# Theoretical and Practical Constraints for Wi-Fi Capacity

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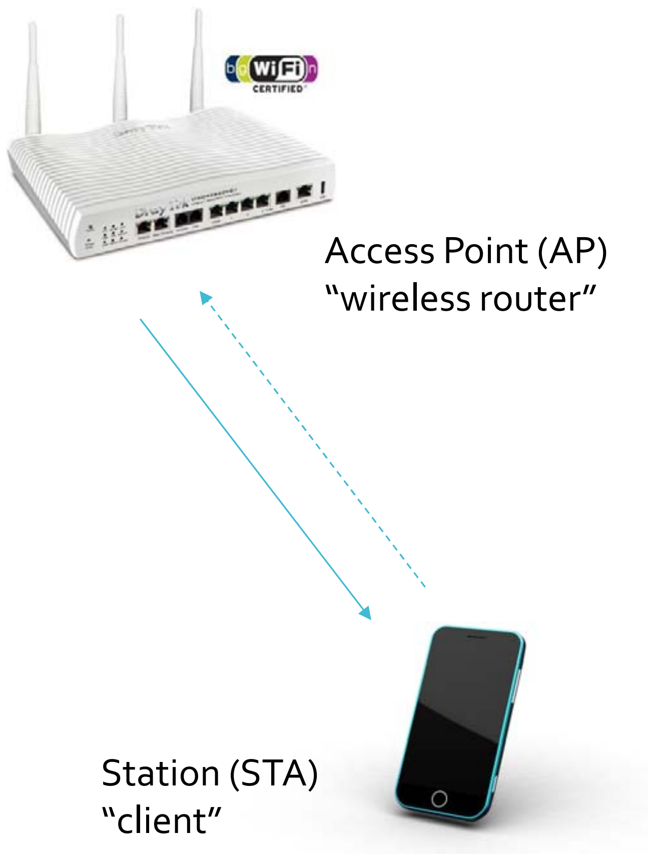
# Outline

- What is Wi-Fi / IEEE 802.11?
  - What radio bands does it use?
  - How is it different from cellular / 3GPP / LTE / 5G?
- Fundamental limits for media access
  - Overhead in channel access
  - Congestion from overlapping service areas
- Fundamental limits for the physical layer
  - Channel capacity
  - Radio channels
- New Ideas in the latest standards

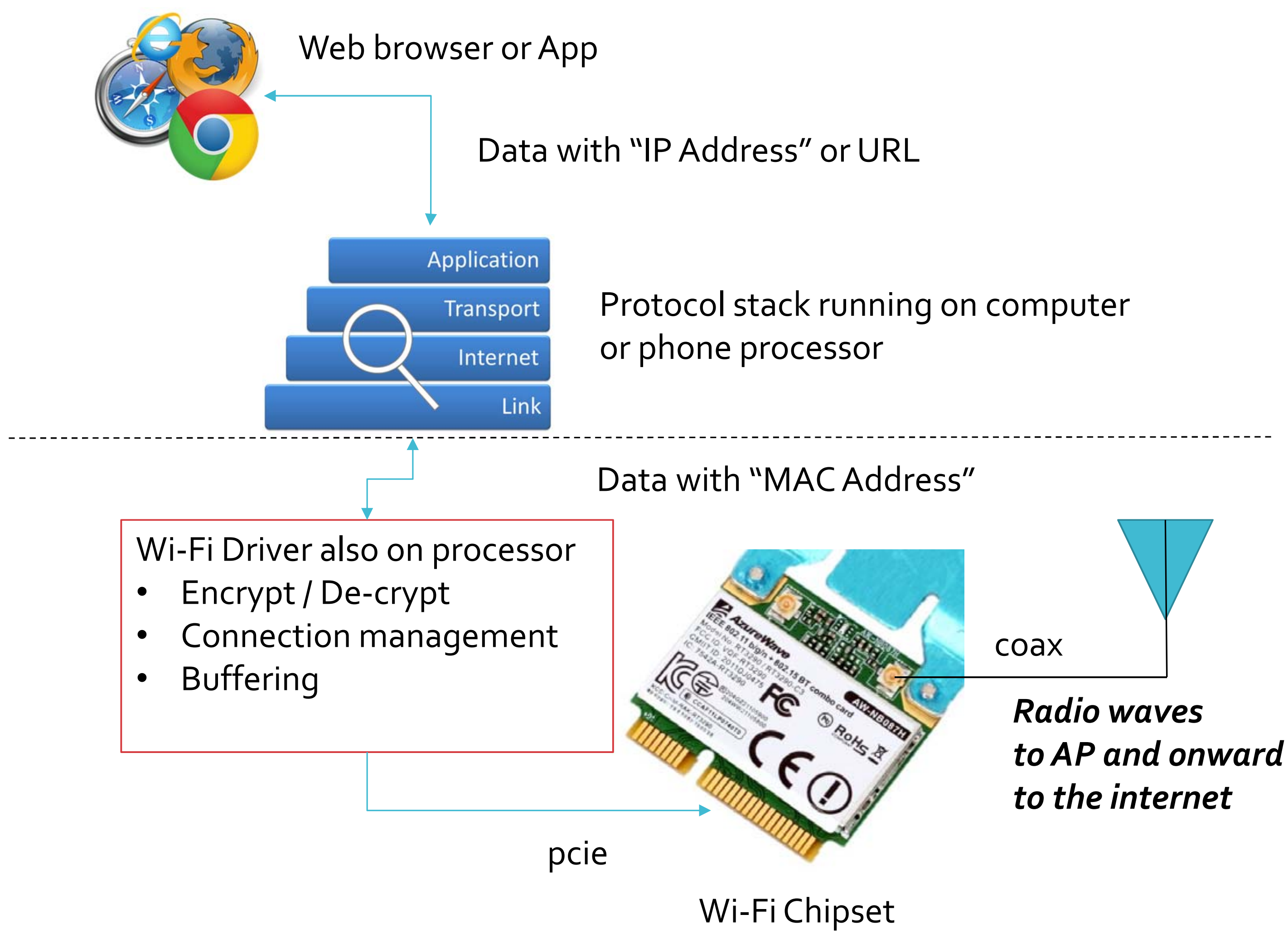
# What is Wi-Fi?




- Wi-Fi is a brand name for devices that have passed a certification test from the Wi-Fi Alliance
- Wi-Fi devices implement the IEEE (Institute of Electrical and Electronics Engineers) 802.11 protocol
  - the letters "a/b/g/n/ac" are amendments
- Wi-Fi devices transmit and receive IP (internet protocol) packets and control traffic

# What is Wi-Fi?

***Inside your phone and PC***

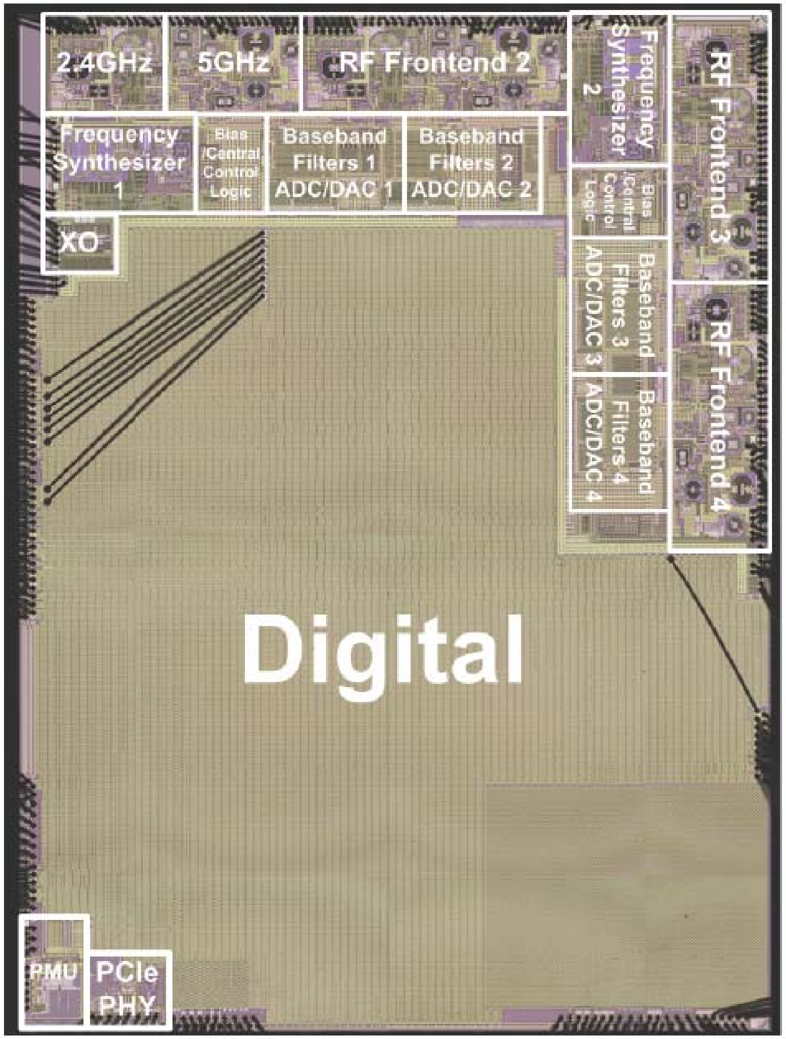


# What is Wi-Fi?

- Wi-Fi is wireless ethernet
  - Media Access Control (MAC) / Physical layer (PHY) for carrying packets over unlicensed radio bands
  - Time division duplexed (i.e. one station transmits at a time)
    - CSMA/CA (Carrier sense multiple access with collision avoidance)
    - Stations listen before transmitting and wait for the channel to be clear
    - Packets are acknowledged by the receiver

- No collision detection
- Stations do not receive while transmitting
- Unacknowledged packets are assumed to be lost and are re-transmitted

# What is Wi-Fi?




- Modern Wi-Fi interfaces can be implemented on a single integrated circuit
- Example Mediatek 4x4 802.11ac chip from ISSCC 2017 “An 802.11ac Dual-Band Reconfigurable Transceiver Supporting up to Four VHT80 Spatial Streams with 116fsrms-Jitter Frequency Synthesizer and Integrated LNA/PA Delivering 256QAM 19dBm per Stream Achieving 1.733Gb/s PHY Rate” by T. Chen et al

# Wi-Fi Radio Bands

- Wi-Fi uses unlicensed spectrum
  - 20, 40, 80 MHz channels are typical
- 2400-2483.5 MHz ISM band
  - Shared with Bluetooth, microwave ovens, etc.
- 5150-5350, 5490-5875 MHz UNII and ISM bands
  - Some sub-bands shared with radar systems
- 57-65 GHz mmwave band (802.11ad)
  - 2.16 GHz channels
- sub 1 GHz 802.11ah

# Wi-Fi versus Cellular

**Wi-Fi**

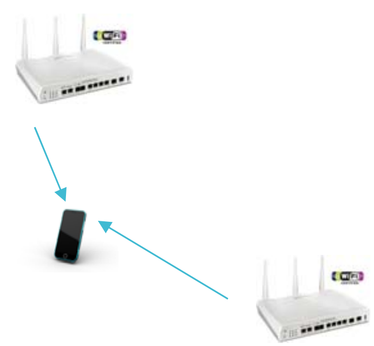
- Unlicensed spectrum
- Primarily indoor
- Balanced costs model (both sides of link have the same design)
- Distributed protocols
    - All stations defer to each other

**Cellular**

- Licensed spectrum
- Originally outdoor
- Asymmetric model – expensive basestation / inexpensive mobile device
- Centralized protocol
    - Base-station controls the medium

# Wi-Fi versus Cellular

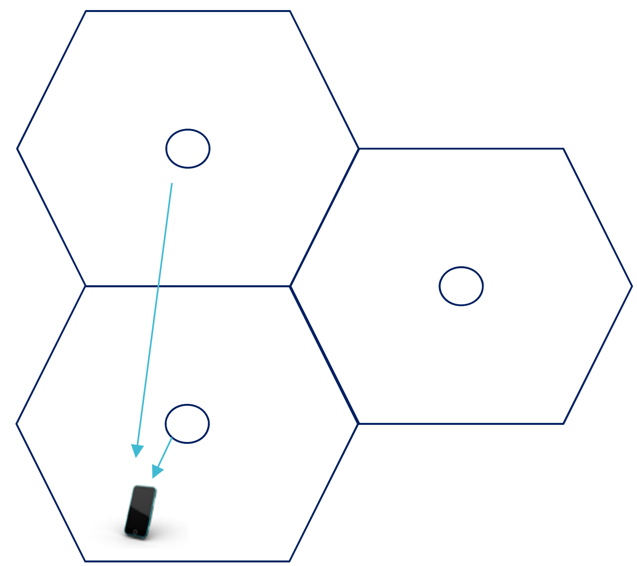
**Wi-Fi**



Uncontrolled interference that is mitigated by protocol design

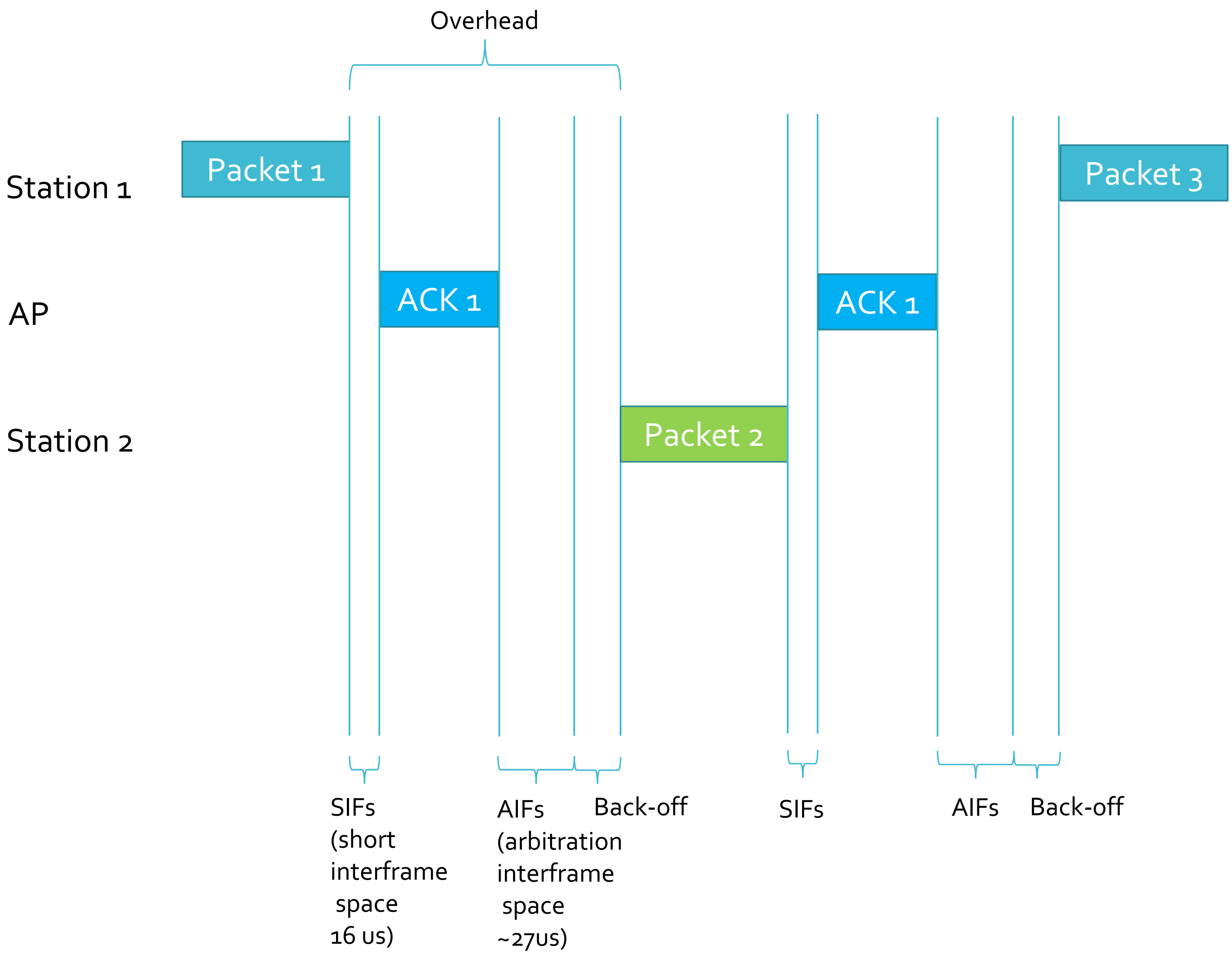
- Networks will naturally share the radio medium

**Cellular**



Controlled interference by operator and system design

# Media Access Distributed Coordination Function (DCF)



# 802.11ac Packet Format

**21.3.2 VHT PPDU format**

A single PPDU format is defined for this PHY: the VHT PPDU format. Figure 21-4 shows the VHT PPDU format.

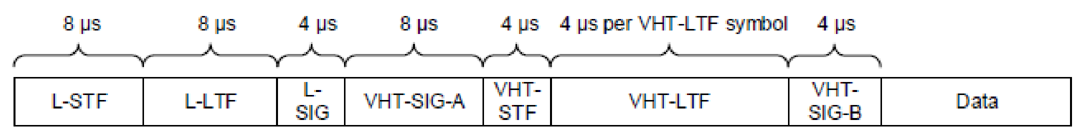



**Figure 21-4—VHT PPDU format**

Legacy header for backward compatibility

Receiver training information

(Overhead)

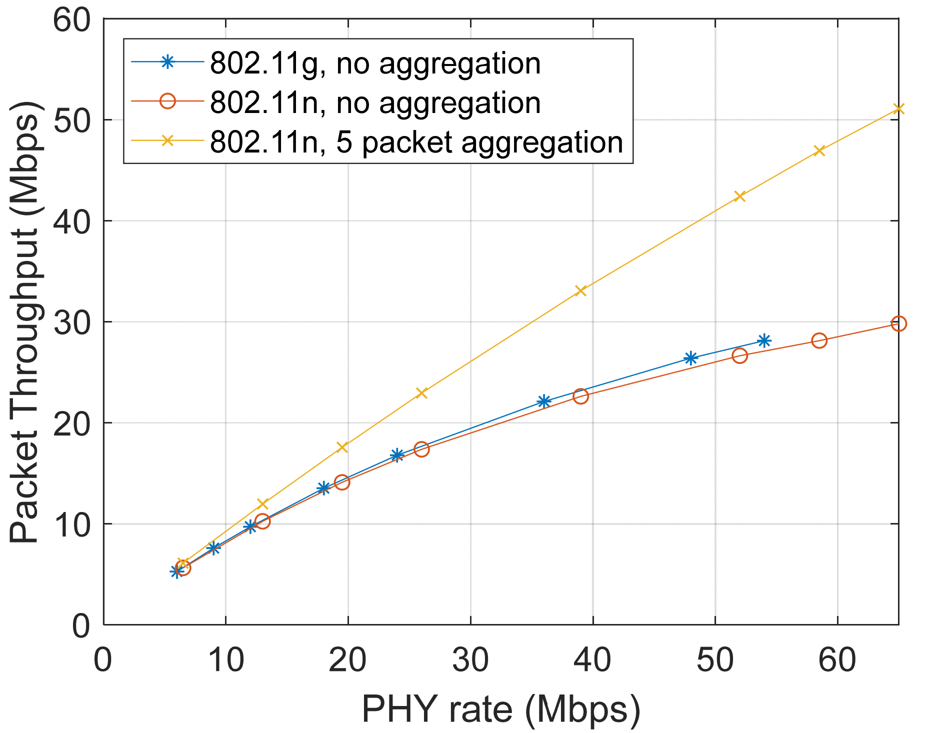
# Throughput

- Throughput is the measure of how fast useful data is carried from source to destination

$$Throughput = \underbrace{\frac{T_{data}}{T_{data} + T_{overhead}}}_{\text{Efficiency}} R_{PHY}$$

- Limited by the maximum PHY rate and by the overhead time
- Minimum average $T_{overhead}$ = 194.5 microseconds
- ***Efficient transmission requires packets longer than 1 millisecond***

# Throughput

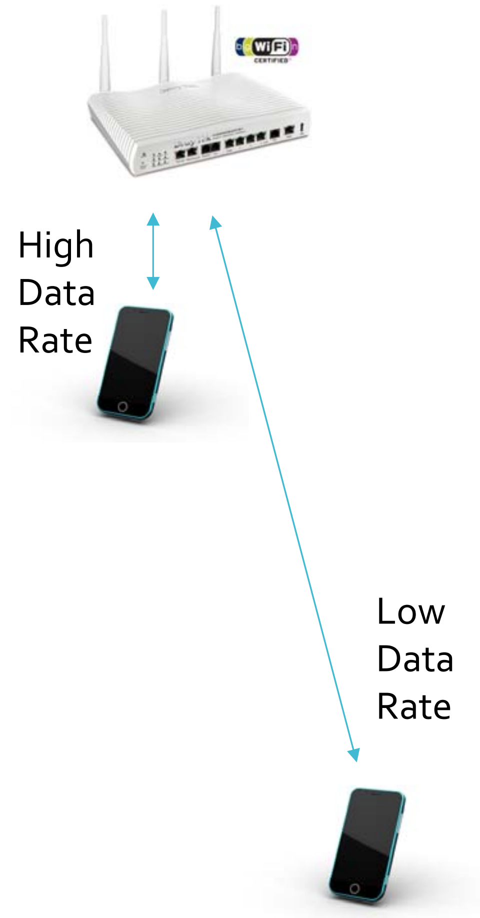



- 802.11n introduced aggregation to put packets together before transmission
- Aggregation increases latency – the time to get data from transmitter to receiver

# Limit #1 – 802.11 DCF Overhead

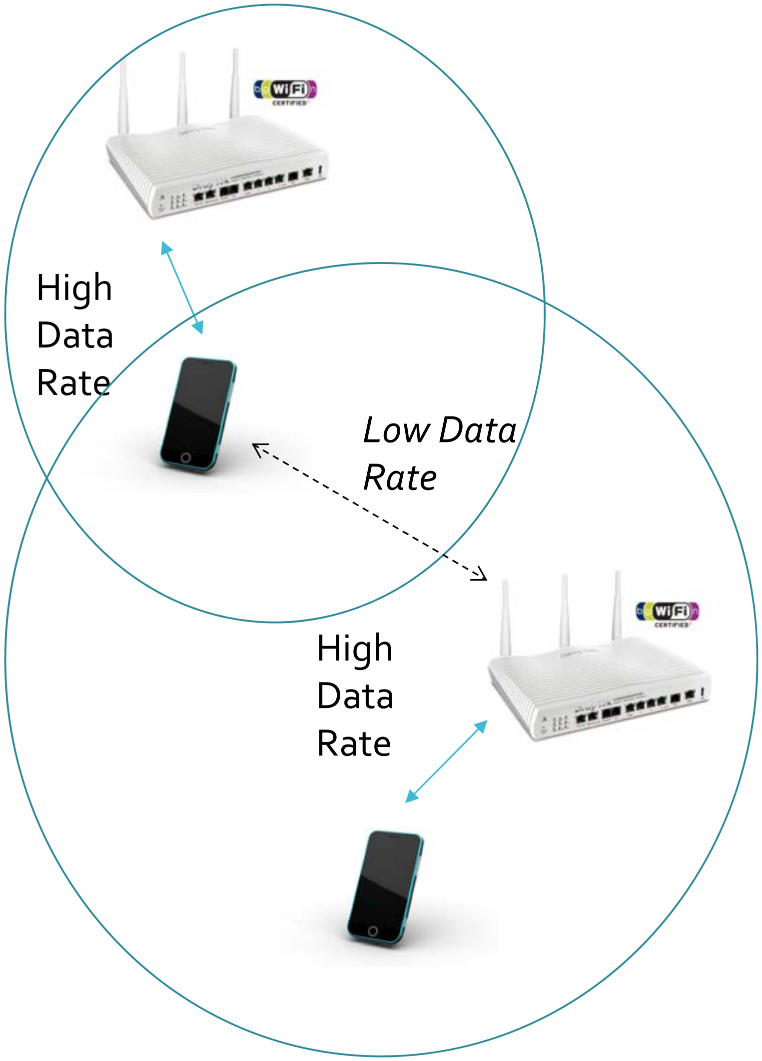
- ***Fairness to legacy devices forces overhead timings to remain fixed***
- ***Higher data rates will increase throughput only for long sequences of aggregated packets***
- ***Only way around this is new spectrum***
  - 60 GHz – WiGig / 802.11ad
  - Shorter overhead times

# Near – Far Problem




- The Near-Far problem affects all wireless systems
- Longer distances reduce signal power at the receiver, which reduces the data rate
- Low data rates are often used for management (broadcast) traffic because the AP does not know how far away the client devices will be
  - 1 Mbps beacons versus 144 Mbps data

# Overlapping BSS (Basic Service Set) Problem




- Overlapping AP coverage on the same channel can be common
- 802.11 DCF protocol has graceful degradation
- Low data rate management traffic wastes bandwidth
- Dense environments become congested

# Limit #2 – Dense Environments

- The dense environment problem is similar to the problem of maintaining conversations at a loud cocktail party
  - 802.11 DCF is akin to letting only one person speak at a time, which works for a small group
- ***802.11ax offers several protocol improvements to help***
  - OBSS Detection – Determine when there is dense overlap
  - BSS Color – Partially overlapping regions can limit their sensitivity to neighboring transmissions
    - Similar to forming sub-groups and tuning out the group next to you
- ***802.11ax won't help much until people upgrade their phones (!)***

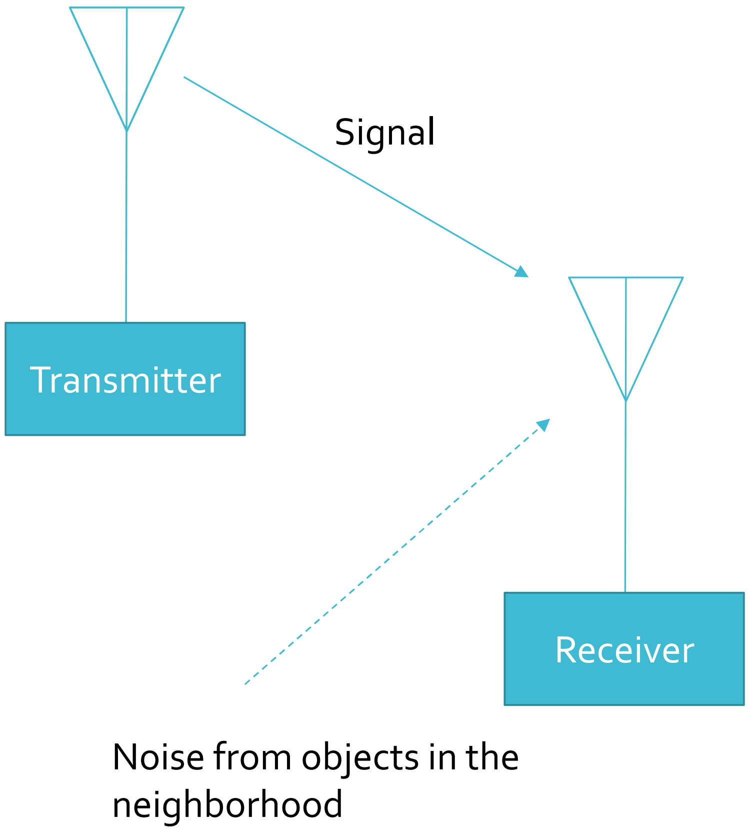
# Fundamental Limits for the Physical Layer

- ***Channel Capacity (bits per second) – The "speed of light" for communications***

$$C = W log_2(1 + \frac{S}{N})$$

- W is bandwidth in Hz
- S is signal power – set by the amount of radio signal picked up by the receive antenna
- N is the noise power – set by the noise from environment and receiver electronics

# Channel Capacity




- Signal power from transmitter (Friis Equation)

$$S = \frac{P_t G_t G_r \lambda^2}{(4\pi R)^2}$$

- Noise power from everywhere (thermal)

$$N = kTB$$

- ***Approaching capacity means increasing data rate at a given range***
- ***To approach capacity we need to know S and N to select the proper signaling***

# 802.11 PHY Header

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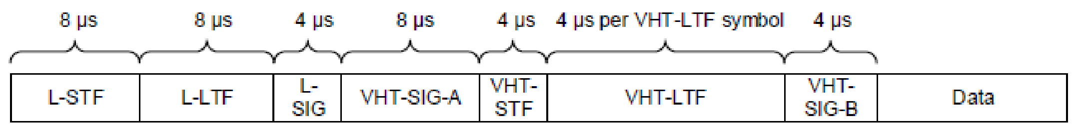


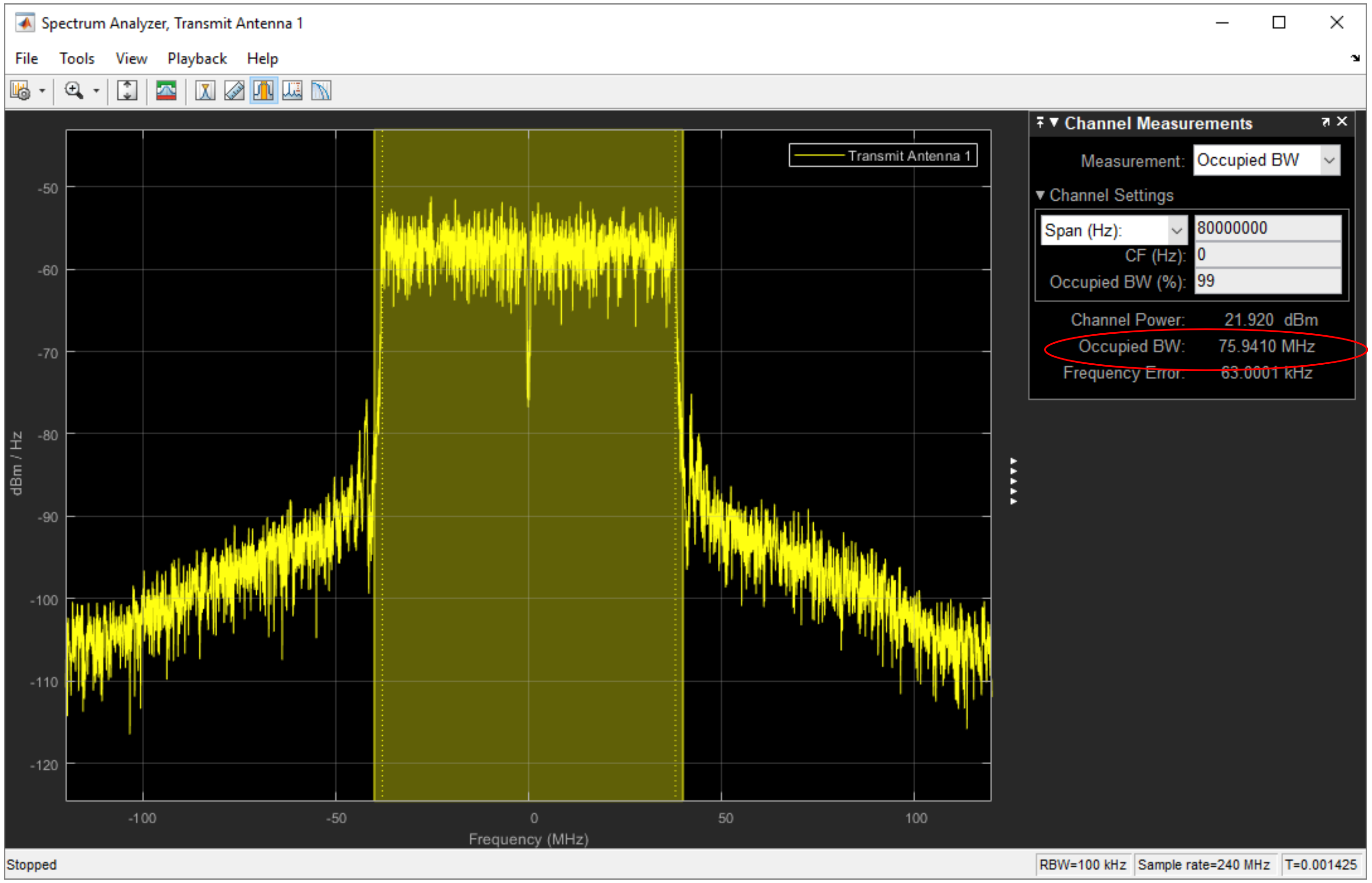

**Figure 21-4—VHT PPDU format**

- To approach channel capacity, the receiver needs to know the radio channel
  - Frequency response, signal level, and noise level
- Transmitter need to tell the receiver how the data will be modulated
- All information appears at the start of a Wi-Fi packet

# 802.11 Modulation

- IEEE 802.11a/g/n/ac/ax employ Orthogonal Frequency Division Multiplexing (OFDM)
  - Data is encoded with either a binary convolution code (BCC) or a low density parity check (LDPC) code
  - Coded data is interleaved into bins
  - Binned data is modulated with BPSK, QPSK, or QAM
  - An FFT (Fast Fourier Transform) is applied to the bins to generated a time domain waveform
  - A cyclic prefix is applied to mitigate against inter-symbol interference
  - The entire signal is modulated onto a microwave carrier, filtered, and amplified

# Example 802.11ac 80 MHz Signal



# Actual Device Sensitivity (Lowest operating signal level)

802.11a
-93 dBm @ 6 Mb/s
-75 dBm @ 54 Mb/s

802.11n (HT20)
-92 dBm @ MCS0
-71 dBm @ MCS7
-89 dBm @ MCS8
-70 dBm @ MCS15
-87 dBm @ MCS16
-70 dBm @ MCS23

802.11n (HT40)
-89 dBm @ MCS0
-69 dBm @ MCS7
-85 dBm @ MCS8
-66 dBm @ MCS15
-88 dBm @ MCS16
-65 dBm @ MCS23

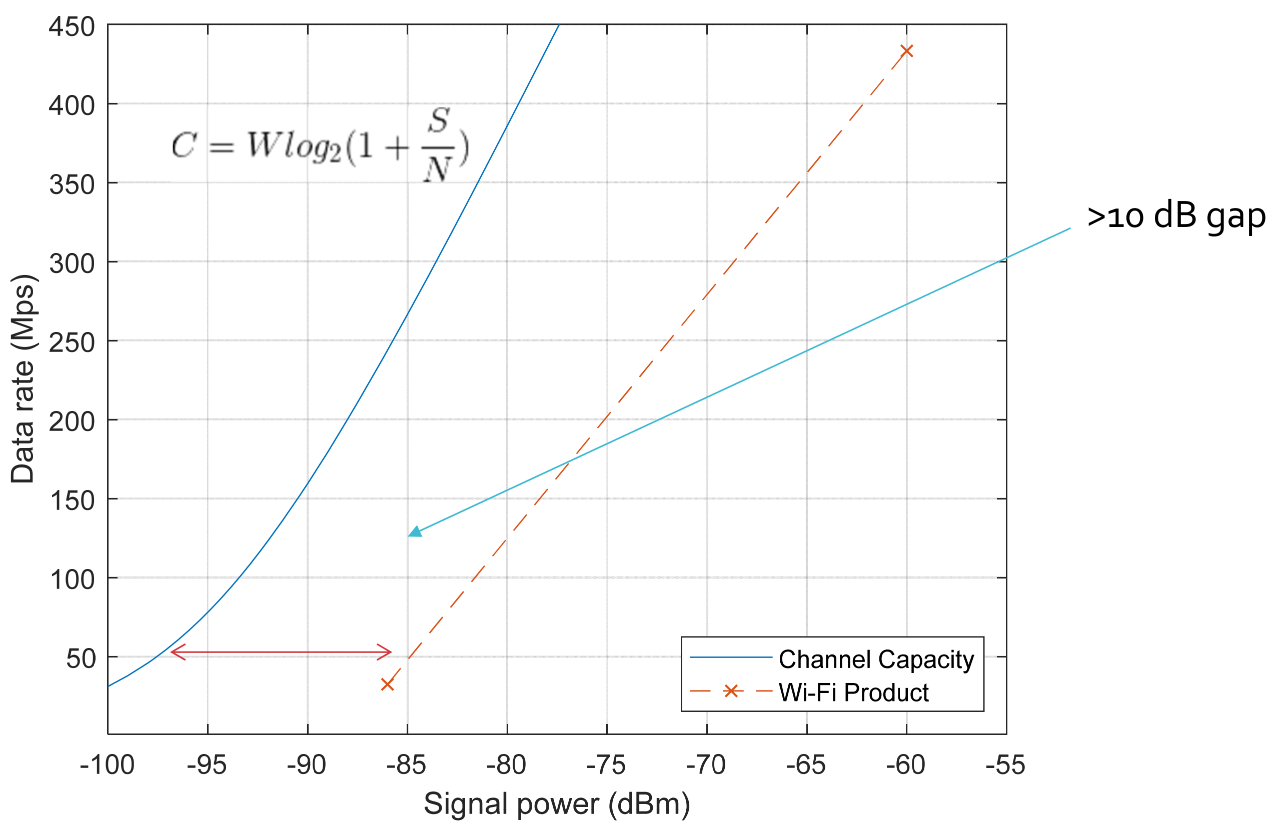
802.11ac (VHT20)
-91 dBm @ Nss=1, MCS0
-67 dBm @ Nss=1, MCS8
-88 dBm @ Nss=2, MCS0
-64 dBm @ Nss=2, MCS8
-87 dBm @ Nss=3, MCS0
-63 dBm @ Nss=3, MCS8

802.11ac (VHT40)
-89 dBm @ Nss=1, MCS0
-63 dBm @ Nss=1, MCS9
-85 dBm @ Nss=2, MCS0
-59 dBm @ Nss=2, MCS9
-84 dBm @ Nss=3, MCS0
-58 dBm @ Nss=3, MCS9

802.11ac (VHT80)
-86 dBm @ Nss=1, MCS0
-60 dBm @ Nss=1, MCS9
-82 dBm @ Nss=2, MCS0
-56 dBm @ Nss=2, MCS9
-80 dBm @ Nss=3, MCS0
-55 dBm @ Nss=3, MCS9

- Claimed receiver sensitivity data from a Cisco product
- https://www.cisco.com/c/en/us/products/collateral/interfaces-modules/aironet-access-point-module-802-11ac/data_sheet_c78-727794.html
- Can compare with noise floor of -174 dBm/Hz

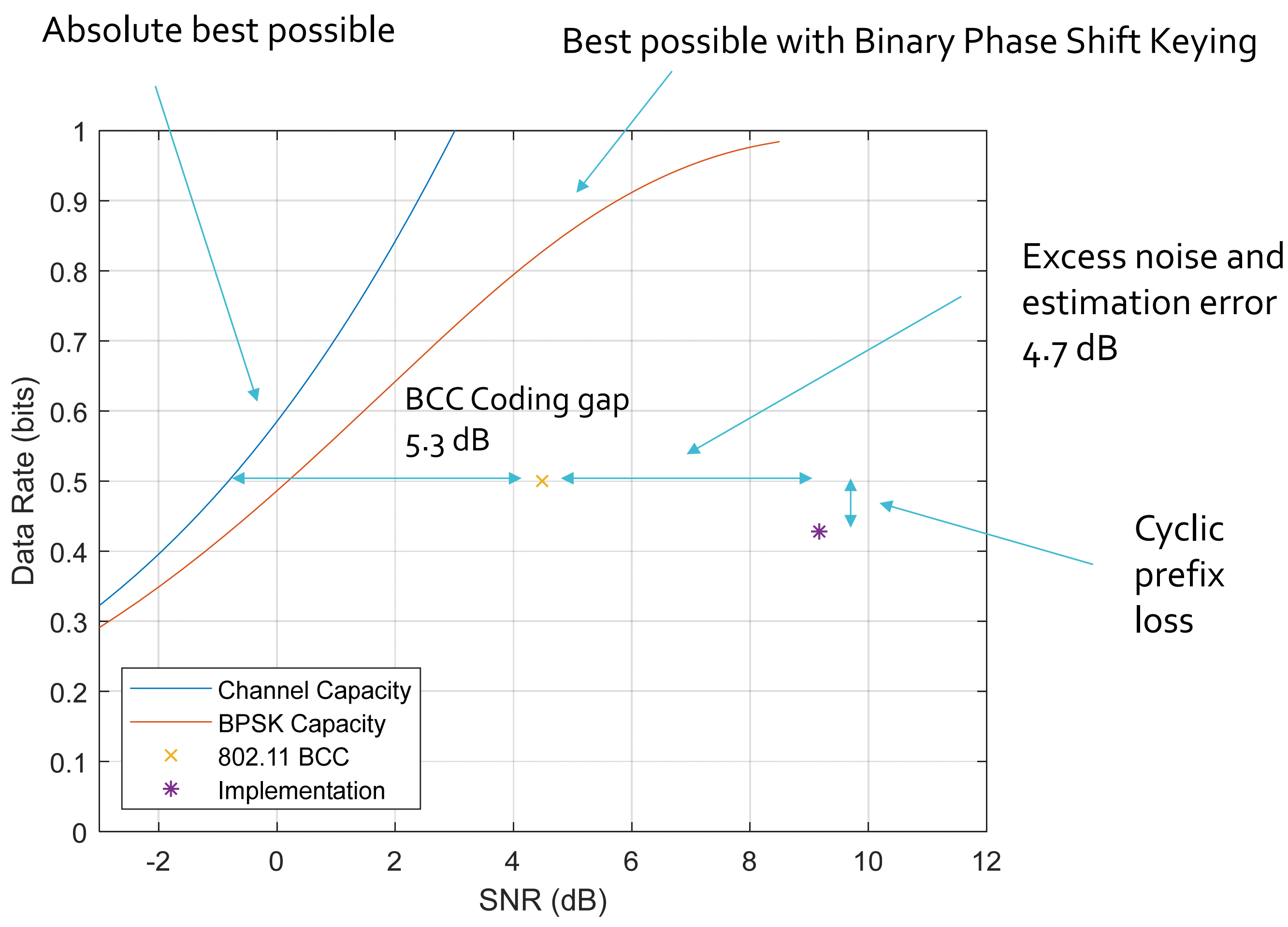
# Channel Capacity versus Data Sheet



# Gap Budget

- Practical system noise figure
  - Loss from antenna to LNA (low noise amplifier)
  - LNA noise figure
- Local oscillator stability (phase noise)
- System design
  - Modulation and Coding
  - Rate reduction to allow compensation for radio channels
  - Residual estimation error from channel preamble
- End-to-end linearity (high SNR regime)
  - Transmit power amplifier
  - DAC / ADC bits

# Gap Details


Absolute best possible
Best possible with Binary Phase Shift Keying
Excess noise and estimation error 4.7 dB
BCC Coding gap 5.3 dB
Cyclic prefix loss
Data Rate (bits)
SNR (dB)
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
-2
0
2
4
6
8
10
12
Channel Capacity
BPSK Capacity
802.11 BCC
Implementation

# Coding (Forward Error Correction)

- Shannon Capacity is a bound assuming infinite delay Gaussian signaling
  - 1 dB loss for binary signaling
  - 4.3 dB loss with mandatory convolutional code
- Long codes require greater computations per bit at the receiver and longer latency to process
- 802.11 has a response time (SIFS) for packets of 16 microseconds which limits the use of long codes

# Channel Estimation Error

- There are two main sources of error
  - Initial Estimation Error
    - Radio channel characteristics are determined at the start of a packet from the known sequences
    - Shorter sequences waste less time but lead to more estimation error
  - Channel changes over the course of the packet
    - Movement of transmitter or receiver
    - Some tracking might be possible
    - Longer packets at highest data rates (i.e. the high throughput ones) are impacted the most

# Overcoming Gaps to Capacity

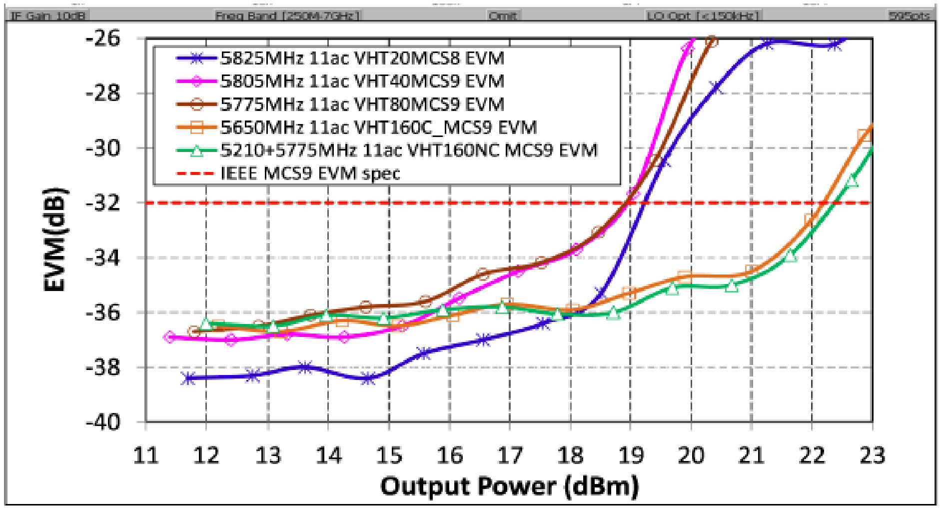
- Reducing any particular gap involves
  - Making packets longer – latency problem
  - Increased cost
  - Increased power consumption
  - Developing a method for backward compatibility
  - Industry inertia

- Industry goals
  - Speed
  - Cost
  - Robustness
  - Operation in dense environments

# High SNR

- Large constellations (up to 256 QAM for 802.11ac / 1024 QAM for 802.11ax)
- Limited by circuit linearity instead of Gaussian noise
- Higher code rates but coding performance goes down

# Transmitter Linearity Limits High SNR



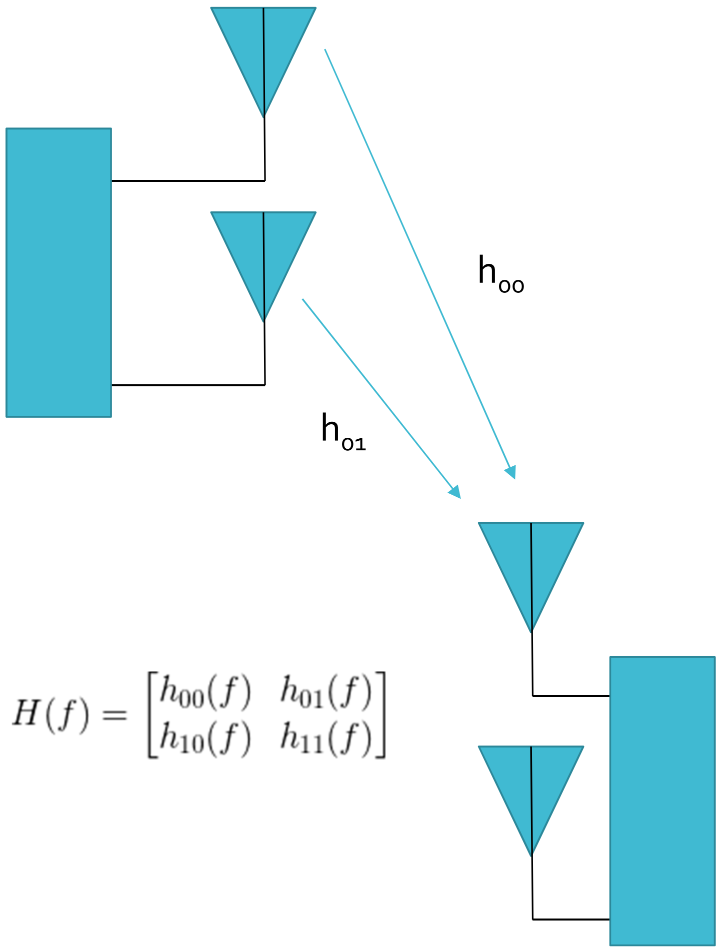

Example Mediatek 4x4 802.11ac chip from ISSCC 2017 "An 802.11ac Dual-Band Reconfigurable Transceiver Supporting up to Four VHT80 Spatial Streams with 116fsrms-Jitter Frequency Synthesizer and Integrated LNA/PA Delivering 256QAM 19dBm per Stream Achieving 1.733Gb/s PHY Rate" by T. Chen et al

- Error Vector Magnitude (EVM) is a measure of non-linear distortion in the Wi-Fi transmitter.
- Distortion looks like noise to the receiver.
- Limits the maximum constellation size (bits per symbol) and resulting PHY data rate.

# Limit #3 Channel Capacity and Circuit Linearity

- At lower SNR, the physical layer can approach capacity to within a few dB
- At higher SNR, the gap to capacity widens because of poorer code performance and practical limitations in electronic circuit linearity (dynamic range)

# Multiple Input Multiple Output (MIMO)




$$H(f) = \begin{bmatrix} h_{00}(f) & h_{01}(f) \\ h_{10}(f) & h_{11}(f) \end{bmatrix}$$

- Wi-Fi added MIMO capabilities in 802.11n and expanded them in 802.11ac and 802.11ax
- Employ multiple antennas and signal processing techniques to generate distinct signal paths over pairs of antennas
- Signal processing can be applied at both the transmitter (beamforming) and at the receiver

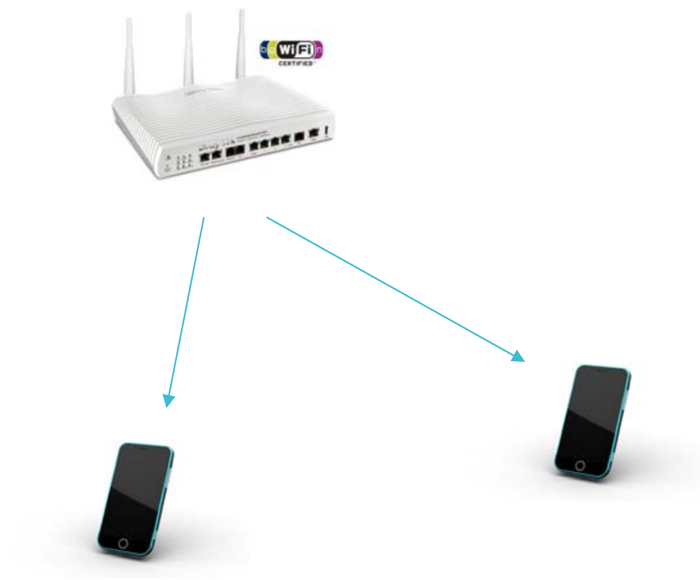
# The Magic of Reflections

$$H = \sum_{k=1}^{N} H_k$$

$$max\ rank(H) \leq N$$

- Each path corresponds with a rank 1 channel matrix $H_k$
- Reflections from walls, floors, and objects in the neighborhood create new paths
  - Spatial multiplexing
- For MIMO to work, it is necessary to have both extra antennas (and transceivers) and reflections from the radio environment
- In practice, cell phones can only usually support 2 Wi-Fi antennas. Notebook PCs can support 3 or 4.

# Single User Versus Multiuser MIMO



802.11n introduced single user MIMO

- 2 – 4 times PHY data rate

802.11ac introduced MU-MIMO

- AP simultaneously transmit to more than one STA

802.11ax introduces uplink MIMO

Extremely High Throughput TIG is looking at expanding MU-MIMO further

# Limit #4 MIMO and Physical Channels

- SU-MIMO increases capacity by spatial multiplexing (2 – 4)
- MU-MIMO increases capacity when multiple receivers are spatially separated

# New Ideas

- mmWave systems (60 GHz) offer great promise to achieve higher data rates with low latency
- Wake Up Radio (802.11ba) will allow devices to snooze with lower power consumption
- Full duplex wireless would allow multiple devices to transmit simultaneously
- Improved methods for handling broadcast / multicast traffic

# Summary

- At lower SNR, Wi-Fi can operate within about 10 dB of the Shannon limit.
- At higher SNR, the gap increases because of limits in device linearity and the ability to estimate time varying radio channels
- MIMO techniques are often used to increase physical layer data rates by a factor of 2 to 4.
- Wi-Fi media access protocols limit channel throughput and increase latency, however they also allow graceful degradation in congested channels.
- Channel sharing improvements will come with 802.11ax, but will require legacy devices to be retired.
- mmWave systems (802.11ad/802.11ay) can achieve the best combination of high data rate and low latency

# Some Numbers for 802.11ac

Table 21-47—VHT-MCSs for optional 80 MHz, $N_{SS}$ = 2

| VHT-MCS Index | Modulation | $R$ | $N_{BPSCS}$ | $N_{SD}$ | $N_{SP}$ | $N_{CBPS}$ | $N_{DBPS}$ | $N_{ES}$ | Data rate (Mb/s) | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | 800 ns GI | 400 ns GI |
| 0 | BPSK | 1/2 | 1 | 234 | 8 | 468 | 234 | 1 | 58.5 | 65.0 |
| 1 | QPSK | 1/2 | 2 | 234 | 8 | 936 | 468 | 1 | 117.0 | 130.0 |
| 2 | QPSK | 3/4 | 2 | 234 | 8 | 936 | 702 | 1 | 175.5 | 195.0 |
| 3 | 16-QAM | 1/2 | 4 | 234 | 8 | 1872 | 936 | 1 | 234.0 | 260.0 |
| 4 | 16-QAM | 3/4 | 4 | 234 | 8 | 1872 | 1404 | 1 | 351.0 | 390.0 |
| 5 | 64-QAM | 2/3 | 6 | 234 | 8 | 2808 | 1872 | 1 | 468.0 | 520.0 |
| 6 | 64-QAM | 3/4 | 6 | 234 | 8 | 2808 | 2106 | 1 | 526.5 | 585.0 |
| 7 | 64-QAM | 5/6 | 6 | 234 | 8 | 2808 | 2340 | 2 | 585.0 | 650.0 |
| 8 | 256-QAM | 3/4 | 8 | 234 | 8 | 3744 | 2808 | 2 | 702.0 | 780.0 |
| 9 | 256-QAM | 5/6 | 8 | 234 | 8 | 3744 | 3120 | 2 | 780.0 | 866.7 |

# Some Numbers for 802.11ad

Table 20-15—DMG SC mode modulation and coding schemes

| MCS | Base MCS field | Extended SC MCS Indication field | Modulation | $N_{CBPS}$ | Repetition | Code rate | Data rate (Mb/s) |
|---|---|---|---|---|---|---|---|
| 1 | 1 | 0 | $\pi$/2-BPSK | 1 | 2 | 1/2 | 385 |
| 2 | 2 | 0 | $\pi$/2-BPSK | 1 | 1 | 1/2 | 770 |
| 3 | 3 | 0 | $\pi$/2-BPSK | 1 | 1 | 5/8 | 962.5 |
| 4 | 4 | 0 | $\pi$/2-BPSK | 1 | 1 | 3/4 | 1155 |
| 5 | 5 | 0 | $\pi$/2-BPSK | 1 | 1 | 13/16 | 1251.25 |
| 6 | 6 | 0 | $\pi$/2-QPSK | 2 | 1 | 1/2 | 1540 |
| 7 | 7 | 0 | $\pi$/2-QPSK | 2 | 1 | 5/8 | 1925 |
| 8 | 8 | 0 | $\pi$/2-QPSK | 2 | 1 | 3/4 | 2310 |
| 9 | 9 | 0 | $\pi$/2-QPSK | 2 | 1 | 13/16 | 2502.5 |
| 9.1 | 6 | 1 | $\pi$/2-QPSK | 2 | 1 | 7/8 | 2695 |
| 10 | 10 | 0 | $\pi$/2-16-QAM | 4 | 1 | 1/2 | 3080 |
| 11 | 11 | 0 | $\pi$/2-16-QAM | 4 | 1 | 5/8 | 3850 |
| 12 | 12 | 0 | $\pi$/2-16-QAM | 4 | 1 | 3/4 | 4620 |
| 12.1 | 7 | 1 | $\pi$/2-16-QAM | 4 | 1 | 13/16 | 5005 |
| 12.2 | 8 | 1 | $\pi$/2-16-QAM | 4 | 1 | 7/8 | 5390 |
| 12.3 | 9 | 1 | $\pi$/2-64-QAM | 6 | 1 | 5/8 | 5775 |
| 12.4 | 10 | 1 | $\pi$/2-64-QAM | 6 | 1 | 3/4 | 6390 |
| 12.5 | 11 | 1 | $\pi$/2-64-QAM | 6 | 1 | 13/16 | 7507.5 |
| 12.6 | 12 | 1 | $\pi$/2-64-QAM | 6 | 1 | 7/8 | 8085 |

# References


1. IEEE Std 802.11-2016 - Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications
2. *Elements of Information Theory*, T. Cover and J. Thomas
3. *Error Control Coding*, S. Lin and D. Costello
4. *Data Networks, 2nd Edition, D. Bertsekas and R. Gallager*
5. *Fundamentals of Wireless Communication, D. Tse and P. Viswanath*
6. *Next Generation Wireless LANs, 2nd Edition, E. Perahia and R. Stacey*