CS/ECE 439: Wireless Networking

MAC Layer – Multi-Rate

GRAINGER ENGINEERING

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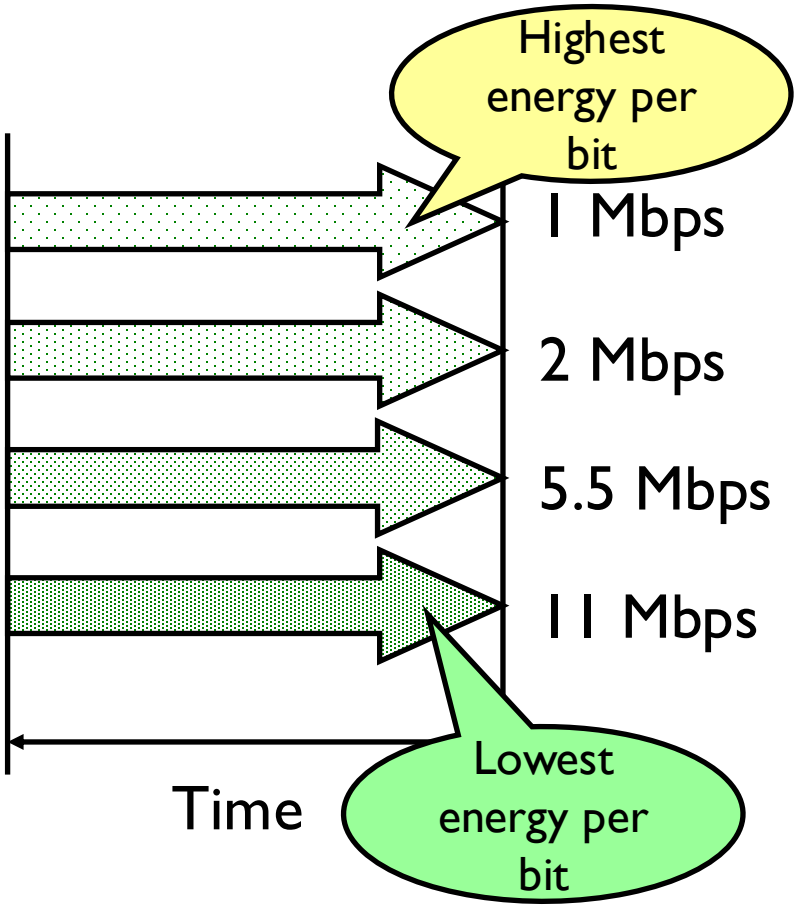
COMPUTER SCIENCE

What is "Data Rate" really?

- Number of bits that you transmit per unit time
  - under a fixed energy budget
- Too many bits/s
  - Each bit has little energy -> Hi BER
- Too few bits/s
  - Less BER but lower throughput

802.11b – Transmission rates

- Optimal rate depends on SINR
  - i.e., interference and current channel conditions



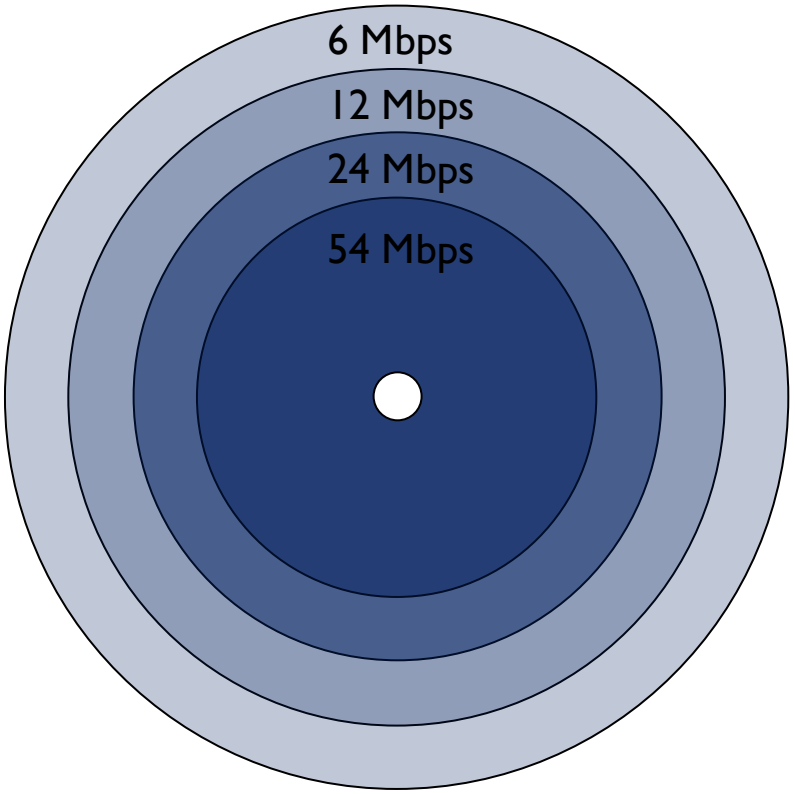
Multi-Rate

- Ability of a wireless card to automatically operate at several different bit-rates
  - (e.g. 1, 2, 5.5, and 11 Mbps for 802.11b)
- Part of most existing wireless standards
- Virtually every wireless card in use today employs multi-rate

Multi-Rate Tradeoffs

- Channel Rate vs. Signal strength
  - All versions of IEEE 802.11 can lower the rate to work at a lower signal strength (SNR)
    - 802.11b (1999) 1–11 Mbps
    - 802.11a/g (1999/2003) 6–54 Mbps
    - Wi-Fi 4, 802.11n (2009) 6.5–600 Mbps
    - Wi-Fi 5, 802.11ac (2013) 6.5–6,933 Mbps
    - Wi-Fi 6, 802.11ax (2021) 0.4–9,608 Mbps
    - Wi-Fi 7, 802.11be (2024) 0.4–23,059 Mbps
  - Increased range → lower signal → lower rate

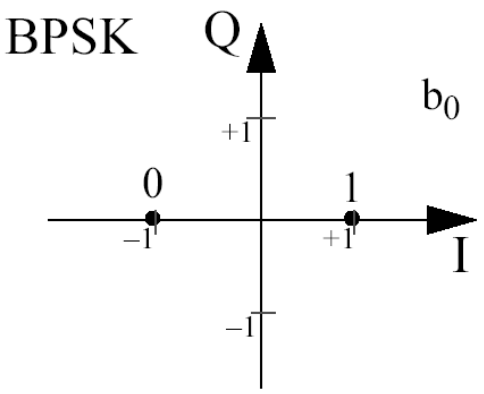
Multi-Rate Tradeoffs



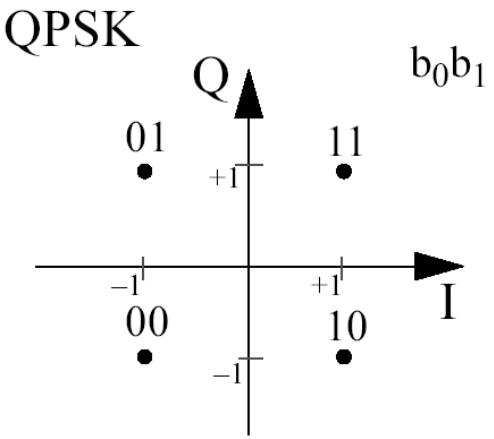
What determines the actual rate?

- Direct relationship between communication rate and the channel quality required for that rate
- As distance increases, channel quality decreases
  - Tradeoff between communication range and link speed
- Multi-rate provides flexibility to meet both consumer demands

Carrier Modulations

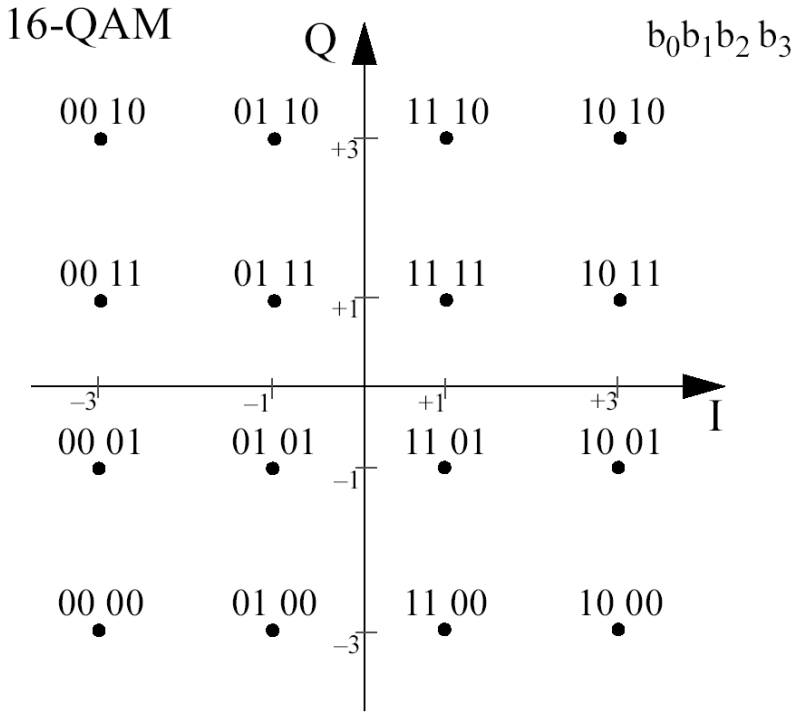


- Binary Phase Shift Keying
  - One bit per symbol



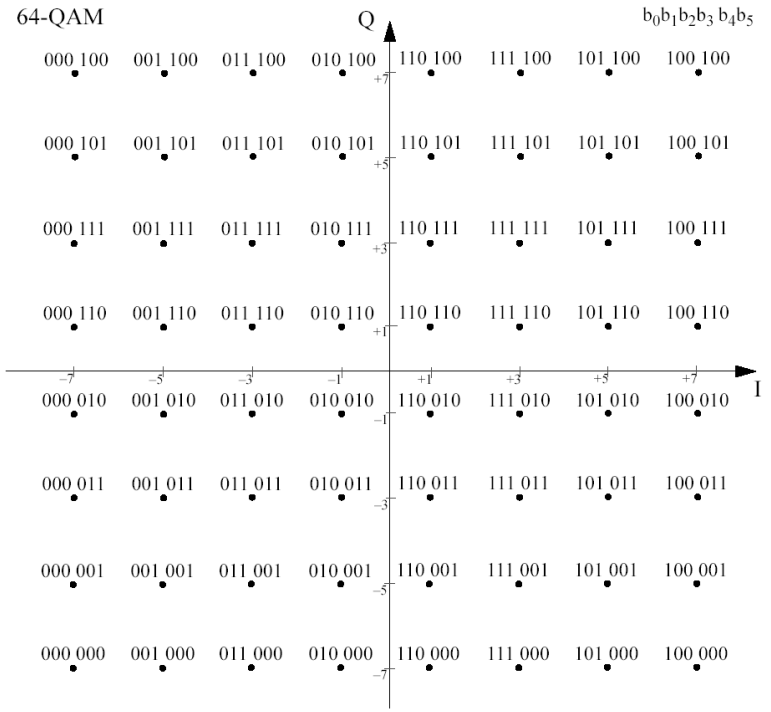
- Quadrature Phase Shift Keying
  - Two bits per symbol

Carrier Modulations



- 16 - Quadrature Amplitude Modulation
  - 4 bits per symbol

Carrier Modulations



- 64 - Quadrature Amplitude Modulation
  - 6 bits per symbol

802.11a Rates by Carrier Modulation and Coding

Data rate (Mbits/s)	Modulation	Coding rate (R)	Coded bits per subcarrier (N_{BPSC})	Coded bits per OFDM symbol (N_{CBPS})	Data bits per OFDM symbol (N_{DBPS})
6	BPSK	1/2	1	48	24
9	BPSK	3/4	1	48	36
12	QPSK	1/2	2	96	48
18	QPSK	3/4	2	96	72
24	16-QAM	1/2	4	192	96
36	16-QAM	3/4	4	192	144
48	64-QAM	2/3	6	288	192
54	64-QAM	3/4	6	288	216

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24	16-QAM	1/2			
36	16-QAM	3/4			
48	64-QAM	2/3	6	288	192
54	64-QAM	3/4	6	288	216

Each modulation scheme can be used with different coding rates

802.11a Rates by Carrier Modulation and Coding

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48	64-QAM	2/3			
54	64-QAM	3/4			

R is the fraction of transmitted bits that carry user data

Remaining bits are used for FEC

R= ½ - 1 data bit is encoded into 2 coded bits

802.11a Rates by Carrier Modulation and Coding

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54	64-QAM	3/4			

Same BPSK, same 48 coded bits.

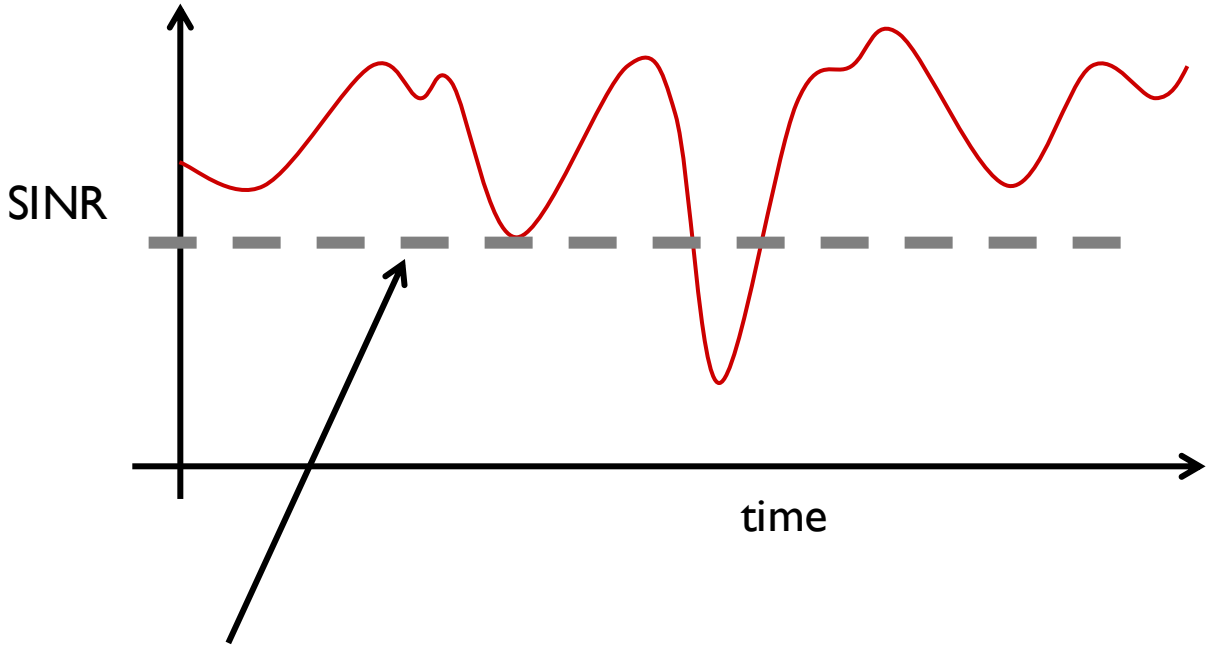
R = 1/2 vs 3/4
24 data bits vs. 36
6 vs. 9 Mbps

From Coding Rate to Data Rate

- Coded bits per OFDM symbol (N_CBPS)
  - 48 data subcarriers x bits per subcarrier
- Data bits per OFDM symbol (N_DBPS)
  - N_CBPS x R
- Data rate
  - N_DBPS / 4 μs (one OFDM symbol lasts 4 μs)

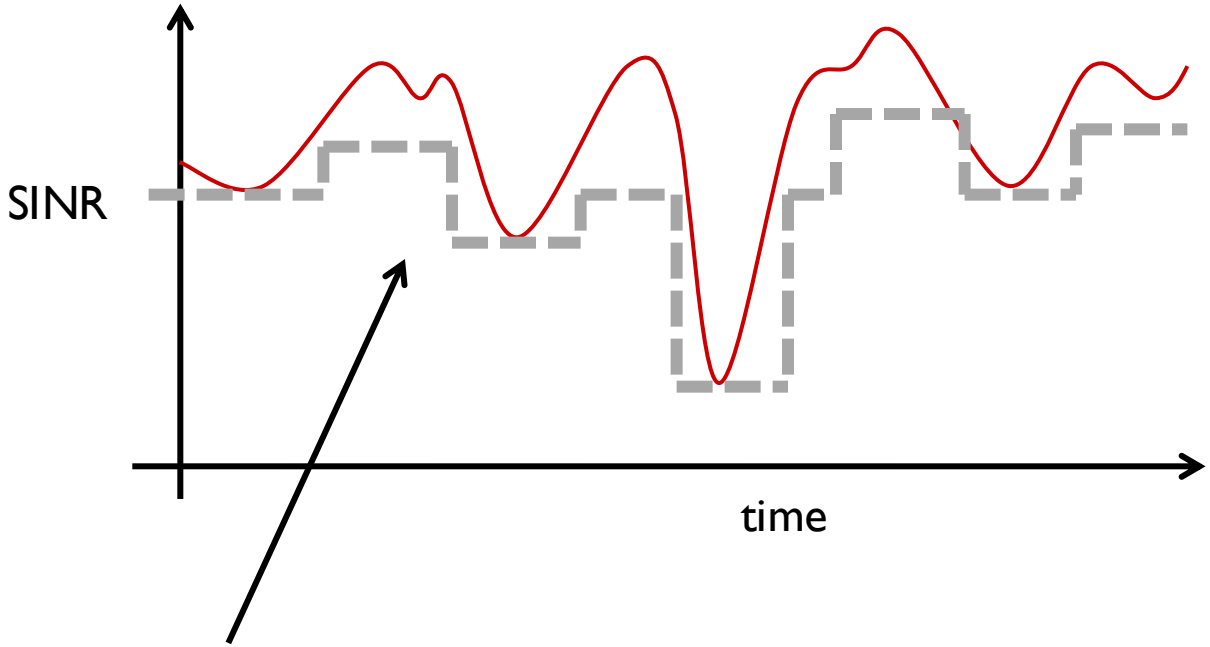
- Examples
  - 6 Mbps
    - BPSK - R = 1/2
      - 48 x 1 x 1/2 = 24 bits per symbol, 24 / 4 μs = 6 Mbps
  - 54 Mbps
    - 64-QAM - R = ¾
      - 48 x 6 x 3/4 = 216 bits per symbol, 216 / 4 μs = 54 Mbps
- R = 2/3 and 3/4 come from puncturing the rate-1/2 code
  - some coded bits are dropped, leaving less protection

How do we choose modulation rates?



- Estimate a value of SINR
- Choose a corresponding rate that would transmit packets correctly most of the times
- Failure in some cases of fading
  - Live with it

Adaptive Rate-Control



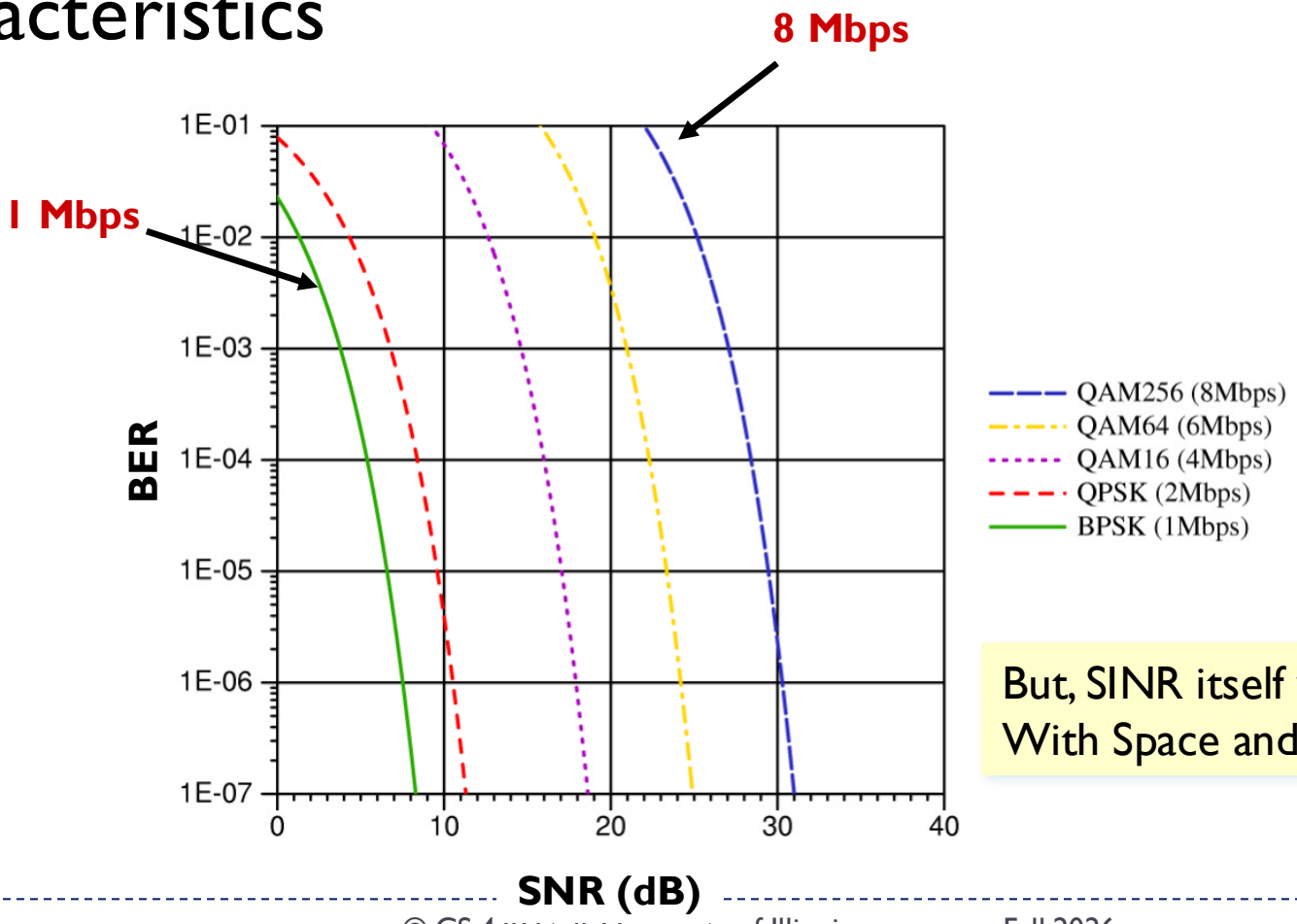
- Observe the current value of SINR
  - Use as indicator of near-future value
- Choose corresponding rate of modulation
- Repeat
  - Controls rate if channel conditions have changed

Seems simple, but …

- Rate control has variety of implications
  - Any single MAC protocol solves part of the puzzle
- Important to understand e2e implications
  - Does routing protocols get affected?
  - Does TCP get affected?
  - …
- Good to make a start at the MAC layer
  - ARF
  - RBAR
  - OAR
  - …

Problem

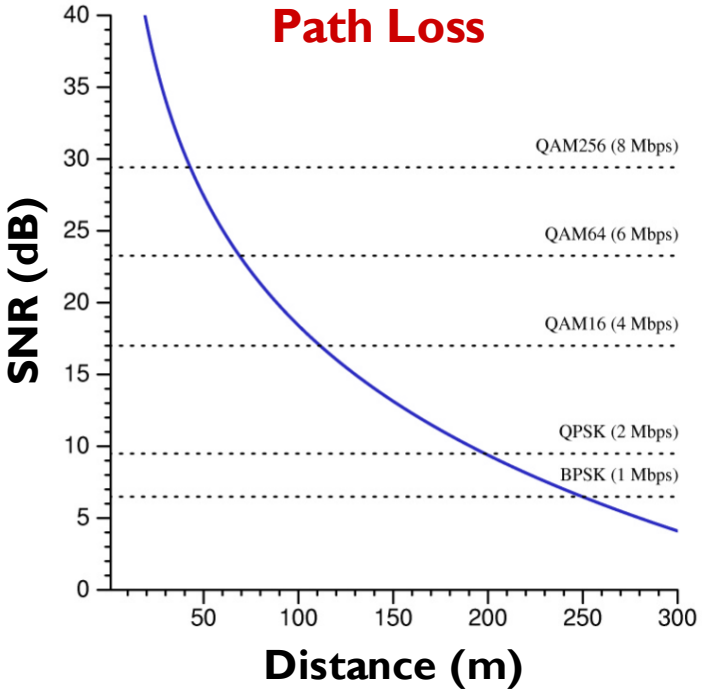
- Modulation schemes have different error characteristics

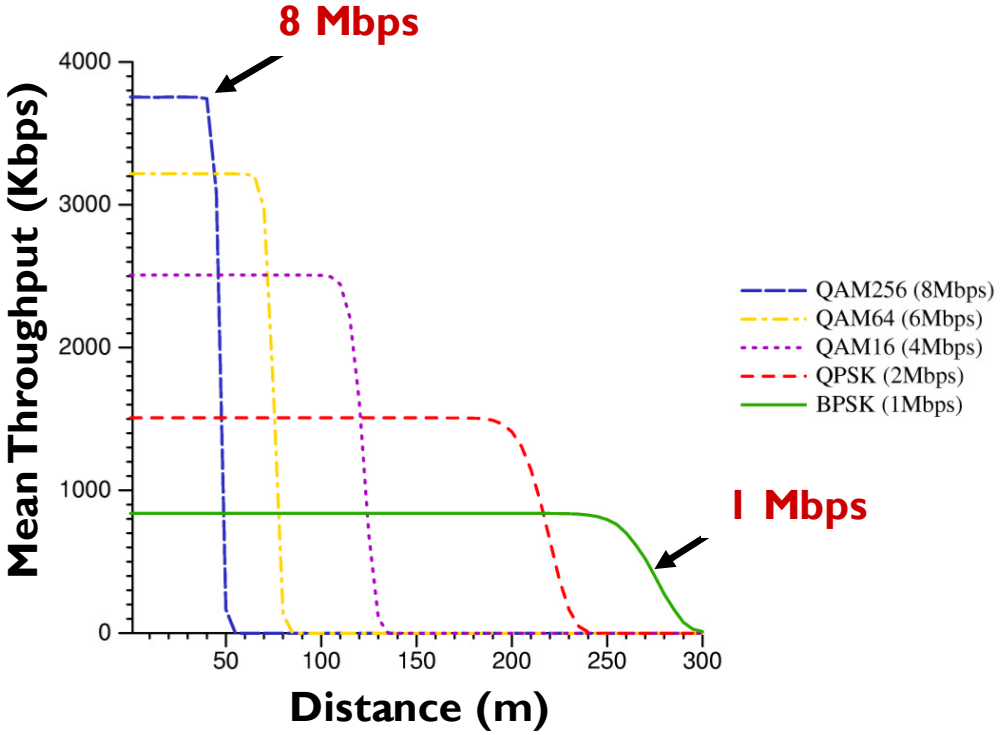


But, SINR itself varies With Space and Time

Impact

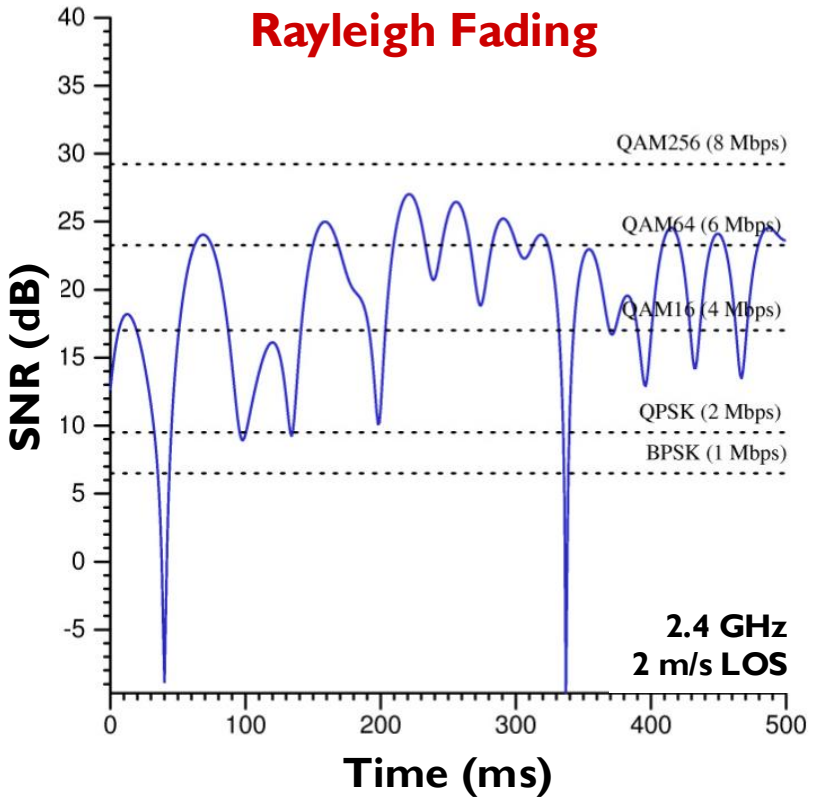
- Large-scale variation with distance (Path loss)



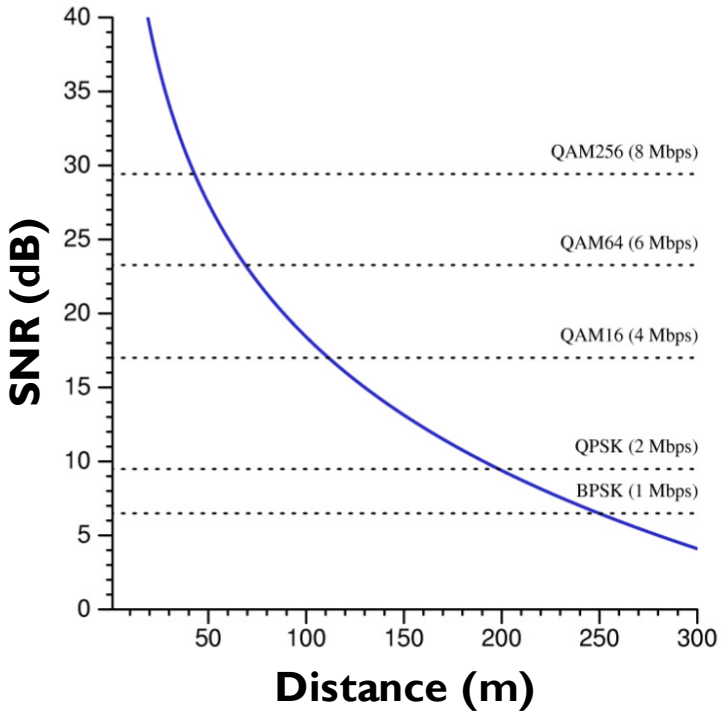


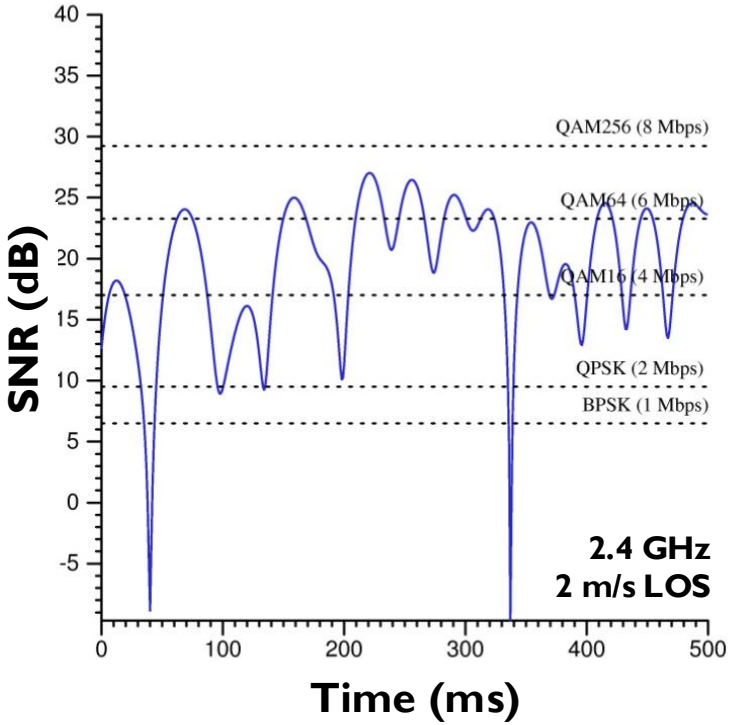
Impact

- Small-scale variation with time (Fading)



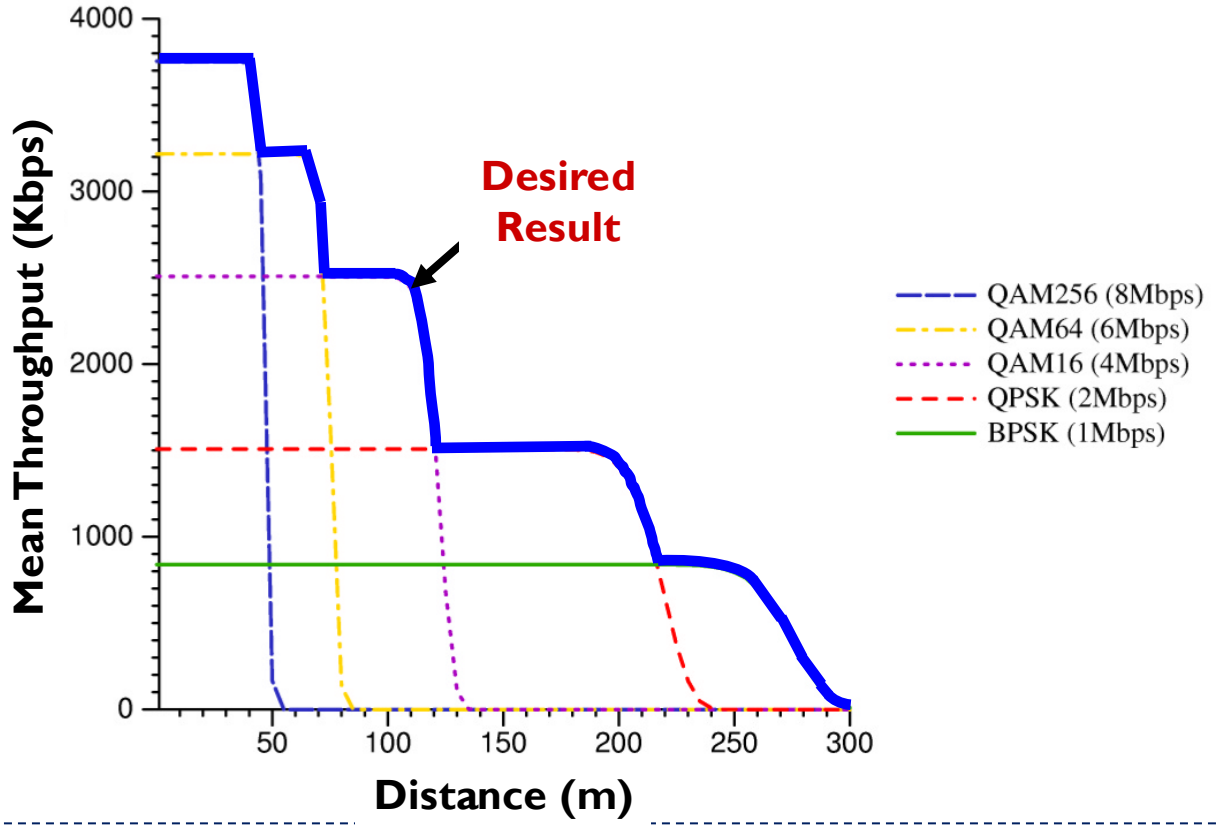
Which modulation scheme is best?





Answer → Rate Adaptation

- Dynamically choose the best modulation scheme for the channel conditions



Design Issues

- How frequently should we adapt the rate?
  - Signal can vary rapidly depending on
    - carrier frequency
    - node speed
    - interference
    - etc.
- For conventional hardware at pedestrian speeds, rate adaptation is feasible on a per-packet basis

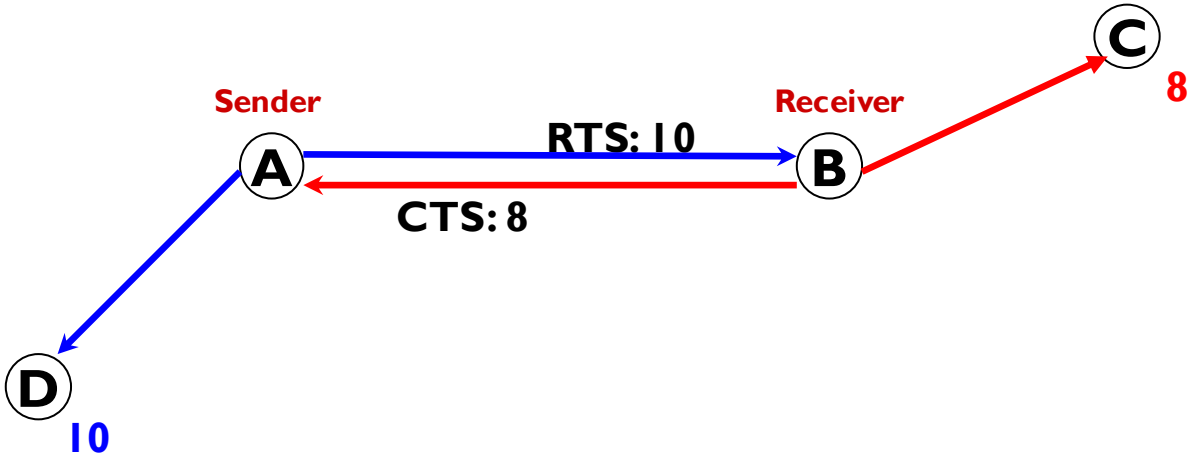
Adaptation → At Which Layer ?

- Cellular networks
  - Adaptation at the physical layer
- Impracticalfor 802.11 in WLANs

Adaptation → At Which Layer ?

- Cellular networks
  - Adaptation at the physical layer
- Impracticalfor legacy 802.11 in WLANs ← Why?

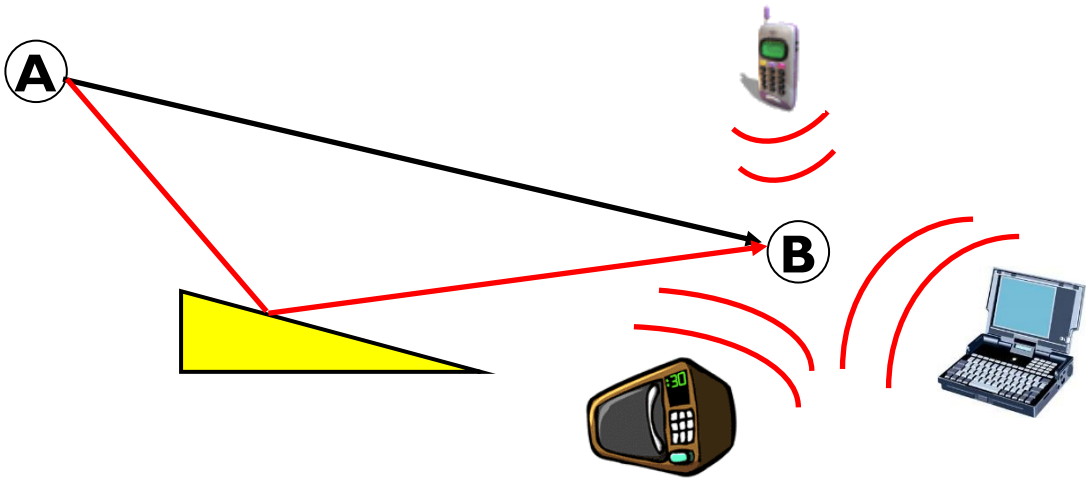
RTS/CTS requires that the *rate be known in advance*



- For WLANs, rate adaptation is best handled at the MAC layer

Who should select the data rate?

- Collision is at the receiver
- Channel conditions are only known at the receiver
  - SS, interference, noise, BER, etc.



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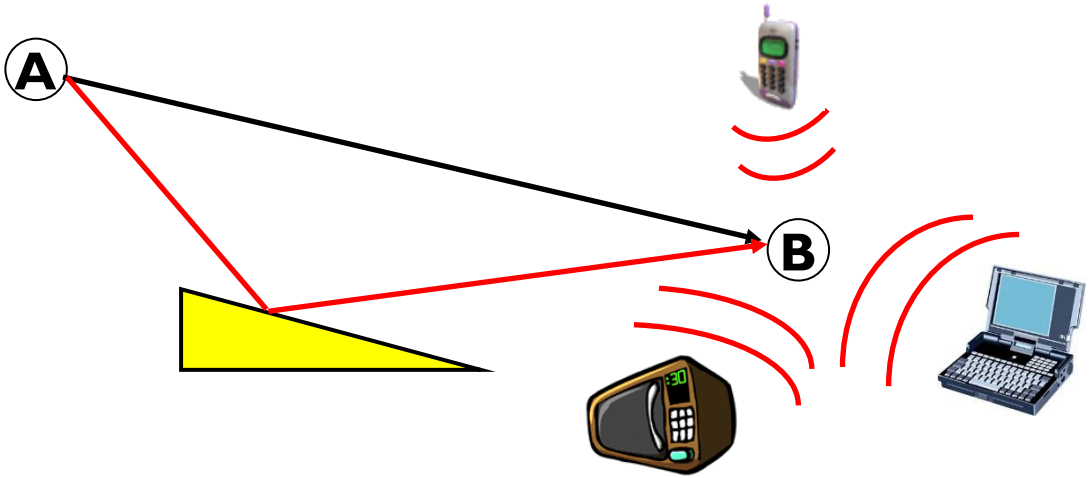
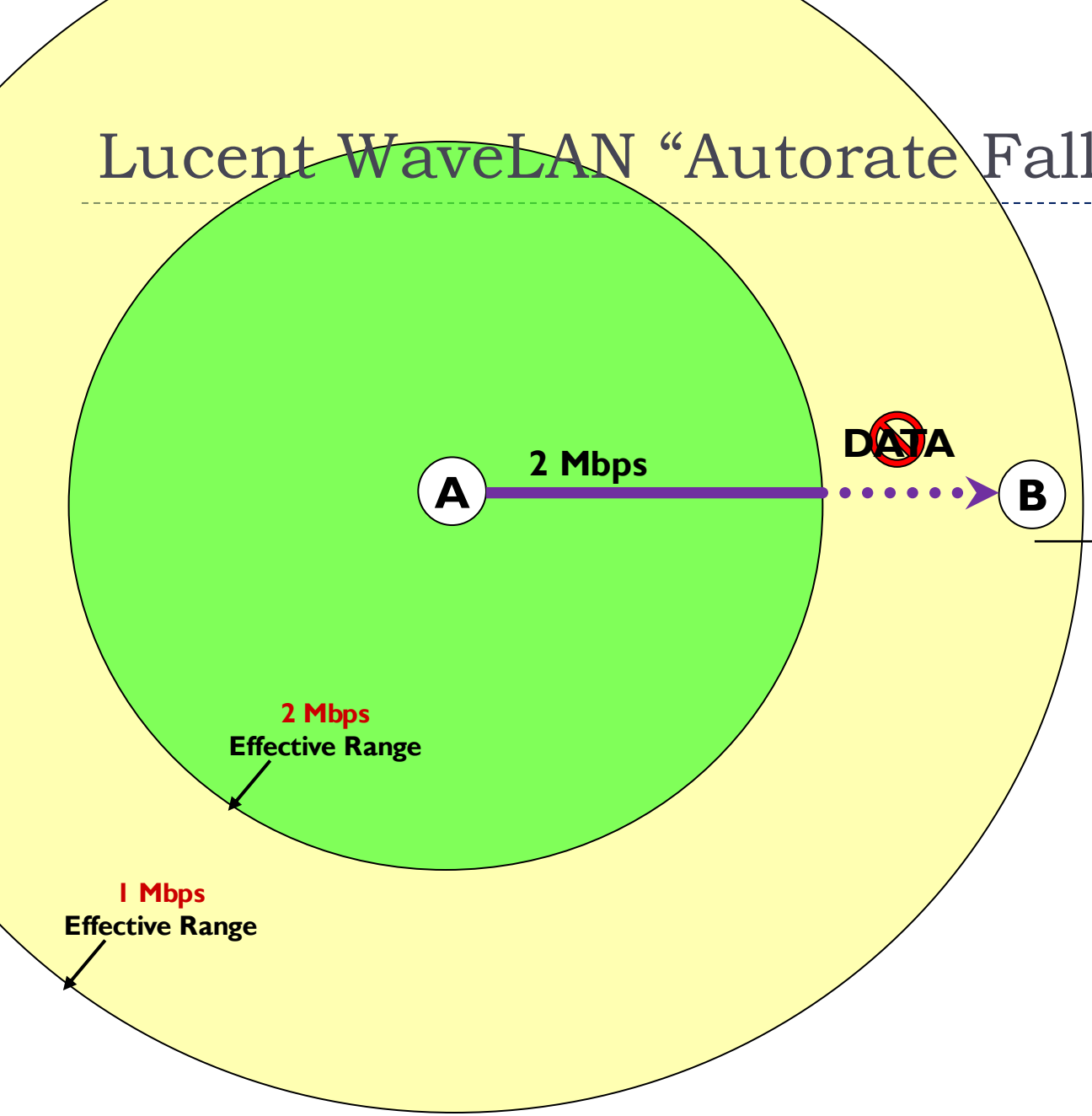


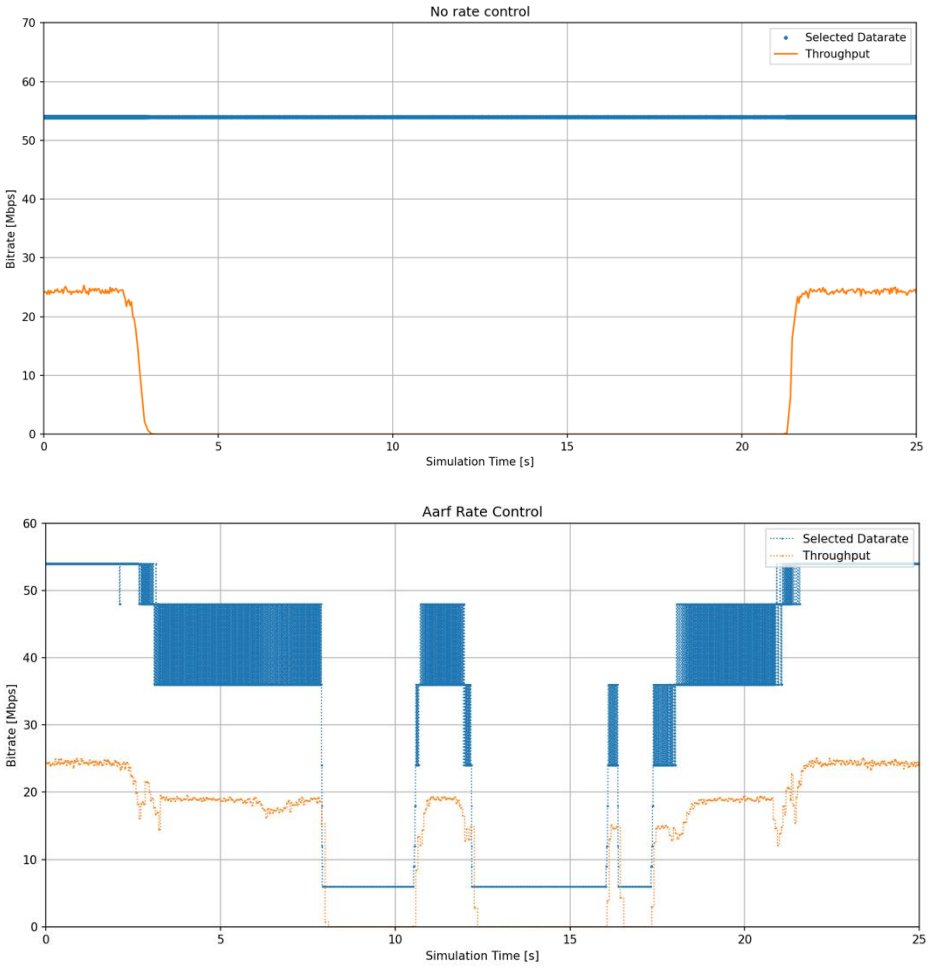
- The receiver is best positioned to select data rate

Lucent WaveLAN "Autorate Fallback" (ARF)

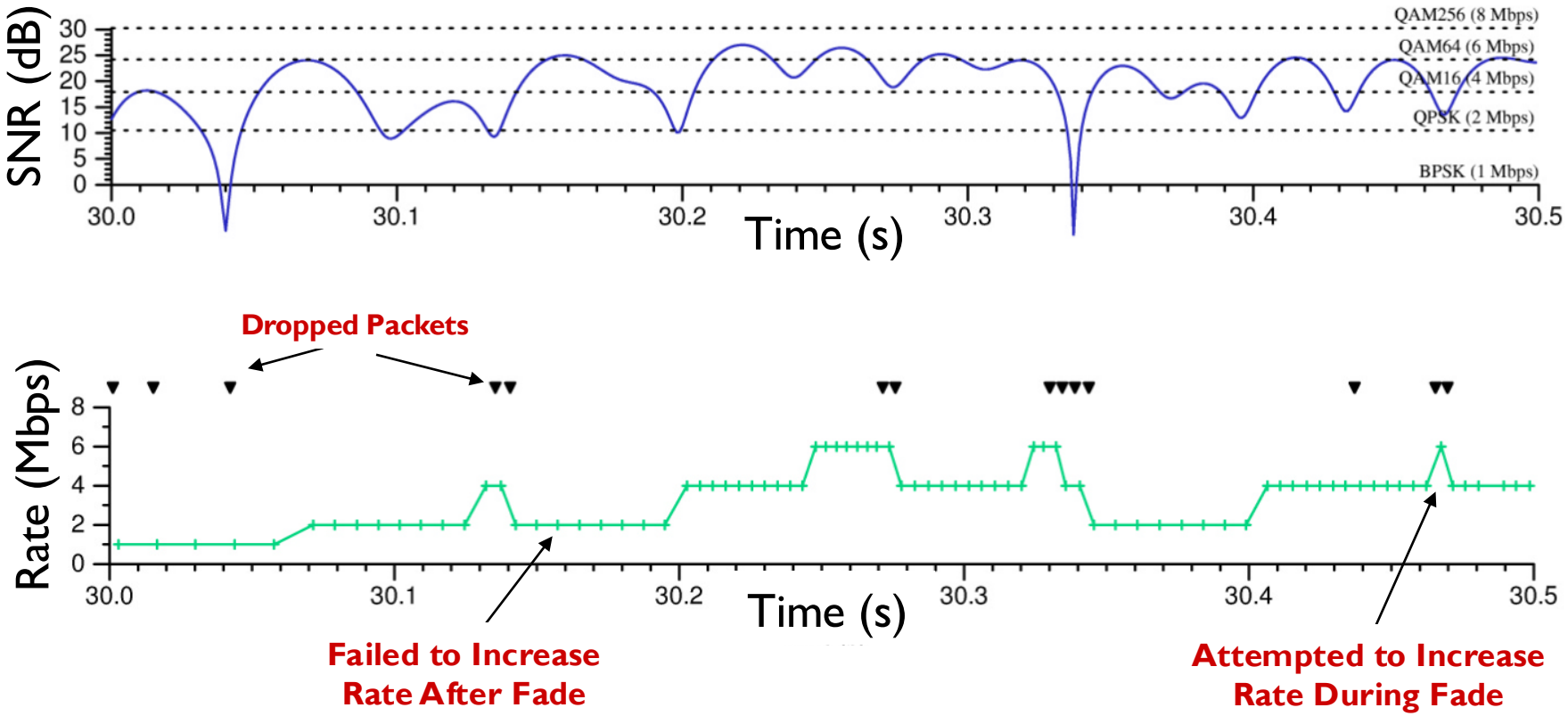


- Lost ACKs indicate link quality
- Sender decreases rate after
  - N consecutive ACKS are lost
- Sender increases rate after
  - Y consecutive ACKS are received or
  - T secs have elapsed since last attempt

Autorate Fallback Example



Performance of ARF



- Slow to adapt to channel conditions
- Choice of N, Y, T may not be best for all situations

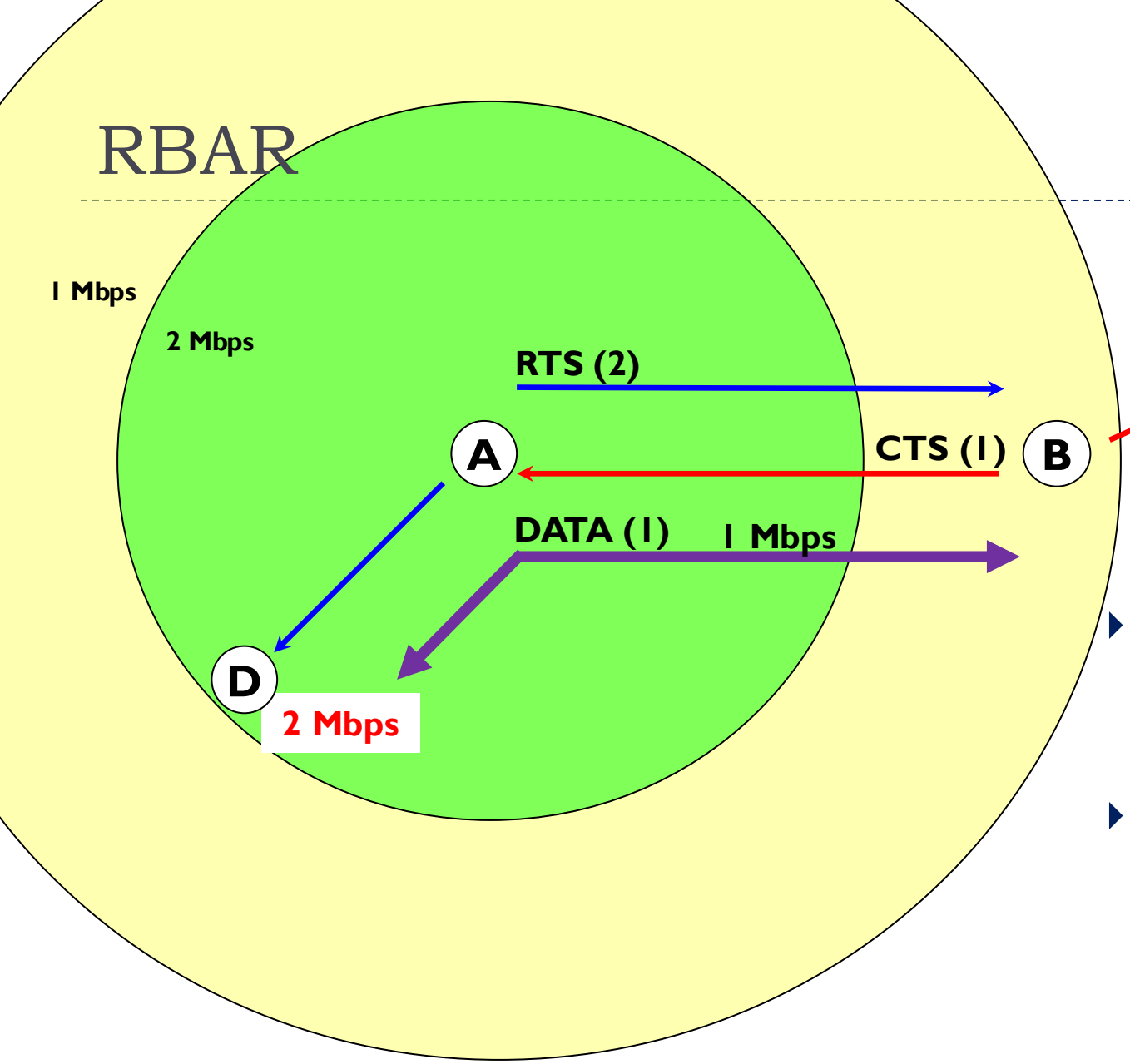
ARF's Blind Spot: Collisions Look Like Bad Channels

- ARF assumes every lost frame means a weak channel
  - But collisions also cause lost ACKs
  - ARF lowers the rate, the frame takes longer, and collisions become more likely
  - Rate collapses even when the channel is fine, especially with many contenders
- Potential Fix: distinguish collisions from channel errors
  - CARA
    - Probe with RTS or use clear-channel assessment to find the cause
  - RRAA
    - Short-term loss-ratio windows, with RTS enabled only when needed

Receiver-Based Autorate (RBAR)

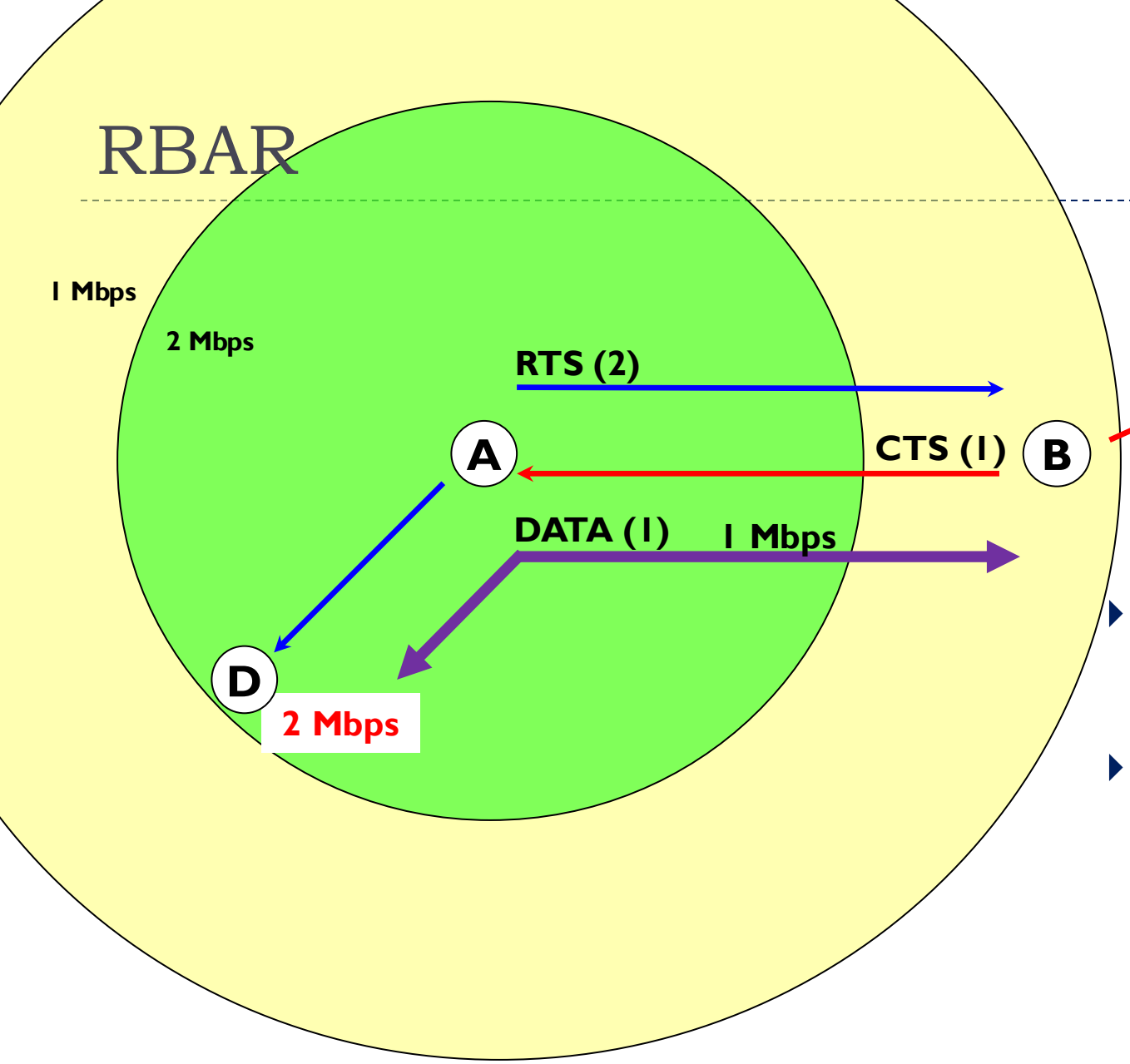
- Move the rate adaptation mechanism to the receiver
  - Better channel quality information = better rate selection
- Utilize the RTS/CTS exchange to
  - Provide the receiver with a signal to sample (RTS)
  - Carry feedback (data rate) to the sender (CTS)

RBAR



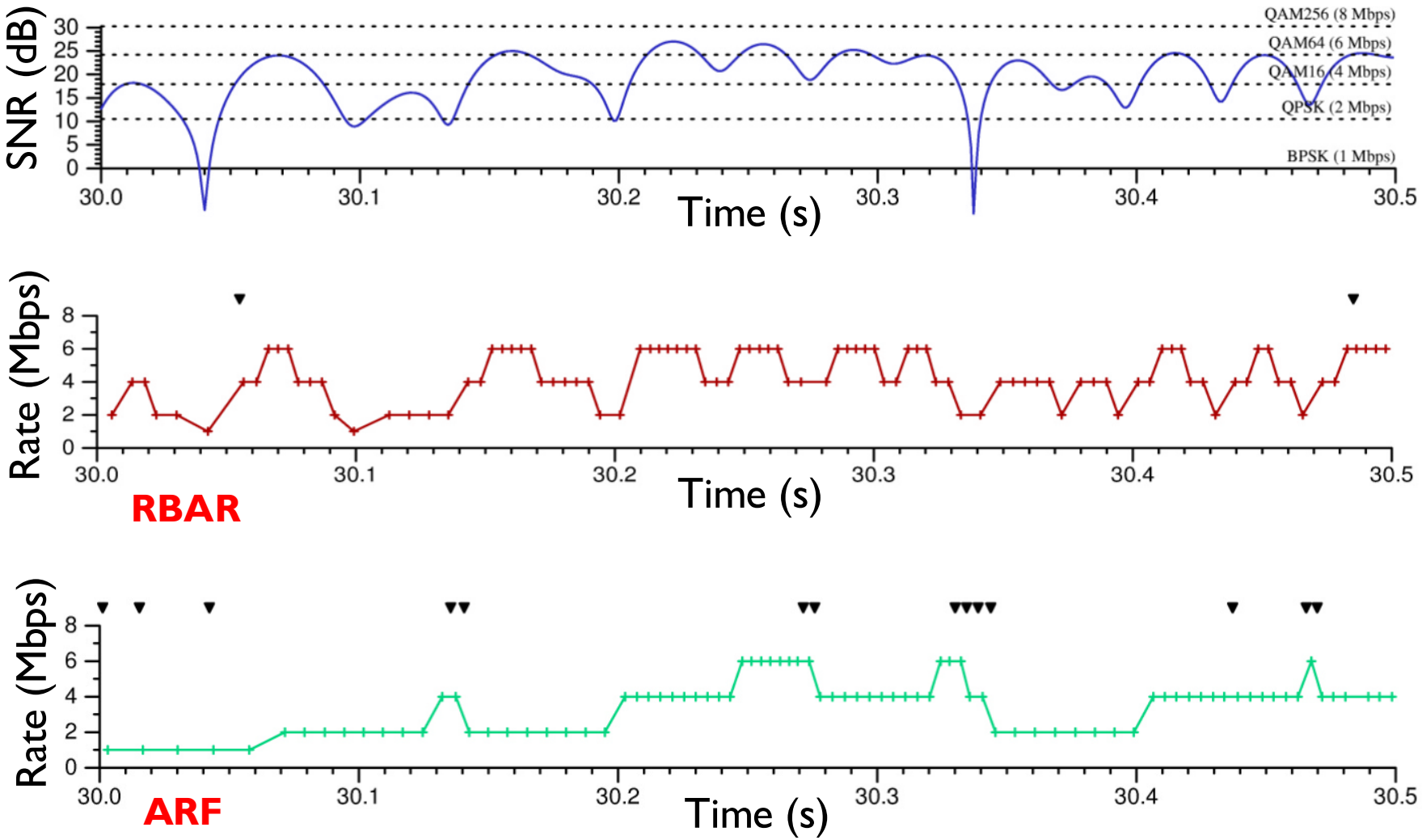
- RTS carries sender's estimate of best rate
- CTS carries receiver's selection of the best rate

RBAR

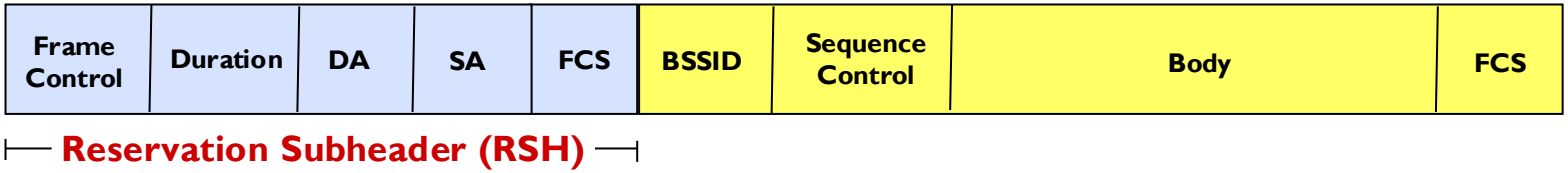


- Nodes that hear RTS/CTS calculate reservation
- If rates differ, special subheader in DATA packet updates nodes that overheard RTS

Performance of RBAR



RBAR Implementation in 802.11



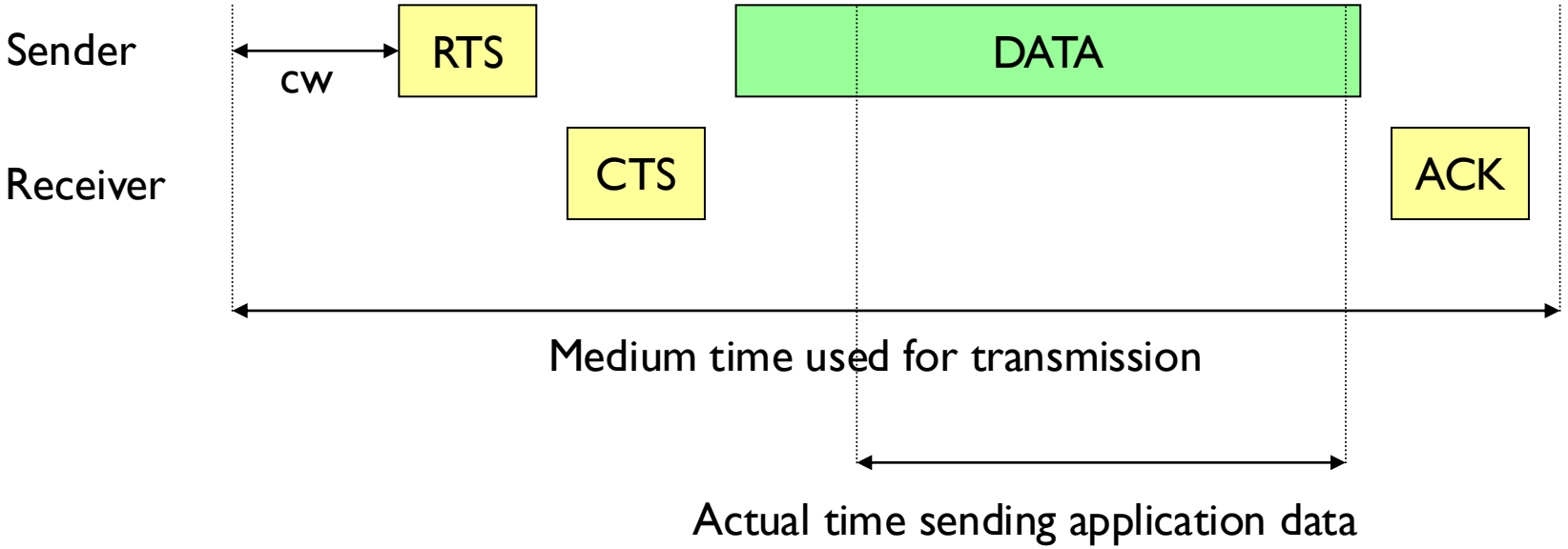
- Encode data rate and packet length in duration field of frames
  - Rate can be changed by receiver
  - Length can be used to select rate
  - Reservations are calculated using encoded rate and length
- New DATA frame type with Reservation Subheader (RSH)
  - Reservation fields protected by additional frame check sequence
  - RSH is sent at same rate as RTS/CTS
- New frame is only needed when receiver suggests rate change

RBAR Summary

- Modulation schemes have different error characteristics
- Significant performance improvement may be achieved by MAC-level adaptive modulation
- Receiver-based schemes may perform best
  - Proposed Receiver-Based Auto-Rate (RBAR) protocol
  - Implementation into 802.11
- Future thoughts …
  - RBAR without use of RTS/CTS
  - RBAR based on the size of packets
  - Routing protocols for networks with variable rate links

802.11 Frame Exchange Overhead

- Not all time is spent sending actual data



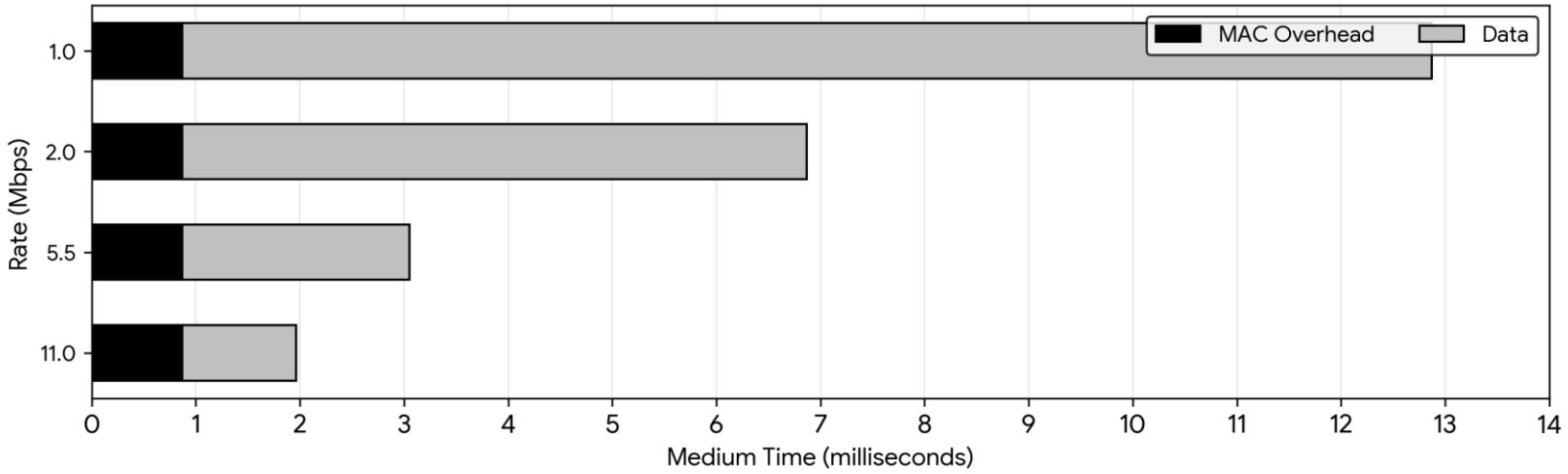
Control and Management Frame Rates

- Not everything is sent at the data rate
  - PLCP preamble and header
    - Fixed legacy format at a basic rate
  - RTS, CTS, ACK
    - Rates come from the basic rate set (highest basic rate not above the data rate)
  - Beacons, broadcast, multicast
    - Typically the lowest basic rate

Control and Management Frame Rates

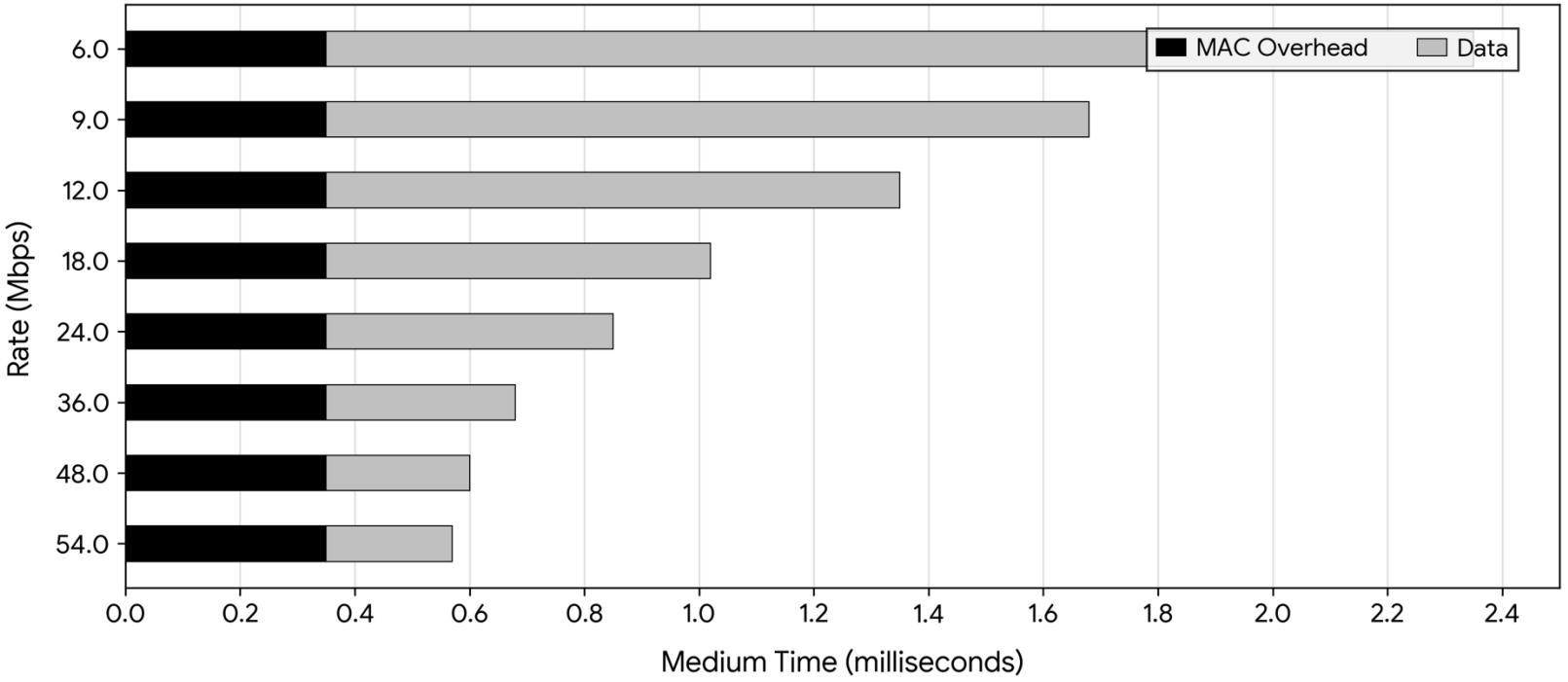
- At what rate should control frames be sent?
- Tradeoffs
  - A frame at 1 Mbps takes 54x as long as the same frame at 54 Mbps
  - Removing low basic rates (1, 2, 5.5 Mbps) reclaims airtime but shrinks coverage

802.11b Frame Exchange Duration



Medium Time consumed to transmit 1500 byte packet

802.11a Frame Exchange Duration



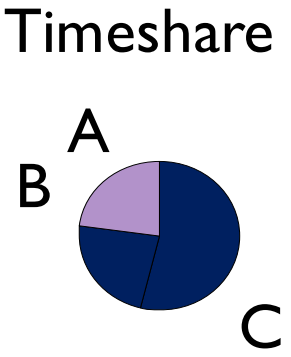
Medium Time consumed to transmit 1500 byte packet

Rate Control and Fairness

- A and B are near the AP (high rate)
- C is far away (often base rate)
  - What does ARF do?
  - What does RBAR do?

Motivation

- Same topology
  - Equal packets per node
  - C (lower rate) uses most of the channel time
- The slowest node gets the most absolute time on channel

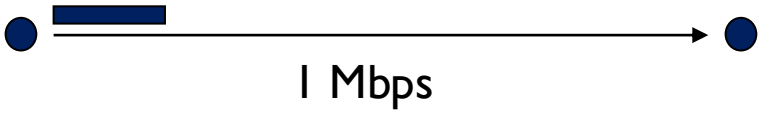


Throughput Fairness vs Temporal Fairness

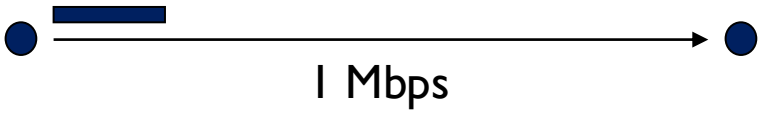
MAC Layer Fairness Models

- Per Packet Fairness
  - Clients should each send the same number of packets
- Temporal Fairness
  - Clients should each be able to send for the same amount of medium time
- In single rate networks these are the SAME!

Per Packet Fairness

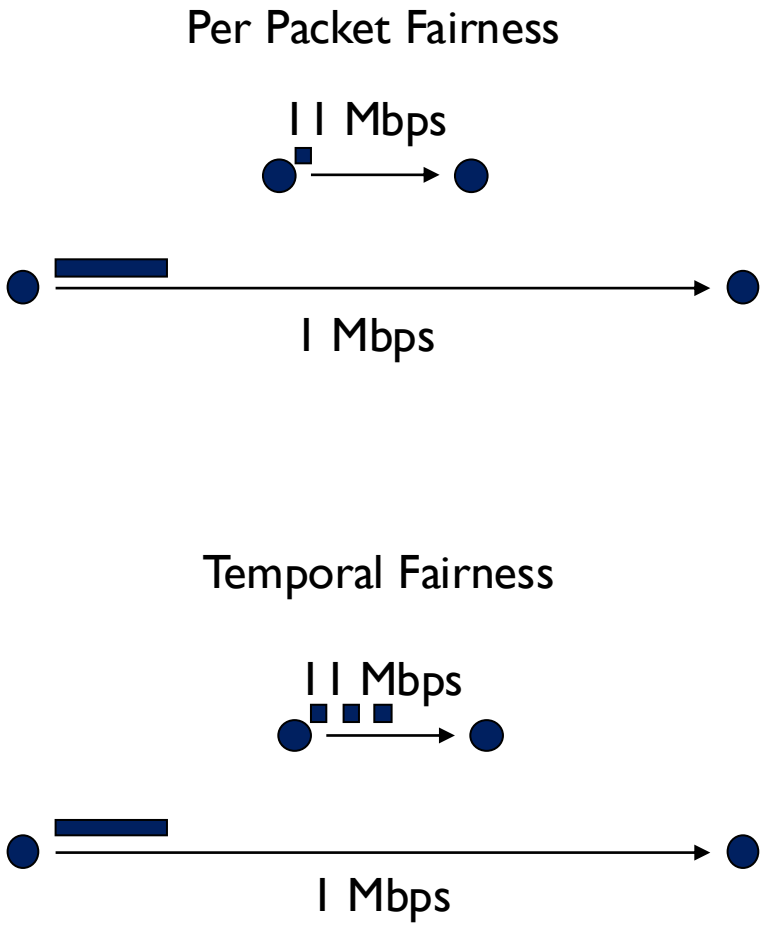


Temporal Fairness



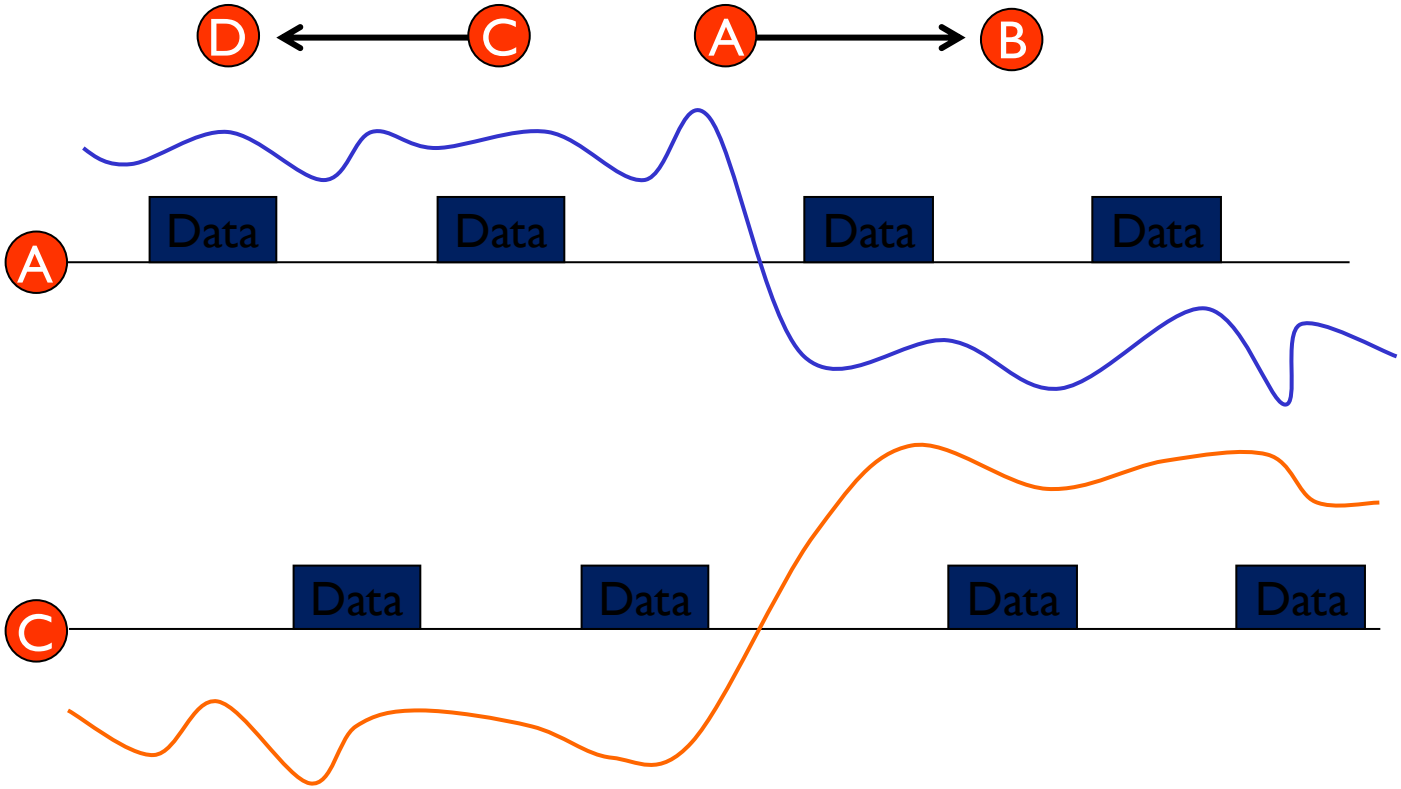
MAC Layer Fairness Models

- In a multi-rate network, these can differ widely!



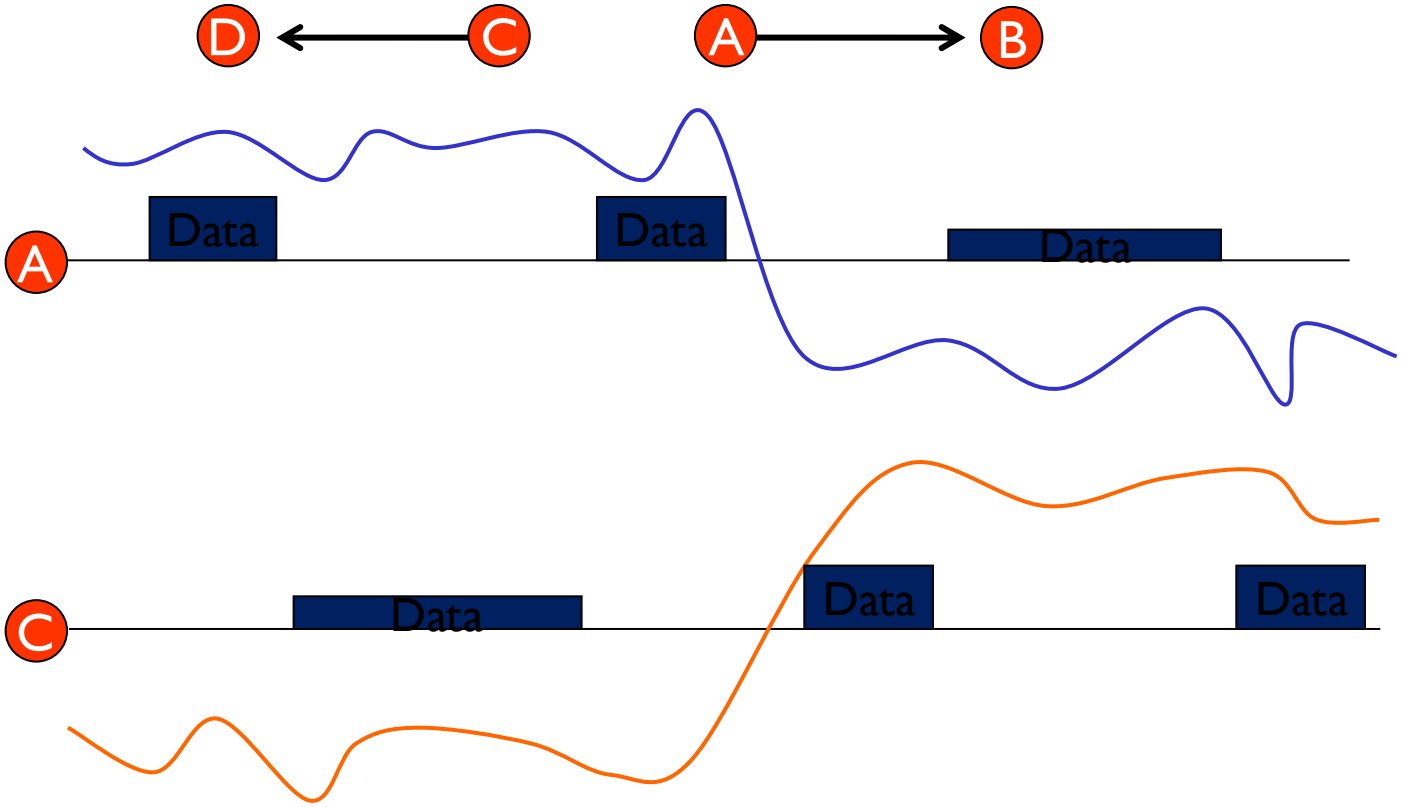
MAC Layer Fairness – Single Rate

- 802.11 alternates between transmitters A and C
  - Fair: each sender gets the same number of packets and the same airtime



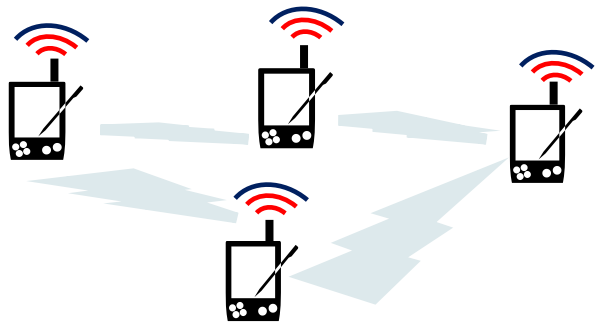
MAC Layer Fairness – Multi-rate

- Why is that bad? A bad channel increases transmit time
  - Fewer packets can be delivered



Opportunistic Scheduling

- Goal
  - Exploit short-time-scale channel quality variations to increase throughput
- Issue
  - Maintaining temporal fairness (time share) of each node
- Challenge
  - Channel info available only upon transmission



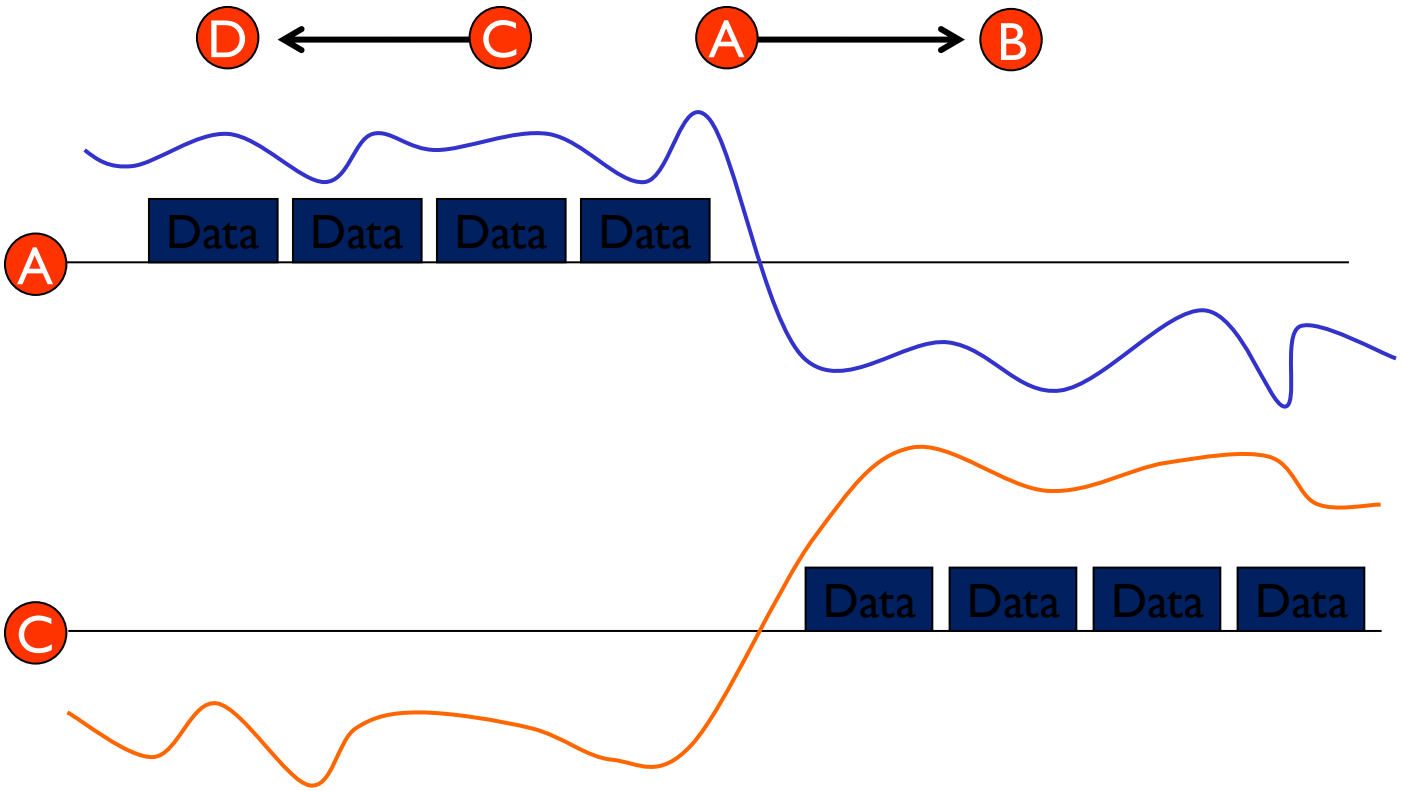
Opportunistic Auto-Rate (OAR)

- In many networks, there is intrinsic diversity
  - Exploiting this diversity can offer benefits
  - Transmit more when channel quality is high
    - else, free the channel quickly

- RBAR does not exploit this diversity
  - It optimizes per-link throughput

OAR Idea

- Basic Idea
  - Bad channel: transmit minimum number of packets
  - Good channel: transmit as much as possible



OAR Protocol Steps

- Transmitter estimates current channel
  - Can use estimation algorithms
  - Can use RBAR, etc.
- If channel better than base rate (lowest rate, e.g., 2 Mbps in 802.11b)
  - Transmit proportionally more packets
    - e.g., if channel can support N Mbps, transmit (N/Base) pkts
- OAR upholds temporal fairness
  - Each node gets same duration to transmit
  - Sacrifices throughput fairness → the network gains!!

Summary

- Rate control can be useful
  - When adapted to channel fluctuations (RBAR)
  - When opportunistically selecting transmitters (OAR)
- Benefits maximal when
  - Channel conditions vary widely in time and space
- Correlation in fluctuation can offset benefits
  - OAR may show negligible gains

Rate Control in Practice: Sampling

- Don't predict from SNR → Measure what works
  - Track delivery probability for each rate
  - Pick rate with lowest expected time per delivered packet
    - Airtime with retries / success probability
  - Send a few frames at other rates to refresh stale statistics
- SampleRate (MIT, 2005)
  - Samples a different rate about once every 10 packets
  - Skips rates that cannot beat the current one even with no losses
- Benefits
  - One lost frame does not trigger a change
  - Rates are ranked by throughput, not just up or down

Minstrel (Linux mac80211 Default)

- Statistics
  - Per-rate success ratio, smoothed with a moving average and refreshed about every 100 ms
- Lookaround
  - About 10% of frames go out at random rates to keep estimates fresh
- Multi-rate retry chain
  - Each frame gets a ranked list: best throughput, second best, most reliable, lowest rate
- Minstrel-HT
  - Extends Minstrel to 802.11n/ac
    - Grouping rates by streams, width, and guard interval
- No receiver cooperation needed, only transmit status from the NIC

802.11n Rates by Carrier Modulation and Coding

MCS	Modulation	Bits per symbol	Coding Ratio	20 MHz 800 ns	20 MHz 400 ns	40 MHz 800 ns	40 MHz 400 ns
1 Spatial Stream — Data Rates (Mbps)							
MCS0	BPSK	1	1/2	6.5	7.2	13.5	15.0
MCS1	QPSK	2	1/2	13.0	14.4	27.0	30.0
MCS2	QPSK	2	3/4	19.5	21.7	40.5	45.0
MCS3	16-QAM	4	1/2	26.0	28.9	54.0	60.0
MCS4	16-QAM	4	3/4	39.0	43.3	81.0	90.0
MCS5	64-QAM	6	2/3	52.0	57.8	108.0	120.0
MCS6	64-QAM	6	3/4	58.5	65.0	121.5	135.0
MCS7	64-QAM	6	5/6	65.0	72.2	135.0	150.0
4 Spatial Streams — Data Rates (Mbps)							
MCS24	BPSK	1	1/2	26.0	28.9	54.0	60.0
MCS25	QPSK	2	1/2	52.0	57.8	108.0	120.0
MCS26	QPSK	2	3/4	78.0	86.7	162.0	180.0
MCS27	16-QAM	4	1/2	104.0	115.6	216.0	240.0
MCS28	16-QAM	4	3/4	156.0	173.3	324.0	360.0
MCS29	64-QAM	6	2/3	208.0	231.1	432.0	480.0
MCS30	64-QAM	6	3/4	234.0	260.0	486.0	540.0
MCS31	64-QAM	6	5/6	260.0	288.9	540.0	600.0

802.11n Rates by Carrier Modulation and Coding

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MCS1	QPSK	2	1/2				
MCS2	QPSK	2	3/4				
MCS3	16-QAM	4	1/2				
MCS4	16-QAM	4	3/4				
MCS5	64-QAM	6	2/3	52.0	57.8	108.0	120.0
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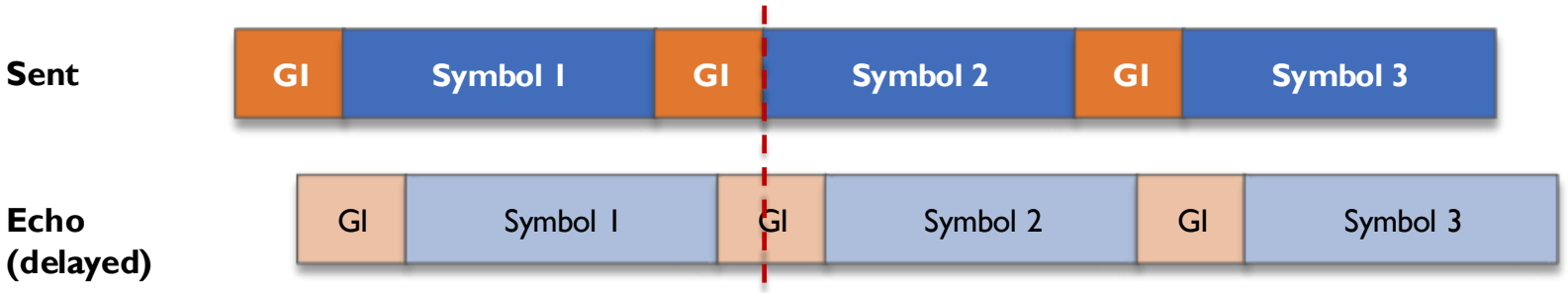
Channel width and guard interval (800 ns or 400 ns)

Guard Intervals

- Multipath: echoes of a symbol arrive after the direct signal
- The guard interval (GI) is a copy of the symbol's tail, sent first (the cyclic prefix)
  - The receiver discards it; echoes delayed less than the GI land inside it
- Trade-off: a longer GI tolerates more echo delay but costs more airtime



Receiver keeps only the data part from here. Symbol 1's echo has ended inside symbol 2's GI, so no overlap.

802.11n Rates by Carrier Modulation and Coding

MCS	Modulation	Bits per symbol	Coding Ratio	20 MHz 800 ns	20 MHz 400 ns	40 MHz 800 ns	40 MHz 400 ns
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MCS2	QPSK	2	3/4				
MCS3	16-QAM	4	1/2				
MCS4	16-QAM	4	3/4				
MCS5	64-QAM	6	2/3	52.0	57.8	108.0	120.0
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MCS30	64-QAM	6	3/4	234.0	260.0	486.0	540.0
MCS31	64-QAM	6	5/6	260.0	288.9	540.0	600.0

Longer guard intervals reduce channel bandwidth

802.11n Rates by Carrier Modulation and Coding

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MCS26	QPSK	2	3/4	78.0	86.7	162.0	180.0
MCS27	16-QAM	4	1/2	104.0			
MCS28	16-QAM	4	3/4	156			
MCS29	64-QAM	6	2/3	208			
MCS30	64-QAM	6	3/4	234			
MCS31	64-QAM	6	5/6	260.0	288.9	540.0	600.0

Number of spatial streams

802.11n Rates by Carrier Modulation and Coding

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MCS2	QPSK	2	3/4	19.5	21.7	40.5	45.0
MCS3	16-QAM	4	1/2				
MCS4	16-QAM	4	3/4				
MCS5	64-QAM	6	2/3				
MCS6	64-QAM	6	3/4				
MCS7	64-QAM	6	5/6				
4 Spatial Streams —							
MCS24	BPSK	1	1/2	26.0	28.9	54.0	60.0
MCS25	QPSK	2	1/2	52.0	57.8	108.0	120.0
MCS26	QPSK	2	3/4	78.0	86.7	162.0	180.0
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MCS29	64-QAM	6	2/3	208.0	231.1	432.0	480.0
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MCS31	64-QAM	6	5/6	260.0	288.9	540.0	600.0

QPSK
R 1/2 → 3/4
13Mbps → 19.5 Mbps (1 stream)
52Mbps → 78Mbps (4 streams)

802.11n Rates by Carrier Modulation and Coding

MCS	Modulation	Bits per symbol	Coding Ratio	20 MHz 800 ns	20 MHz 400 ns	40 MHz 800 ns	40 MHz 400 ns
1 Spatial Stream — Data Rates (Mbps)							
MCS0	BPSK	1	1/2	6.5	7.2	13.5	15.0
MCS1	QPSK	2	1/2	13.0	14.4		
MCS2	QPSK	2	3/4	19.5	21.7		
MCS3	16-QAM	4	1/2	26.0	28.9		
MCS4	16-QAM	4	3/4	39.0	43.3		
MCS5	64-QAM	6	2/3	52.0	57.8		
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MCS7	64-QAM	6	5/6	65.0	72.2		
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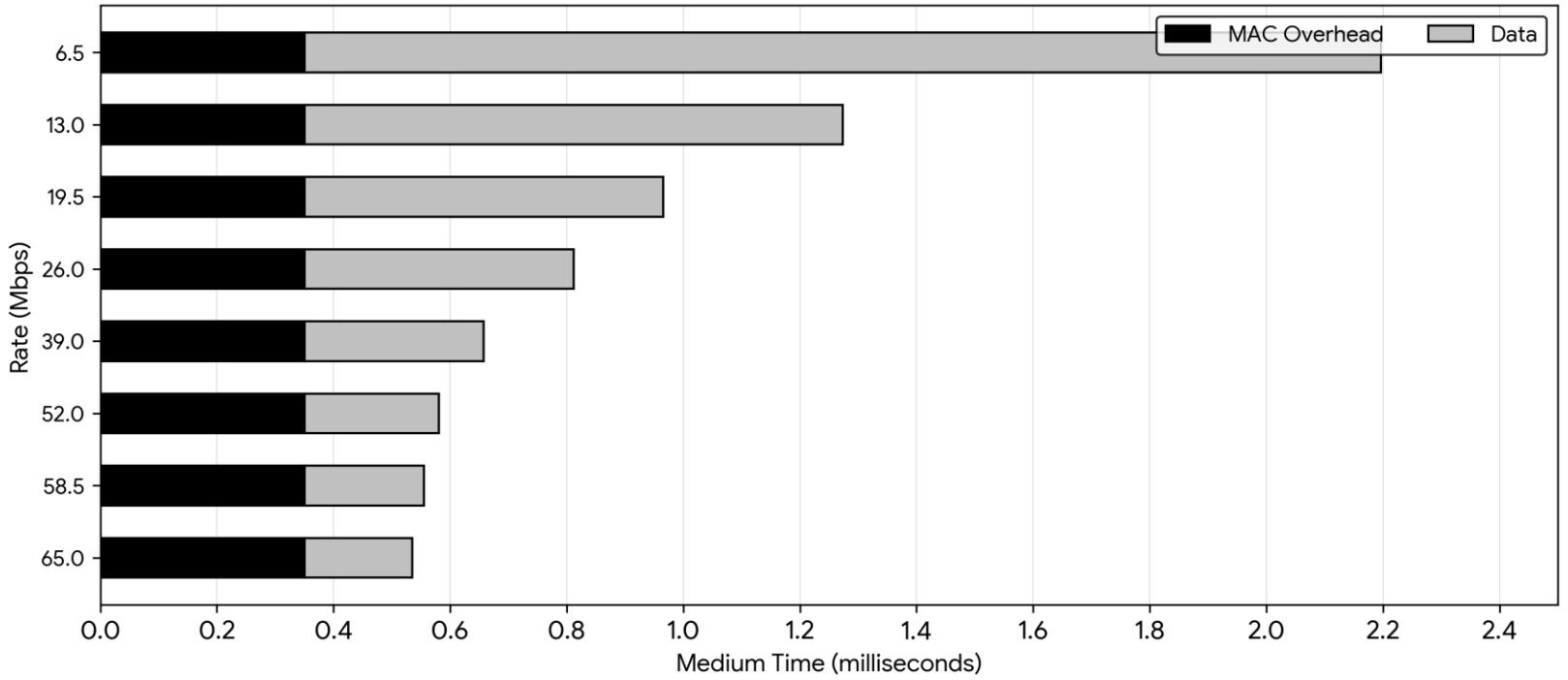
MCS24	BPSK	1	1/2	26.0	28.9		
MCS25	QPSK	2	1/2	52.0	57.8		
MCS26	QPSK	2	3/4	78.0	86.7		
MCS27	16-QAM	4	1/2	104.0	115.6		
MCS28	16-QAM	4	3/4	156.0	173.3		
MCS29	64-QAM	6	2/3	208.0	231.1		
MCS30	64-QAM	6	3/4	234.0	260.0	486.0	540.0
MCS31	64-QAM	6	5/6	260.0	288.9	540.0	600.0

Same rate, different configurations

52 Mbps (20 MHz)
1 stream at 64-QAM 2/3
4 streams at QPSK 1/2

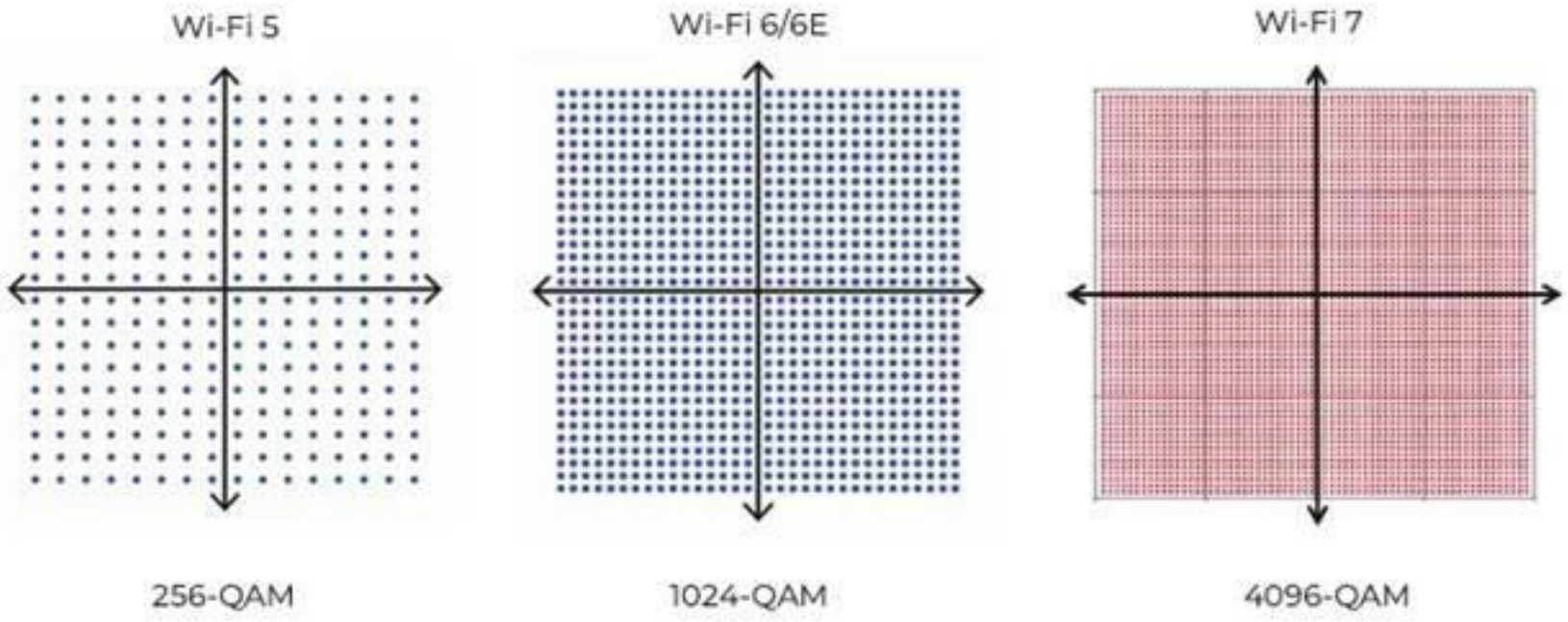
Best choice depends on the channel
Extra streams need high SNR and rich scattering

802.11n Frame Exchange Duration



Medium Time consumed to transmit 1500 byte packet

Next Level Carrier Modulations



8 bits per symbol

10 bits per symbol

12 bits per symbol

802.11ac Rates by Carrier Modulation and Coding

		Bits	Coding	20 Mhz		40 Mhz		80 Mhz		160 Mhz	
MCS	Modulation	per symbol	Ratio	800 ns	400 ns	800 ns	400 ns	800 ns	400 ns	800 ns	400 ns
1 Spatial Stream				Data Rates(Mbps)							
MCS0	BPSK	1	½	6.5	7.2	13.5	15.0	29.3	32.5	58.5	65.0
MCS1	QPSK	2	½	13.0	14.4	27.0	30.0	58.5	65.0	117.0	130.0
MCS2	QPSK	2	¾	19.5	21.7	40.5	45.0	87.8	97.5	175.5	195.0
MCS3	16-QAM	4	½	26.0	28.9	54.0	60.0	117.0	130.0	234.0	260.0
MCS4	16-QAM	4	¾	39.0	43.3	81.0	90.0	175.5	195.0	351.0	390.0
MCS5	64-QAM	6	2/3	52.0	57.8	108.0	120.0	234.0	260.0	468.0	520.0
MCS6	64-QAM	6	¾	58.5	65.0	121.5	135.0	263.3	292.5	526.5	585.0
MCS7	64-QAM	6	5/6	65.0	72.2	135.0	150.0	292.5	325.0	585.0	650.0
MCS8	256-QAM	8	¾	78.0	86.7	162.0	180.0	351.0	390.0	702.0	780.0
MCS9	256-QAM	8	5/6	N/A	N/A	180.0	200.0	390.0	433.3	780.0	866.7
8 Spatial streams				Data Rates(Mbps)							
MCS0	BPSK	1	½	52.0	57.8	108.0	120.0	234.0	260.0	468.0	520.0
MCS1	QPSK	2	½	104.0	115.6	216.0	240.0	468.0	520.0	936.0	1040
MCS2	QPSK	2	¾	156.0	173.3	324.0	360.0	702.0	780.0	1404	1560
MCS3	16-QAM	4	½	208.0	231.1	432.0	480.0	936.0	1040	1872	2080
MCS4	16-QAM	4	¾	312.0	346.7	648.0	720.0	1404	1560	2808	3120
MCS5	64-QAM	6	2/3	416.0	482.2	884.0	960.0	1872	2080	3744	4160
MCS6	64-QAM	6	¾	468.0	520.0	972.0	1080	1200	2340	4120	4680
MCS7	64-QAM	6	5/6	520	577.8	1080	1200	2340	2600	4680	5200
MCS8	256-QAM	8	¾	624.0	693.3	1296	1440	2808	3120	5616	6240
MCS9	256-QAM	8	5/6	N/A	N/A	1440	1600	3120	3466	6240	6933

802.11ac Rates by Carrier Modulation and Coding

MCS	Modulation	Bits per symbol	Coding Ratio	20 Mhz		40 Mhz		80 Mhz		160 Mhz	
				800 ns	400 ns	800 ns	400 ns	800 ns	400 ns	800 ns	400 ns
1 Spatial Stream				Data Rates(Mbps)							
MCS0	BPSK	1	½	6.5	7.2						
MCS1	QPSK	2	½	13.0	14.4						
MCS2	QPSK	2	¾	19.5	21.7						
MCS3	16-QAM	4	½	26.0	28.9						
MCS4	16-QAM	4	¾	39.0	43.3						
MCS5	64-QAM	6	2/3	52.0	57.8	108.0	120.0	234.0	260.0	468.0	520.0
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MCS0	BPSK	1	½	52.0	57.8	108.0	120.0	234.0	260.0	468.0	520.0
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MCS9	256-QAM	8	5/6	N/A	N/A	1440	1600	3120	3466	6240	6933

Channel width and guard interval (800 ns or 400 ns)

802.11ac Rates by Carrier Modulation and Coding

MCS	Modulation	Bits per symbol	Coding Ratio	20 Mhz		40 Mhz		80 Mhz		160 Mhz	
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MCS4	16-QAM	4	¾	312.0	346.						0
MCS5	64-QAM	6	2/3	416.0	482.						0
MCS6	64-QAM	6	¾	468.0	520.						0
MCS7	64-QAM	6	5/6	520	577.						0
MCS8	256-QAM	8	¾	624.0	693.						0
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Number of spatial streams

802.11ac Rates by Carrier Modulation and Coding

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MCS2	QPSK	2	¾	19.5	21.7						.0
MCS3	16-QAM	4	½	26.0	28.9						.0
MCS4	16-QAM	4	¾	39.0	43.3						.0
MCS5	64-QAM	6	2/3	52.0	57.8						.0
MCS6	64-QAM	6	¾	58.5	65.0						.0
MCS7	64-QAM	6	5/6	65.0	72.2						.0
MCS8	256-QAM	8	¾	78.0	86.7						.0
MCS9	256-QAM	8	5/6	N/A	N/A						.7
8 Spatial streams				Data Rates(M							
MCS0	BPSK	1	½	52.0	57.8						.0
MCS1	QPSK	2	½	104.0	115.						0
MCS2	QPSK	2	¾	156.0	173.						0
MCS3	16-QAM	4	½	208.0	231.						0
MCS4	16-QAM	4	¾	312.0	346.						0
MCS5	64-QAM	6	2/3	416.0	482.						0
MCS6	64-QAM	6	¾	468.0	520.						0
MCS7	64-QAM	6	5/6	520	577.						0
MCS8	256-QAM	8	¾	624.0	693.						0
MCS9	256-QAM	8	5/6	N/A	N/A	1440	1600	3120	3466	6240	6933

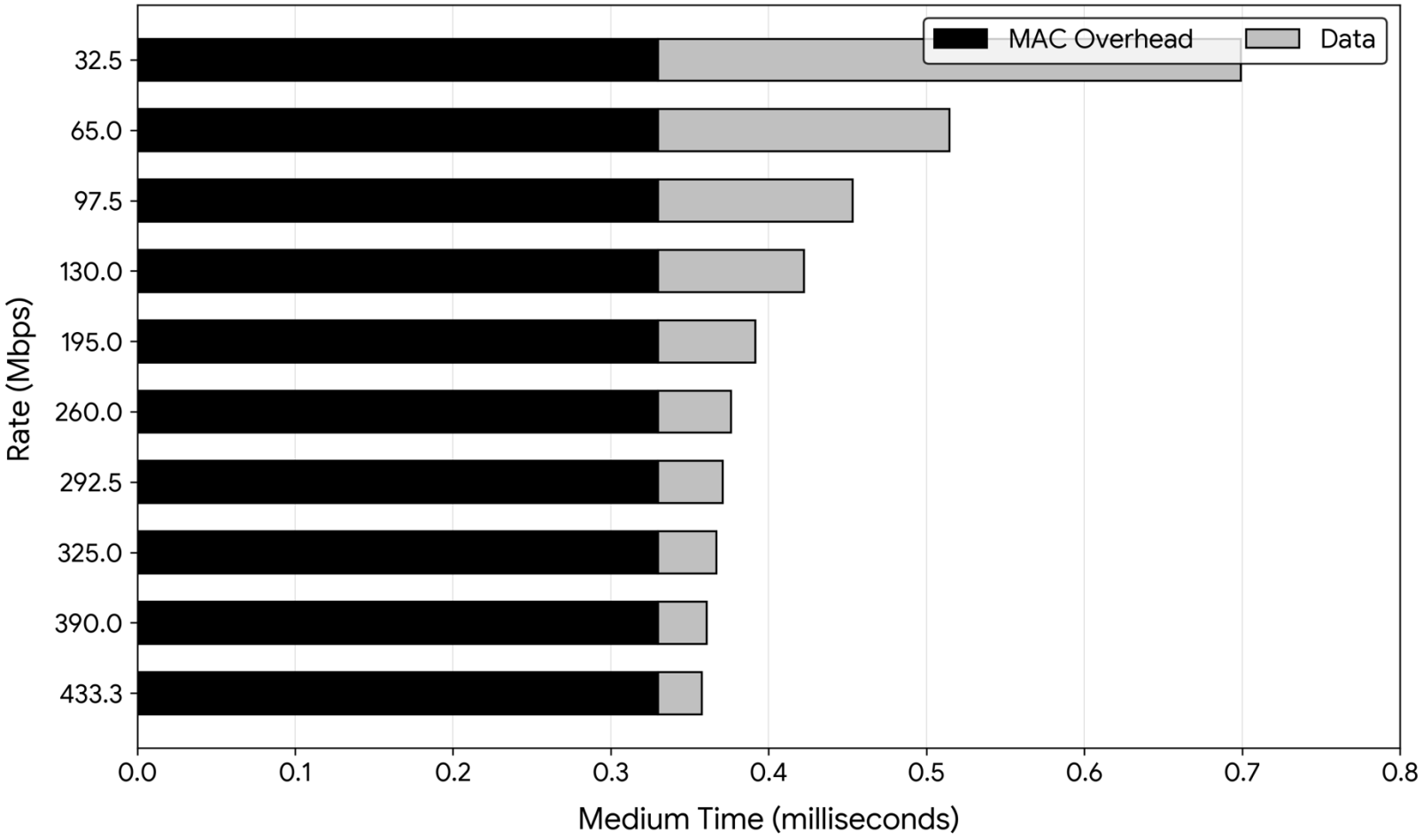
Same rate, different configurations

52 Mbps (20 MHz)
1 stream at 64-QAM 2/3
8 streams at BPSK 1/2

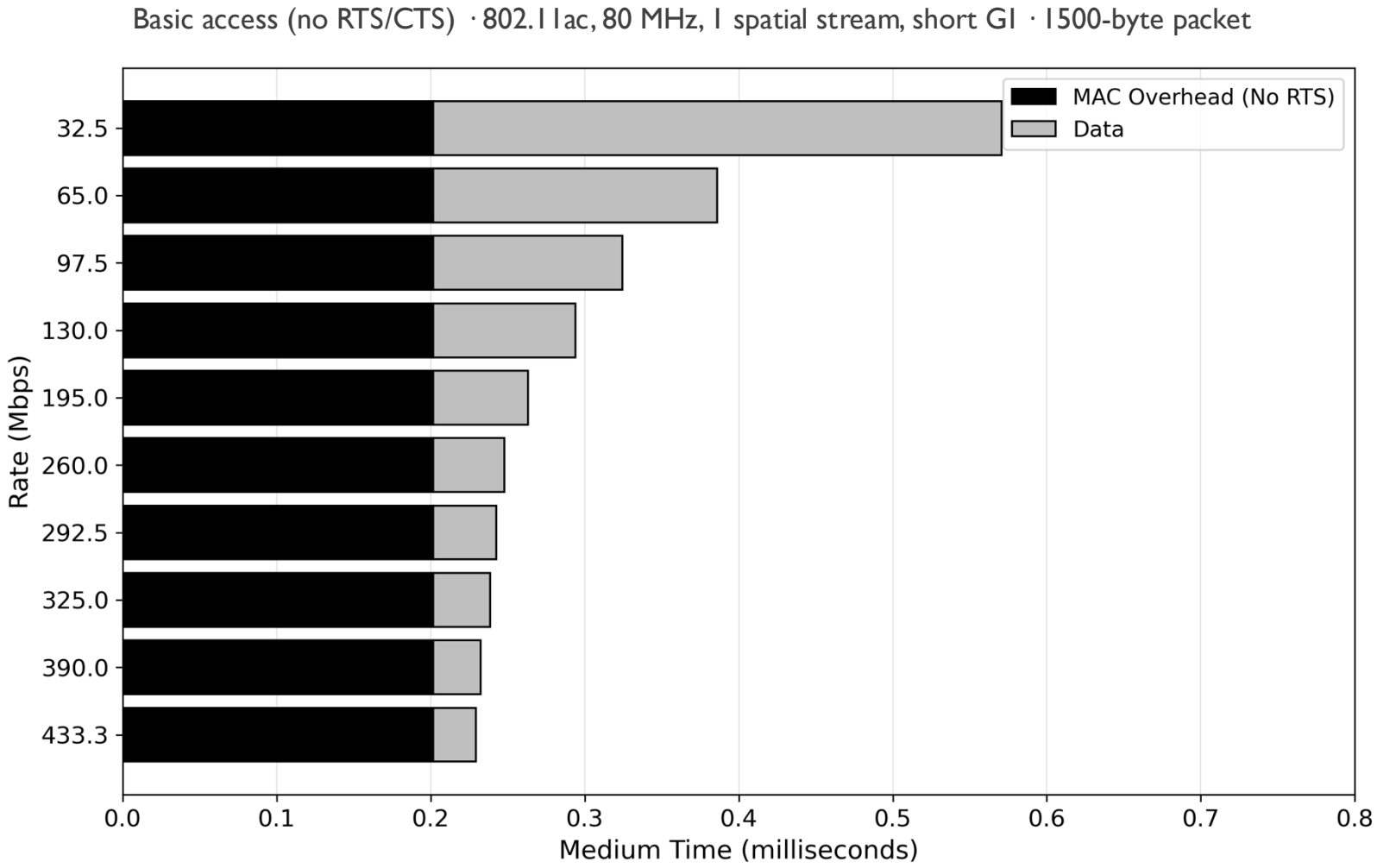
Best choice depends on the channel
Extra streams need high SNR and rich scattering

802.11ac Frame Exchange Duration

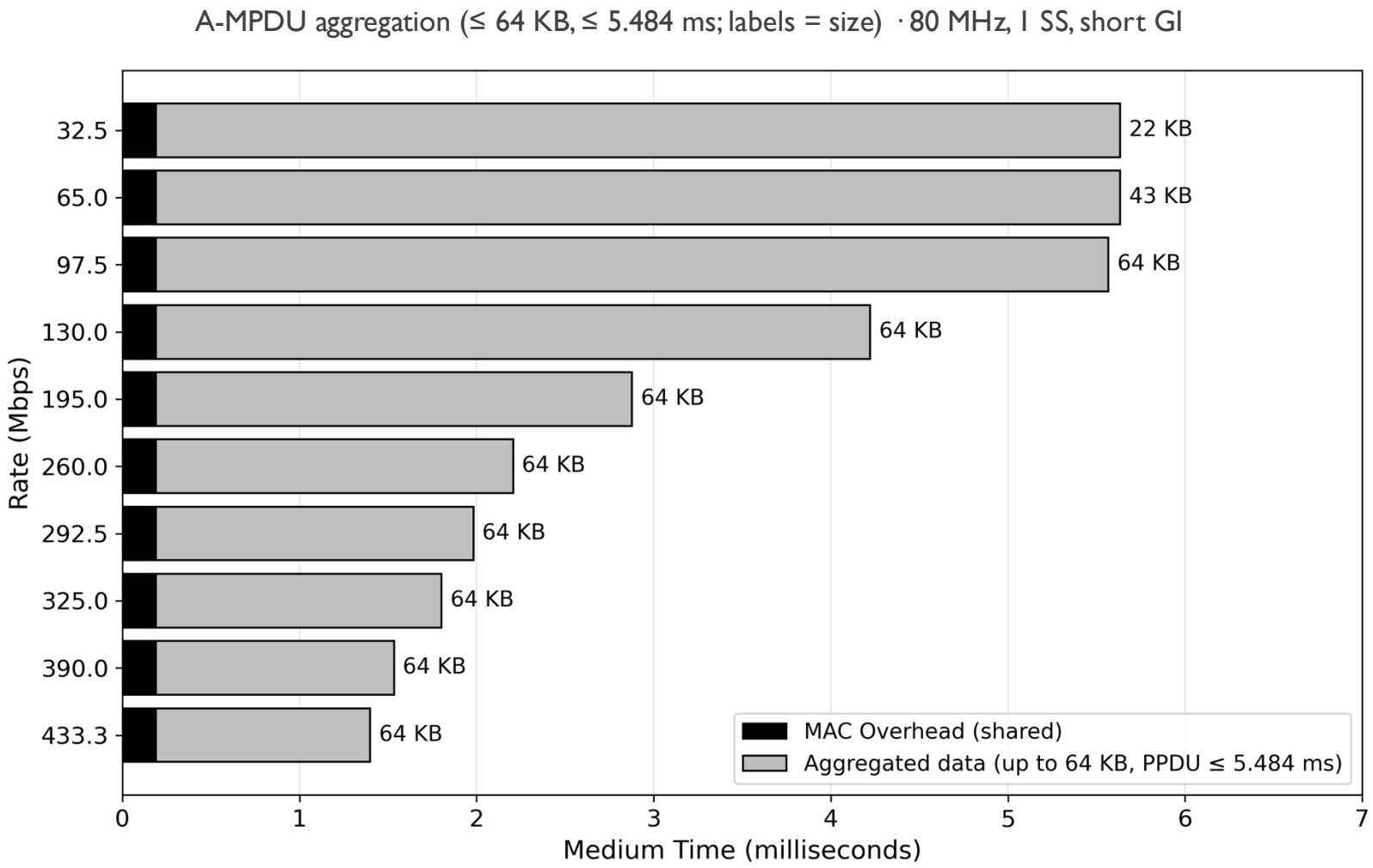
With RTS/CTS · 802.11ac, 80 MHz, 1 spatial stream, short GI (MCS 0–9) · 1500-byte packet



802.11ac Frame Exchange (no RTS)



802.11ac (no RTS + Frame Aggregation)

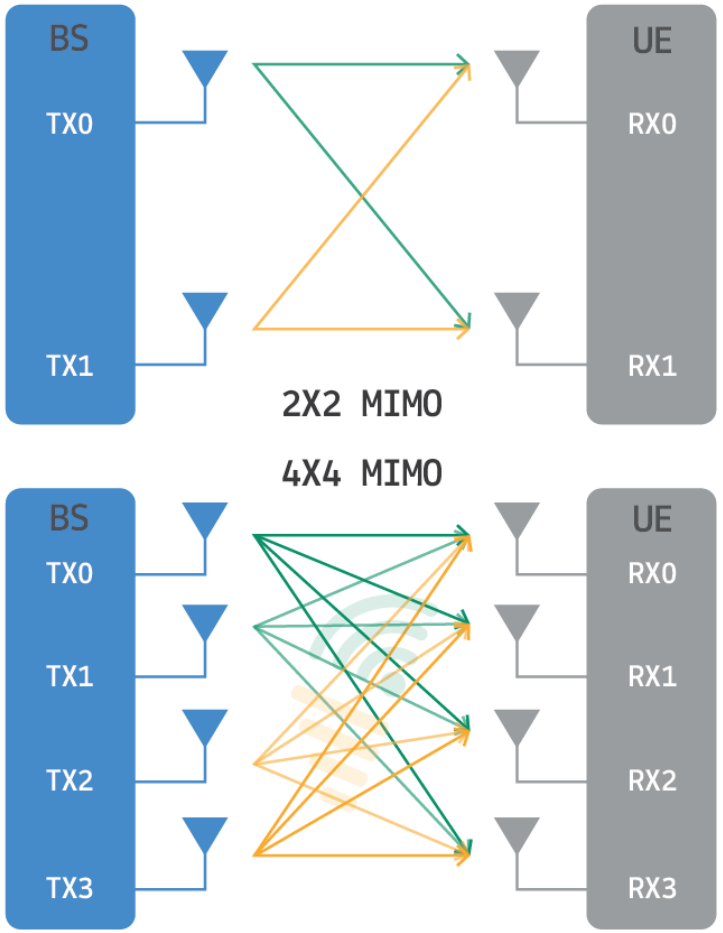


Aggregation and Rate Control

- A-MPDU
  - One PPDU carries many subframes, acknowledged by a Block Ack bitmap
- Feedback is now per subframe
  - Early subframes OK and later ones lost suggests the channel changed mid-PPDU
- Long aggregates at high rates are riskier
  - The channel estimate from the preamble goes stale during a long PPDU
- Tradeoff
  - Longer aggregate
    - Less overhead, but more airtime wasted on a failure, and more latency
  - The controller must choose the rate and the aggregate size together

802.11n/ac Rate Control

- What is the best configuration?
  - 2x2?
  - 4x4?
  - Others?
- Even more complex with ac (up to 8x8)



Rate Control in the MIMO Era

- Choices multiply
  - MCS x streams x bandwidth x guard interval
    - 802.11n: 77 MCS indices
    - 802.11ac: roughly 10 x 8 x 4 x 2 = 640 combinations (not all valid)
- Practical approach
  - Search within groups and prefer fewer streams when the channel is poor or correlated
  - More active streams also cost more power

802.11ax Rates by Carrier Modulation and Coding

MCS Index	Spatial Stream	Modulation	Coding	OFDM (802.11ax)											
				20MHz			40MHz			80MHz			160MHz		
				0.8µs GI	1.6µs GI	3.2µs GI	0.8µs GI	1.6µs GI	3.2µs GI	0.8µs GI	1.6µs GI	3.2µs GI	0.8µs GI	1.6µs GI	3.2µs GI
0	1	BPSQ	1/2	8.6	8.1	7.3	17.2	16.3	14.6	36.0	34.0	30.6	72.1	68.1	61.3
1	1	QPSK	1/2	17.2	16.3	14.6	34.4	32.5	29.3	72.1	68.1	61.3	144.1	136.1	122.5
2	1	QPSK	3/4	25.8	24.4	21.9	51.6	48.8	43.9	108.1	102.1	91.9	216.2	204.2	183.8
3	1	16-QAM	1/2	34.4	32.5	29.3	68.8	65.0	58.5	144.1	136.1	122.5	288.2	272.2	245.0
4	1	16-QAM	3/4	51.6	48.8	43.9	103.2	97.5	87.8	216.2	204.2	183.8	432.4	408.3	367.5
5	1	64-QAM	2/3	68.8	65.0	58.5	137.6	130.0	117.0	288.2	272.2	245.0	576.5	544.4	490.0
6	1	64-QAM	3/4	77.4	73.1	65.8	154.9	146.3	131.6	324.3	306.3	275.6	648.5	612.5	551.3
7	1	64-QAM	5/6	86.0	81.3	73.1	172.1	162.5	146.3	360.3	340.3	306.3	720.6	680.6	612.5
8	1	256-QAM	3/4	103.2	97.5	87.8	206.5	195.0	175.5	432.4	408.3	367.5	864.7	816.7	735.0
9	1	256-QAM	5/6	114.7	108.3	97.5	229.4	216.7	195.0	480.4	453.7	408.3	960.8	907.4	816.7
10	1	1024-QAM	3/4	129.0	121.9	109.7	258.1	243.8	219.4	540.4	510.4	459.4	1080.9	1020.8	918.8
11	1	1024-QAM	5/6	143.4	135.4	121.9	286.8	270.8	243.8	600.5	567.1	510.4	1201.0	1134.3	1020.8
0	2	BPSQ	1/2	17.2	16.3	14.6	34.4	32.5	29.3	72.1	68.1	61.3	144.1	136.1	122.5
1	2	QPSK	1/2	34.4	32.5	29.3	68.8	65.0	58.5	144.1	136.1	122.5	288.2	272.2	245.0
2	2	QPSK	3/4	51.6	48.8	43.9	103.2	97.5	87.8	216.2	204.2	183.8	432.4	408.3	367.5
3	2	16-QAM	1/2	68.8	65.0	58.5	137.6	130.0	117.0	288.2	272.2	245.0	576.5	544.4	490.0
4	2	16-QAM	3/4	103.2	97.5	87.8	206.5	195.0	175.5	432.4	408.3	367.5	864.7	816.7	735.0
5	2	64-QAM	2/3	137.6	130.0	117.0	275.3	260.0	234.0	576.5	544.4	490.0	1152.9	1088.9	980.0
6	2	64-QAM	3/4	154.9	146.3	131.6	309.7	292.5	263.3	648.5	612.5	551.3	1297.1	1225.0	1102.5
7	2	64-QAM	5/6	172.1	162.5	146.3	344.1	325.0	292.5	720.6	680.6	612.5	1441.2	1361.1	1225.0
8	2	256-QAM	3/4	206.5	195.0	175.5	412.9	390.0	351.0	864.7	816.7	735.0	1729.4	1633.3	1470.0
9	2	256-QAM	5/6	229.4	216.7	195.0	458.8	433.3	390.0	960.8	907.4	816.7	1921.6	1814.8	1633.3
10	2	1024-QAM	3/4	258.1	243.8	219.4	516.2	487.5	438.8	1080.9	1020.8	918.8	2161.8	2041.7	1837.5
11	2	1024-QAM	5/6	286.8	270.8	243.8	573.5	541.7	487.5	1201.0	1134.3	1020.8	2402.0	2268.5	2041.7
0	3	BPSQ	1/2	25.8	24.4	21.9	51.6	48.8	43.9	108.1	102.1	91.9	216.2	204.2	183.8
1	3	QPSK	1/2	51.6	48.8	43.9	103.2	97.5	87.8	216.2	204.2	183.8	432.4	408.3	367.5
2	3	QPSK	3/4	77.4	73.1	65.8	154.9	146.3	131.6	324.3	306.3	275.6	648.5	612.5	551.3
3	3	16-QAM	1/2	103.2	97.5	87.8	206.5	195.0	175.5	432.4	408.3	367.5	864.7	816.7	735.0
4	3	16-QAM	3/4	154.9	146.3	131.6	309.7	292.5	263.3	648.5	612.5	551.3	1297.1	1225.0	1102.5
5	3	64-QAM	2/3	206.5	195.0	175.5	412.9	390.0	351.0	864.7	816.7	735.0	1729.4	1633.3	1470.0
6	3	64-QAM	3/4	232.3	219.4	197.4	464.6	438.8	394.9	972.8	918.8	826.9	1945.6	1837.5	1653.8
7	3	64-QAM	5/6	258.1	243.8	219.4	516.2	487.5	438.8	1080.9	1020.8	918.8	2161.8	2041.7	1837.5
8	3	256-QAM	3/4	309.7	292.5	263.3	619.4	585.0	526.5	1297.1	1225.0	1102.5	2594.1	2450.0	2205.0
9	3	256-QAM	5/6	344.1	325.0	292.5	688.2	650.0	585.0	1441.2	1361.1	1225.0	2882.4	2722.2	2450.0
10	3	1024-QAM	3/4	387.1	365.6	329.1	774.3	731.3	658.1	1621.3	1531.3	1378.1	3242.6	3062.5	2756.3
11	3	1024-QAM	5/6	430.1	406.3	365.6	860.3	812.5	731.3	1801.5	1701.4	1531.3	3602.9	3402.8	3062.5

802.11ax Rates by Carrier Modulation and Coding

MCS Index	Spatial Stream	Modulation	Coding	OFDM (802.11ax)											
				20MHz			40MHz			80MHz			160MHz		
				0.8µs GI	1.6µs GI	3.2µs GI	0.8µs GI	1.6µs GI	3.2µs GI	0.8µs GI	1.6µs GI	3.2µs GI	0.8µs GI	1.6µs GI	3.2µs GI
0	1	BPSQ	1/2	8.6	8.1	7.3	17.2	16.3	14.6	36.0	34.0	30.6	72.1	68.1	61.3
1	1	QPSK	1/2	17.2	16.3	14.6	34.4	32.5	29.3	72.1	68.1	61.3	144.1	136.1	122.5
2	1	QPSK	3/4	25.8	24.4	21.9	51.6	48.8	43.9	108.1	102.1	91.9	216.2	204.2	183.8
3	1	16-QAM	1/2	34.4	32.5	29.3	68.8	65.0	58.5						
4	1	16-QAM	3/4	51.6	48.8	43.9	103.2	97.5	87.8						
5	1	64-QAM	2/3	68.8	65.0	58.5	137.6	130.0	117.0						
6	1	64-QAM	3/4	77.4	73.1	65.8	154.9	146.3	131.6						
7	1	64-QAM	5/6	86.0	81.3	73.1	172.1	162.5	146.3						
8	1	256-QAM	3/4	103.2	97.5	87.8	206.5	195.0	175.5						
9	1	256-QAM	5/6	114.7	108.3	97.5	229.4	216.7	195.0						
10	1	1024-QAM	3/4	129.0	121.9	109.7	258.1	243.8	219.4						
11	1	1024-QAM	5/6	143.4	135.4	121.9	286.8	270.8	243.8						
0	2	BPSQ	1/2	17.2	16.3	14.6	34.4	32.5	29.3						
1	2	QPSK	1/2	34.4	32.5	29.3	68.8	65.0	58.5						
2	2	QPSK	3/4	51.6	48.8	43.9	103.2	97.5	87.8	216.2	204.2	183.8	432.4	408.3	367.5
3	2	16-QAM	1/2	68.8	65.0	58.5	137.6	130.0	117.0	288.2	272.2	245.0	576.5	544.4	490.0
4	2	16-QAM	3/4	103.2	97.5	87.8	206.5	195.0	175.5	432.4	408.3	367.5	864.7	816.7	735.0
5	2	64-QAM	2/3	137.6	130.0	117.0	275.3	260.0	234.0	576.5	544.4	490.0	1152.9	1088.9	980.0
6	2	64-QAM	3/4	154.9	146.3	131.6	309.7	292.5	263.3	648.5	612.5	551.3	1297.1	1225.0	1102.5
7	2	64-QAM	5/6	172.1	162.5	146.3	344.1	325.0	292.5	720.6	680.6	612.5	1441.2	1361.1	1225.0
8	2	256-QAM	3/4	206.5	195.0	175.5	412.9	390.0	351.0	864.7	816.7	735.0	1729.4	1633.3	1470.0
9	2	256-QAM	5/6	229.4	216.7	195.0	458.8	433.3	390.0	960.8	907.4	816.7	1921.6	1814.8	1633.3
10	2	1024-QAM	3/4	258.1	243.8	219.4	516.2	487.5	438.8	1080.9	1020.8	918.8	2161.8	2041.7	1837.5
11	2	1024-QAM	5/6	286.8	270.8	243.8	573.5	541.7	487.5	1201.0	1134.3	1020.8	2402.0	2268.5	2041.7
0	3	BPSQ	1/2	25.8	24.4	21.9	51.6	48.8	43.9	108.1	102.1	91.9	216.2	204.2	183.8
1	3	QPSK	1/2	51.6	48.8	43.9	103.2	97.5	87.8	216.2	204.2	183.8	432.4	408.3	367.5
2	3	QPSK	3/4	77.4	73.1	65.8	154.9	146.3	131.6	324.3	306.3	275.6	648.5	612.5	551.3
3	3	16-QAM	1/2	103.2	97.5	87.8	206.5	195.0	175.5	432.4	408.3	367.5	864.7	816.7	735.0
4	3	16-QAM	3/4	154.9	146.3	131.6	309.7	292.5	263.3	648.5	612.5	551.3	1297.1	1225.0	1102.5
5	3	64-QAM	2/3	206.5	195.0	175.5	412.9	390.0	351.0	864.7	816.7	735.0	1729.4	1633.3	1470.0
6	3	64-QAM	3/4	232.3	219.4	197.4	464.6	438.8	394.9	972.8	918.8	826.9	1945.6	1837.5	1653.8
7	3	64-QAM	5/6	258.1	243.8	219.4	516.2	487.5	438.8	1080.9	1020.8	918.8	2161.8	2041.7	1837.5
8	3	256-QAM	3/4	309.7	292.5	263.3	619.4	585.0	526.5	1297.1	1225.0	1102.5	2594.1	2450.0	2205.0
9	3	256-QAM	5/6	344.1	325.0	292.5	688.2	650.0	585.0	1441.2	1361.1	1225.0	2882.4	2722.2	2450.0
10	3	1024-QAM	3/4	387.1	365.6	329.1	774.3	731.3	658.1	1621.3	1531.3	1378.1	3242.6	3062.5	2756.3
11	3	1024-QAM	5/6	430.1	406.3	365.6	860.3	812.5	731.3	1801.5	1701.4	1531.3	3602.9	3402.8	3062.5

Guard interval

Longer guard intervals help in dense multipath environments

802.11ax Rates by Carrier Modulation and Coding

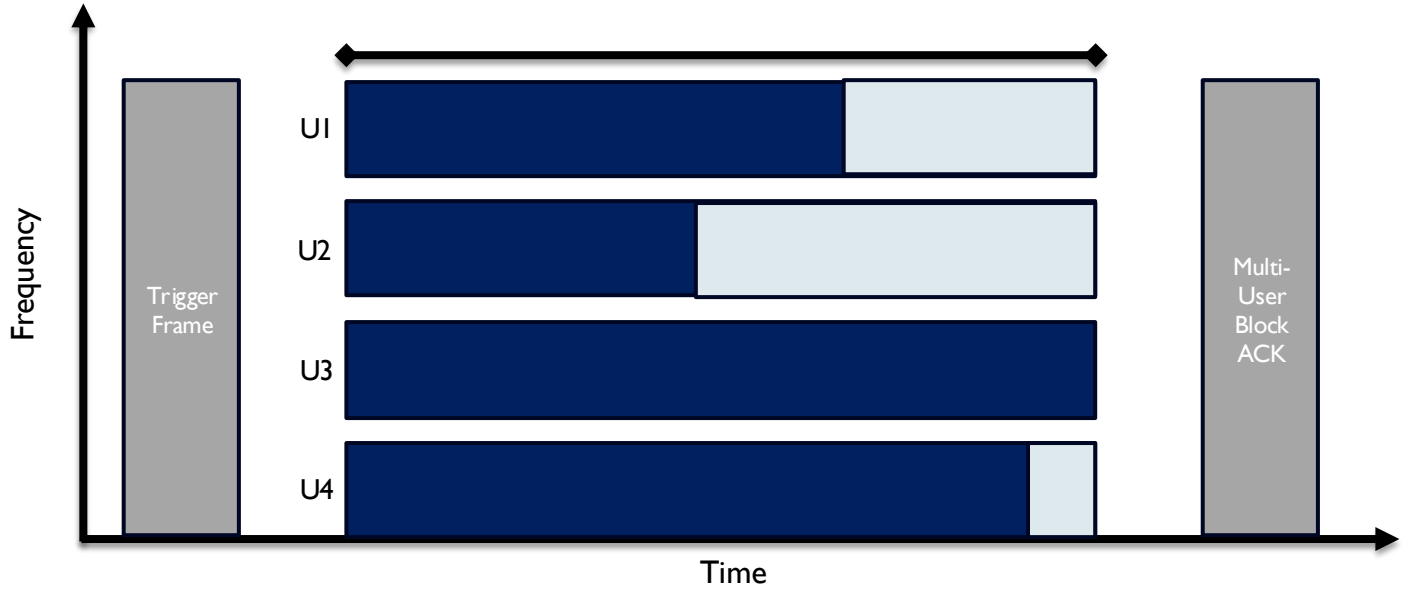
MCS Index	Spatial Stream	Modulation	Coding	OFDM (8					
				20MHz			40MHz		
				0.8µs GI	1.6µs GI	3.2µs GI	0.8µs GI	1.6µs GI	3.2µs GI
0	1	BPSQ	1/2	8.6	8.1	7.3	17.2	16.3	14.6
1	1	QPSK	1/2	17.2	16.3	14.6	34.4	32.5	29.3
2	1	QPSK	3/4	25.8	24.4	21.9	51.6	48.8	43.9
3	1	16-QAM	1/2	34.4	32.5	29.3	68.8	65.0	58.5
4	1	16-QAM	3/4	51.6	48.8	43.9	103.2	97.5	87.8
5	1	64-QAM	2/3	68.8	65.0	58.5	137.6	130.0	117.0
6	1	64-QAM					9	146.3	131.6
7	1	64-QAM					1	162.5	146.3
8	1	256-QAM					5	195.0	175.5
9	1	256-QAM					4	216.7	195.0
10	1	1024-QAM					1	243.8	219.4
11	1	1024-QAM					8	270.8	243.8
0	2	BPSQ	1/2	17.2	16.3	14.6	34.4	32.5	29.3
1	2	QPSK	1/2	34.4	32.5	29.3	68.8	65.0	58.5
2	2	QPSK	3/4	51.6	48.8	43.9	103.2	97.5	87.8
3	2	16-QAM	1/2	68.8	65.0	58.5	137.6	130.0	117.0
4	2	16-QAM	3/4	103.2	97.5	87.8	206.5	195.0	175.5
5	2	64-QAM	2/3	137.6	130.0	117.0	275.3	260.0	234.0
6	2	64-QAM	3/4	154.9	146.3	131.6	309.7	292.5	263.3
7	2	64-QAM	5/6	172.1	162.5	146.3	344.1	325.0	292.5

Guard interval

Longer guard intervals do reduce bandwidth

802.11ax Rate Control: OFDMA

- OFDMA needs to allocate the RUs without RTS/CTS
  - Typically proprietary algorithms



802.11ax Rate Control

- OFDMA changes what "rate control" even means
  - AP assigns both an MCS AND a Resource Unit (RU) size per user, every scheduling interval
  - Trigger-based uplink
    - AP must predict a client's channel quality and assign MCS before it hears the client transmit
- Rate control now interacts with spatial reuse (BSS coloring)
  - A weak/errored reception could be real interference, or just an overlapping-BSS transmission with different color
  - Rate control algorithms must tell these apart before lowering rate

802.11be Rate Control

- MCS 12–13 add 4096-QAM (12 bits/symbol, vs. 10 for 1024-QAM)
  - Needs very high SNR — mainly usable at short range, close to the AP
- New challenge: rate control under Multi-Link Operation (MLO)
  - A device can be connected on 2.4/5/6 GHz simultaneously, and each link has its own channel quality
  - Rate must be chosen per link, not once per device
  - Classic algorithms (ARF, RBAR, OAR) all assumed a single link
    - Extending per-link, cross-link-aware rate adaptation to MLO is an active research area

Long-Range Modes: DCM and ER SU

- The lowest regular MCS is not always enough at the cell edge
- 802.11ax
  - DCM (Dual Carrier Modulation)
    - Same bits on two subcarriers; frequency diversity at half the rate
  - ER SU PPDU
    - 20 MHz, 1 stream, MCS 0-2, with repeated and power-boosted preamble fields
- 802.11be
  - MCS 14 and 15 add more robust BPSK-DCM options, mainly for 6 GHz
- Wi-Fi 8's ELR PPDU continues the same idea