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

<table>
<thead>
<tr>
<th>Rate (Mbps)</th>
<th>Energy per bit</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Highest</td>
</tr>
<tr>
<td>2</td>
<td></td>
</tr>
<tr>
<td>5.5</td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>Lowest</td>
</tr>
</tbody>
</table>
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

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

- Mode 1: BPSK(6Mbps) FEC=1/2
- Mode 2: BPSK(9Mbps) FEC=3/4
- Mode 3: QPSK(12Mbps) FEC=1/2
- Mode 4: QPSK(18Mbps) FEC=3/4
- Mode 5: 16-QAM(24Mbps) FEC=1/2
- Mode 6: 16-QAM(36Mbps) FEC=3/4
- Mode 7: 64-QAM(48Mbps) FEC=2/3
- Mode 8: 64-QAM(54Mbps) FEC=3/4
802.11 Frame Exchange Overhead

- Not all time is spent sending actual data

Sender

Receiver

Medium time used for transmission

Actual time sending application data

RTS

DATA

CTS

ACK

cw
Multi-rate Frame in 802.11b

Figure 127—Long PLCP PPDU format
802.11b Frame Exchange Duration

Medium Time consumed to transmit 1500 byte packet

Rate (Mbps):
- 11.0 Mbps: 4.55 Mbps
- 5.5 Mbps: 3.17 Mbps
- 2.0 Mbps: 1.54 Mbps
- 1.0 Mbps: 0.85 Mbps

Medium Time (milliseconds):
- 0
- 1
- 2
- 3
- 4
- 5
- 6
- 7
- 8
- 9
- 10
- 11
- 12
- 13
- 14

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Multi-rate Frame in 802.11a

<table>
<thead>
<tr>
<th>RATE</th>
<th>Reserved</th>
<th>LENGTH</th>
<th>Parity</th>
<th>Tail</th>
<th>SERVICE</th>
<th>PSDU</th>
<th>Tail</th>
<th>Pad Bits</th>
</tr>
</thead>
<tbody>
<tr>
<td>4 bits</td>
<td>1 bit</td>
<td>12 bits</td>
<td>1 bit</td>
<td>6 bits</td>
<td>16 bits</td>
<td></td>
<td>6 bits</td>
<td></td>
</tr>
</tbody>
</table>

- **PLCP Header**
  - **Coded/OFDM (BPSK, r = 1/2)**
  - **Coded/OFDM (RATE is indicated in SIGNAL)**

<table>
<thead>
<tr>
<th>PLCP Preamble</th>
<th>SIGNAL</th>
<th>DATA</th>
</tr>
</thead>
<tbody>
<tr>
<td>12 Symbols</td>
<td>One OFDM Symbol</td>
<td>Variable Number of OFDM Symbols</td>
</tr>
</tbody>
</table>

52 us
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

SINR vs. time
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)

Path Loss

Mean Throughput (Kbps)

Distance (m)

SNR (dB)

Distance (m)

4 Mbps

8 Mbps

1 Mbps

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Impact

- Small-scale variation with time (Fading)

Rayleigh Fading

- SNR (dB)
- Time (ms)
- 2.4 GHz
- 2 m/s LOS

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Which modulation scheme is best?
Answer → Rate Adaptation

- Dynamically choose the best modulation scheme for the channel conditions

![Graph showing mean throughput vs. distance](image)

Desired Result

- QAM256 (8Mbps)
- QAM64 (6Mbps)
- QAM16 (4Mbps)
- QPSK (2Mbps)
- BPSK (1Mbps)
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
Adaptation → At Which Layer?

- Cellular networks
  - Adaptation at the physical layer
- Impractical for 802.11 in WLANs

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
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)
• RTS carries sender’s estimate of best rate
• CTS carries receiver’s selection of the best rate
Nodes that hear RTS/CTS calculate reservation.

If rates differ, special subheader in DATA packet updates nodes that overheard RTS.
Performance of RBAR

SNR (dB) vs. Time (s)

Rate (Mbps) vs. Time (s)

RBAR

ARF
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

- 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

![Graph showing mean throughput (Kbps) vs distance (m) for different modulation schemes.]

- **A**
- **B**

Legend:
- QAM256 (8Mbps)
- QAM64 (6Mbps)
- QAM16 (4Mbps)
- QPSK (2Mbps)
- BPSK (1Mbps)
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?

[Diagram showing A, B, and C with a router and a truck]
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

<table>
<thead>
<tr>
<th></th>
<th>802.11 Packet Fairness</th>
<th>OAR Temporal Fairness</th>
</tr>
</thead>
<tbody>
<tr>
<td>11 Mbps Link</td>
<td>0.896</td>
<td>3.533</td>
</tr>
<tr>
<td>1 Mbps Link</td>
<td>0.713</td>
<td>0.450</td>
</tr>
<tr>
<td>Total Throughput</td>
<td>1.609</td>
<td>3.983</td>
</tr>
</tbody>
</table>

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

Is this diagram correct?
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

<table>
<thead>
<tr>
<th>Protocol</th>
<th>Channel Condition</th>
<th>BAD</th>
<th>MEDIUM</th>
<th>GOOD</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Pkts</td>
<td>Rate</td>
<td>Pkts</td>
<td>Rate</td>
</tr>
<tr>
<td>802.11</td>
<td>1</td>
<td>2</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>802.11b</td>
<td>1</td>
<td>2</td>
<td>1</td>
<td>5.5</td>
</tr>
<tr>
<td>OAR</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>5.5</td>
</tr>
</tbody>
</table>

- 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