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</th>
<th>Energy per Bit</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Mbps</td>
<td>Highest</td>
</tr>
<tr>
<td>2 Mbps</td>
<td></td>
</tr>
<tr>
<td>5.5 Mbps</td>
<td></td>
</tr>
<tr>
<td>11 Mbps</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 ($N_{BPSC}$)</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
802.11 Frame Exchange Overhead

- Not all time is spent sending actual data
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

<table>
<thead>
<tr>
<th>Rate (Mbps)</th>
<th>MAC Overhead</th>
<th>Data</th>
<th>Medium Time (milliseconds)</th>
</tr>
</thead>
<tbody>
<tr>
<td>11.0</td>
<td>0.85 Mbps</td>
<td>4.55 Mbps</td>
<td>14</td>
</tr>
<tr>
<td>5.5</td>
<td>1.54 Mbps</td>
<td>3.17 Mbps</td>
<td>10</td>
</tr>
<tr>
<td>2.0</td>
<td></td>
<td>1.54 Mbps</td>
<td>7</td>
</tr>
<tr>
<td>1.0</td>
<td></td>
<td>0.85 Mbps</td>
<td>4</td>
</tr>
</tbody>
</table>

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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)
- PLCP Preamble 12 Symbols
- SIGNAL One OFDM Symbol
- DATA Variable Number of OFDM Symbols

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
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

![Graph showing BER vs. SNR for different modulation schemes and data rates.]

But, SINR itself varies with space and time.
Impact

- Large-scale variation with distance (Path loss)

**Path Loss**

- SNR (dB) vs. Distance (m)
- Mean Throughput (Kbps) vs. Distance (m)

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

8 Mbps vs. 1 Mbps
Impact

- Small-scale variation with time (Fading)

![Rayleigh Fading Graph]

- $\text{SNR (dB)}$
- Time (ms)
- Rayleigh Fading
- QAM256 (8 Mbps)
- QAM64 (6 Mbps)
- QAM16 (4 Mbps)
- QPSK (2 Mbps)
- BPSK (1 Mbps)
- 2.4 GHz
- 2 m/s LOS

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Which modulation scheme is best?

![Graph showing SNR vs Distance and SNR vs Time for different modulation schemes at 2.4 GHz, 2 m/s LOS.]
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 $\rightarrow$ 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, a special subheader in the DATA packet updates nodes that overheard the RTS.
Performance of RBAR

SNR (dB) vs. Time (s)

RBAR

Rate (Mbps) vs. Time (s)

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)]

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

Nodes A and 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

### Per Packet Fairness

<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>
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 $\rightarrow$ the network gains!!
## OAR Protocol

<table>
<thead>
<tr>
<th>Protocol</th>
<th>Channel Condition</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>BAD</td>
</tr>
<tr>
<td></td>
<td>Pkts</td>
</tr>
<tr>
<td>802.11</td>
<td>1</td>
</tr>
<tr>
<td>802.11b</td>
<td>1</td>
</tr>
<tr>
<td>OAR</td>
<td>1</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