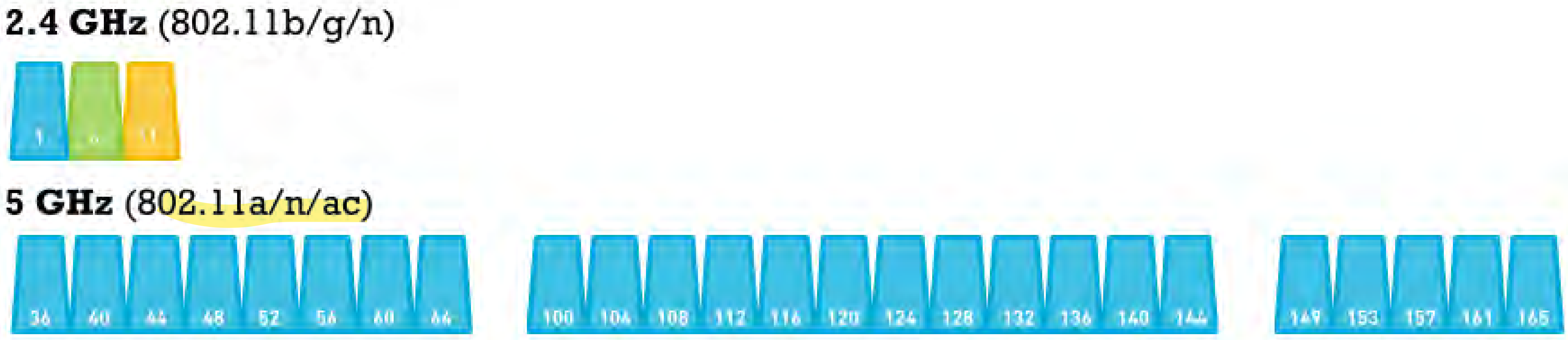
45 channels

23 non-overlapping channels

Also used by weather stations and military radar

Wi-Fi Channels





Channel Bandwidth

Channel width controls how broad the signal is for carrying data

The wider the channel, the more data can be carried without increasing the power level

Original 802.11a and g specified 20 MHz channel width

- Throughput varies from 6 – 288 mb/s per channel depending on # of antennas and modulation scheme

2.4 GHz permits:

- 14 overlapping 20 MHz channels
- 3 non-overlapping 20 MHz channels (1, 6, 11, +13 for non-US)

5 GHz permits:

- 25 non-overlapping 20 MHz channels

Channel Bonding

Two or more channels are combined for redundancy or increased throughput

Channel bonding allows multiple channels to create wider (but fewer) channels:

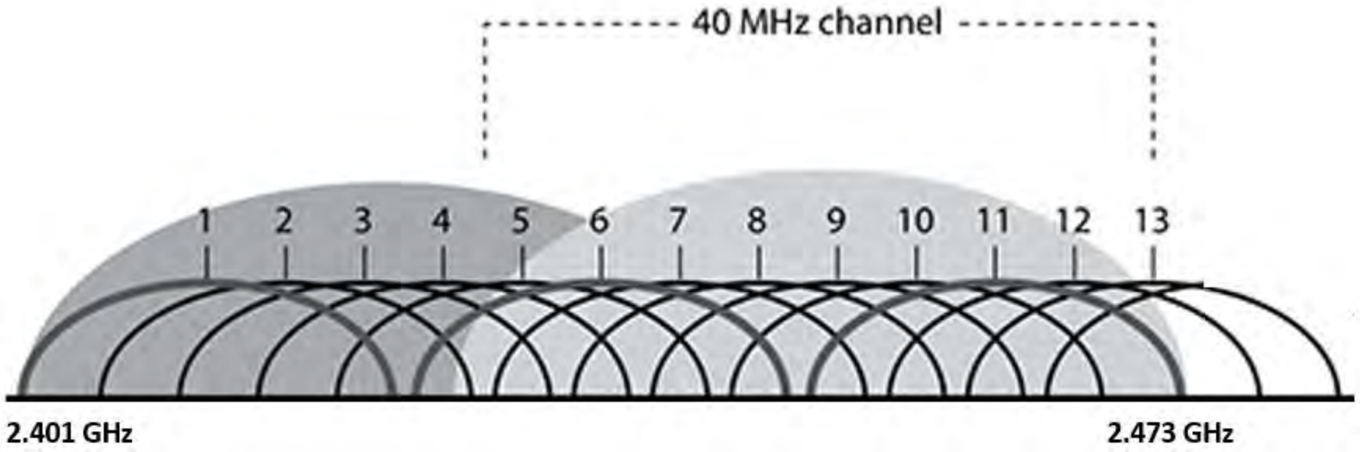
- 40 MHz - 802.11n
- 80 / 160 MHz - 802.11ac

2.4 GHz allows:

- (2) 40 MHz channels

5 GHz

- (12) 40 MHz channels -
- (6) 80 MHz channels
- (2) 160 MHz channels



Wi-Fi Regulatory Issues

5 GHz usage

- 5 GHz channels 36 - 48 (80 MHz total) are allowed by most regulatory domains worldwide for low-power, indoor/outdoor Wi-Fi
- 5 GHz channels 52 – 64, 100 - 144 are used by both Wi-Fi and government weather radar systems; Wi-Fi must use DFS sensing
- Higher 5 GHz channels are allowed for Wi-Fi in the US, but not by all countries

5 GHz Dynamic Frequency Selection (DFS) restrictions

- DFS channels are 5 GHz channels used by military and meteorological radar
- DFS channels cover half of the 5 GHz range
- 802.11n could only bond 2 channels to provide 40 MHz of carrier bandwidth (~150 mb/s)
- Many countries (incl. US) require 5 GHz Wi-Fi networks and clients to employ radar detection and avoidance
- Wi-Fi can only use DFS channels indoors
- If radar is detected, the Wi-Fi network must switch to a different channel
- DFS detection and avoidance is built into 801.11h

FCC New Rules for Wi-Fi

In April 2020, the US Federal Communications Commission (FCC) adopted new rules for Wi-Fi

It opened 1200 MHz of bandwidth in the 6 GHz range

- As a reference, 2.4 GHz offers only 70 MHz of bandwidth
- Very wide bandwidth provides 160 MHz-wide channels (bonding 8 channels)
- Strictly limited to 802.11ax and higher devices

Antennas

Unidirectional/Omnidirectional

Omnidirectional antennas radiate signal from a 360-degree field

- They generally are long rod-like cylinders

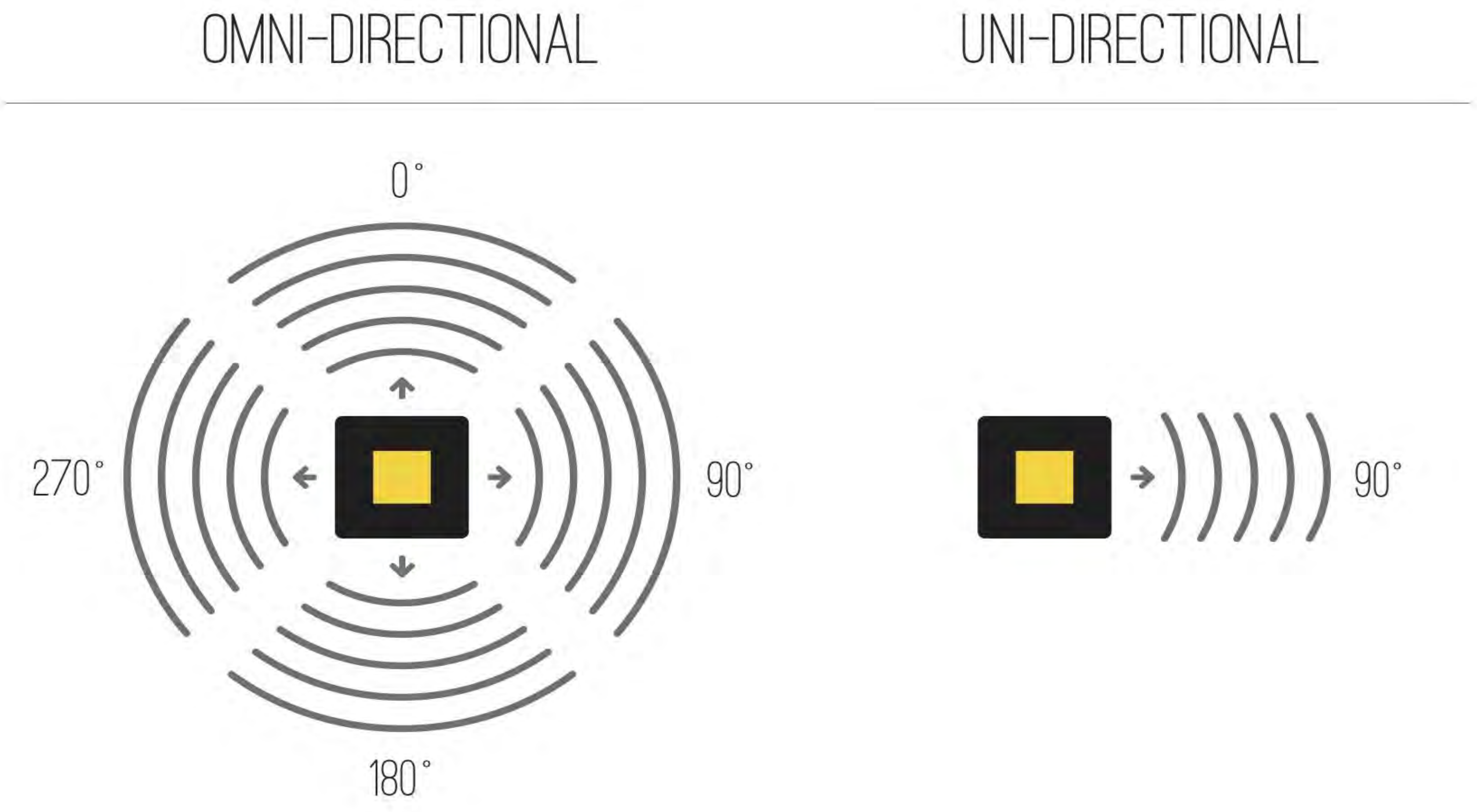
Unidirectional antennas radiate signal in a 45-90 degree directional field

- A narrower field focuses the signal
- Allows the signal to travel farther

Regardless of Omni or Uni, another considerations is gain

- the higher the dBi (gain) the further it will reach

Antenna Direction



Wi-Fi Antenna Examples

14 dBi directional

25 dBi directional YAGI

5 dBi omni

9 dBi omni

Multiple Input Multiple Output (MIMO)

The use of multiple transmit and receive antennas on a radio

Multiplies the capacity of a radio link

Send multiple “streams” of data at the same time

First used in Wi-Fi 802.11n

- Also used in cellular 3G & 4G, and WIMAX 4G

Multi User MIMO (MU-MIMO)

AKA Next-Gen AC or AC Wave 2

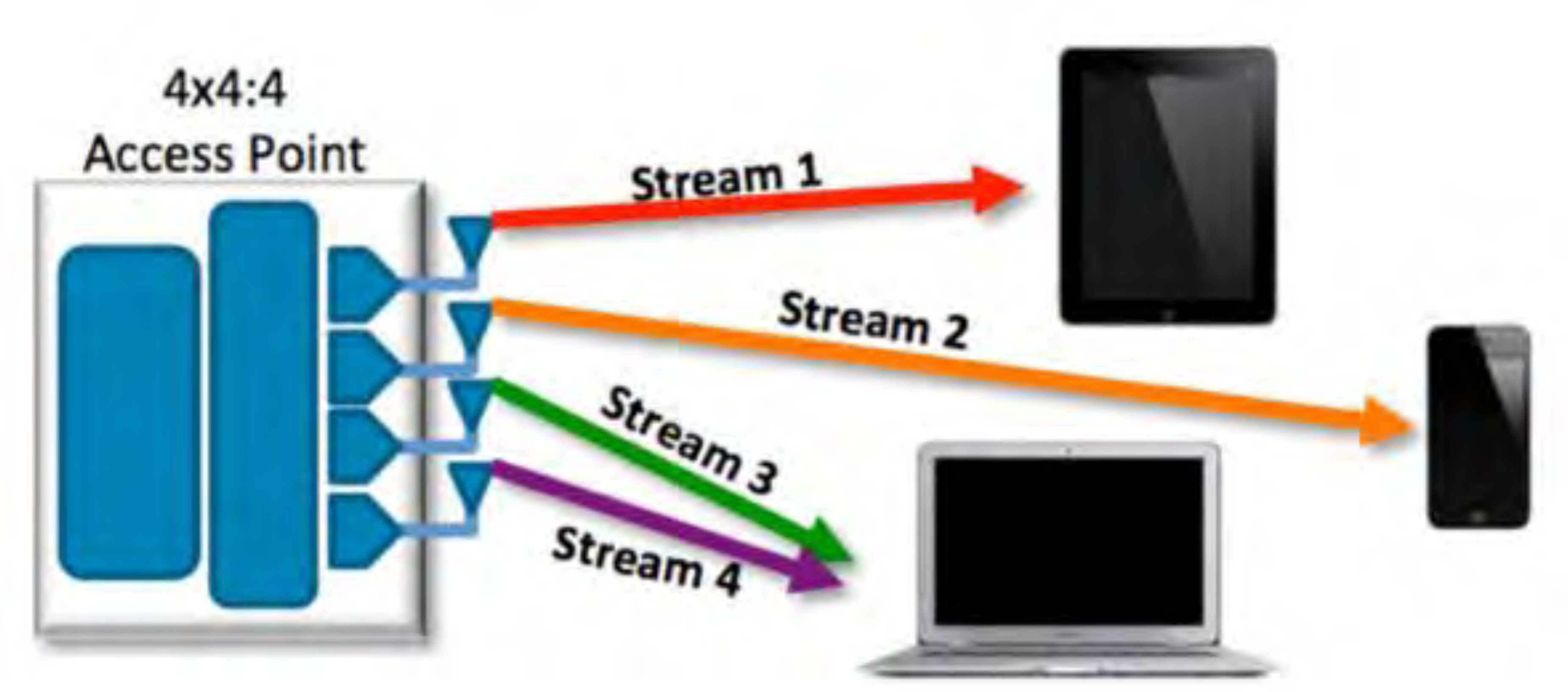
Allows a Wi-Fi router to communicate with multiple devices simultaneously

Decreases the time each device has to wait for a signal

Dramatically speeds up a network

Most routers today use MU-MIMO antennas

MU-MIMO Example



Examples of Routers with MU-MIMO Antennas

Wi-Fi Service Sets

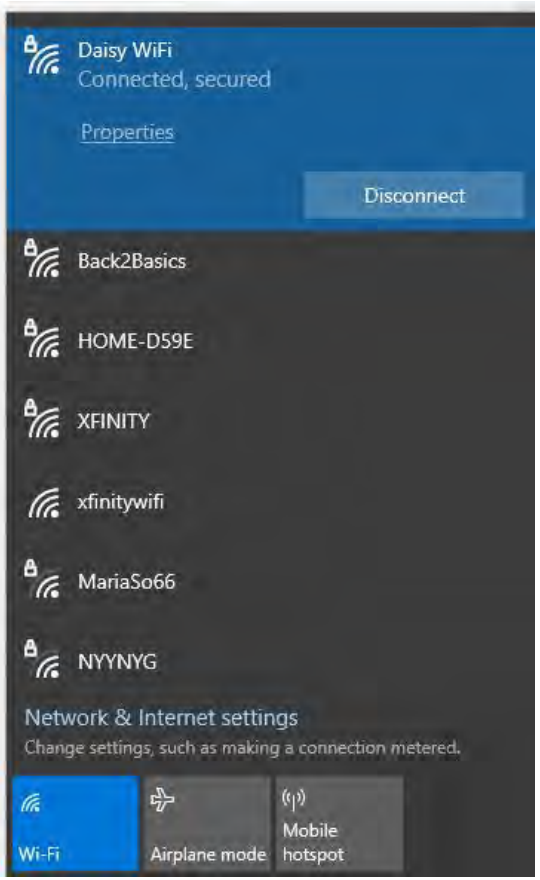
Service Set Identifier (SSID)

The friendly name given to a wireless network

Need not be unique

Can be hidden (not advertised)

- You can still connect to the WLAN if you know the SSID
- You'll have to manually enter the SSID



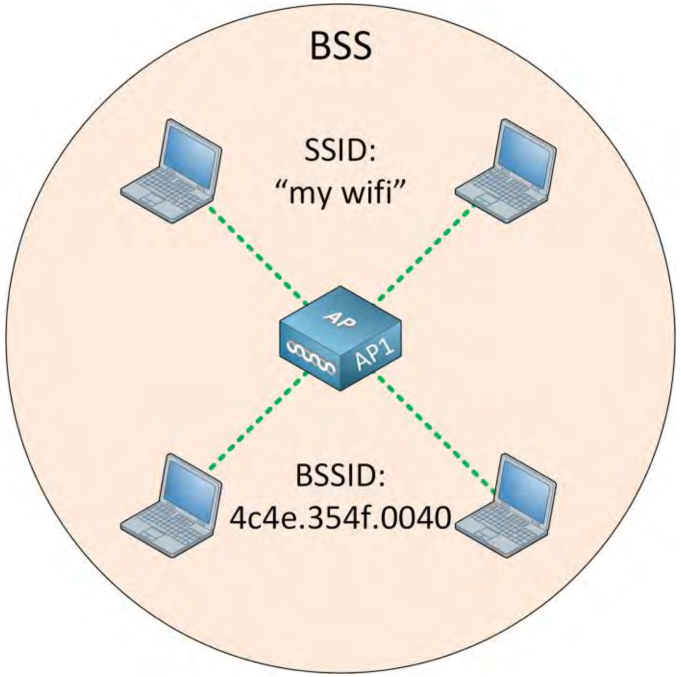
Basic Service Set (BSS)

Simple WLAN with ONE:
- Wireless access point
- SSID (AP advertises itself)
- Channel
- BSSID (MAC address of AP)

Typically can accommodate up to 10 clients

Usually an extension of the LAN

Traffic might also be routed straight to the Internet



Extended Service Set (ESS)

Several interconnected BSSs acting as one

APs that are physically close to each other will use different channels

- Avoid interfering with each other

All participating BSSs use the same SSID

- To the client, the ESS appears as a single BSS

Depending on the product, the ESS might provide several SSIDs

- Each WAP in the ESS can accept connections to any or all of the SSIDs
- To the client, each SSID appears to be a different system, with its own security and network settings

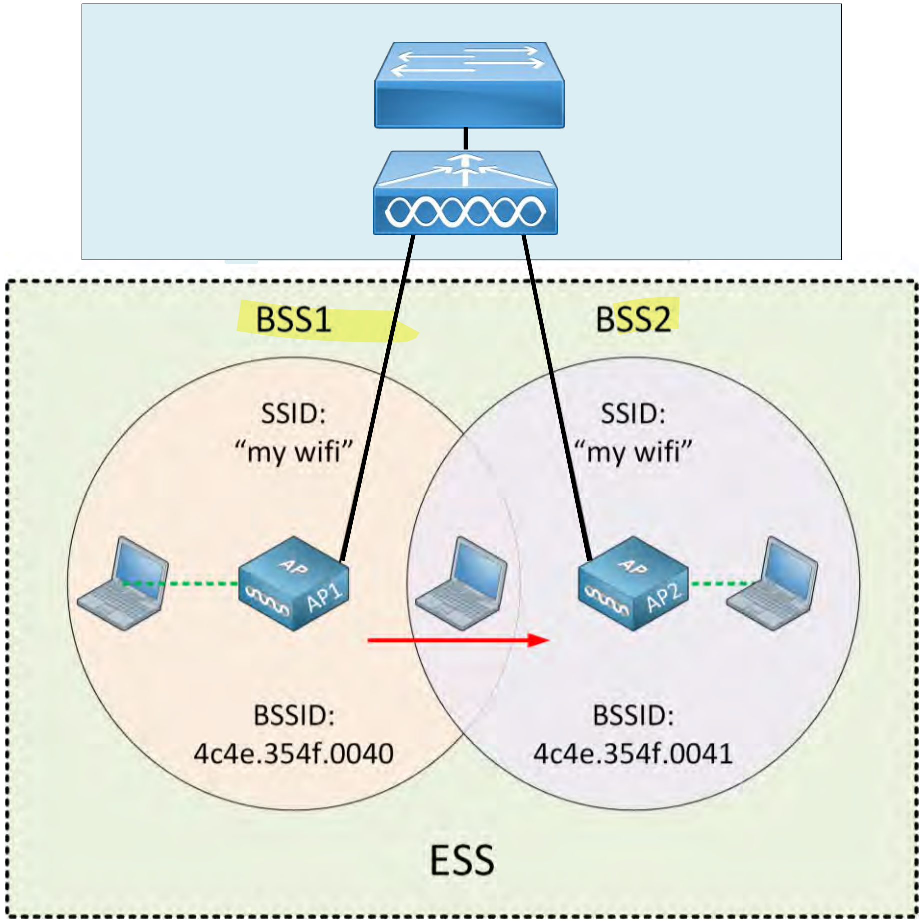
APs in an ESS are typically managed by a separate WLAN controller

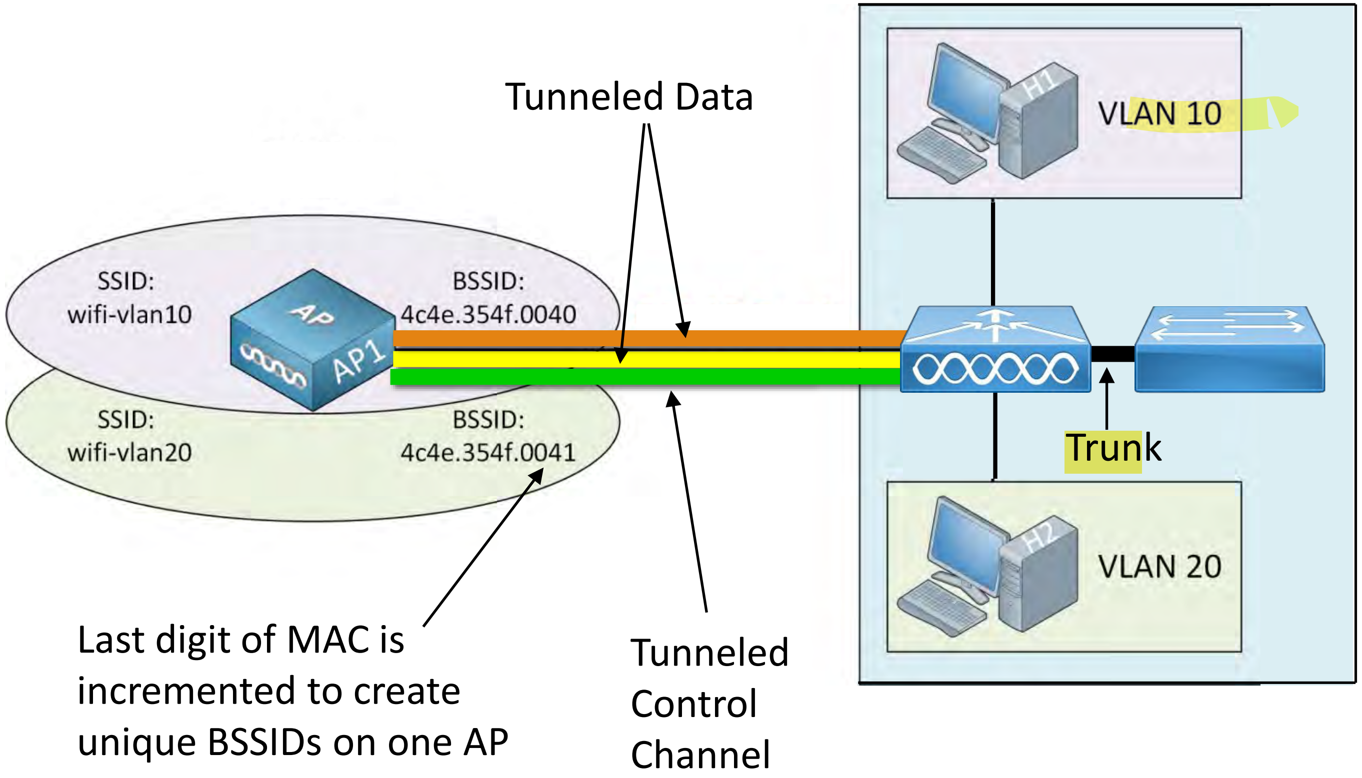
- The controller sends configuration information, including load balancing user traffic, to the APs
- Controller traffic and user data is tunneled between the controller and AP(s)

Can have thousands of active clients

- Depending on the product, each AP can handle up to 50 clients at a time

ESS Examples





Independent Basic Service Set (IBSS)

Ad-hoc network between devices

Two or more devices to communicate directly with each other

No access point

Full mesh topology

Typically maximum 10 devices

Roaming

A wireless client leaves one BSSID and authenticates/associates to a new BSSID

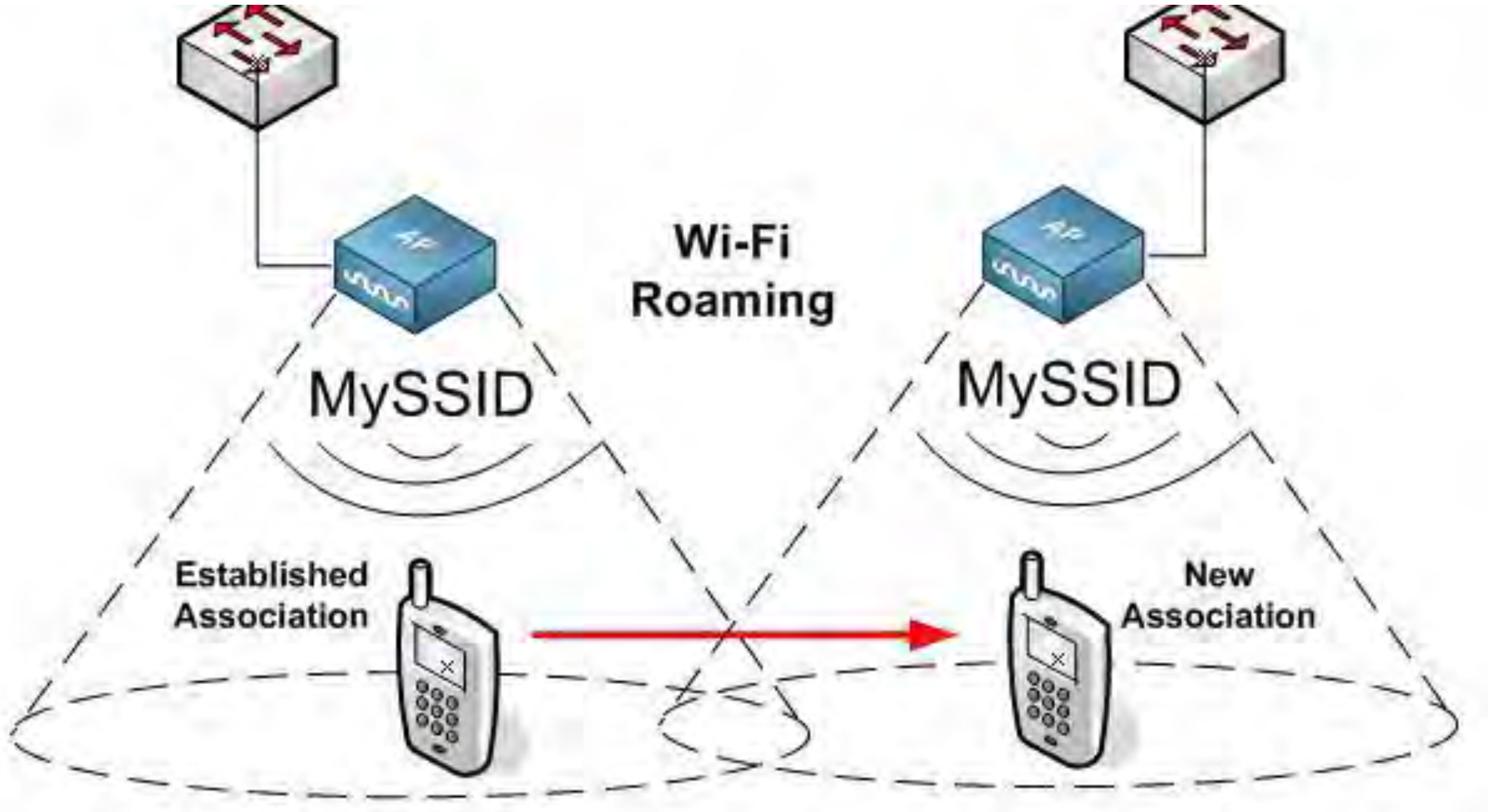
- Switch from an AP with a weaker signal to one with a stronger signal
- Done automatically as the user moves from one area to the next

Ideally, there is no disruption of service

Critical for seamless user experience

Requires the WLAN to be well-designed with no gaps in signal coverage

Roaming Example



Wi-Fi Security

Wi-Fi Security Standards

Encryption Standard	Authentication	Encryption Algorithm	Comment
WEP	40-bit Pre-shared key Extended with 24-bit initialization vector (IV)	40/64-bit RC4	Susceptible to replay attacks Can crack a key in seconds
WPA	Temporal Key Integrity Protocol (TKIP)	64-bit RC4 (personal) 128-bit RC4 (enterprise)	Anti-replay re-keying mechanism Every packet has a unique encryption key
WPA2 personal	Pre-shared key CCMP (128 bit key + 48-bit IV)	128-bit AES	Imperfect 4-way authentication handshake Susceptible to KRACK vulnerability
WPA2 enterprise	802.1x authentication	128-bit AES	Enterprise RADIUS server makes spoofing authentication difficult

Wi-Fi Security Standards (cont'd)

Encryption Standard	Authentication	Encryption Algorithm	Comment
WPA3	Simultaneous Authentication of Equals (SAE)	128-bit personal 192-bit enterprise	Uses zero-knowledge proof No elements of the password are transmitted over the network Session key derived from the process QR codes can be used to gain network connection details

Cellular

Cellular Network

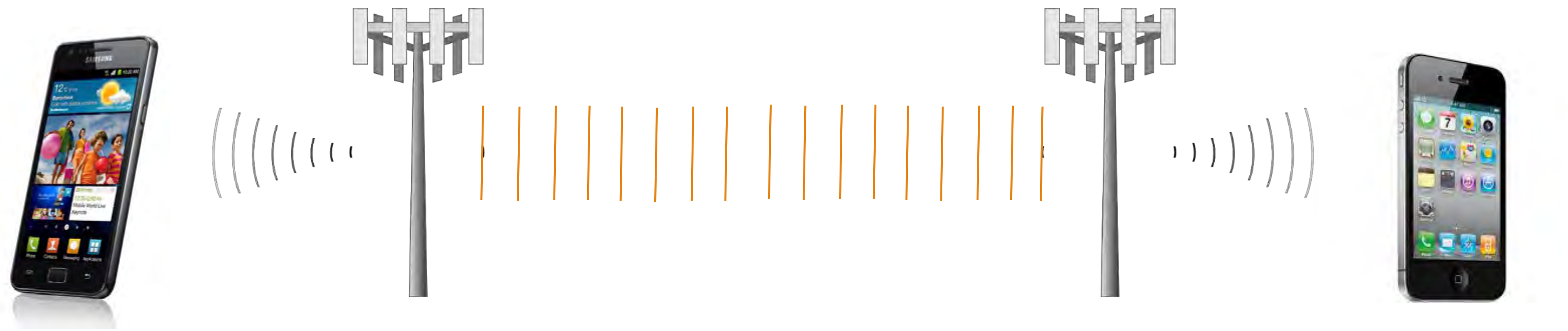
A type of WAN where the last link is wireless

Uses cellular technology

- Cell phones connect to cell towers
- Cell towers connect to each other

The network is distributed over land areas called cells

Each cell is served by at least one (but usually three) transceivers



Benefits of Cellular

More capacity than a single large transmitter

- The same frequency can be used for multiple connections as long as they are in different cells

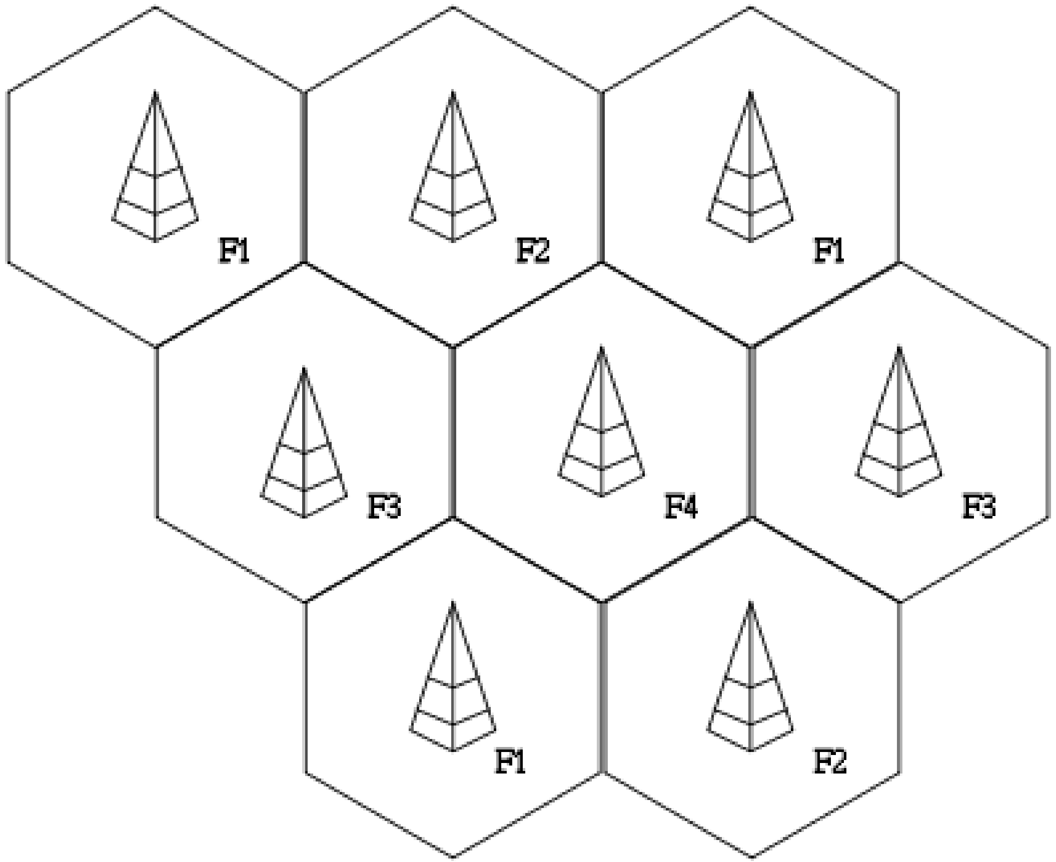
Mobile devices use less power than with a single transmitter or satellite

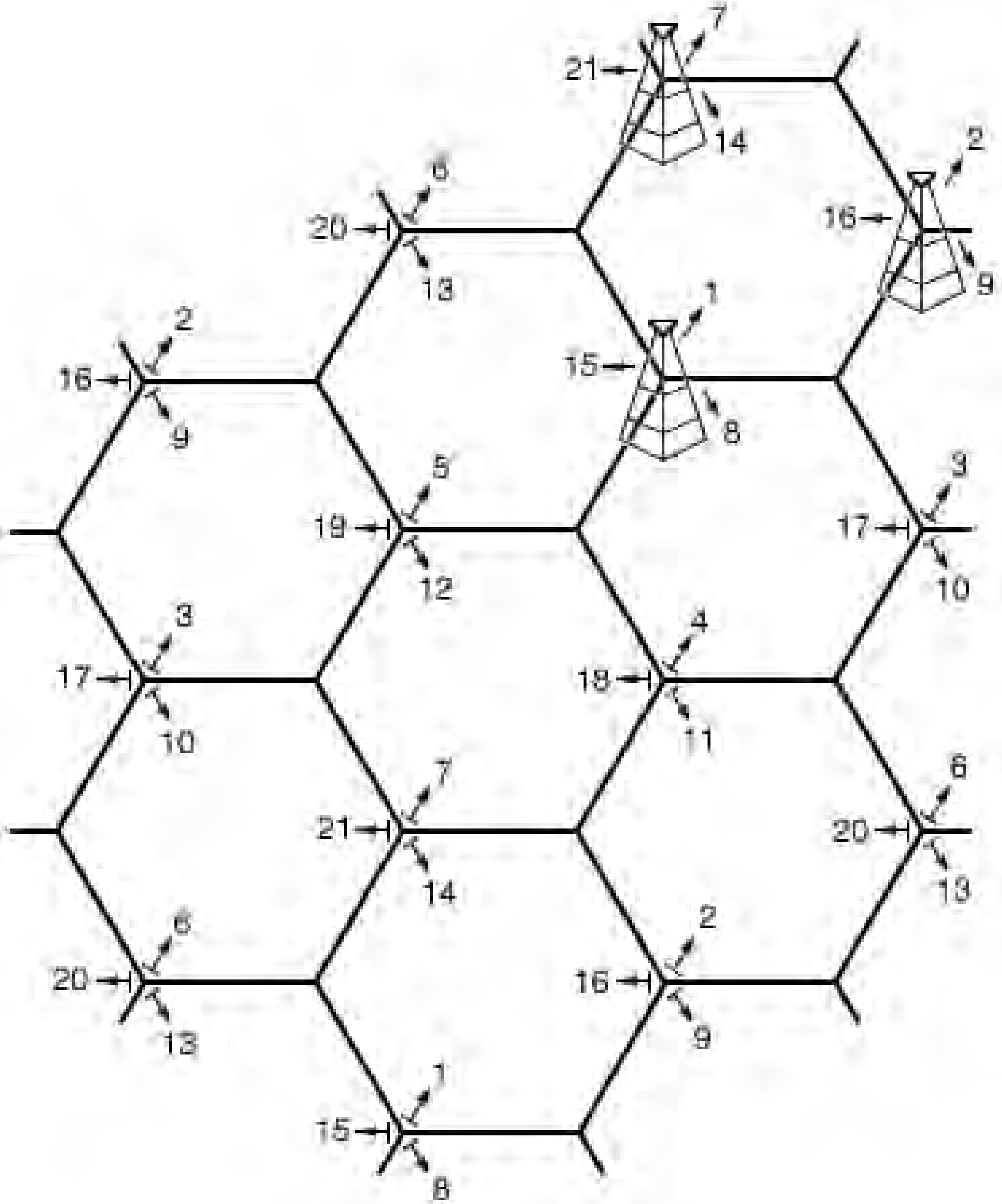
- The cell towers are closer

Larger coverage area than a single terrestrial transmitter

- Additional cell towers can be added indefinitely and are not limited by the horizon

Cell Tower Placement





3G and 4G Cellular

Refers to a set of standards that cell phones must meet to use that designation

Each “G” is a generation in the evolution of cellular technology

3G – Made smart phones possible with:

- Web browsing, email, video downloads, picture sharing, etc.
- Required minimum speeds: 2 mb/s stationary, 384 kb/s mobile

4G – Designed to provide higher speed and lower latency at a lower cost:

- IP telephony, gaming, high-def and 3D mobile TV, video conferencing, cloud computing
- Uses OFDM modulation and MIMO antennas
- Max speed: 1 gb/s stationary, 100 mb/s mobile

GSM

Global System for Mobile communications

Worldwide the most popular cellular network type
- 80% of the world uses it

Callers are authenticated based on a removable SIM card

Uses time division multiplexing to separate users into time slots so they can share the same channel

CDMA

Code Division Multiple Access

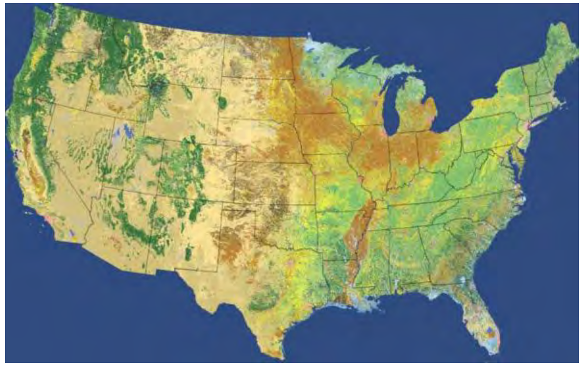
US competitor to GSM

- Also used by some Asian carriers

Uses network-based authentication

- Carriers retain more control
- You can only switch to a new phone with the carrier's permission

Uses spread-spectrum and special coding to spread a call over the entire frequency range



Note: Both CDMA (Sprint, Verizon) and GSM (AT&T, T-Mobile) are used in the US

Long-Term Evolution (LTE)

A worldwide standard for broadband data on mobile devices

Based (partly) on GSM

3G LTE download speed ~= 7 mb/s

4G LTE download speed 100 – 1000 mb/s

Notes:

4G LTE does not quite meet all of the minimum ITU specifications to be called “4G”

LTE can refer to other types of wireless broadband (not just cellular)

5G Cellular

Adds new frequency band for dramatically faster speeds and lower latency

Uses 4G to help establish and maintain the call

Provides about the same performance as 4G when using older low- and mid-bands

Adds the new High-band 5G ("millimeter wave") 20 – 100 GHz range

- Very wide bandwidth, much shorter distance (800 ft drop-off)
- Currently used for high-density hotspots like college campuses and football stadiums
- 5 – 10 gb/s @ <1 ms latency (goal is for 26 gb/s)

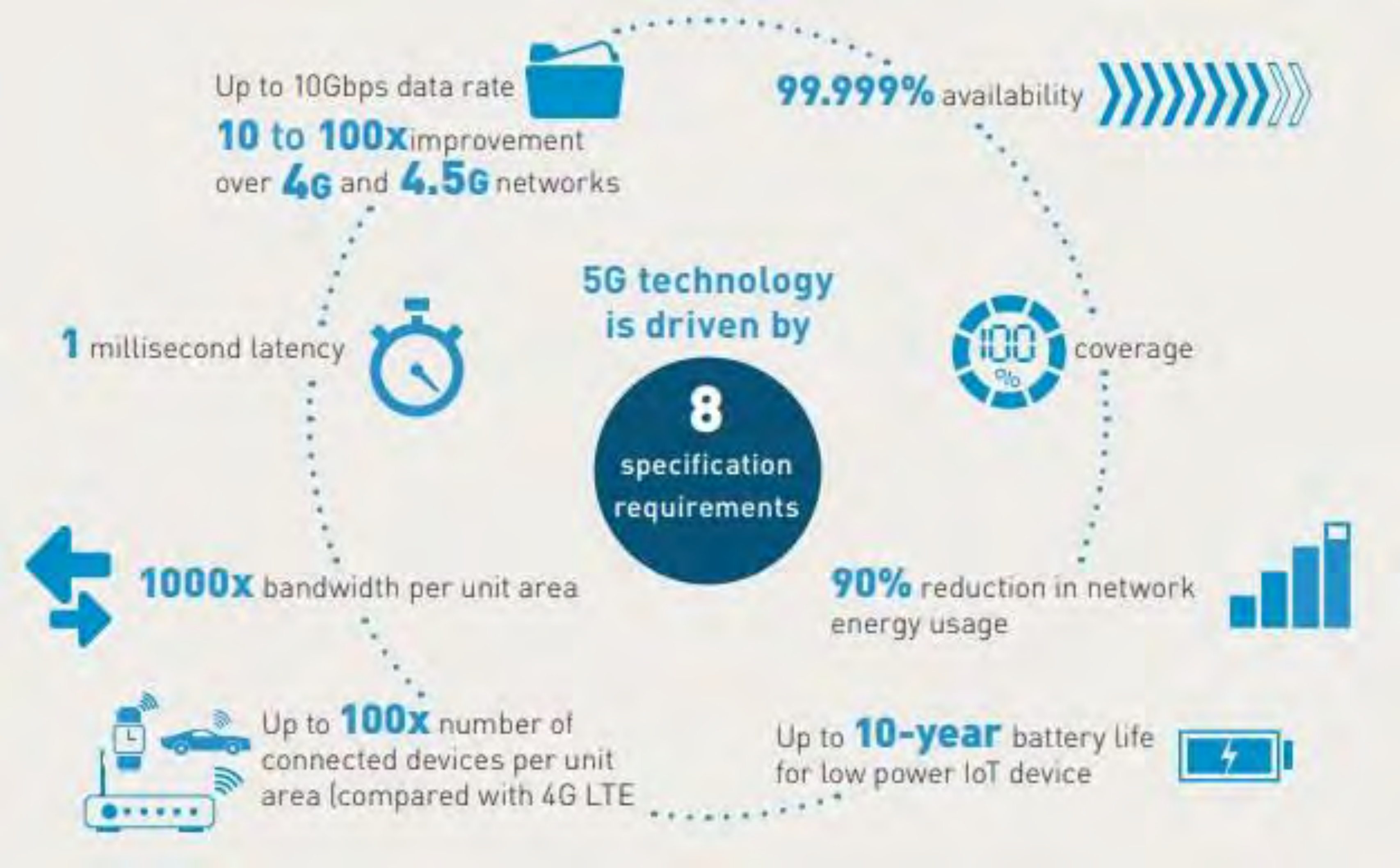
Requires "Massive MIMO" (mMIMO) antenna design at the base station

- An antenna could be a grid array of 256 transmitting, and 256 receiving antennas

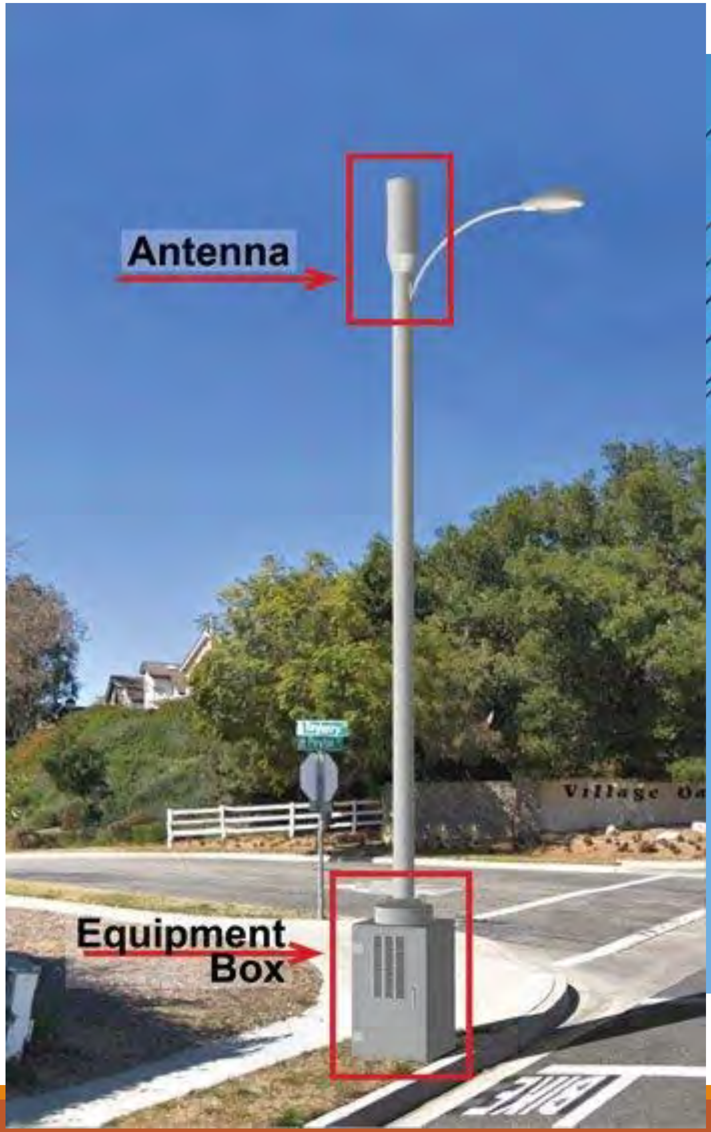
Providers will have to install many low-power "small cells" to their infrastructure for complete coverage

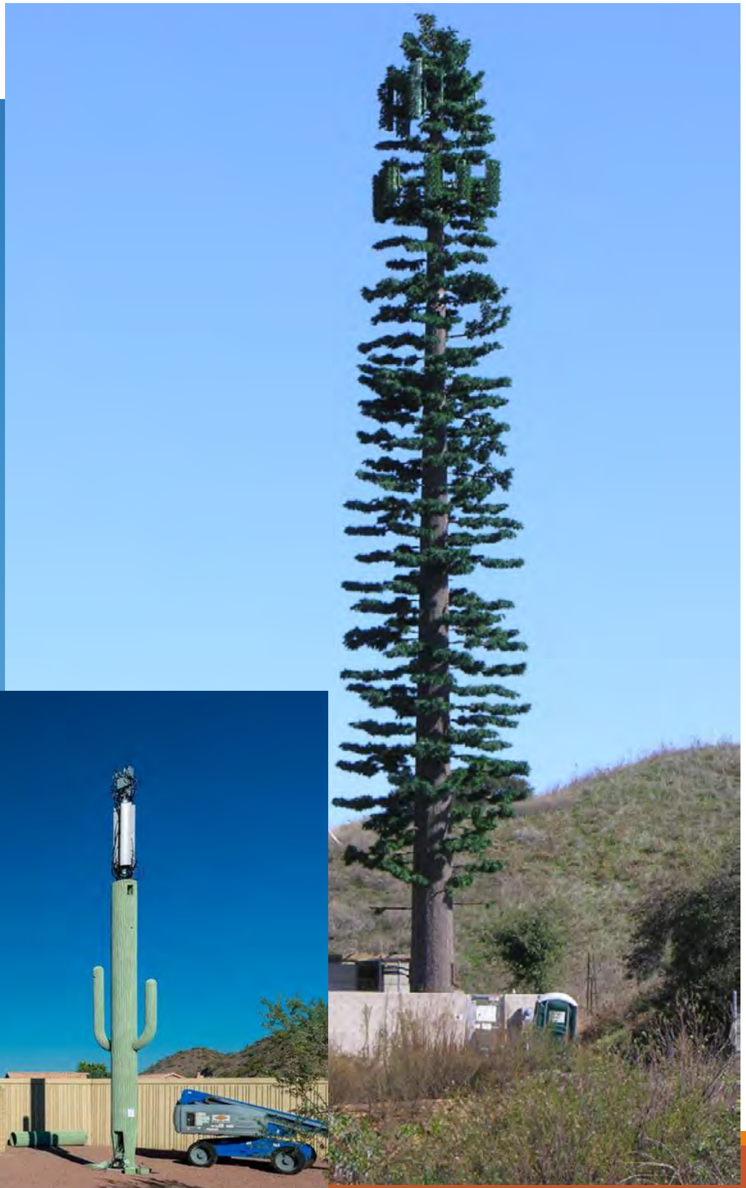
Very well suited for M2M networks and low-latency IoT

5G Specification Requirements

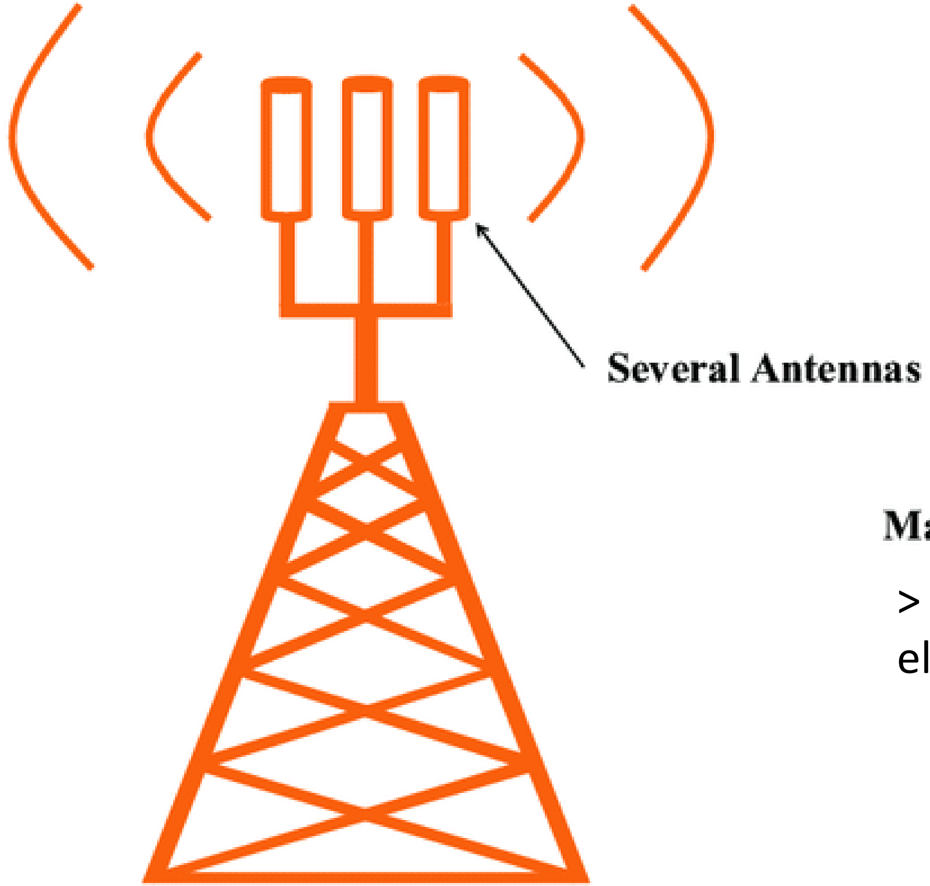


Small Cell Examples

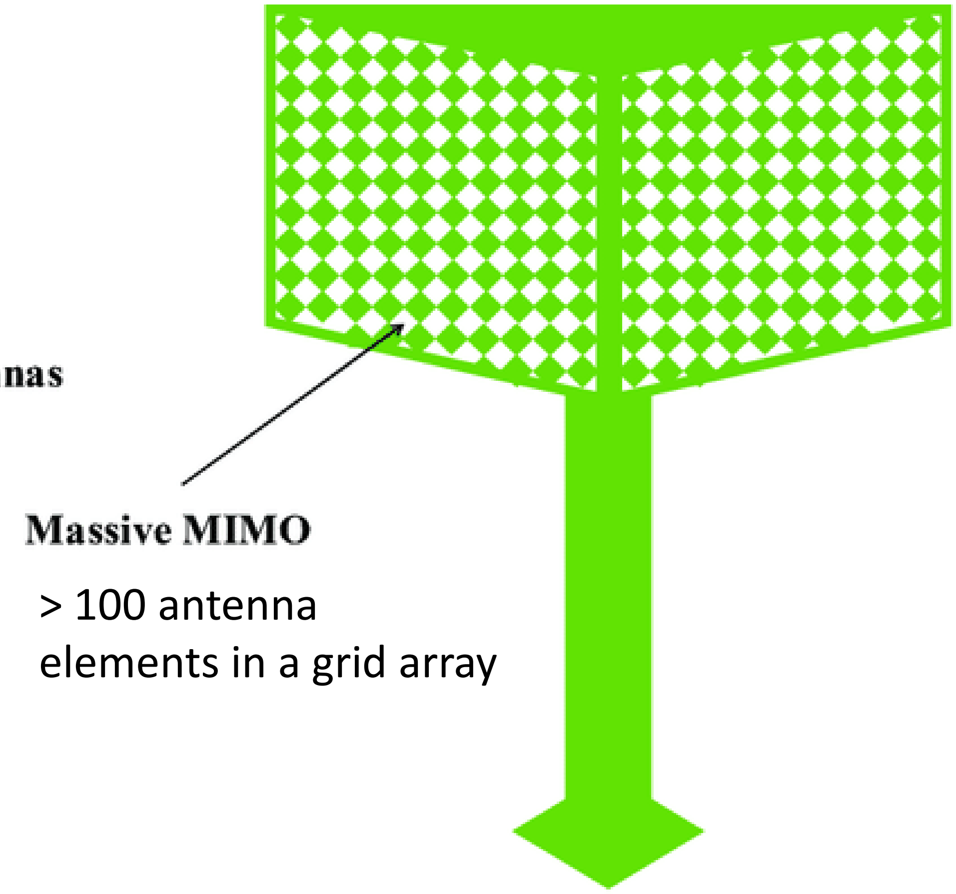




4G and 5G Macro Base Stations



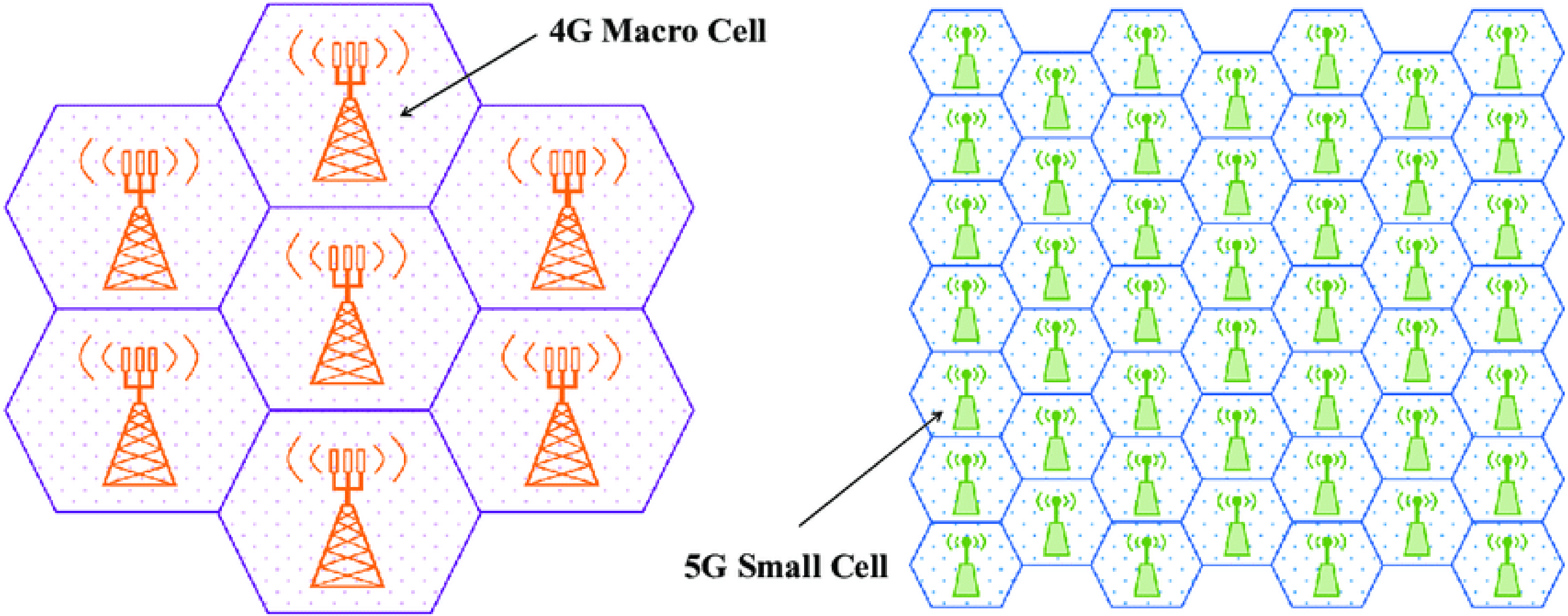
4G Macro Base Station



> 100 antenna
elements in a grid array

5G Macro Base Station

4G Macro vs 5G Small Cells



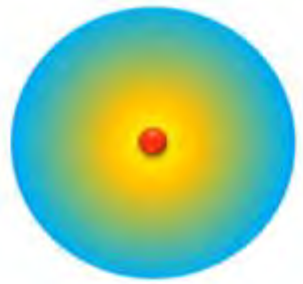
Beamforming

A technique focuses radio signals towards a single receiver

- Introduced in Wi-Fi 802.11n

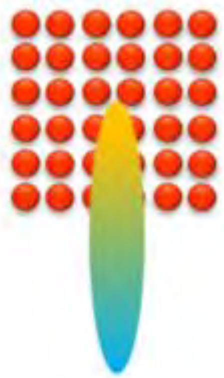
Multiple smaller streams (signals) combine to form a stronger stream at the receiver

- A single user is tracked with multiple streams assigned to them
- The phase of each stream is changed so that as it reflects off surfaces around the user it arrives at the user at the same time as the other streams
- This is more efficient and better at cancelling interference than radiating one large stream in all directions



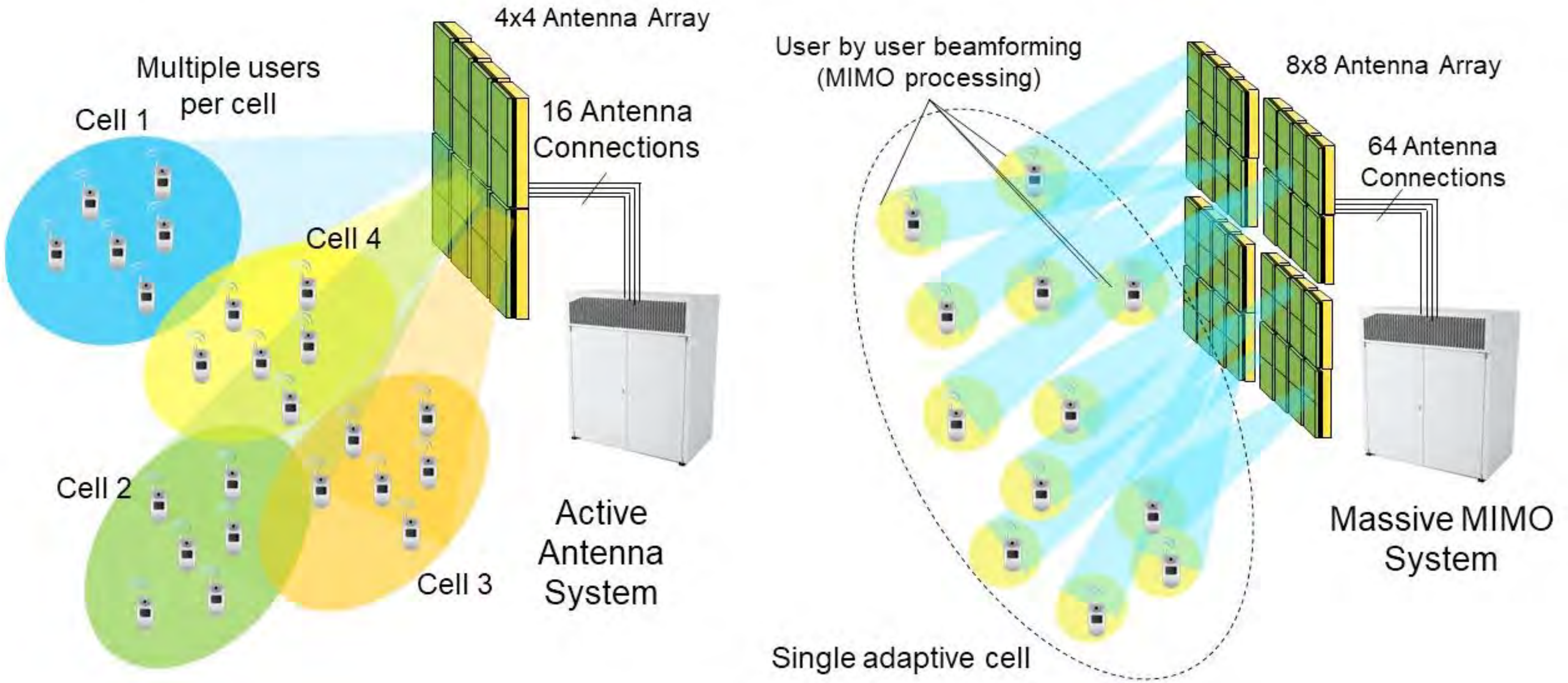
Single Antenna

Two Antennas



Multiple Antennas

mMIMO Beamforming



mMIMO vs Single Antenna Performance