IEEE 802.11 WLANS

- WiFi Evolutions -

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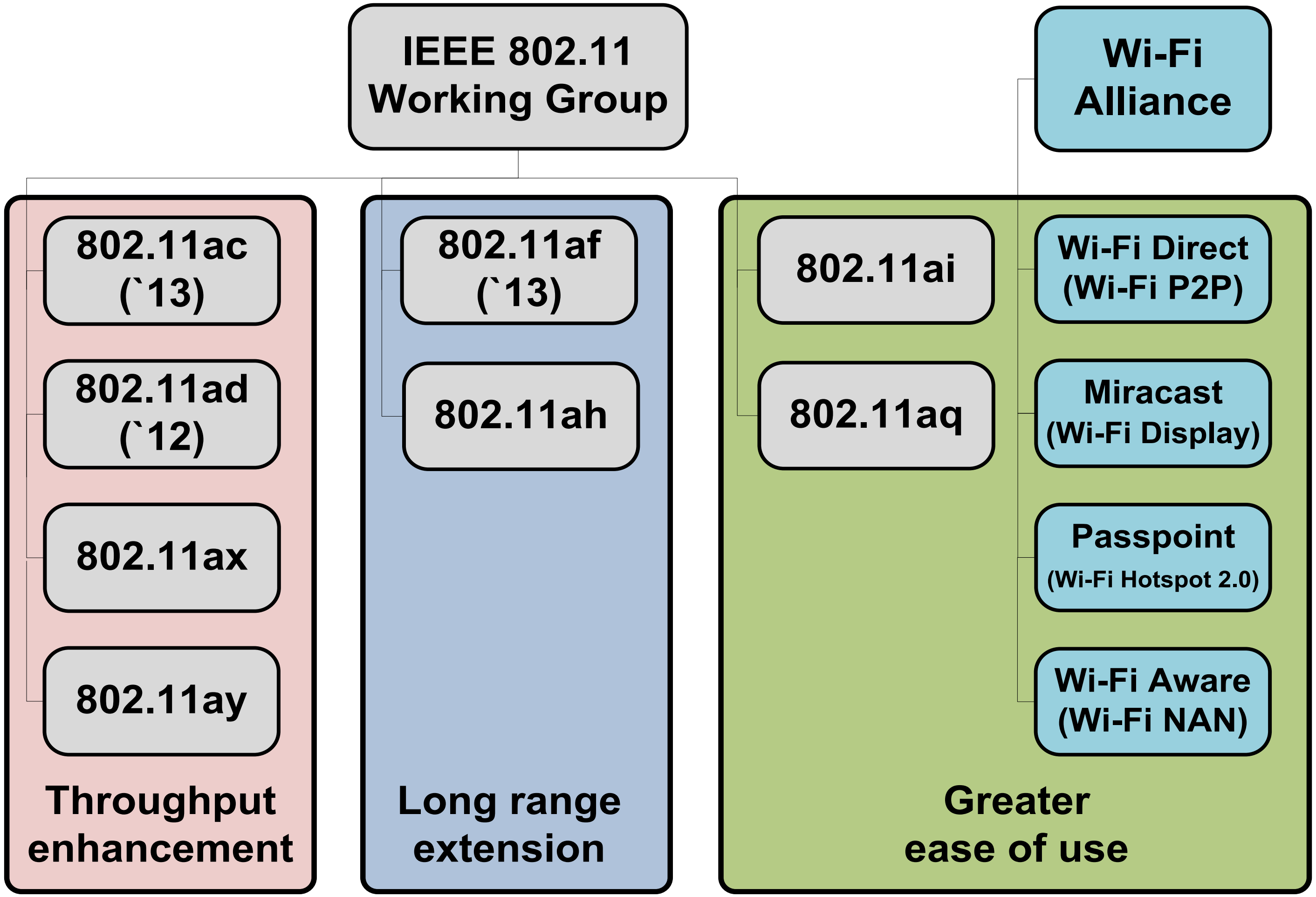
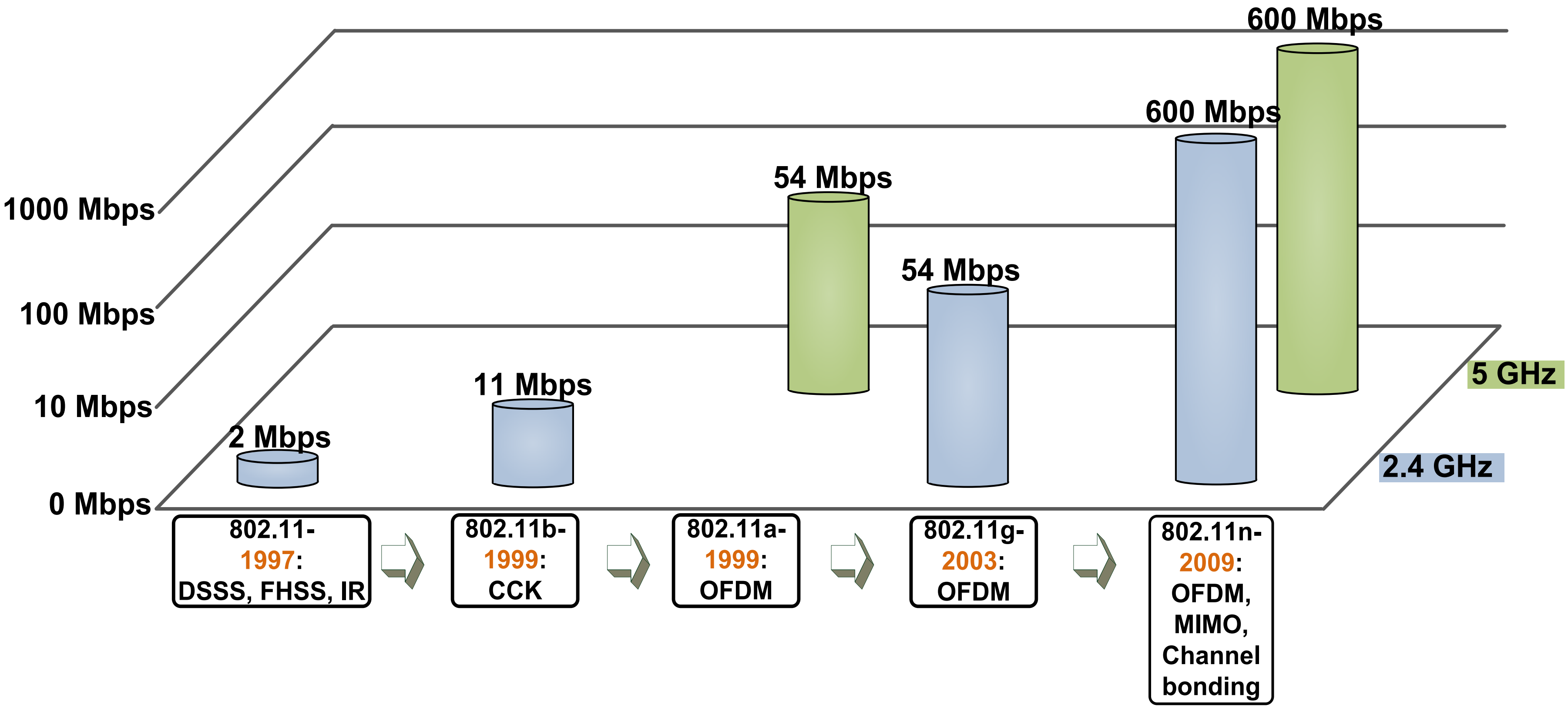
Adapted from Prof. Sunghyun Choi's slides

Wi-Fi Evolution for Performance and Functionality



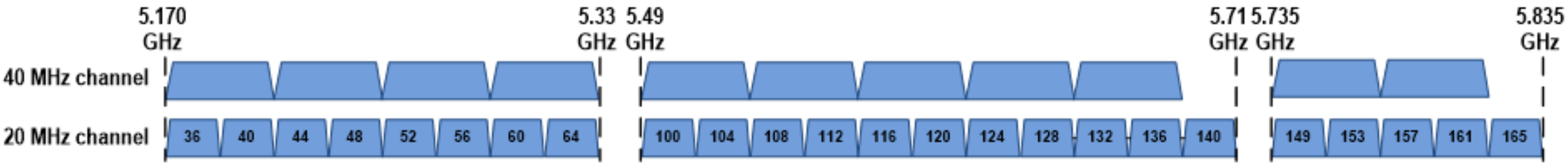
Wi-Fi Evolution – Throughput Extension

- IEEE 802.11 a/b/g/n PHY
  - Peak data rate kept increasing



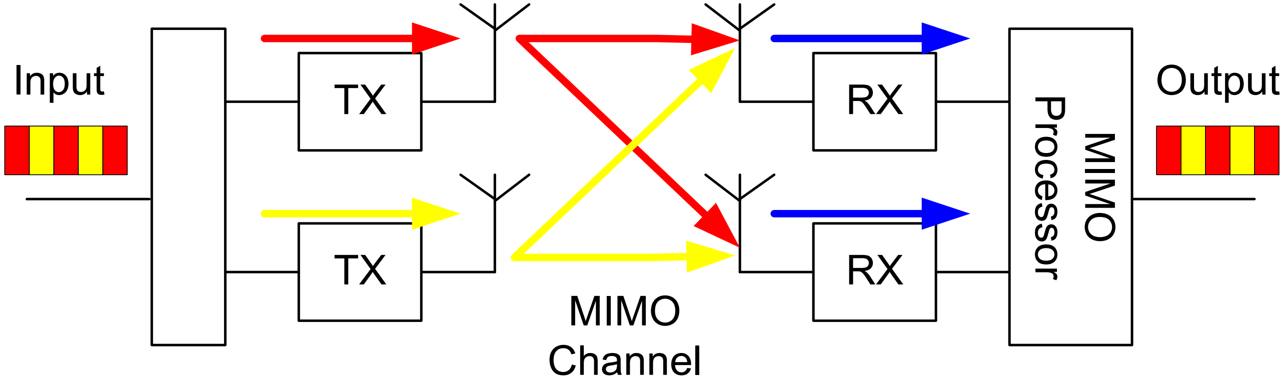
802.11n High Throughput (HT) PHY

- Both 2.4 GHz and 5 GHz operations
- OFDM enhancement
  - Uses 52 data sub-carriers instead of 48 (of 802.11a)
  - Support short CP (0.4 usec) along with long CP (0.8 usec)
- Channel bonding
  - Using 40 MHz instead of 20 MHz (of 802.11a)
  - 108 data sub-carriers with 40 MHz bandwidth

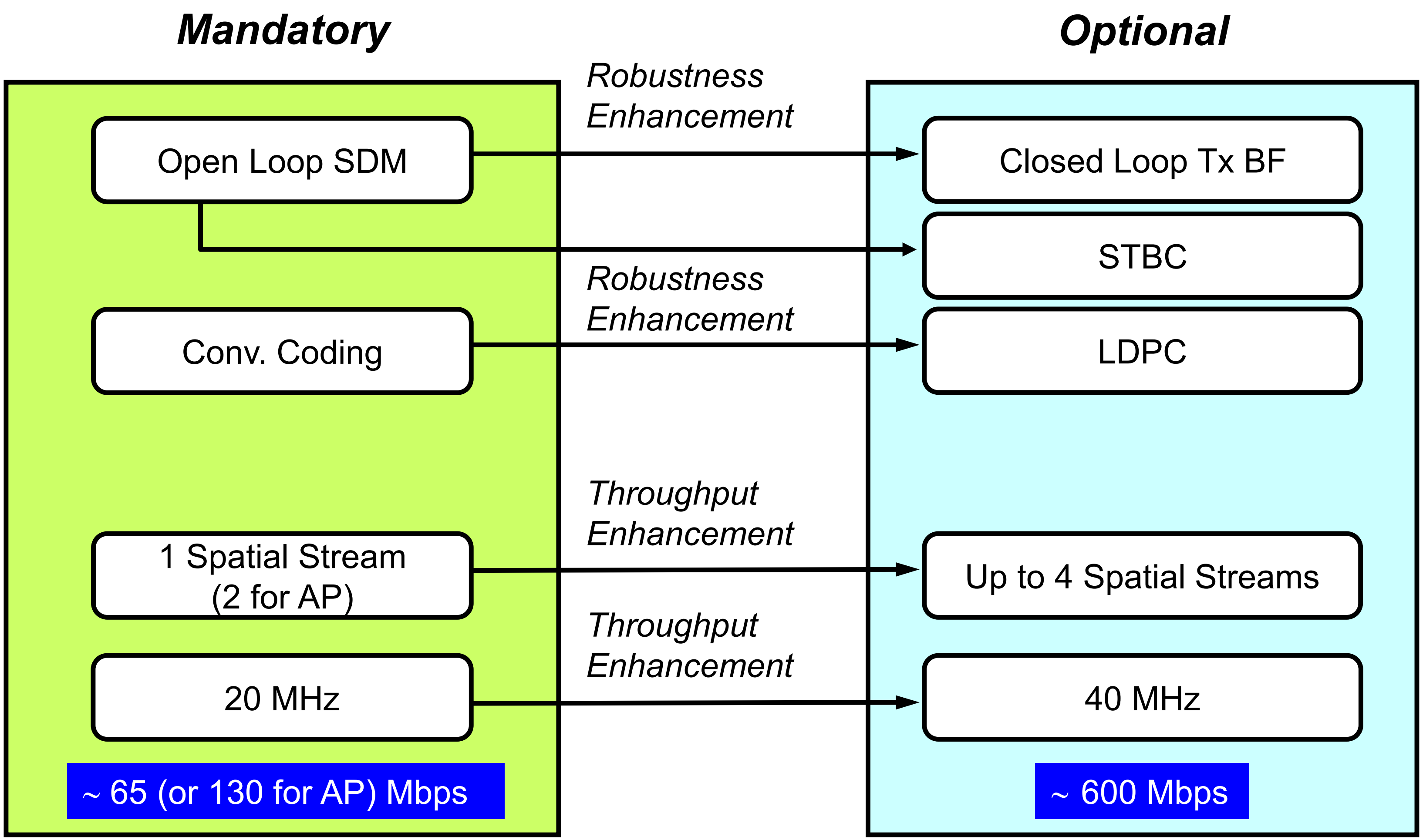


802.11n High Throughput (HT) PHY

- Multi-Input Multi-Output (MIMO)
  - Spatial channels of different antenna pairs are often uncorrelated
  - Data rate (via SDM) or reliability (via STBC) can be improved
    - SDM: spatial division multiplexing
    - STBC: space-time block code



802.11n PHY Architecture



802.11n Data Rates

Modulation	R	Data Rate (Mbps)											
		SS=1				SS=2				SS=4			
		20 MHz		40 MHz		20 MHz		40 MHz		20 MHz		40 MHz	
		800 ns	400 ns	800 ns	400 ns	800 ns	400 ns	800 ns	400 ns	800 ns	400 ns	800 ns	400 ns
BPSK	1/2	**6.5**	7.2	13.5	15.0	**13.0**	14.4	27.0	30.0	26.0	28.9	54.0	60.0
QPSK	1/2	**13.0**	14.4	27.0	30.0	**26.0**	28.9	54.0	60.0	52.0	57.8	108.0	120.0
QPSK	3/4	**19.5**	21.7	40.5	45.0	**39.0**	43.3	81.0	90.0	78.0	86.7	162.0	180.0
16-QAM	1/2	**26.0**	28.9	54.0	60.0	**52.0**	57.8	108.0	120.0	104.0	115.6	216.0	240.0
16-QAM	3/4	**39.0**	43.3	81.0	90.0	**78.0**	86.7	162.0	180.0	156.0	173.3	324.0	360.0
64-QAM	2/3	**52.0**	57.8	108.0	120.0	**104.0**	115.6	216.0	240.0	208.0	231.1	432.0	480.0
64-QAM	3/4	**58.5**	65.0	121.5	135.0	**117.0**	130.0	243.0	270.0	234.0	260.0	486.0	540.0
64-QAM	5/6	**65.0**	72.2	135.0	150.0	**130.0**	144.4	270.0	300.0	260.0	288.9	540.0	600.0

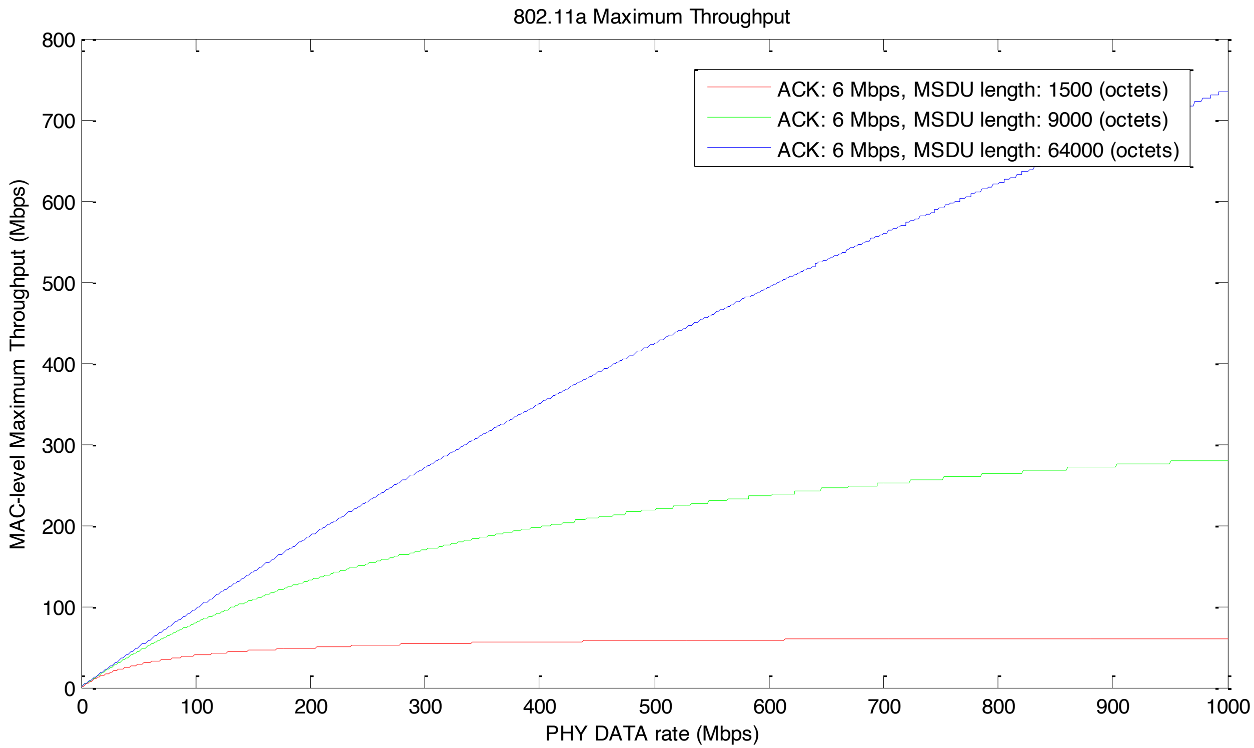
* SS=Spatial Stream <= min(# Tx Antennas, # Rx Antennas)

How to Determine Data Rate

- $Nsym = M \times R \times N_{SC} \times N_{SS}$
  - Nsym = # bits / OFDM symbol
  - M = # bits / mod. symbol = 1, 2, 4 or 6
    (for BPSK, QPSK, 16-QAM, or 64-QAM)
  - R = code rate = 1/2, 2/3, 3/4, or 5/6
  - N_{SC} = # subcarriers = 52 or 108
    (for 20 MHz or 40 MHz)
  - N_{SS} = # spatial streams = 1, 2, 3, or 4
- Rate = Nsym / TOFDM
  - TOFDM = OFDM symbol duration
    = 4 or 3.6 μsec (for normal or short cyclic prefix)
- Example for 600 Mbps
  - $(6 \times 5/6 \times 108 \times 4) / 3.6 = 600$ Mbps
    (for 64-QAM, 5/6 rate, 40 MHz, 4x4 MIMO, short CP)

Protocol Overhead Impact

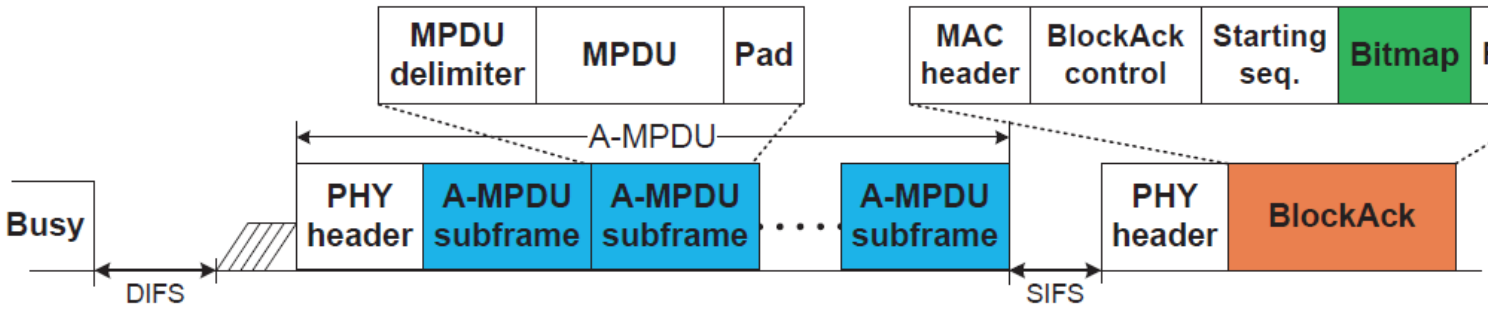
- Throughput is severely limited even with extremely high PHY data rate if frame length is not long enough!



Maximum throughput with hypothetical frame lengths and PHY rates

802.11n MAC A-MPDU

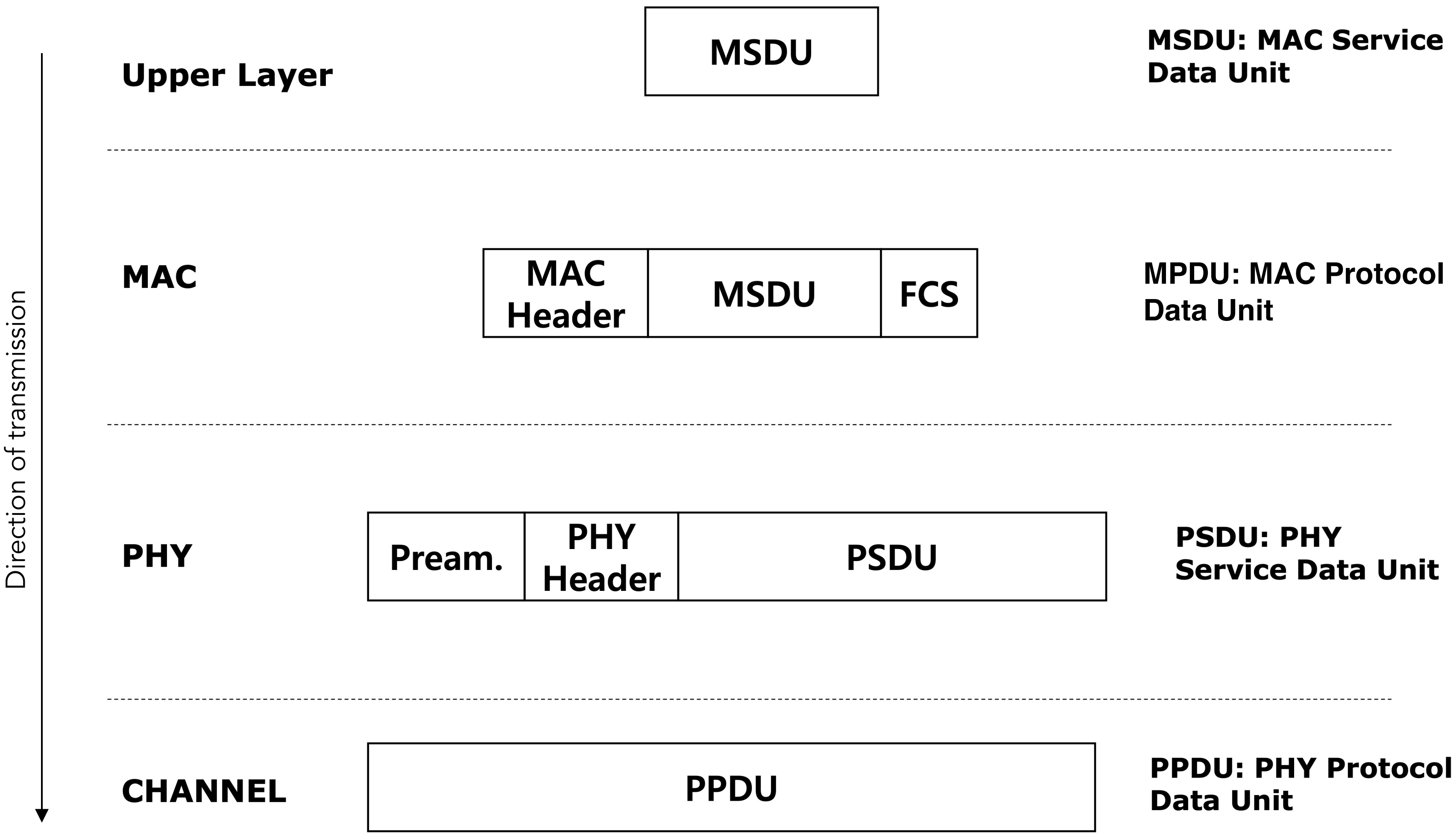
- Aggregate MAC protocol data unit (A-MPDU)
  - Core technology of IEEE 802.11n



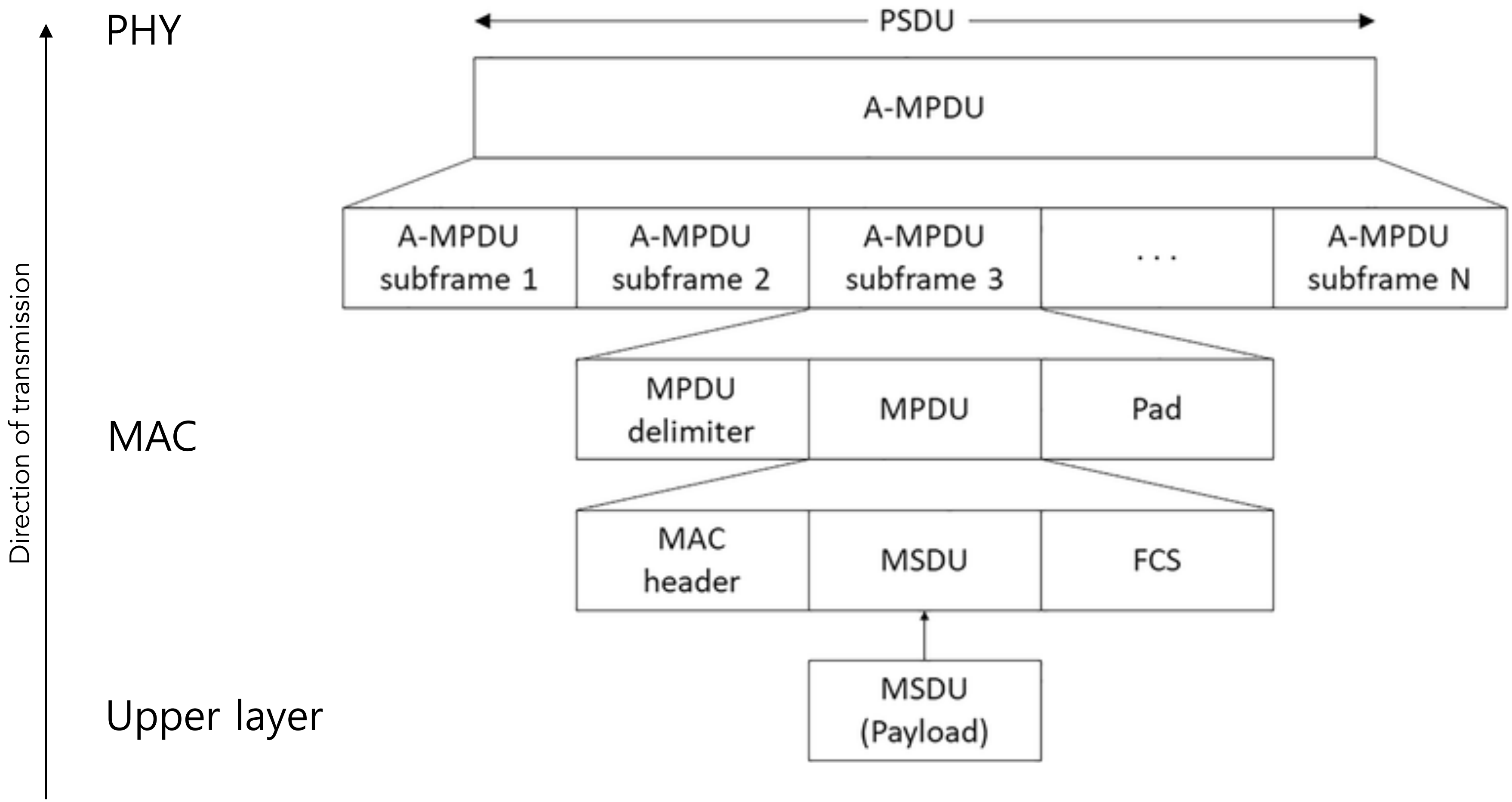
  - Packing several MPDUs into a single A-MPDU (up to 10 msec)
  - Amortizing protocol overhead over multiple frames
  - Positive/negative acknowledgement for individual MPDUs (subframes) using BlockAck

➔ Aggregating more subframes results in much higher throughput!

Transmission with No Aggregation

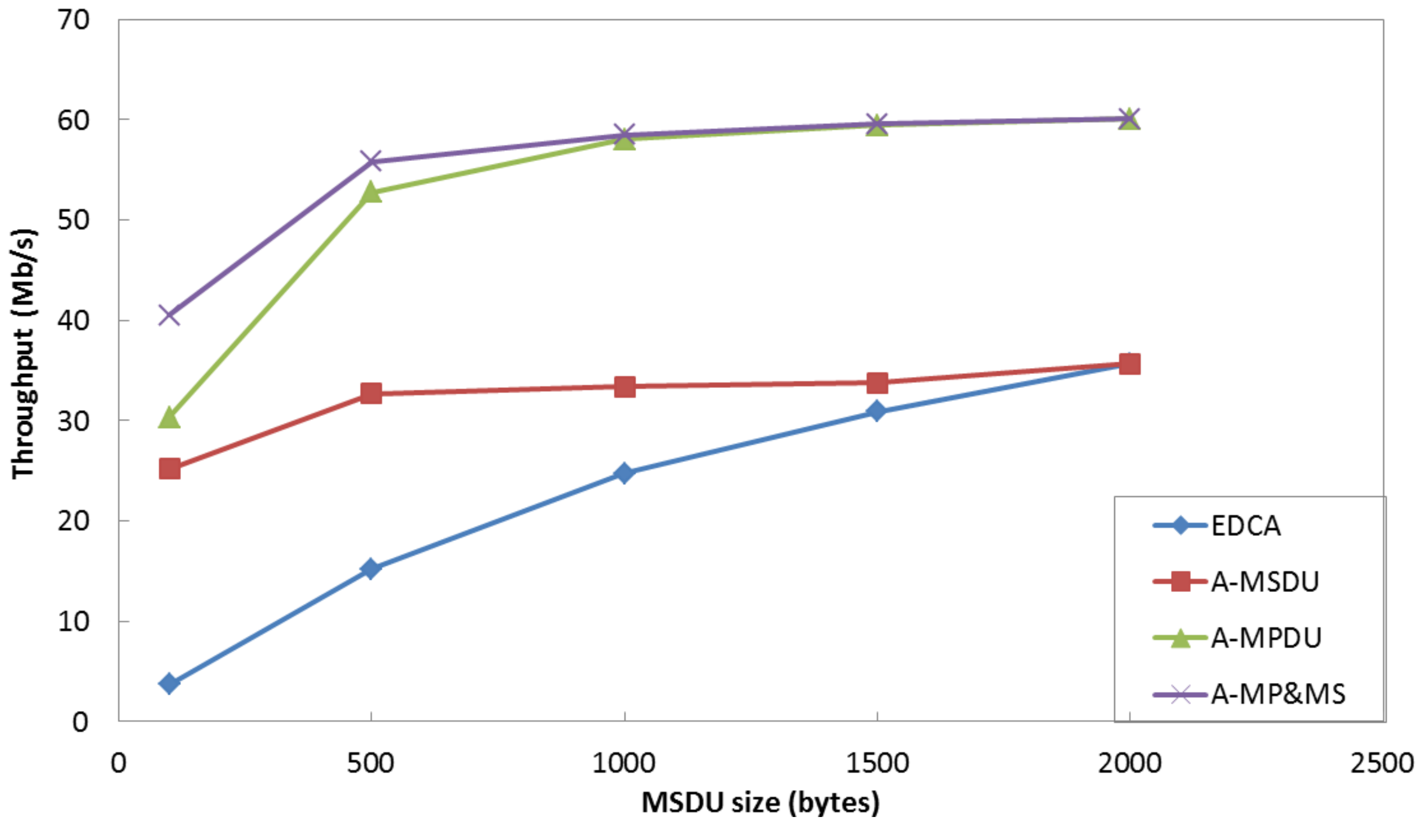


802.11n MAC A-MPDU



Performance of Aggregation

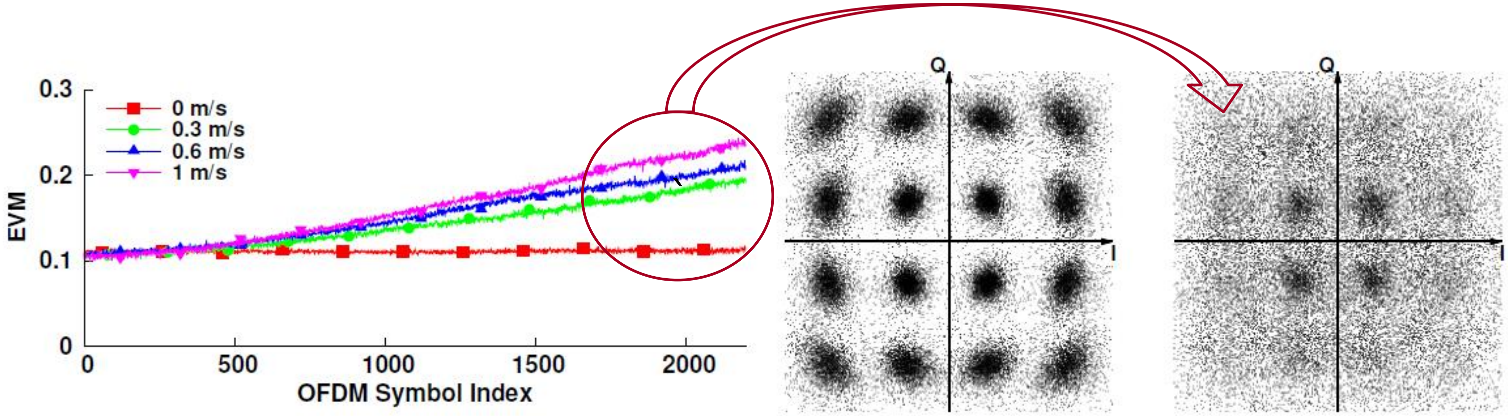
- Frame aggregation improves throughput (but, FER is in the trade-off)



Throughput for single transmitter and receiver at 65 Mbps

Limitation of Wi-Fi Channel Estimation

- Testbed experiment: Error Vector Magnitude (EVM) and IQ constellation
- Microsoft Sora SDR platform (Rx) and Qualcomm Atheros AR9380 (Tx)
  - As mobility increases, EVM increases!



(a) Pilot symbol dispersion.

(b) Data symbol dispersion at the front part of A-MPDU.

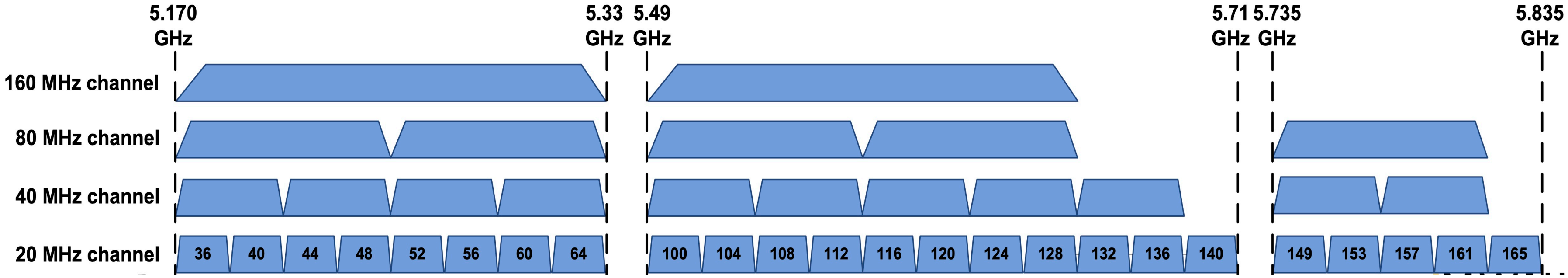
(c) Data symbol dispersion at the latter part of A-MPDU.

Symbol dispersion increases in the presence of mobility. All symbols are corrected by CSI and pilots.

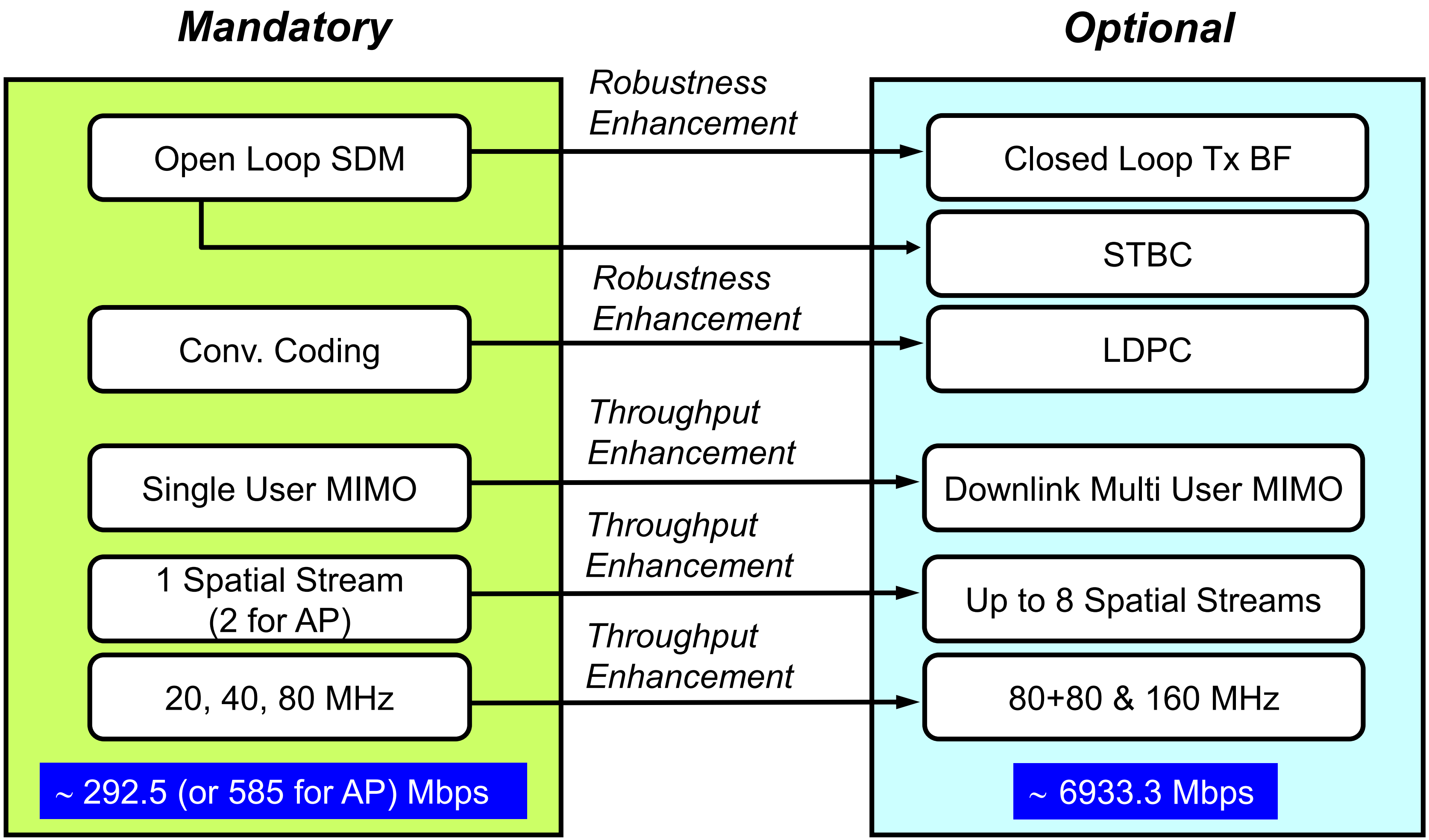
Rx symbol dispersion at the latter part of AMPDU is much larger than that at the front part of A-MPDU.

IEEE 802.11ac: Very High Throughput

- Wider channel bandwidth
  - 5 GHz-only successor to 802.11n
  - 20/40/80/160/80+80 MHz channels
- Downlink Multi-User MIMO (MU-MIMO)
  - Transmit multiple independent spatial streams to multiple users with few antennas simultaneously
- Higher order modulation
  - Up to 256-Quadrature Amplitude Modulation (256-QAM)



802.11ac PHY Architecture



802.11ac Data Rates (1)

Modulation	R	Data Rate (Mbps)															
		SS=1				SS=2				SS=4				SS=8			
		20 MHz		40 MHz		20 MHz		40 MHz		20 MHz		40 MHz		20 MHz		40 MHz	
		800 ns	400 ns	800 ns	400 ns	800 ns	400 ns	800 ns	400 ns	800 ns	400 ns	800 ns	400 ns	800 ns	400 ns	800 ns	400 ns
BPSK	1/2	6.5	7.2	13.5	15	13.0	14.4	27	30	26.0	28.9	54	60	52.0	57.8	108	120
QPSK	1/2	13.0	14.4	27	30	26.0	28.9	54	60	52.0	57.8	108	120	104.0	115.6	216	240
QPSK	3/4	19.5	21.7	40.5	45	39.0	43.3	81	90	78.0	86.7	162	180	156.0	173.3	324	360
16-QAM	1/2	26.0	28.9	54	60	52.0	57.8	108	120	104.0	115.6	216	240	208.0	231.1	432	480
16-QAM	3/4	39.0	43.3	81	90	78.0	86.7	162	180	156.0	173.3	324	360	312.0	346.7	648	720
64-QAM	2/3	52.0	57.8	108	120	104.0	115.6	216	240	208.0	231.1	432	480	416.0	462.2	864	960
64-QAM	3/4	58.5	65.0	121.5	135	117.0	130.0	243	270	234.0	260.0	486	540	468.0	520.0	972	1080
64-QAM	5/6	65.0	72.2	135	150	130.0	144.4	270	300	260.0	288.9	540	600	520.0	577.8	1080	1200
256-QAM	3/4	78.0	86.7	162	180	156.0	173.3	324	360	312.0	346.7	648	720	624.0	693.3	1296	1440
256-QAM	5/6			180	200			360	400			720	800			1440	1600

* SS=Spatial Stream <= min(# Tx Antennas, # Rx Antennas)

802.11ac Data Rates (2)

Modulation	R	Data Rate (Mbps)															
		SS=1				SS=2				SS=4				SS=8			
		80 MHz		160 MHz		80 MHz		160 MHz		80 MHz		160 MHz		80 MHz		160 MHz	
		800 ns	400 ns	800 ns	400 ns	800 ns	400 ns	800 ns	400 ns	800 ns	400 ns	800 ns	400 ns	800 ns	400 ns	800 ns	400 ns
BPSK	1/2	29.3	32.5	58.5	65	58.5	65	117	130	117	130	234	260	234	260	468	520
QPSK	1/2	58.5	65	117	130	117	130	234	260	234	260	468	520	468	520	936	1040
QPSK	3/4	87.8	97.5	175.5	195	175.5	195	351	390	351	390	702	780	702	780	1404	1560
16-QAM	1/2	117	130	234	260	234	260	468	520	468	520	936	1040	936	1040	1872	2080
16-QAM	3/4	175.5	195	351	390	351	390	702	780	702	780	1404	1560	1404	1560	2808	3120
64-QAM	2/3	234	260	468	520	468	520	936	1040	936	1040	1872	2080	1872	2080	3744	4160
64-QAM	3/4	263.3	292.5	526.5	585	526.5	585	1053	1170	1053	1170	2106	2340	2106	2340	4212	4680
64-QAM	5/6	292.5	325	585	650	585	650	1170	1300	1170	1300	2340	2600	2340	2600	4680	5200
256-QAM	3/4	351	390	702	780	702	780	1404	1560	1404	1560	2808	3120	2808	3120	5616	6240
256-QAM	5/6	390	433.3	780	866.7	780	866.7	1560	1733.3	1560	1733.3	3120	3466.7	3120	3466.7	6240	6933.3

* SS=Spatial Stream <= min(# Tx Antennas, # Rx Antennas)

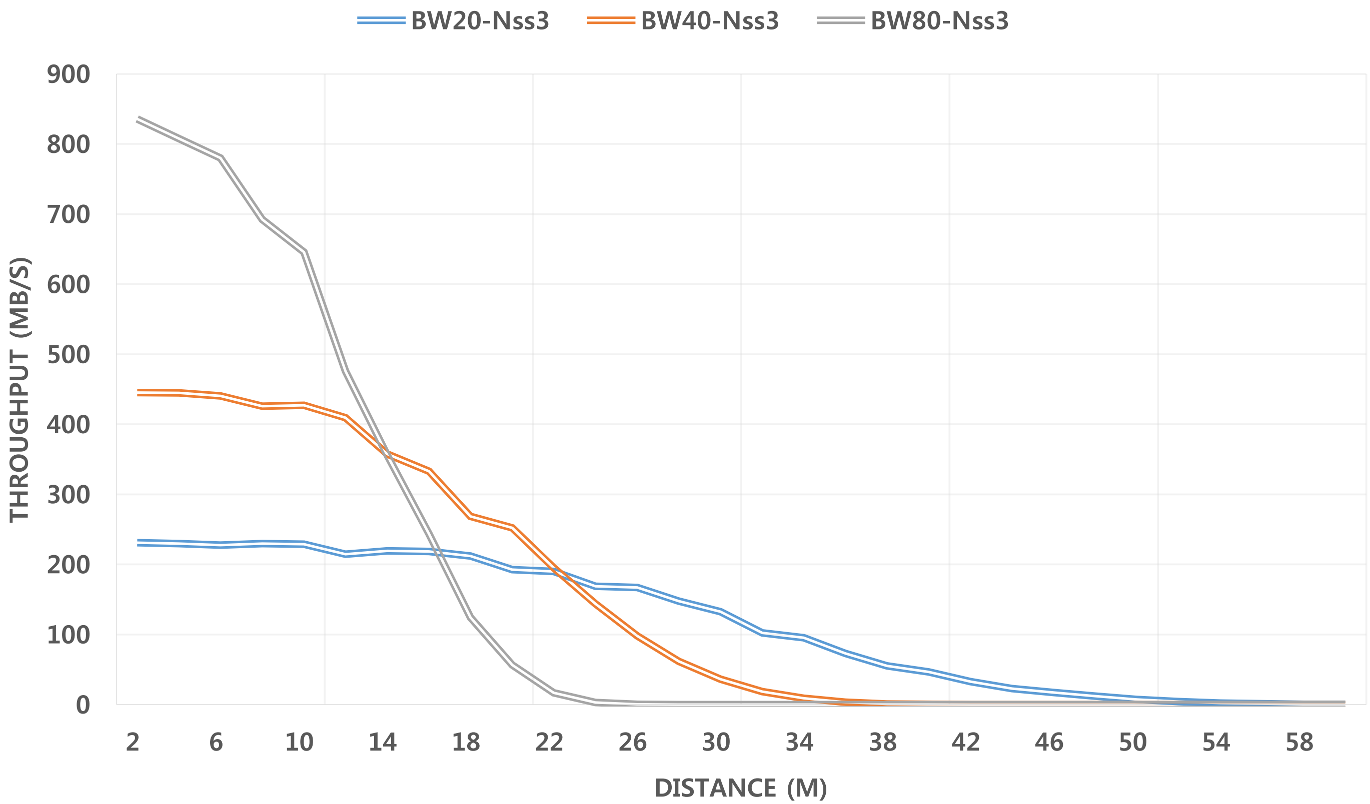
IEEE 802.11ac Simulation

- Simulation environment

Parameter	Value
Simulator	**ns-3** network simulator Version: ns-3.21 Implemented features: Channel Bonding (20,40,80 MHz) Spatial Multiplexing (up to 4 streams) Frame aggregation (A-MPDU)
Topology	One-to-one (1 AP & 1 client)
RF parameter	Transmit power: 16 dBm, Antenna Gain: 1 dB
Fading model	Path-loss model TGax path-loss model: PL(d) = 40.05 + 20*log10(f_c/2.4e9) + 20*log10(min(d,5)) + (d>5) * 35*log10(d/5) – d = distance between the two nodes – f_c = frequency [GHz]
	Fading model Jakes fading model (Doppler velocity: 0.1 m/s)
Traffic	Downlink UDP (1460 bytes) Saturated condition (UDP source rate > PHY data rate)

IEEE 802.11ac Performance

- Throughput for various bandwidth
  - Data rate (R): MCS 8 fixed (260/540/1170 Mb/s for 20/40/80 MHz)
  - Number of spatial streams (N_{SS}): 3



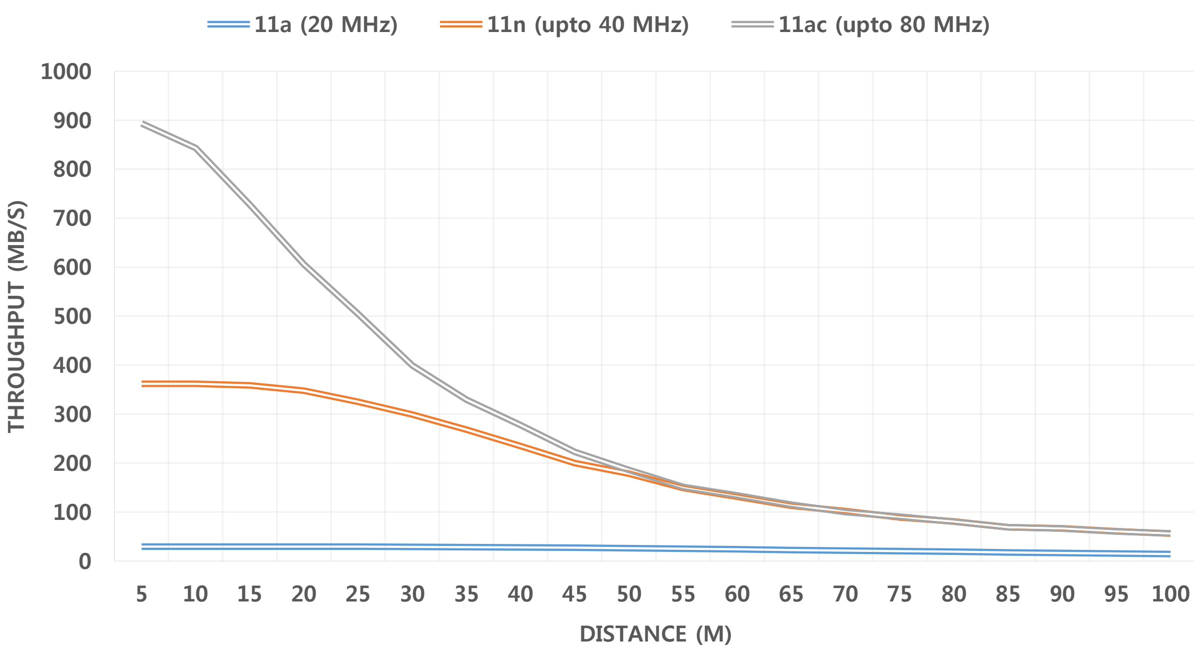
IEEE 802.11ac Performance

- Peak throughput comparison
  - Genie rate control: Genie ideally determines the best R/N_{SS}/BW

802.11a
- 6/9/12/18/24/36/48/54 Mbps
- Bandwidth: 20 MHz
- No frame aggregation

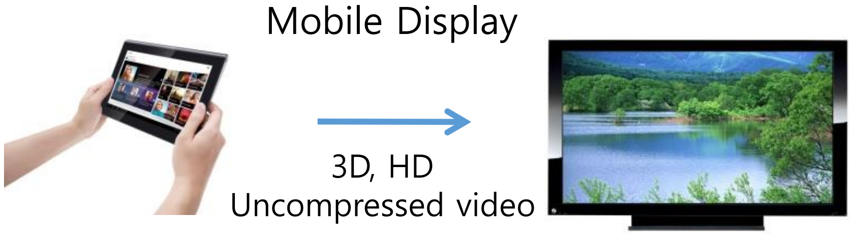
802.11n
- MCS 0-7 & up-to 3 streams
- Bandwidth: 20/40 MHz
- A-MPDU (10 ms, 65,535 Bytes)

802.11ac
- MCS 0-9 & up-to 3 streams
- Bandwidth: 20/40/80 MHz A
- MPDU (5.484 ms, 1,048,575 Bytes)



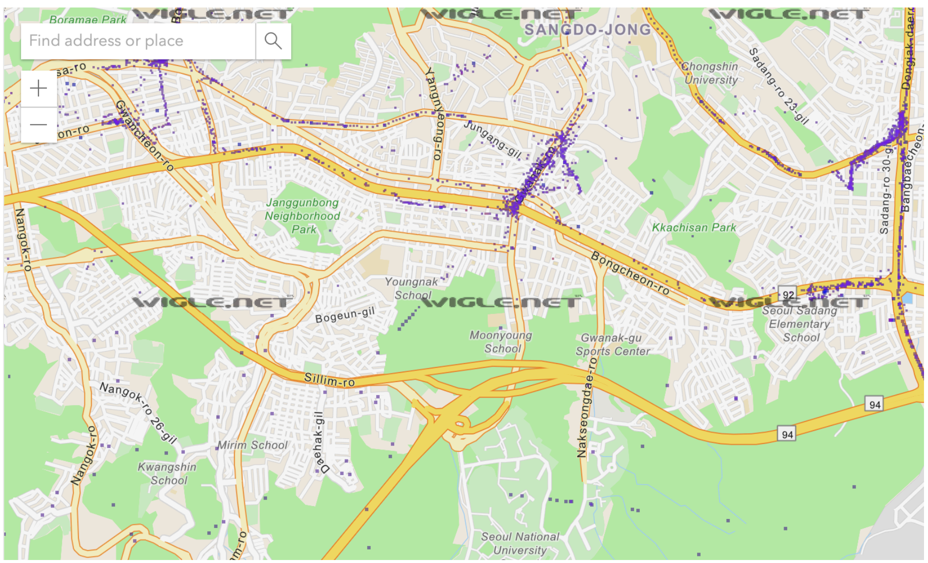
IEEE 802.11ay: Next Generation 60 GHz

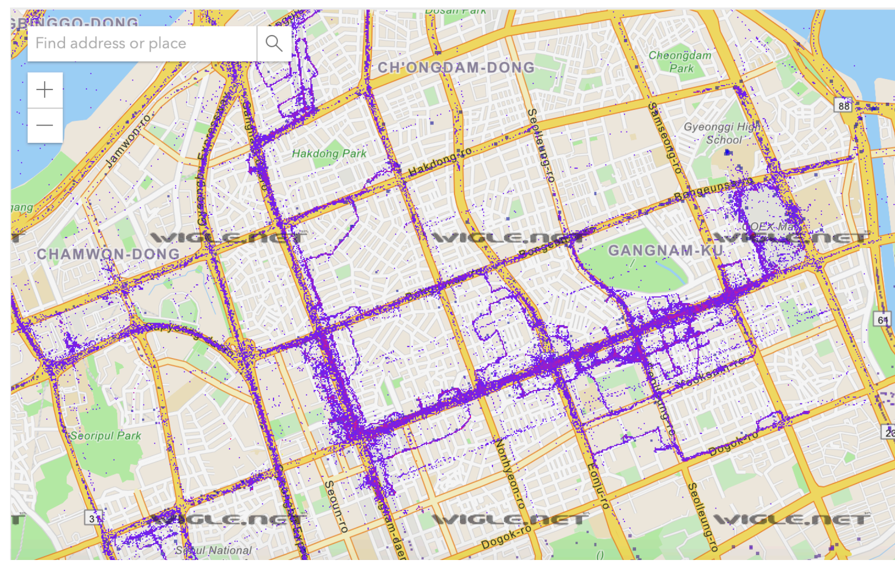
- Extension of 802.11ad
  - Improved throughput (~20 Gb/s)
  - Improved reliability/robustness
- Main use cases
  - Wireless docking and display
  - Indoor and outdoor wireless backhaul
- Extended PHY feature
  - Channel bonding (2, 3, and 4)
  - MIMO (≥ 2 streams)
- Unspecified MAC feature yet



IEEE 802.11ax: High Efficiency WLAN (HEW)

- So far, focus on theoretical peak throughput (802.11n/ac/ad)
- Start to consider "real-world" performance
  - Dense deployment followed by inter-WLAN interference
- Enhance 802.11 PHY and MAC in 2.4 GHz and 5 GHz
  - For improving spectrum efficiency and areal throughput in real world densely deployed (indoor & outdoor) environment





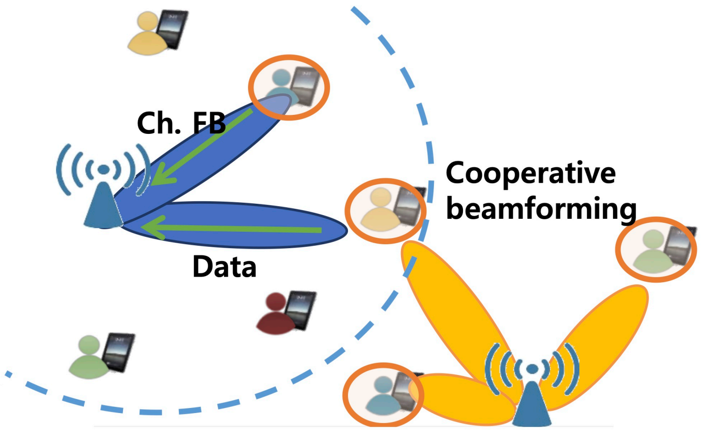
https://wigle.net

IEEE 802.11ax Scope

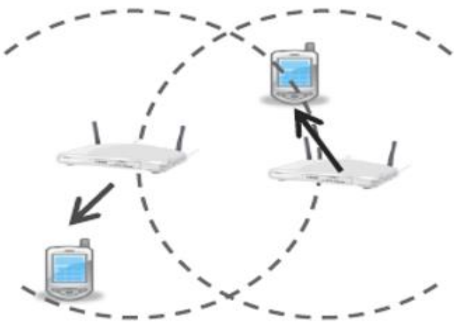
- Scope defined in Project Authorization Request (PAR)
  - At least 4X improvements in the average throughput per STA
    - Throughput is measured at MAC data service access point
    - 5-10X improvements are expected depending on technology and scenario
  - Improving power efficiency per STA
  - Indoor and outdoor operations in frequency bands between 1 GHz and 6 GHz
  - Enabling backward compatibility and coexistence with legacy IEEE 802.11 devices operating at same band

IEEE 802.11ax Candidate Approaches

Uplink MU-MIMO & OBSS cooperation



Dynamic Sensitivity Control (DSC)



Orthogonal Frequency Division Multiple Access (OFDMA)