

CS 498wn: Wireless Networking

MAC Layer – Multi-Rate

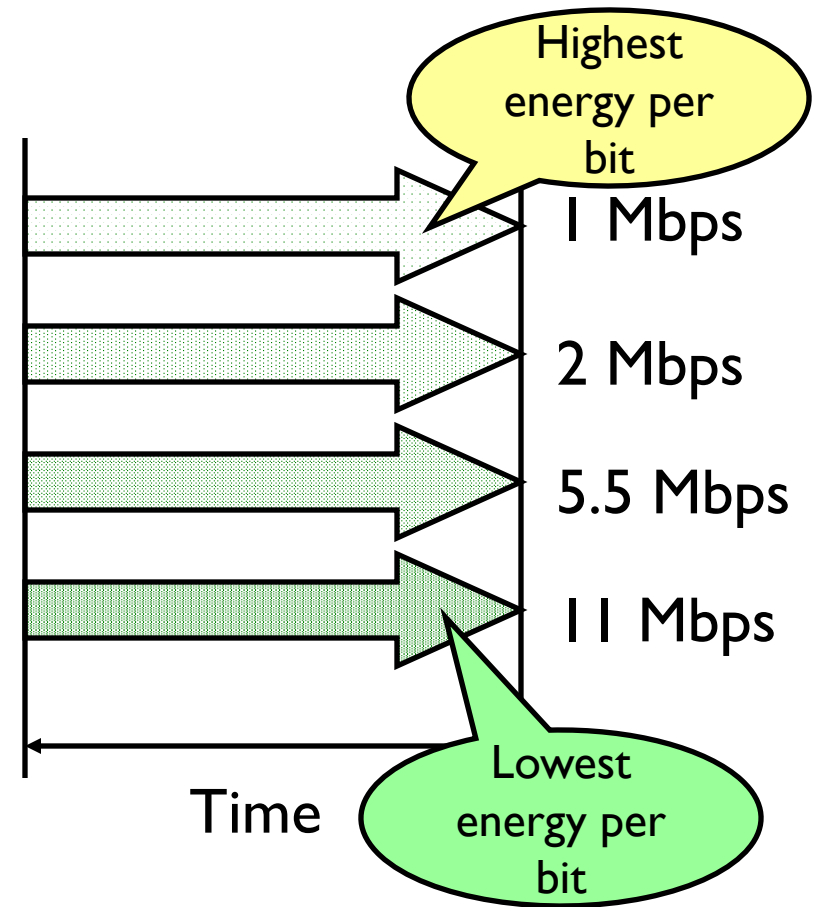
What is “Data Rate” really?

- ▶ 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

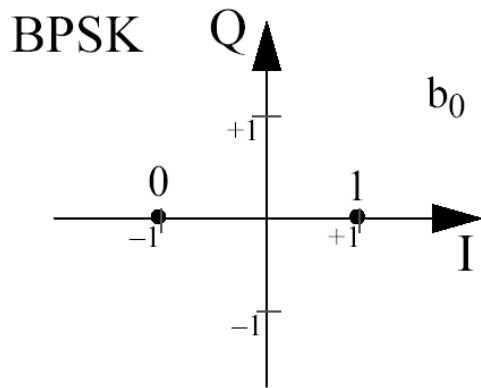


What is Multi-Rate?

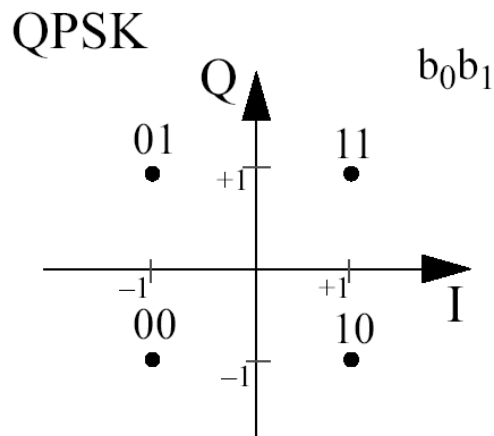
- ▶ Ability of a wireless card to automatically operate at several different bit-rates
 - ▶ (e.g. 1, 2, 5.5, and 11 Mbps for 802.11b)
- ▶ Part of many existing wireless standards
 - ▶ (802.11b, 802.11a, 802.11g, HiperLAN2...)
- ▶ Virtually every wireless card in use today employs multi-rate



Example Carrier Modulations

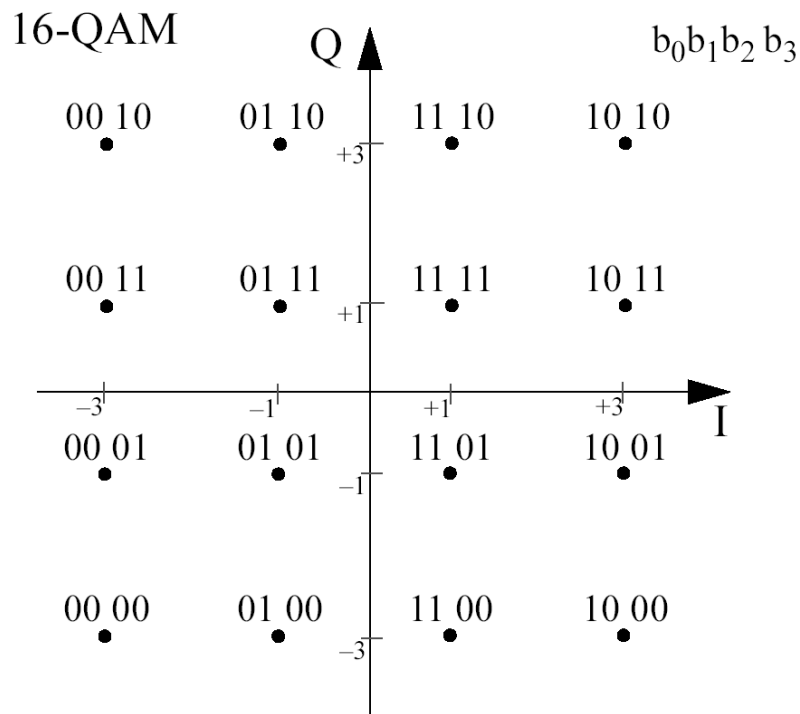


- ▶ **Binary Phase Shift Keying**
 - ▶ One bit per symbol
 - ▶ Made by the carrier and its inverse



- ▶ **Quadrature Phase Shift Keying**
 - ▶ Two bits per symbol
 - ▶ Uses quadrature carrier in addition to normal carrier
 - ▶ (90° phase shift of carrier)
 - ▶ 4 permutations for the inverse or not of the two carriers

Example Carrier Modulations (cont.)

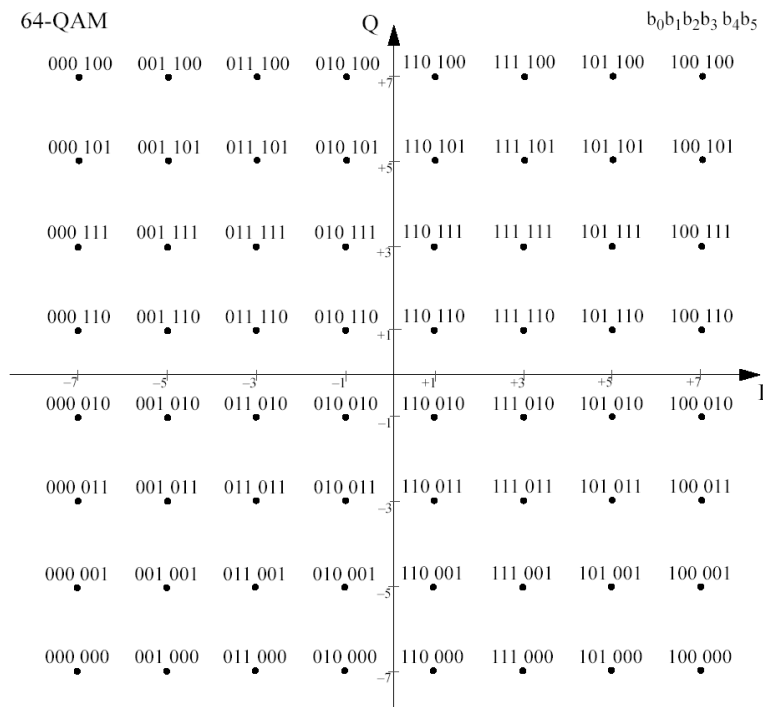


- ▶ 16 - Quadrature Amplitude Modulation
 - ▶ 4 bits per symbol
 - ▶ Also uses quadrature carrier
 - ▶ Each carrier is multiplied by +3, +1, -1, or -3
 - ▶ (amplitude modulation)
 - ▶ 16 possible combinations of the two multiplied carriers

Example Carrier Modulations (cont.)

▶ 64 - Quadrature Amplitude Modulation

- ▶ 6 bits per symbol
- ▶ Also uses quadrature carrier
- ▶ Each carrier is multiplied by +7, +5, +3, +1, -1, -3, -5, or -7 (amplitude modulation)
- ▶ 64 possible combinations of the two multiplied carriers

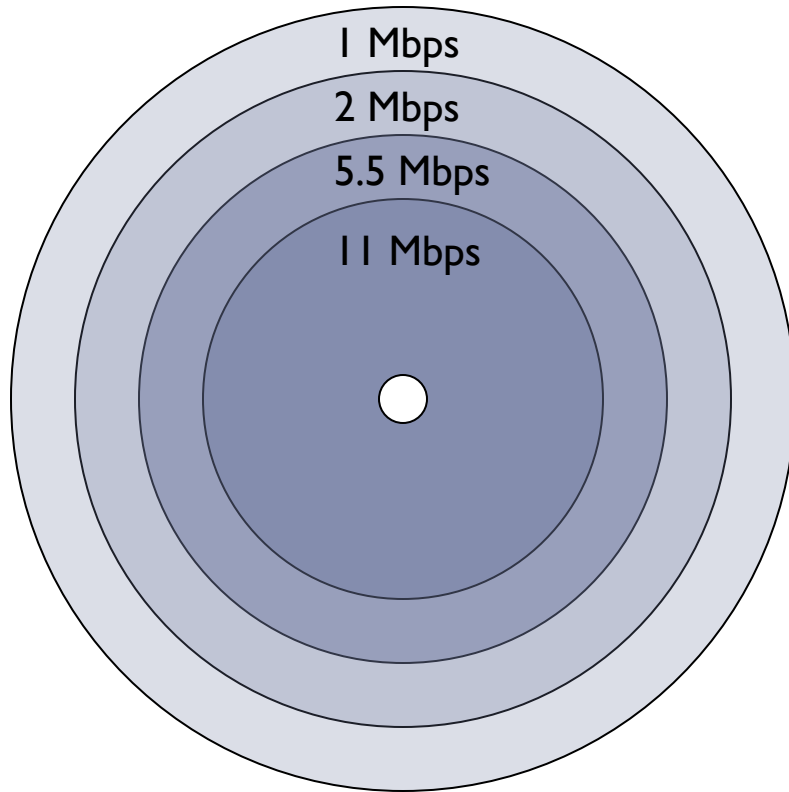


802.11a Rates resulting from Carrier Modulation and Coding

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

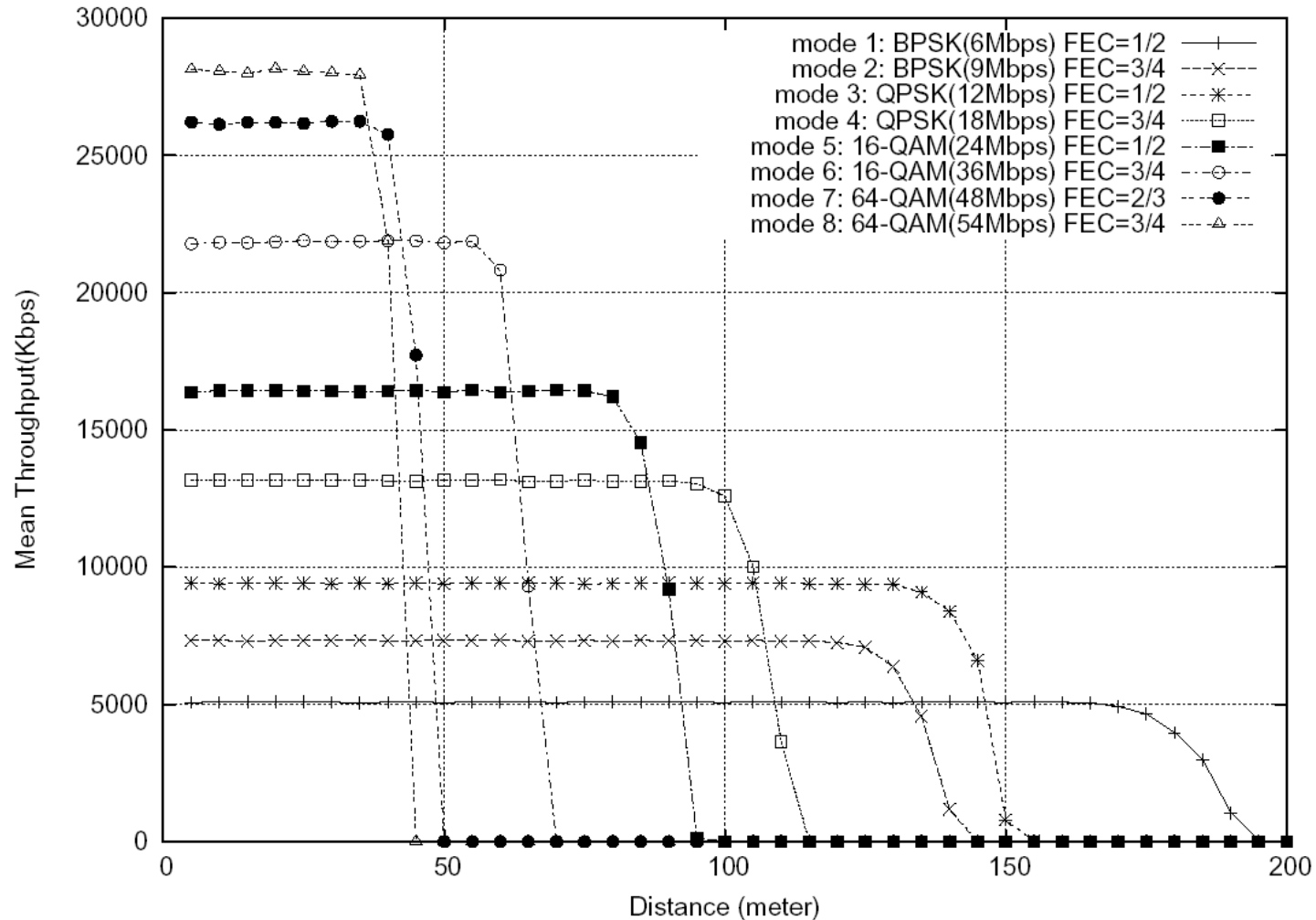


Advantage of Multi-Rate?



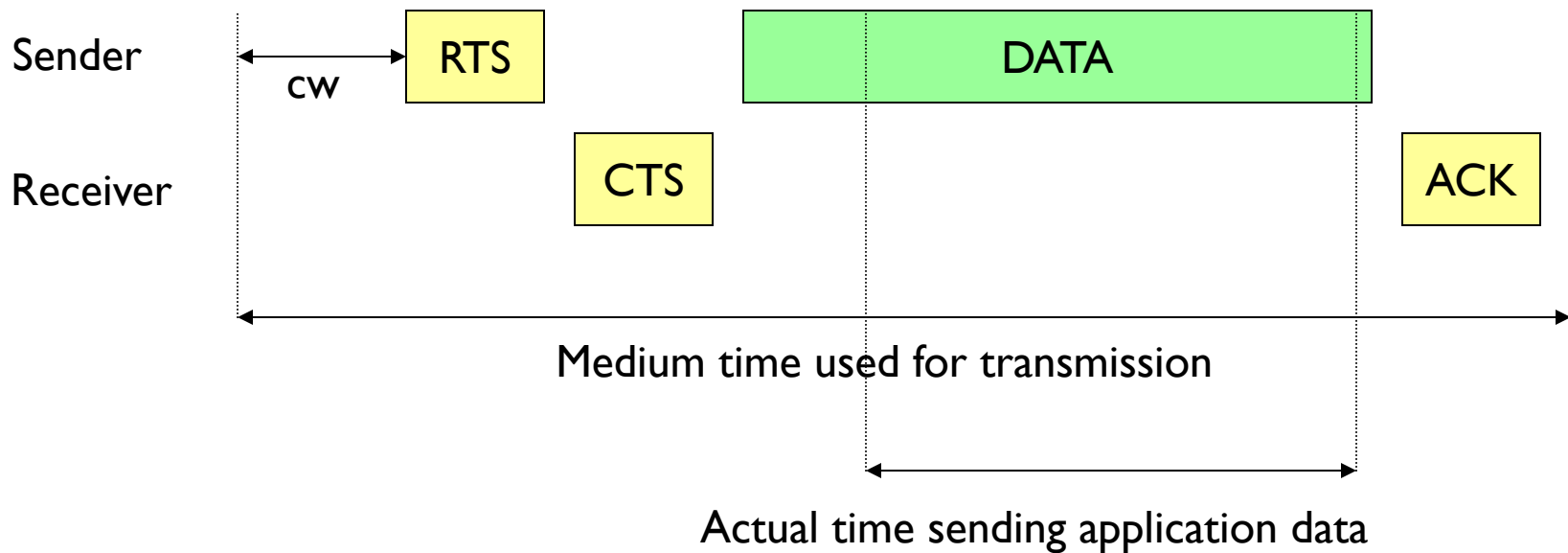
- ▶ Direct relationship between communication rate and the channel quality required for that rate
- ▶ As distance increases, channel quality decreases
 - ▶ Tradeoff between communication range and link speed
- ▶ Multi-rate provides flexibility to meet both consumer demands

Throughput vs. Distance for 802.11a



802.11 Frame Exchange Overhead

- ▶ Not all time is spent sending actual data



Multi-rate Frame in 802.11b

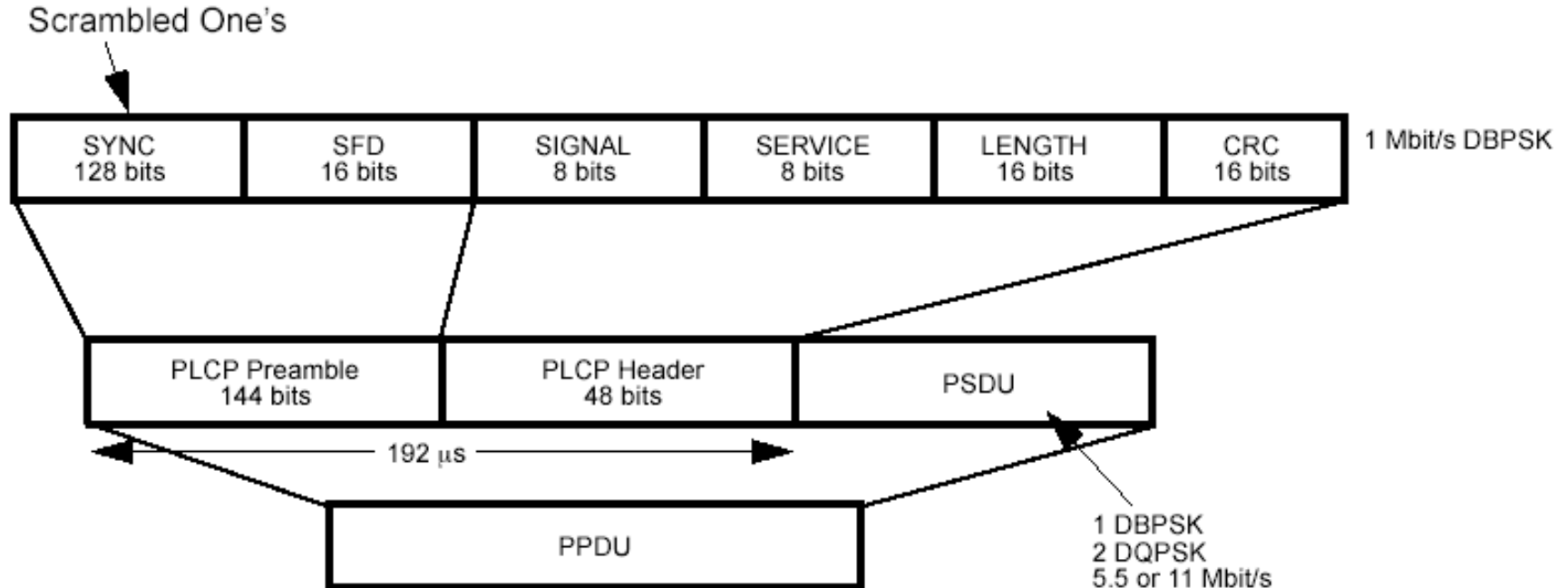
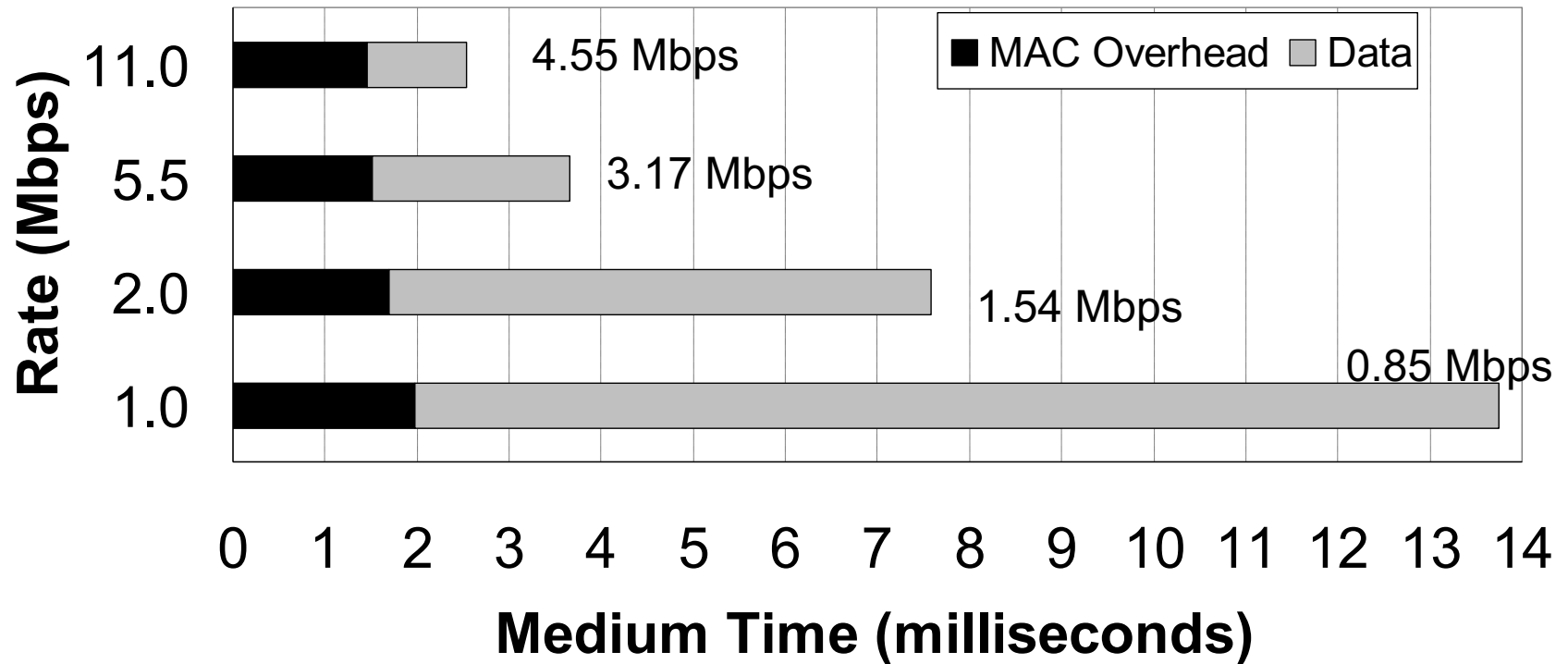


Figure 127—Long PLCP PDU format

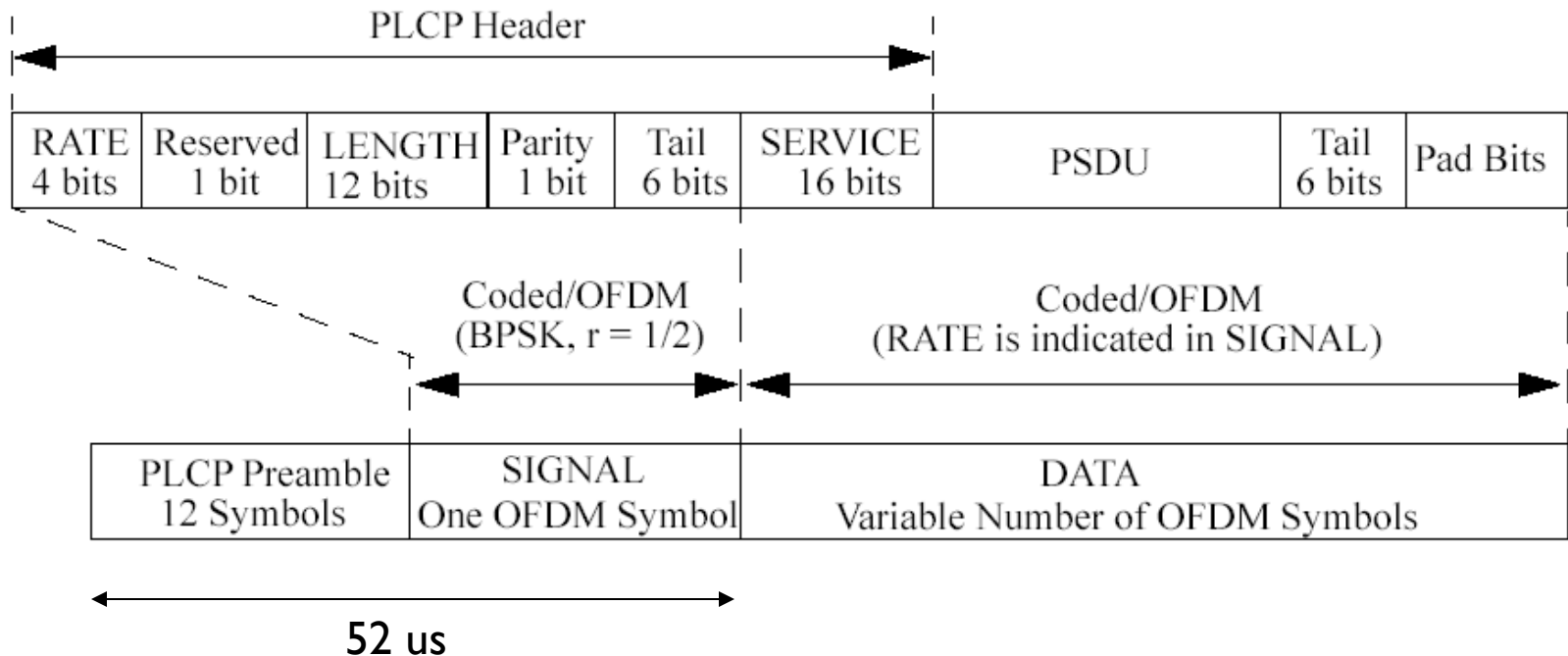
802.11b Frame Exchange Duration



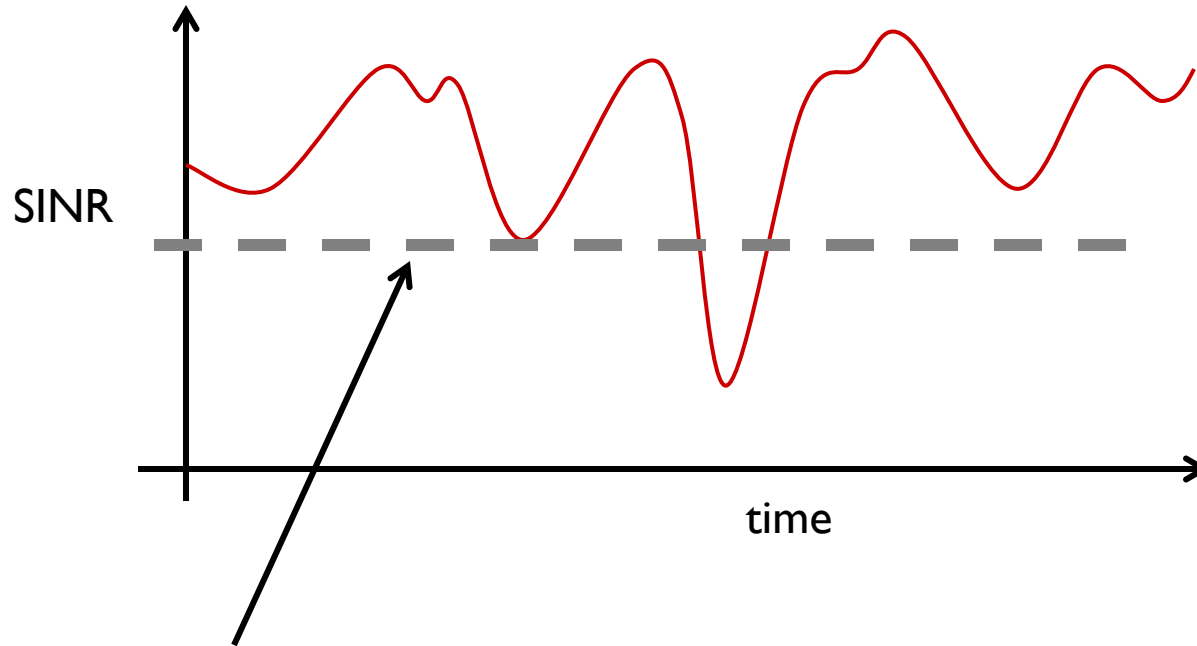
Medium Time consumed to transmit 1500 byte packet



Multi-rate Frame in 802.11a

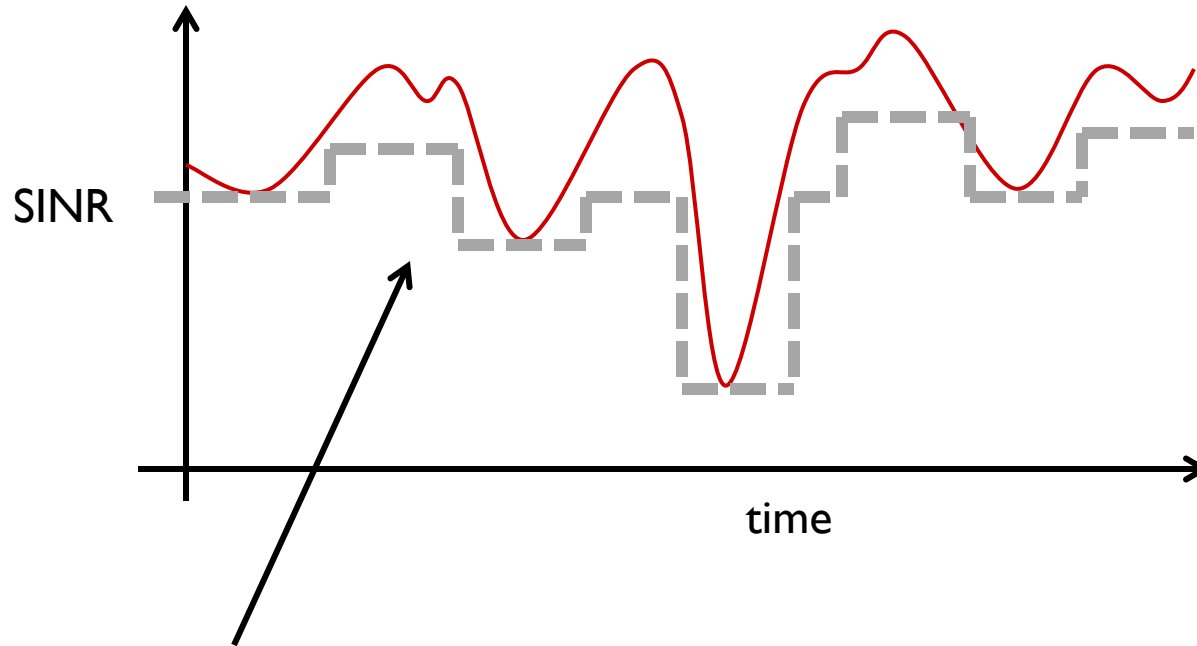


How do we choose modulation rates?



- ▶ 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



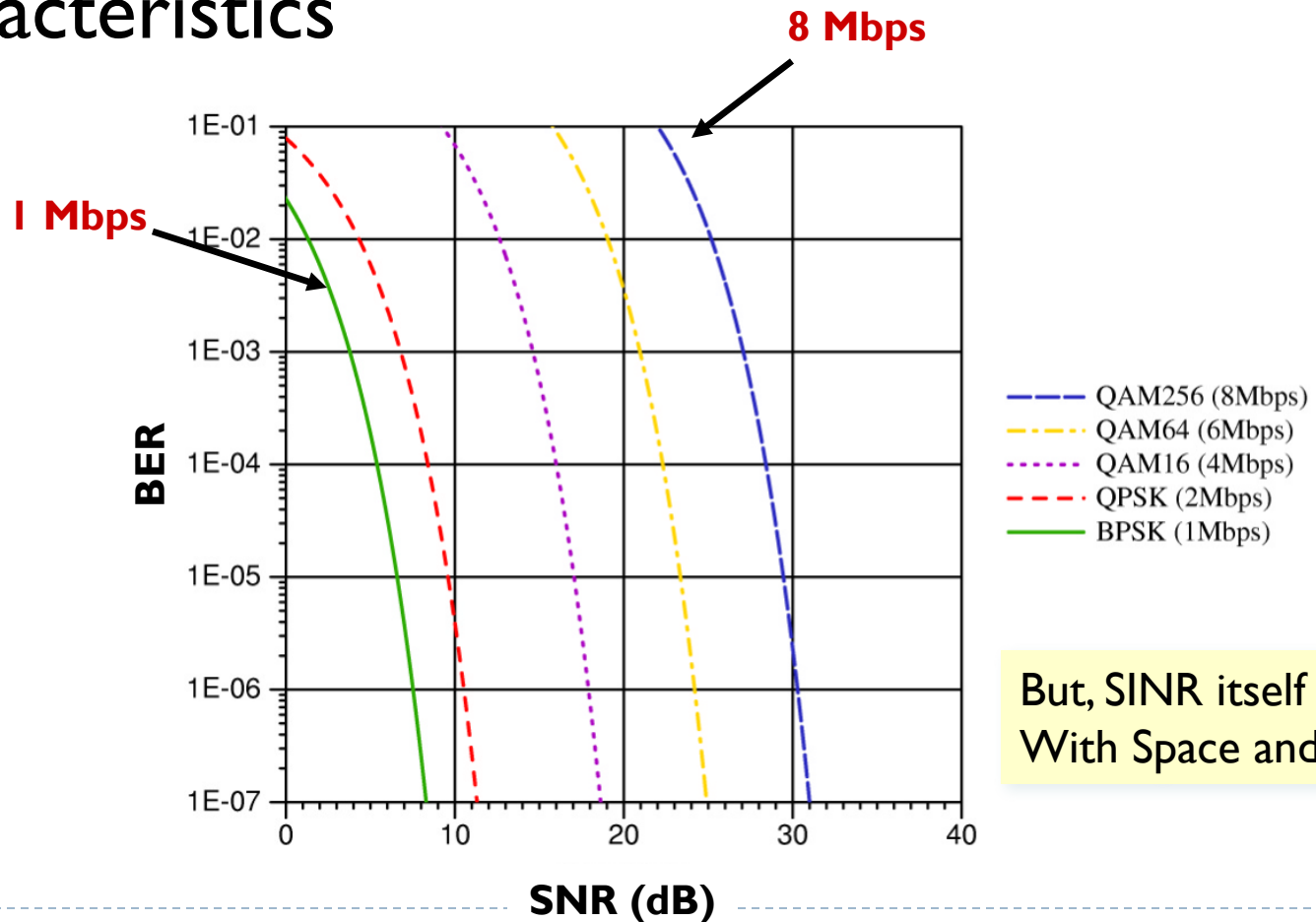
- ▶ Observe the current value of SINR
 - ▶ Use as indicator of near-future value
- ▶ Choose corresponding rate of modulation
- ▶ Repeat
 - ▶ Controls rate if channel conditions have changed

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

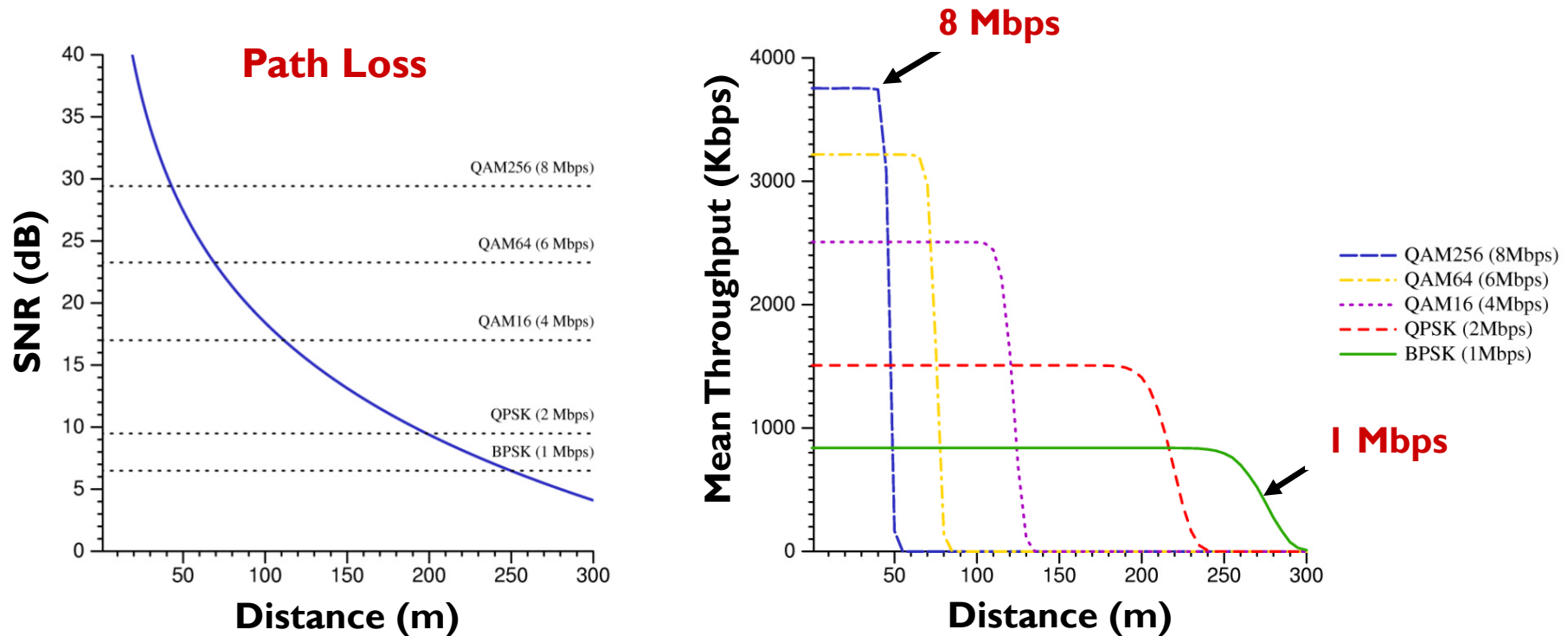
- ▶ Modulation schemes have different error characteristics



But, SINR itself varies
With Space and Time

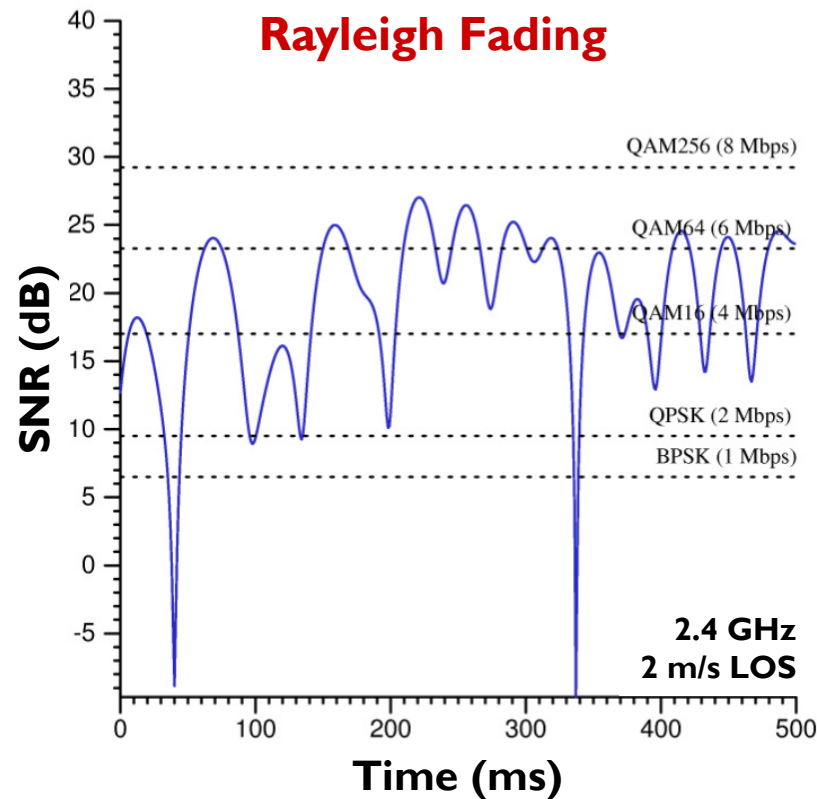
Impact

► Large-scale variation with distance (Path loss)

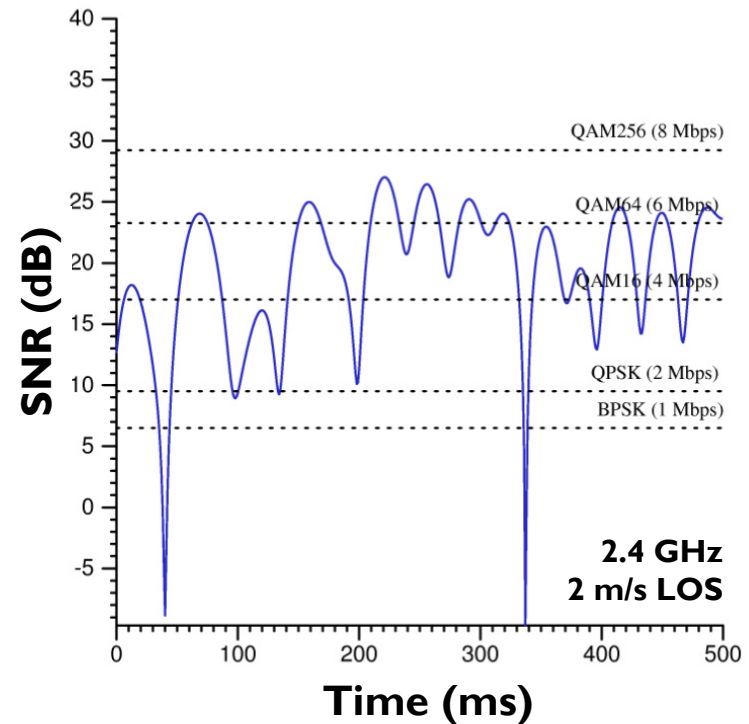
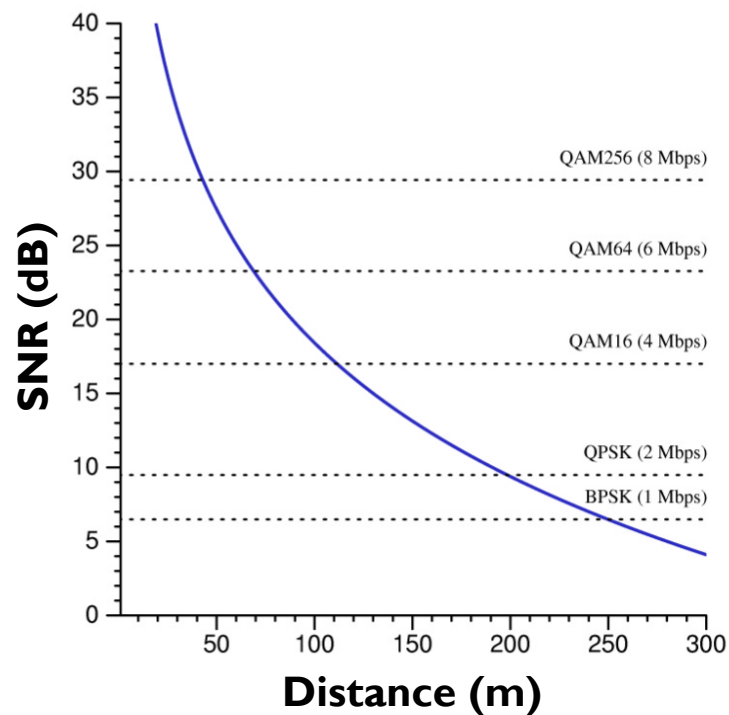


Impact

► Small-scale variation with time (Fading)

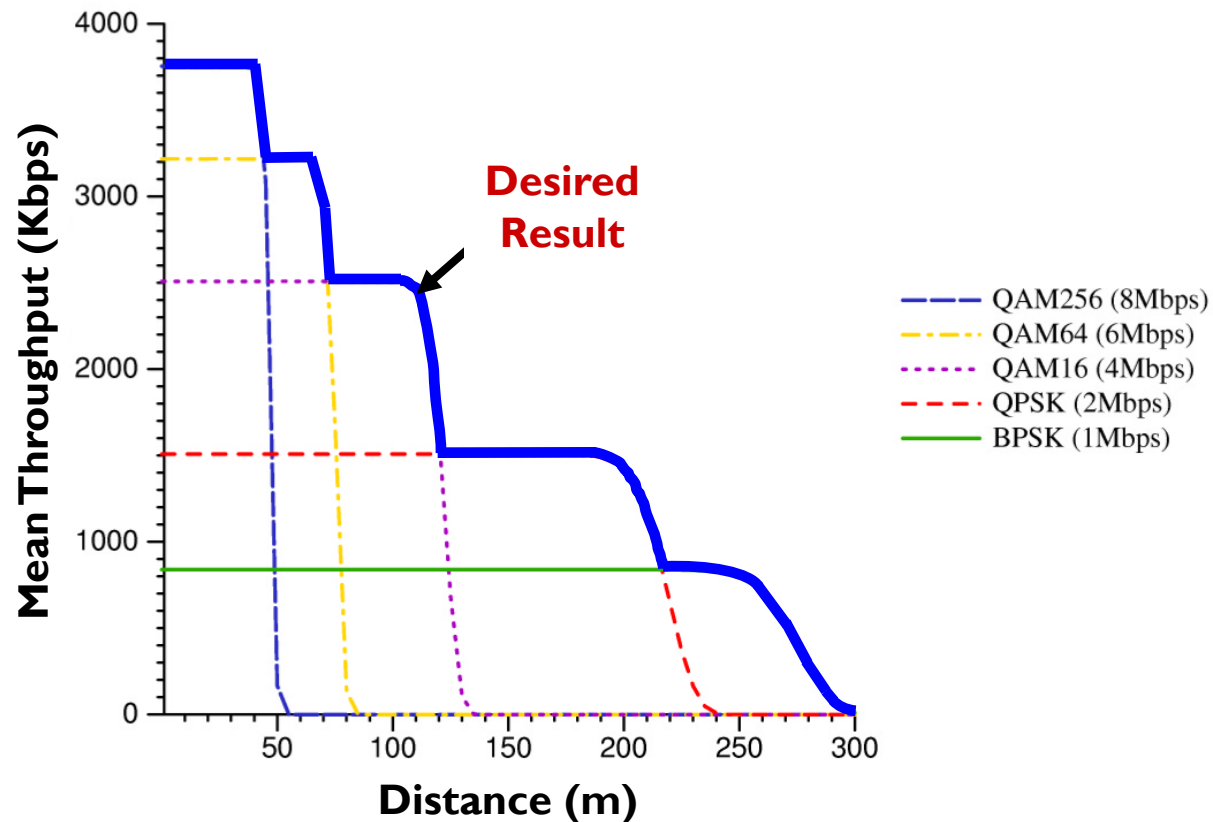


Which modulation scheme is best?



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
- ▶ Impractical for 802.11 in WLANs

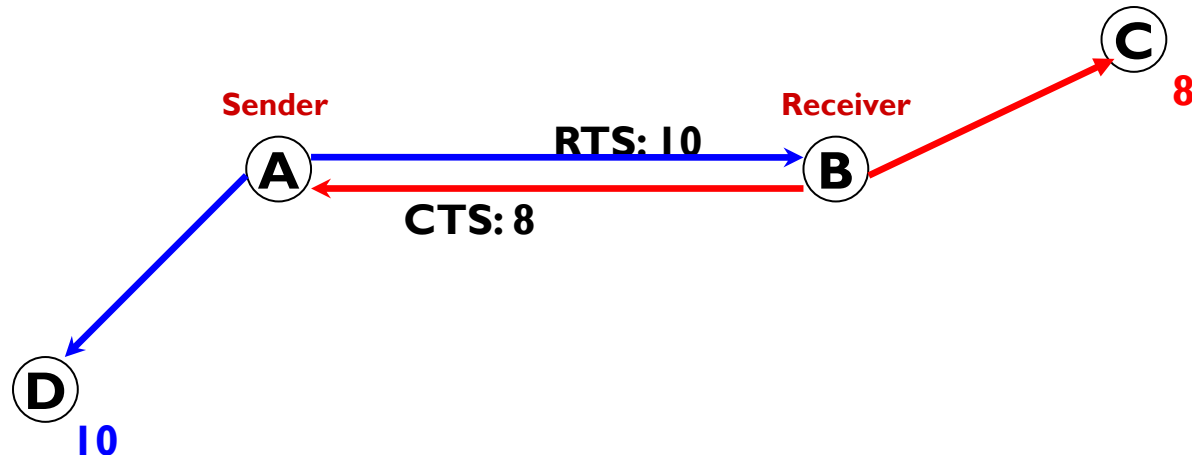
← Why?

Adaptation → At Which Layer ?

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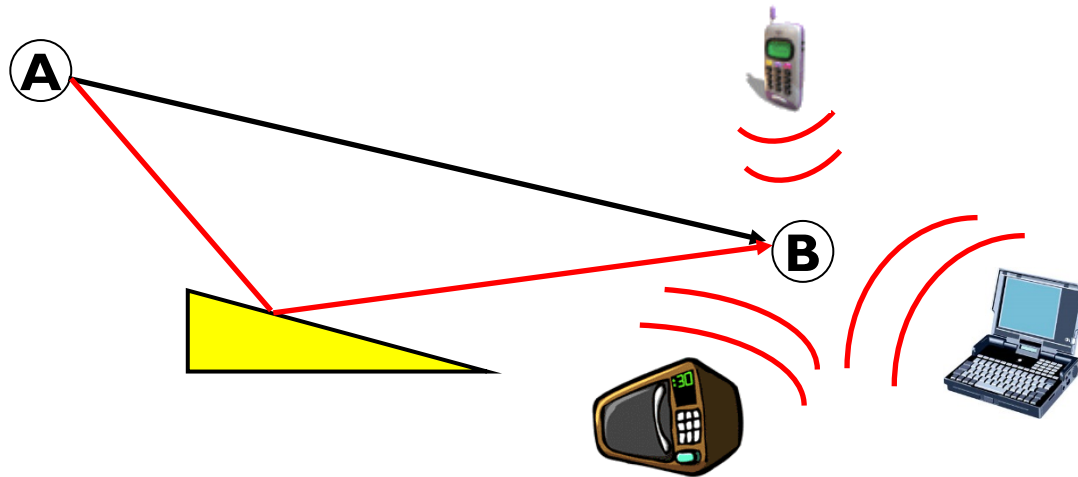
← Why?

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



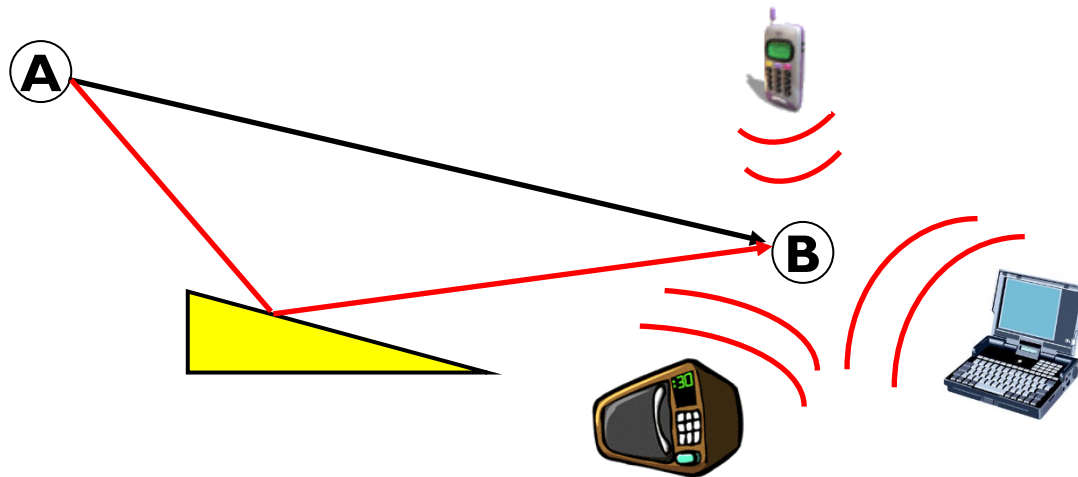
- ▶ For WLANs, rate adaptation is best handled at the MAC layer

Who should select the data rate?



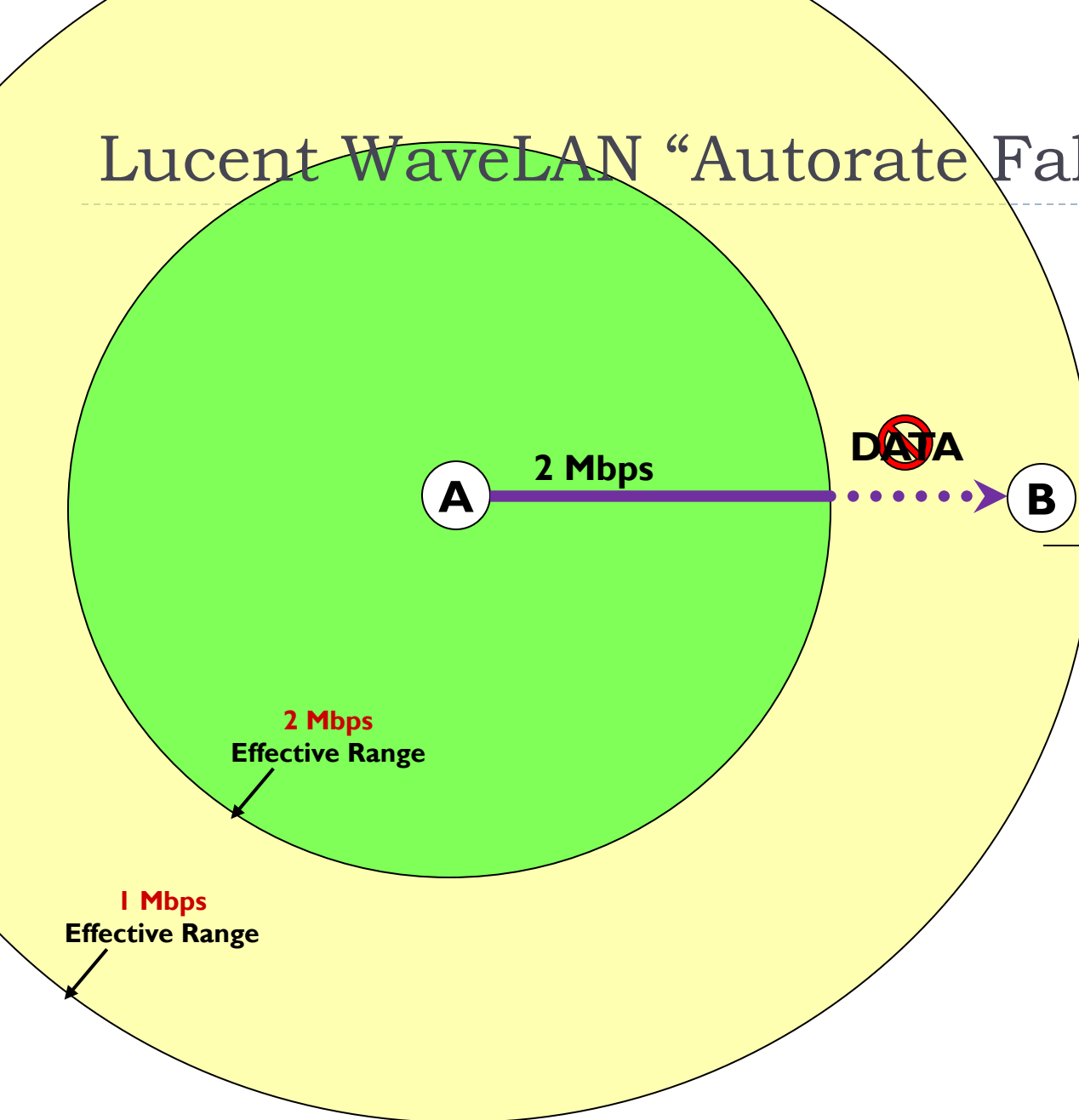
Who should select the data rate?

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



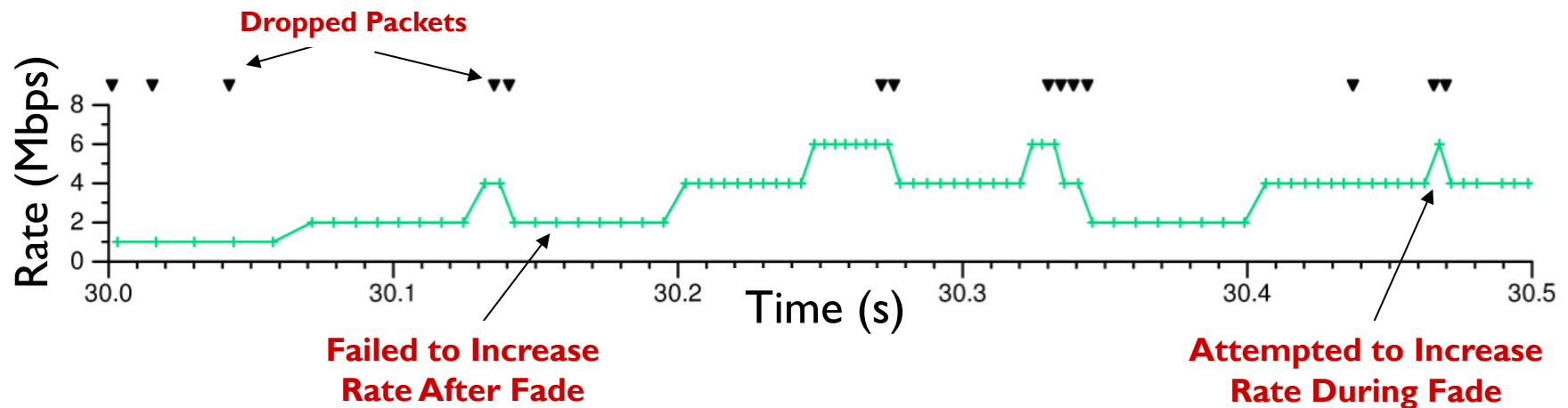
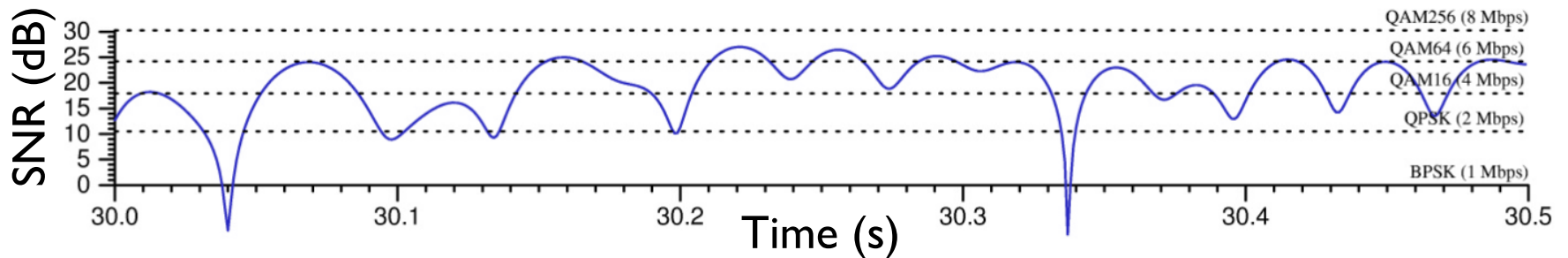
- ▶ The receiver is best positioned to select data rate

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

Performance of ARF

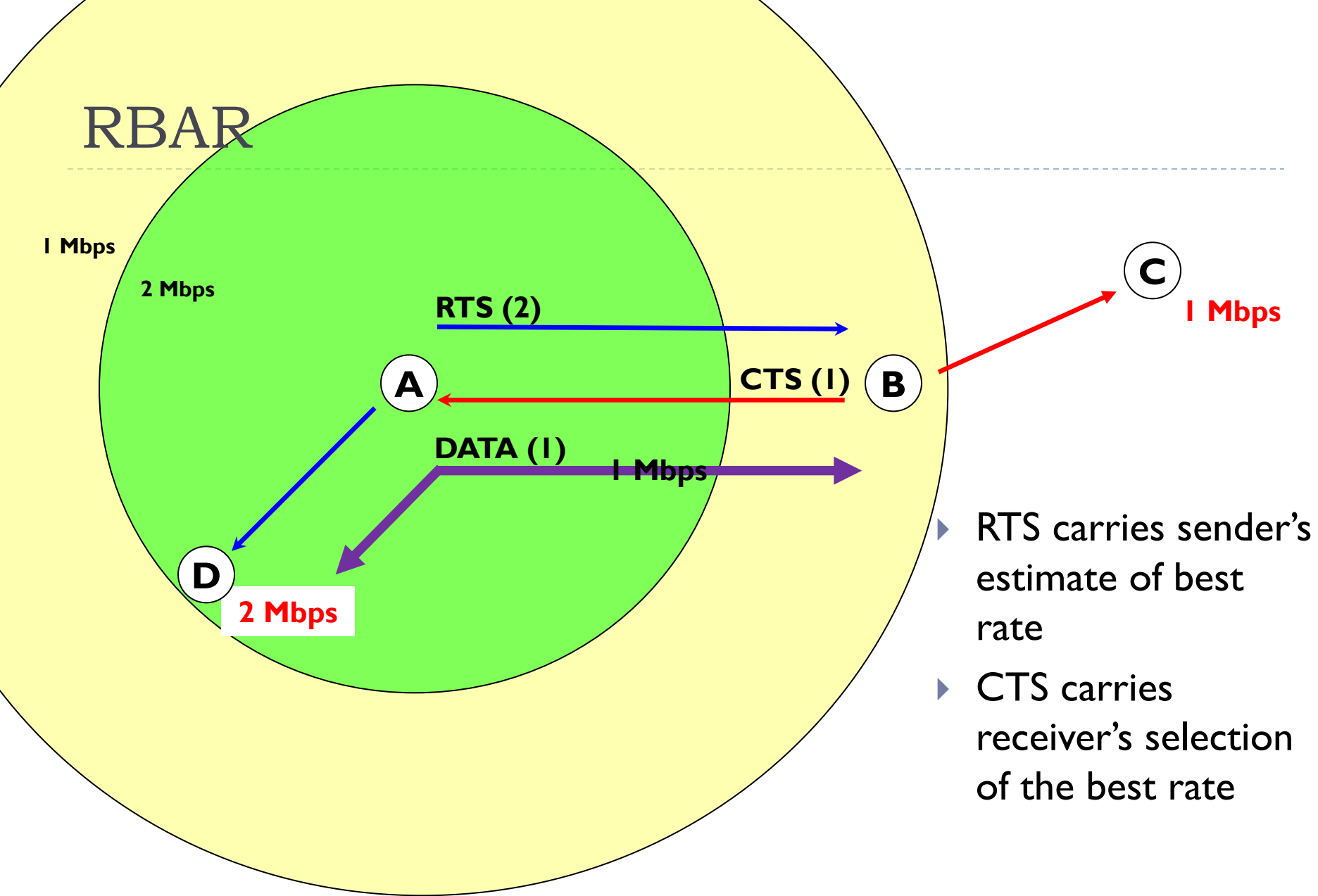


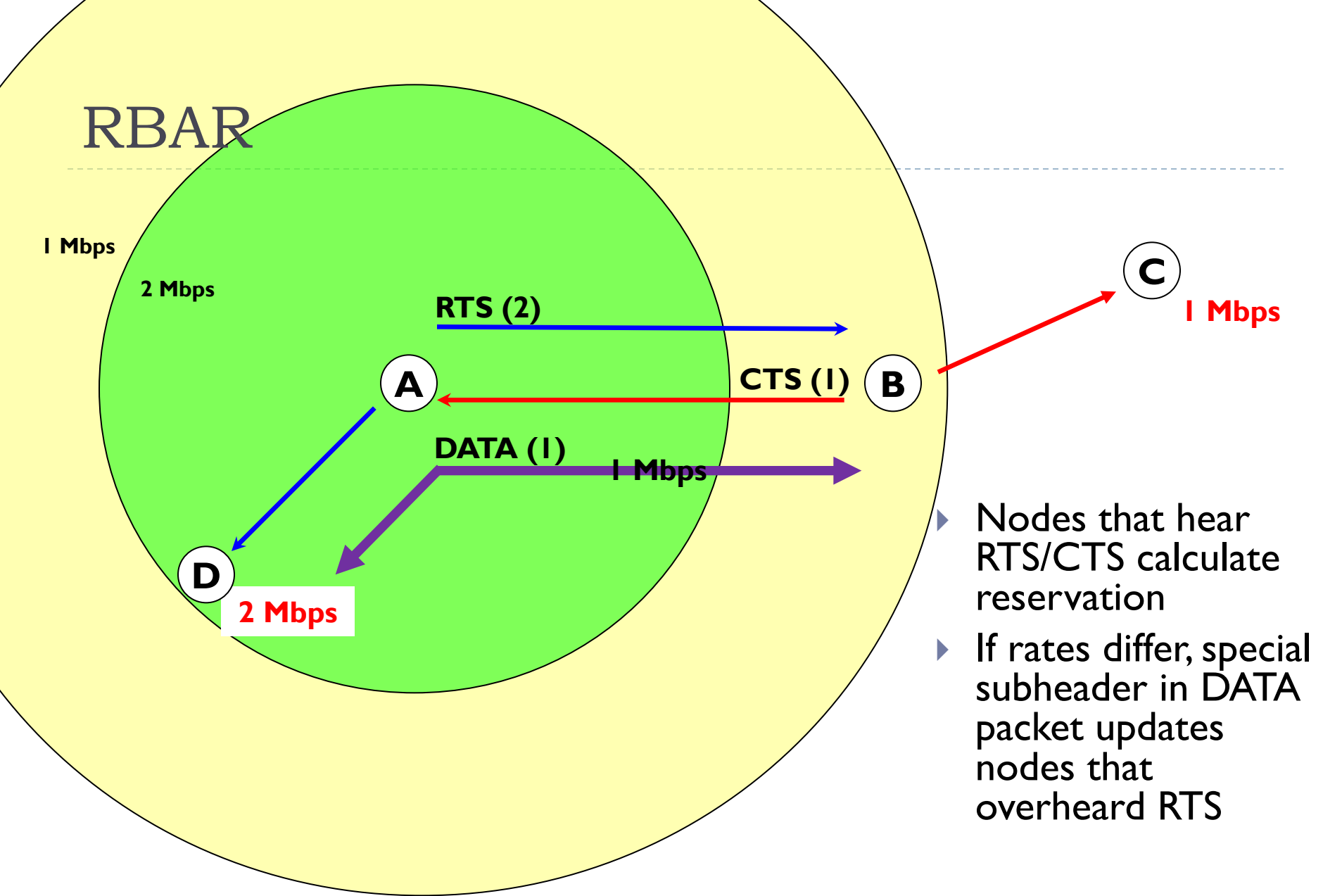
- ▶ Slow to adapt to channel conditions
- ▶ Choice of N, Y, T may not be best for all situations

Receiver-Based Autorate (RBAR)

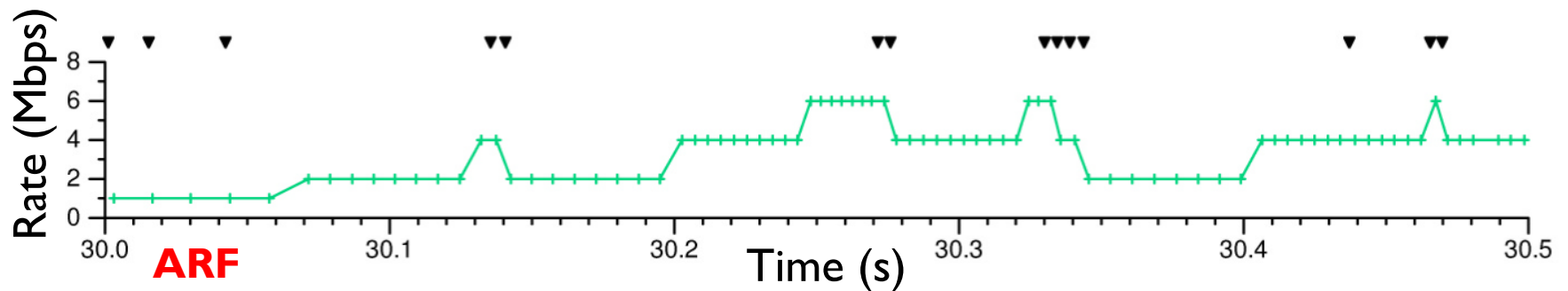
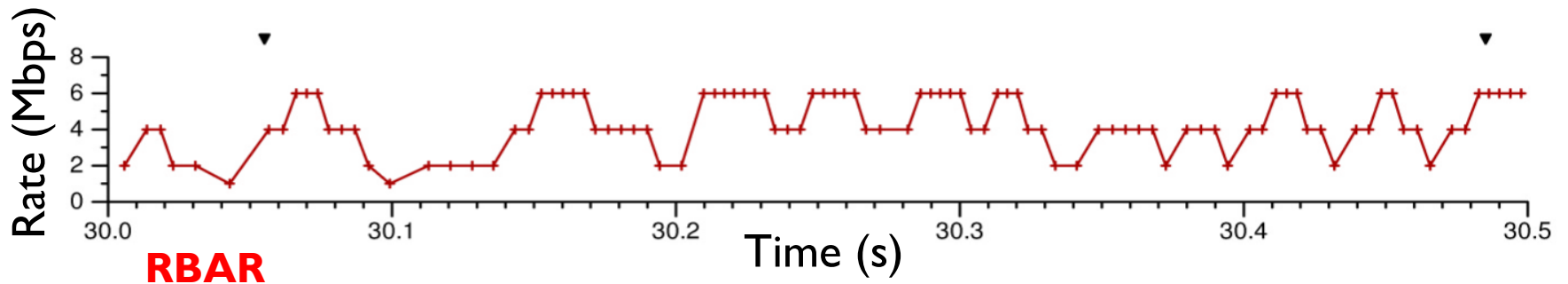
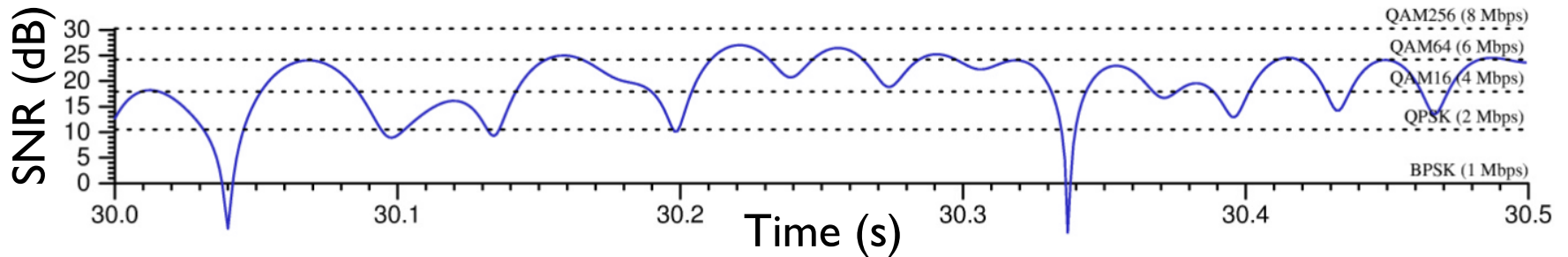
- ▶ Move the rate adaptation mechanism to the receiver
 - ▶ Better channel quality information = better rate selection
- ▶ Utilize the RTS/CTS exchange to
 - ▶ Provide the receiver with a signal to sample (RTS)
 - ▶ Carry feedback (data rate) to the sender (CTS)





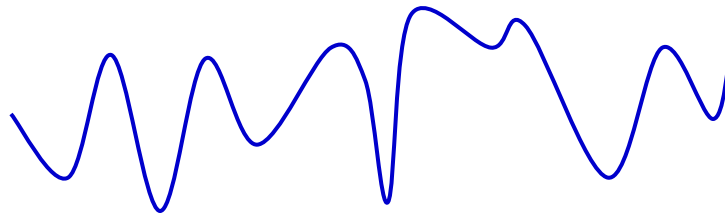


Performance of RBAR

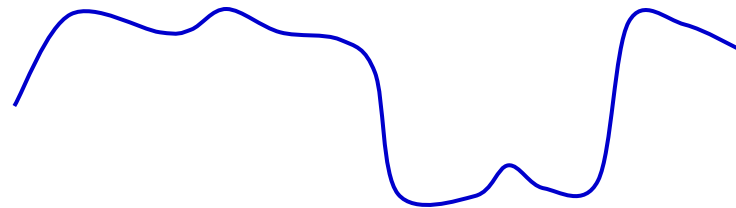


Question to the class

- ▶ There are two types of fading
 - ▶ Short term fading

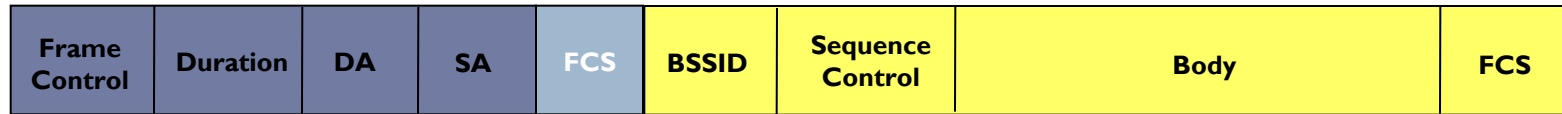


- ▶ Long term fading



- ▶ Under which fading is RBAR better than ARF?
- ▶ Under which fading is RBAR comparable to ARF?
- ▶ Think of some case when RBAR may be worse than ARF

Implementation into 802.11



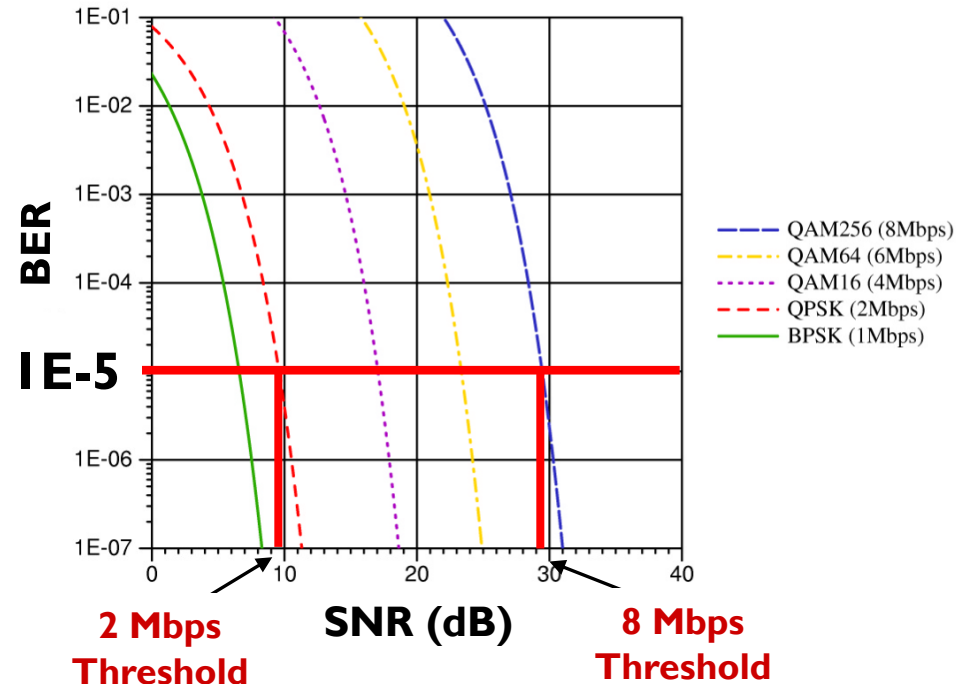
— **Reservation Subheader (RSH)** —

- ▶ 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

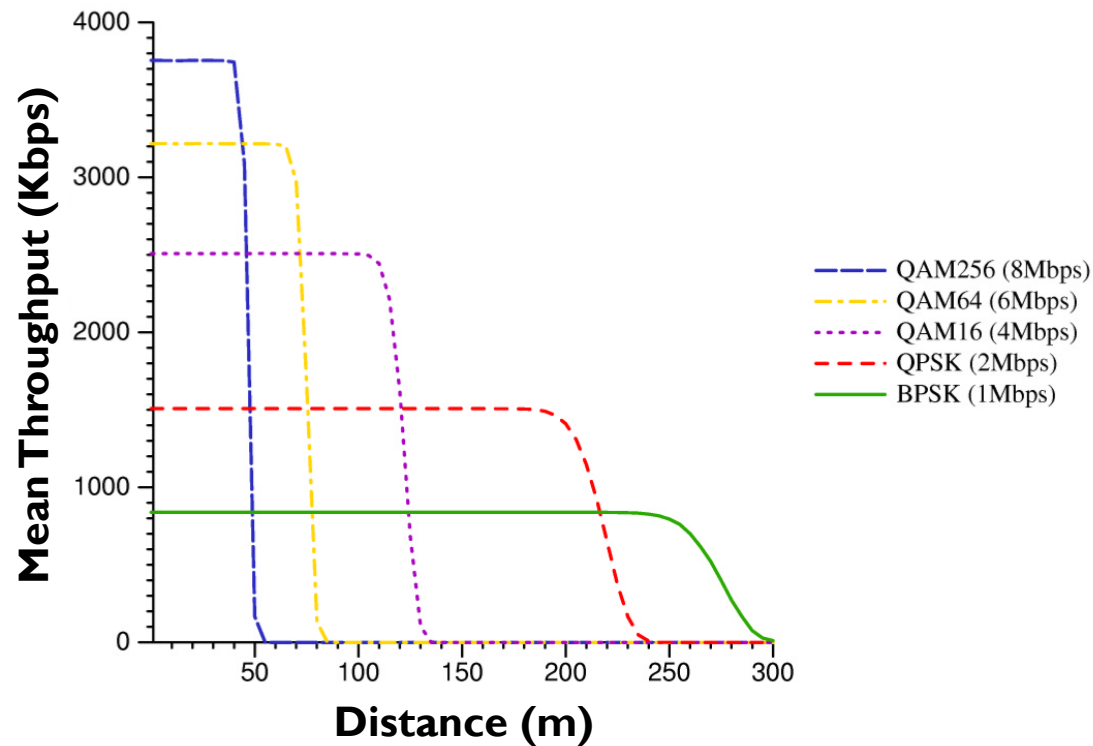


Evaluation

- ▶ Environment
 - ▶ Rayleigh fading
- ▶ Scenarios
 - ▶ Single-hop
- ▶ Protocols
 - ▶ RBAR and ARF
- ▶ RBAR
 - ▶ Channel quality prediction
 - ▶ SNR sample of RTS
 - ▶ Rate selection:
 - ▶ Threshold-based
 - ▶ Sender estimated rate:
 - ▶ Static (1 Mbps)



Single-Hop Scenario

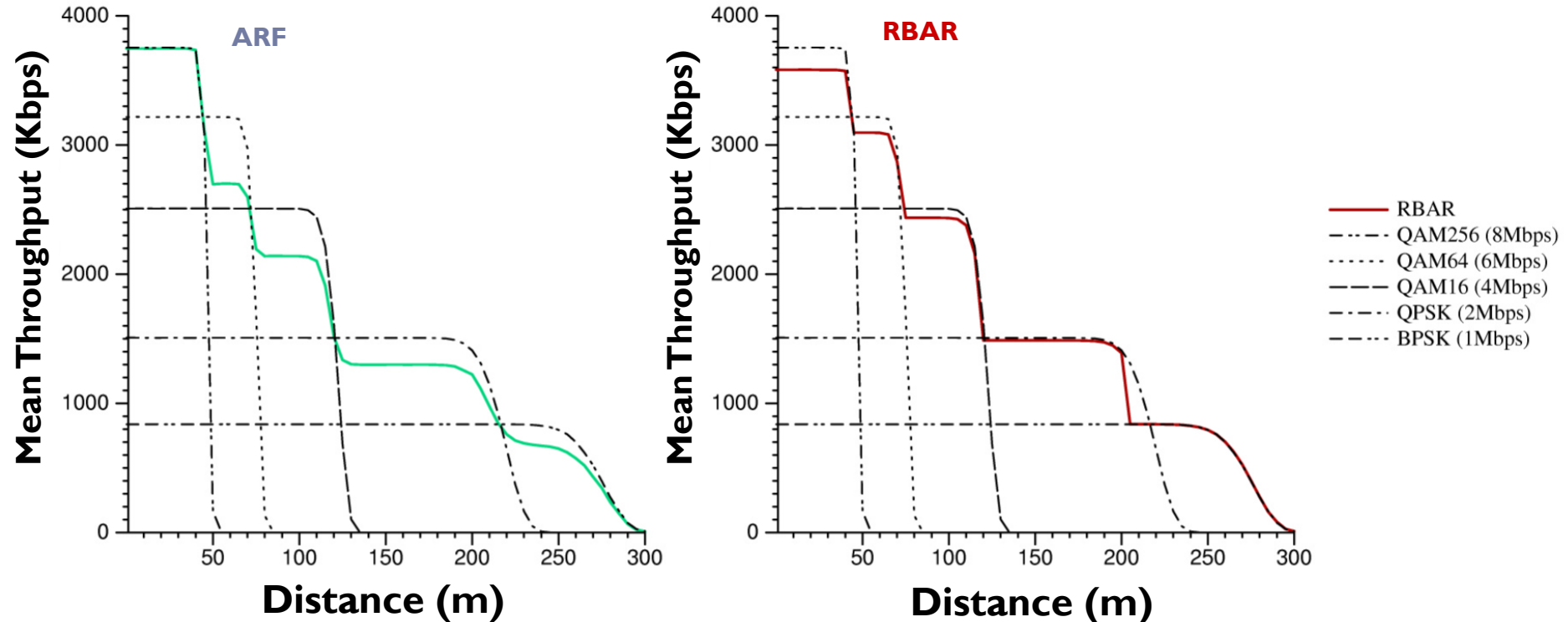


A

B

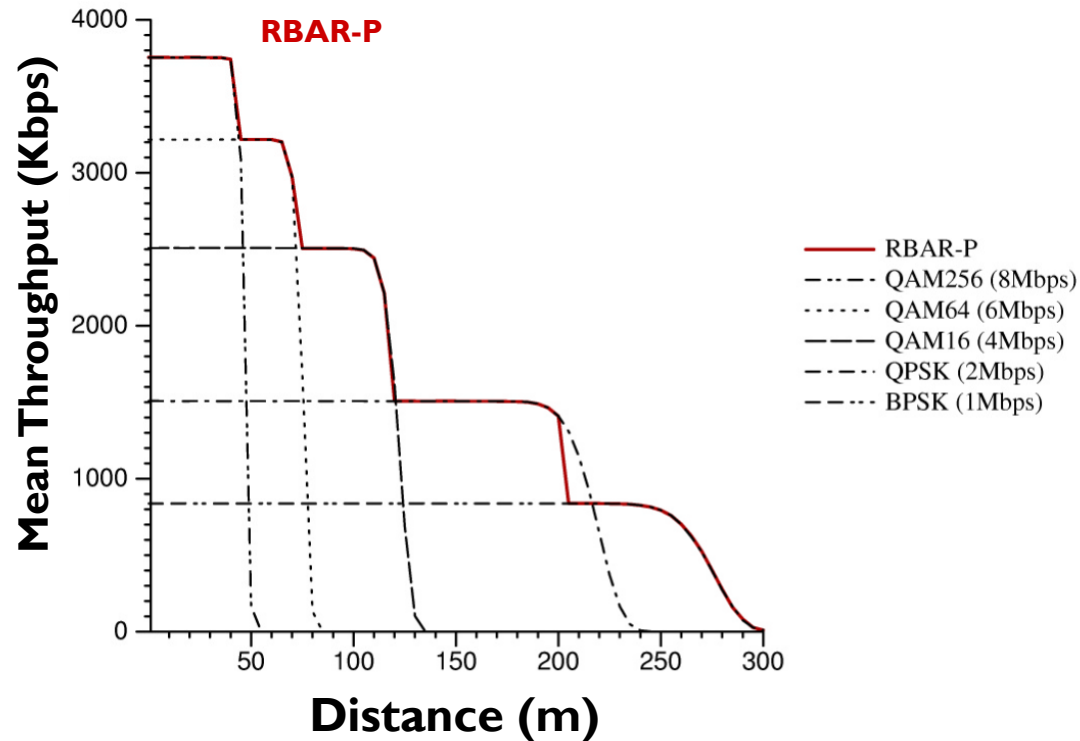


No Mobility - UDP Performance



- ▶ RSH overhead seen at high data rates
 - ▶ Can be reduced using some initial rate estimation algorithm
- ▶ Limitations of simple threshold-based rate selection seen
- ▶ Generally, still better than ARF

No Mobility - UDP Performance



- ▶ RBAR-P – RBAR using a simple initial rate estimation algorithm
 - ▶ Previous rate used as estimated rate in RTS
- ▶ Better high-rate performance
- ▶ Other initial rate estimation and rate selection algorithms are a topic of future work

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

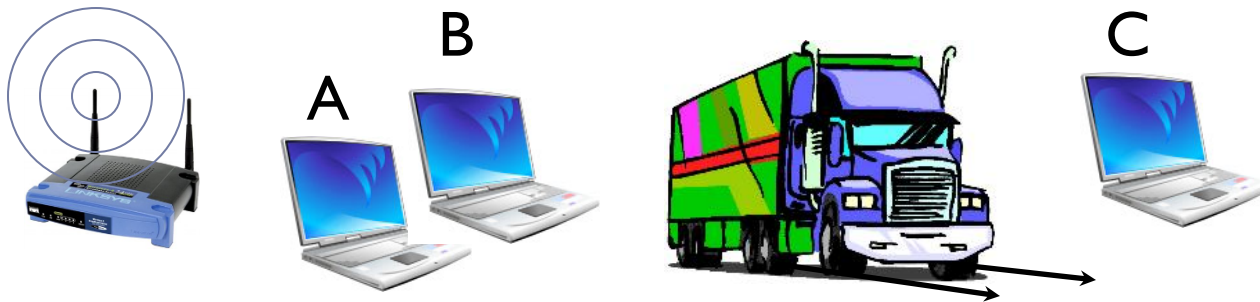


Can we do better?

- ▶ Consider the situation below

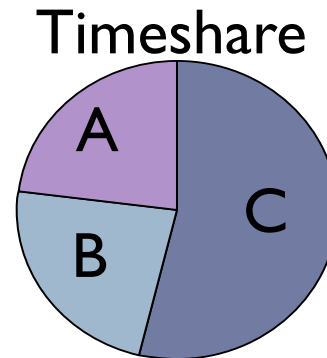
- ▶ ARF?

- ▶ RBAR?



Motivation

- ▶ What if A and B are both at 56Mbps, and C is often at 2Mbps?
- ▶ Slowest node gets the most absolute time on channel?



Throughput Fairness vs Temporal Fairness

MAC Layer Fairness Models

- ▶ **Per Packet Fairness**

- ▶ If two adjacent senders continuously are attempting to send packets, they should each send the same number of packets

- ▶ **Temporal Fairness**

- ▶ If two adjacent senders are continuously attempting to send packets, they should each be able to send for the same amount of medium time.

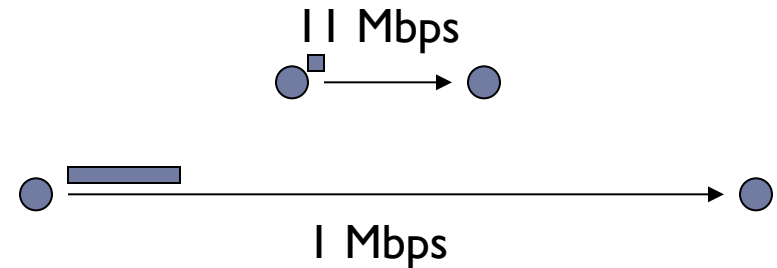
- ▶ **In single rate networks these are the SAME!**



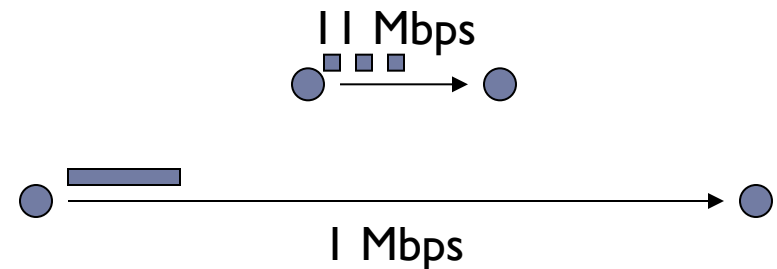
Temporal Fairness Example

	802.11 Packet Fairness	OAR Temporal Fairness
11 Mbps Link	0.896	3.533
1 Mbps Link	0.713	0.450
Total Throughput	1.609	3.983

Per Packet Fairness



Temporal Fairness



Opportunistic Scheduling

▶ Goal

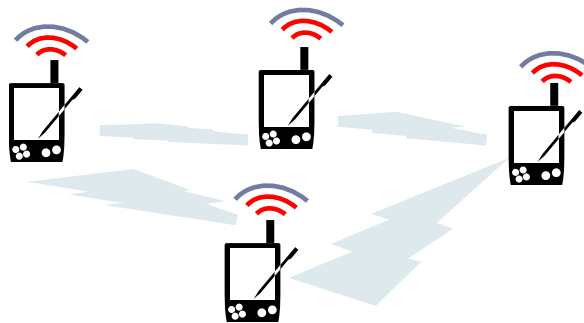
- ▶ Exploit short-time-scale channel quality variations to increase throughput

▶ Issue

- ▶ Maintaining temporal fairness (time share) of each node

▶ Challenge

- ▶ Channel info available only upon transmission



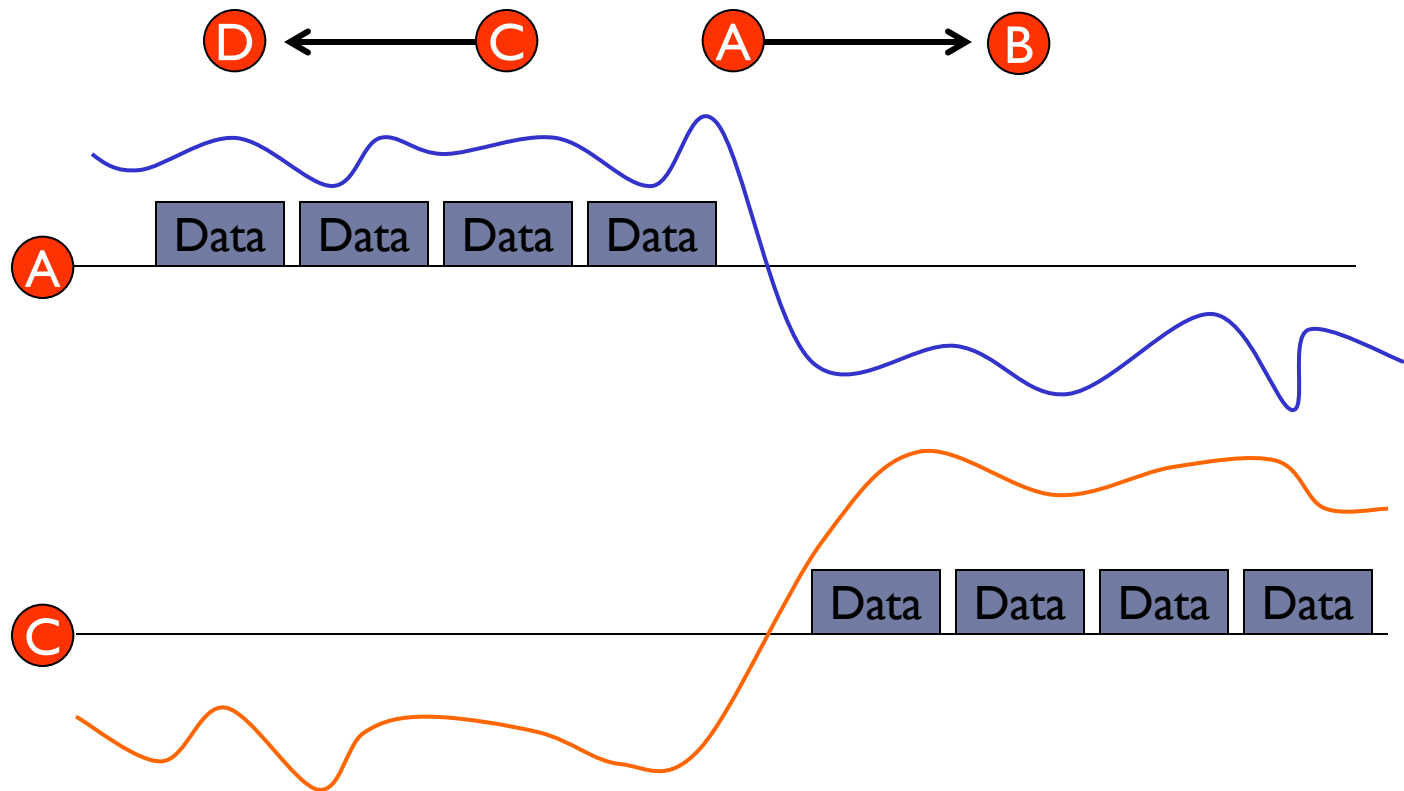
Opportunistic Auto-Rate (OAR)

- ▶ 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

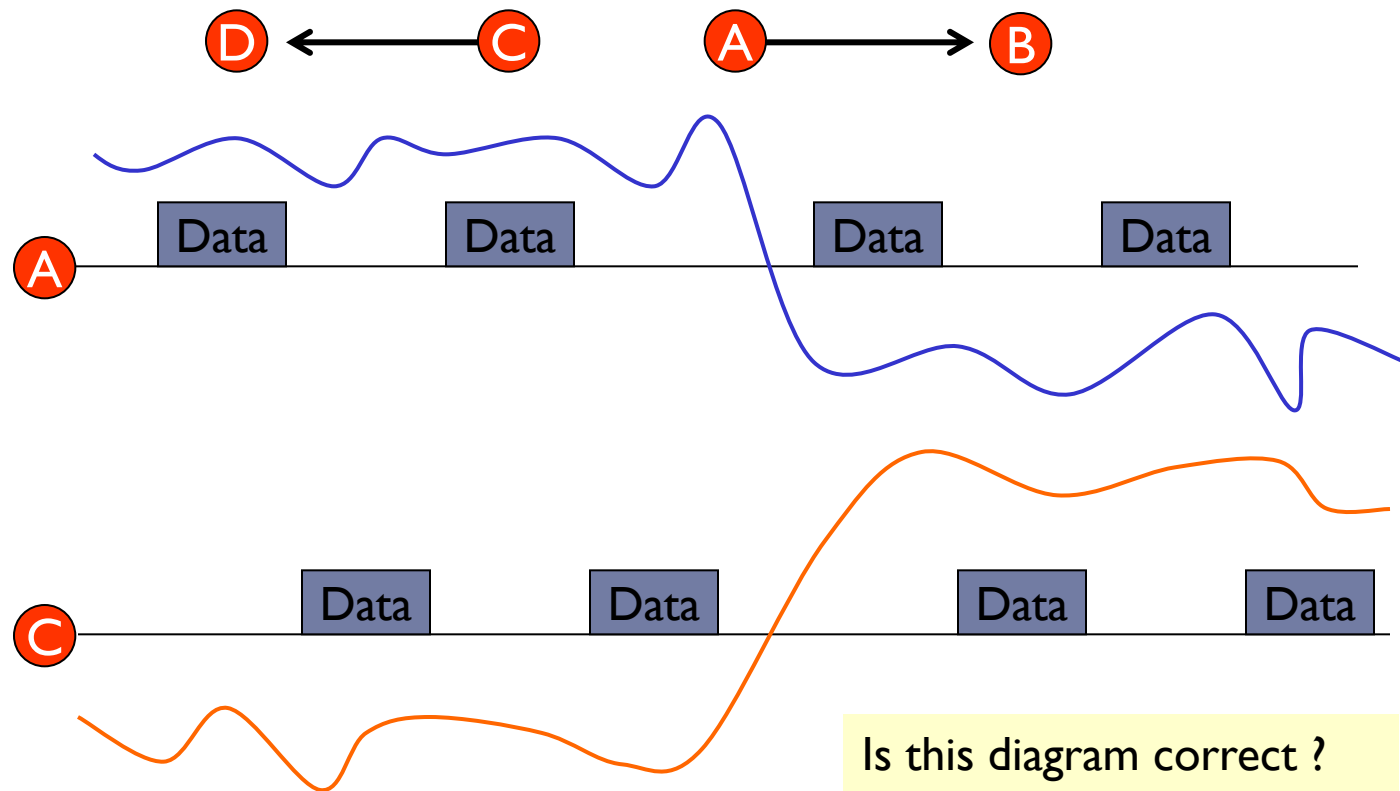
► Basic Idea

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



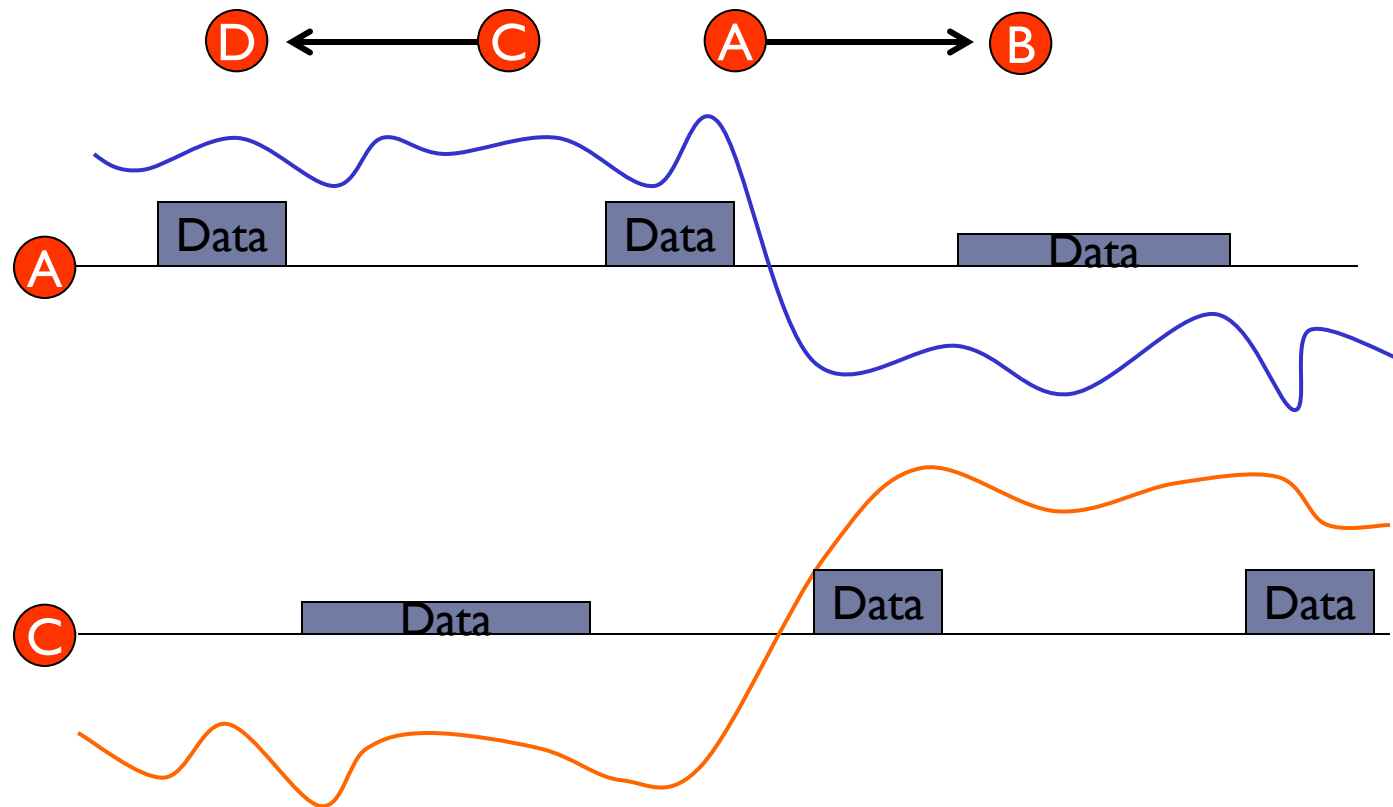
Why is OAR better?

- ▶ 802.11 alternates between transmitters A and C
 - ▶ Why is that bad



Why is OAR better ?

- ▶ Bad channel reduces SINR \rightarrow increases transmit time
 - ▶ Fewer packets can be delivered



OAR Protocol Steps

- ▶ **Transmitter estimates current channel**
 - ▶ Can use estimation algorithms
 - ▶ Can use RBAR, etc.
- ▶ **If channel better than base rate (2 Mbps)**
 - ▶ Transmit proportionally more packets
 - ▶ e.g., if channel can support 11 Mbps, transmit $(11/2 \sim 5)$ pkts
- ▶ **OAR upholds temporal fairness**
 - ▶ Each node gets same duration to transmit
 - ▶ Sacrifices throughput fairness → the network gains!!



OAR Protocol

Protocol	Channel Condition					
	BAD		MEDIUM		GOOD	
	Pkts	Rate	Pkts	Rate	Pkts	Rate
802.11	1	2	1	2	1	2
802.11b	1	2	1	5.5	1	11
OAR	1	2	3	5.5	5	11

- ▶ Rates in IEEE 802.11b: 2, 5.5, and 11 Mbps

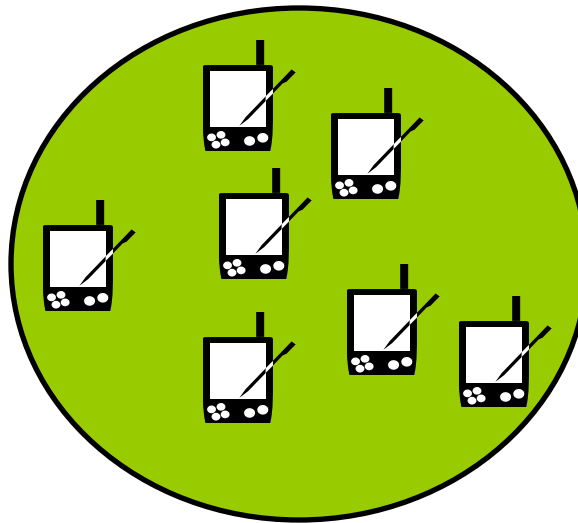
Evaluation

- ▶ **Simulation experiments**

- ▶ Fully connected network: all nodes in radio range of each other
 - ▶ Number of Nodes, channel condition, mobility, node location



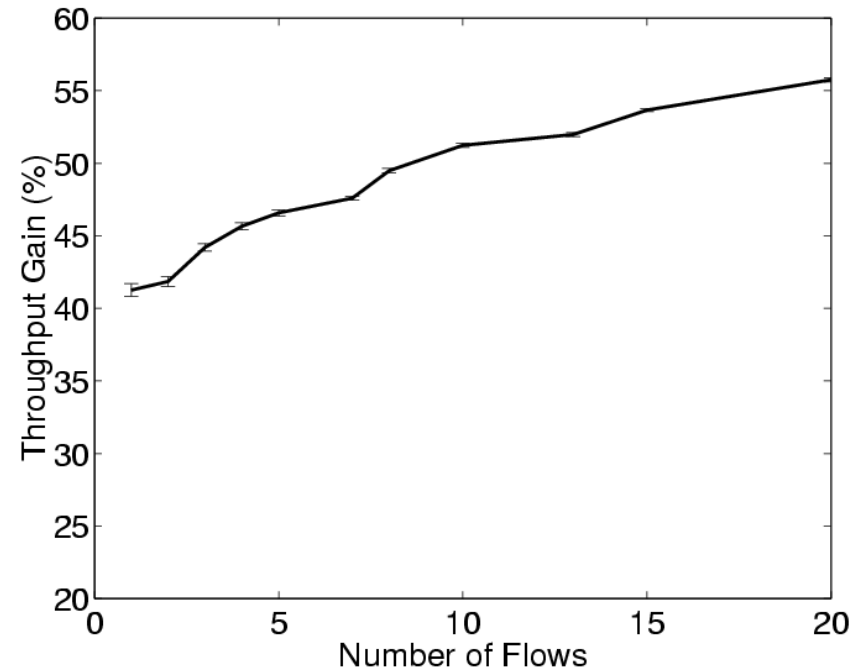
Fully Connected Setup



- ▶ Every node can communicate with everyone
- ▶ Each node's traffic is at a constant rate and continuously backlogged
- ▶ Channel quality is varied dynamically

Fully Connected Throughput Results

- ▶ **OAR vs. RBAR**
 - ▶ 42% to 56% gain
- ▶ **Gain increases with the number of flows**
- ▶ **Note**
 - ▶ Both RBAR and OAR are significantly better than standard 802.11
 - ▶ 230% and 398% respectively



OAR thoughts

- ▶ **OAR does not offer benefits when**
 - ▶ Neighboring nodes do not experience diverse channel conditions
 - ▶ Coherence time is shorter than N packets

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



What lies ahead ?

- ▶ **Dual of rate-control is power control**
 - ▶ One might be better than the other
 - ▶ Decision often depends on the scenario → open problem

