Rate Adaptation in 802.11

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Outline

• Introduction
  • Intuition
  • Basic techniques

• Techniques
  • General Designs
  • Robust Rate Adaptation for 802.11 (2006)
  • Efficient Channel-aware Rate Adaptation in Dynamic Environments (2008)
  • MIMO Rate Adaptation for 802.11n (2010)
Introduction

Why Rate Adapt?

Definition:
- Rate Adaptation – dynamically change the transmission rate to adapt to the time-varying and location-depends channel quality

Reasons:
- Signal fading due to distance.
- Tradeoff between data-rate and range
- Interference from other sources
Challenges

1. Which measurements can be used?
   - Physical Layer
     - SINR, RSS, RSSI
   - Link-Layer
     - Probe packets
     - Consecutive success/losses

2. How do we estimate the best transmission rate?
   - Sequential rate adjustment
     - Increment or decrement rate until optimal is found
   - Best rate adjustments
     - Immediately jump to the optimal rate

General Designs

802.11A/B
General Design Critiques (1)

Decrease rate upon severe packet loss
- Motivation:
  - packet loss ≈ bad channel quality
- Limitation:
  - Packet loss ≠ bad channel
  - Hidden Terminals – decrease rate will increase likelihood of collision

Consecutive success/fail to increase/decrease rate
- Motivation:
  - adapt based on consecutive fails/losses
- Limitation:
  - As more packets fail, likely next packet is success (vice-versa)

<table>
<thead>
<tr>
<th></th>
<th>ARF</th>
<th>AARF</th>
<th>SampleRate</th>
<th>FixedRate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Goodput (Mbps)</td>
<td>0.65</td>
<td>0.36</td>
<td>0.58</td>
<td>1.24</td>
</tr>
<tr>
<td>Loss Ratio</td>
<td>6%</td>
<td>60%</td>
<td>50%</td>
<td>60%</td>
</tr>
</tbody>
</table>

Table 1: Performance of different rate adaptation algorithms in the presence of hidden stations.

Figure 2: CDF of an additional success/failure transmission after a consecutive success/failure transmission.

General Design Critiques (2)

Use physical layer metrics to infer new rate
- Motivation:
  - Physical measurement leads to accurate determination of channel quality
- Limitation:
  - No correlation between SNR and delivery probability
  - SNR variation makes rate estimation inaccurate

Use probe packets to test new rates
- Motivation
  - send frames at different rates to determine optimal rate
- Limitation:
  - Needs many probe packets to fully represent channel quality
  - E.g. Current rate (0% loss), higher rate (40% loss). A single packet can’t measure this and it may fail.

Figure 3: Evolution of SNR over time.
General Design Critiques (3)

Long-term smoothing
- Motivation:
  - Use long-term statistics to evaluate channel quality
- Limitations:
  - Over-fitting – may not capture short-term gains in wireless channel
  - Mobility – long-term data is too slow to adapt to someone walking
  - Mutual information – packet loss is random and uncorrelated

<table>
<thead>
<tr>
<th>Sampling intervals (ms)</th>
<th>5000</th>
<th>1000</th>
<th>500</th>
<th>100</th>
</tr>
</thead>
<tbody>
<tr>
<td>UDP Goodput (Mbps)</td>
<td>14.9</td>
<td>15.3</td>
<td>16.5</td>
<td>17.1</td>
</tr>
</tbody>
</table>

Table 2: Performance of ONOE with different sampling intervals.

Figure 6: Mutual Information of two packets separated by $\tau$ ms in time.

Robust Rate Adaptation Algorithm (RRAA)

802.11A/B
Robust Rate Adaptation Algorithm

Motivation

Goals:
- Robust against random loss
  - Maintain a stable rate in the presence of random loss
- Responsive to drastic channel changes
  - Quickly respond as a user is walking towards/away
  - Respond properly to source of interference

Challenges (review):
- How to estimate channel quality?
- How to determine the best rate to switch to?

Design

Loss Estimation
- Short-Term Frame-Loss Ratio

Rate Change
- Maximize Throughput

Adaptive RTS Filter
- Selectively use RTS/CTS for hidden terminals
- Uses additive increase-multiplicative decrease algorithm.
- * No RTS/CTS in 802.11a

Figure 5: Modules and interactions in RRAA.
Robust Rate Adaptation Algorithm
Loss Estimation and Rate Change

- Short-Term Frame-Loss Ratio
  - Loss-ratio:
    \[ P = \frac{\#\text{ lost frames}}{\#\text{ transmitted frames}} \]
  - Window size:
    - Increase with higher rates

Rate Change
- Change based on threshold
  \[ R_{\text{new}} = \begin{cases} R^+ & P > P_{\text{MTL}} \\ R^- & P < P_{\text{MTL}} \end{cases} \]
  \[ P^*(R) = 1 - \frac{\text{Throughput}(R^-)}{\text{Throughput}(R^+)} = 1 - \frac{\text{tx.time}(R^-)}{\text{tx.time}(R^+)} \]
  \[ P_{\text{MTL}} = aP^*(R), \text{ where } a \geq 1 \]
  \[ P_{\text{GFI}} = \frac{aP^*(R^+)}{\beta} \]

<table>
<thead>
<tr>
<th>Rate (Mbps)</th>
<th>Critical Loss Ratio (%)</th>
<th>( P_{\text{MTL}} )</th>
<th>( P_{\text{GFI}} )</th>
<th>ewnd</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td>N/A</td>
<td>50.00</td>
<td>N/A</td>
<td>6</td>
</tr>
<tr>
<td>9</td>
<td>31.45</td>
<td>14.34</td>
<td>39.32</td>
<td>10</td>
</tr>
<tr>
<td>12</td>
<td>22.94</td>
<td>18.61</td>
<td>28.68</td>
<td>20</td>
</tr>
<tr>
<td>18</td>
<td>29.78</td>
<td>13.25</td>
<td>37.22</td>
<td>20</td>
</tr>
<tr>
<td>24</td>
<td>21.20</td>
<td>16.81</td>
<td>26.50</td>
<td>40</td>
</tr>
<tr>
<td>36</td>
<td>26.90</td>
<td>11.50</td>
<td>33.63</td>
<td>40</td>
</tr>
<tr>
<td>48</td>
<td>18.40</td>
<td>4.70</td>
<td>23.00</td>
<td>40</td>
</tr>
<tr>
<td>54</td>
<td>7.52</td>
<td>N/A</td>
<td>9.40</td>
<td>40</td>
</tr>
</tbody>
</table>

Table 3: RRAA implementation parameters for 802.11a.
\( \alpha = 1.25, \beta = 2 \)

Robust Rate Adaptation Algorithm Implementation

Modification:
- No floating point calculation
  - Loss ratio ⇒ # lost packets in a window
  - Thresholds ⇒ # lost packets threshold

Experimental Design
- Static Clients
  - AP and STA are stationary throughout the experiment
  - Goal: Asses how algorithm responds to random channel loss
- Mobile Clients
  - STA moves
  - Goal: Asses responsiveness of algorithm
- Setting with Hidden Terminal
  - Goal: Asses algorithm in presence of hidden terminals
- Field Trials
  - Goal: Real-life test
Robust Rate Adaptation Algorithm
Results – Static Clients

- Result – RRAA is more robust to random channel losses
- RRAA-Basic > RRAA

Figure 10: TCP/UDP performance of ARF, AARF, SampleRate, RRAA-BASIC and RRAA. The numbers pointed by arrows are performance gains of RRAA (in 802.11b) or RRAA-BASIC (in 802.11a) over the worst one.

* P5 out-of-range in 802.11a

Figure 1: Experimental floor plan.

Robust Rate Adaptation Algorithm
Results – Mobile Clients

Result:
- RRAA maintains higher throughput than others.
- RRAA is more responsive to channel variation

Figure 12: UDP goodput in 802.11b with client mobility.
Robust Rate Adaptation Algorithm Results – Hidden Terminals

Graph:
- Blue Box – Average throughput
- Small bars – Percentage of time in each rate

Results:
- Other algorithms reduce rates due to loss from hidden terminals
- RRAA is 11 and 5.5 Mbps for most of the time
- Adaptive RTS helps filter hidden terminal losses

![Graph showing throughput and rate decision distribution in hidden-terminal case](image)

Figure 13: UDP throughput and rate decision distribution in the hidden-terminal case (802.11b).

Robust Rate Adaptation Algorithm Results – Field Trial

Experiment
- Time:
  - 4-10pm
- Wireless Config:
  - Channel 6
- Traffic:
  - 7-11 APs on channel 6
  - 77-151 Clients on channel 6
  - People walking in corridor

![Graph showing TCP performance](image)

Figure 14: TCP performance in field Trials.
Robust Rate Adaptation Algorithm

Conclusion

Short-term frame estimation helps exploit opportunistic gains

Rate adaptation algorithms must infer packet-loss cause

Adaptive RTS/CTS help with contention but has overhead

CHannel-Aware Rate adaptation algorithm (CHARM)

802.11B/G
CHARM

Motivation

Goals:
- Use accurate channel information to adapt quicker

Challenges (review):
- How to estimate channel quality?
- How to determine the best rate to switch to?

CHARM

Design (1)

1. Monitor Path Loss
   - $PL = P_{tx} + G_{tx} + G_{rx} - RSS$
   - $RSS \approx RSSI$
   - Channel Reciprocity
   - Accurate but noisy

- NLOS
- Stationary
- High-traffic

- Moving
- AP in room
- STA moves in hallway
CHARM Design (2)

2. Predict Path loss
   ◦ Use weighted average – recent data has higher weight
   \[ RSSI_{avg} = \frac{RSSI_{avg} \cdot f(dt) + RSSI_{curr}}{1 + f(dt)} \]
   ◦ Transient fades – 1 abnormal packet

3. Update SINR threshold
   ◦ Adapts based on performance
   ◦ Updates every few seconds
   ◦ Every receiver is different
   ◦ Count of success/fails below/above threshold and adapt accordingly.

4. Select Rate
   ◦ For every packet

CHARM Results – Static Nodes

Results
   ◦ CHARM achieves higher throughput in good signal environments
   ◦ CHARM has no improvements in poor signal environments.

Other techniques:
   ◦ AMRR
     • Adapt based on success rates of recent packets
   ◦ ONOE
     • Picks highest rate with loss=50%
   ◦ SampleRate
     • Select based on lowest packet transmission time
     • Slow to adapt to new channel conditions
CHARM Results – Mobile Transmitter

Results:
- CHARM can achieve higher throughput
- CHARM can recover quickly

CHARM Results – Hidden Terminals (emulator-based)

Results:
- RTS/CTS causes 18% loss in throughput
- CHARM achieves equal throughput to fixRate, SampleRate
  - ONOE and AMRR based on packet loss
- CHARM achieves better throughput without RTS/CTS
CHARM
Conclusion
Mobile clients causes highly dynamic wireless channels
CHARM is able to quickly learn about the channel and adapt

MIMO Rate Adaptation in 802.11n
802.11n Differences

MIMO
- different loss patterns
- Single Stream (SS) - diversity oriented
- Double Stream (DS) – spatial multiplexing

Channel Bonding
- 20 MHz/40 MHz channels

Frame aggregation
- Transmit several frames at once

802.11n has more rate options (6.5-600 Mbps)
- More opportunity for rate adaptation

MIMO Rate Adaptation
Applying RA in 802.11n

RAs Results:
- Other protocols don’t achieve best rate
- Best rate is 162 Mbps

<table>
<thead>
<tr>
<th>Rates (MHz)</th>
<th>Atheros RA</th>
<th>RA A</th>
<th>Sample Rate</th>
<th>Fixed Rate Goodput (Mbps)</th>
<th>Fixed Rate SFER</th>
</tr>
</thead>
<tbody>
<tr>
<td>40.625</td>
<td>49%</td>
<td>-</td>
<td>49.06</td>
<td>96.23</td>
<td>0.12%</td>
</tr>
<tr>
<td>54.625</td>
<td>49%</td>
<td>-</td>
<td>48.98</td>
<td>96.23</td>
<td>0.12%</td>
</tr>
<tr>
<td>81.25</td>
<td>49%</td>
<td>-</td>
<td>72.94</td>
<td>72.94</td>
<td>0.07%</td>
</tr>
<tr>
<td>108.0</td>
<td>51%</td>
<td>47%</td>
<td>96.40</td>
<td>96.40</td>
<td>0.15%</td>
</tr>
<tr>
<td>121.55</td>
<td>51%</td>
<td>53%</td>
<td>96.31</td>
<td>96.31</td>
<td>0.16%</td>
</tr>
<tr>
<td>135.0</td>
<td>-</td>
<td>-</td>
<td>74.01</td>
<td>74.01</td>
<td>17.92%</td>
</tr>
<tr>
<td>162.0</td>
<td></td>
<td></td>
<td>128.46</td>
<td>128.46</td>
<td>54.61%</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Goodput (Mbps)</th>
<th>SFER (5%)</th>
<th>SFER (10%)</th>
<th>SFER (25%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>71.40</td>
<td>0.55%</td>
<td>13.24%</td>
<td>7.25%</td>
</tr>
</tbody>
</table>

Table 1: Rate distribution, Goodput and SFER of existing RA algorithms at P4.
MIMO Rate Adaptation
Applying RA in 802.11n

Observations:
- Error-Rate is not monotonic with Transmission Rate
  - (different from 802.11a/b/g)
  - Other protocols assumes this
  - Peaks at 108-121
- Throughput is correlated with aggregation

MIMO Rate Adaptation
Applying RA in 802.11n

Observations
- There is monotonicity for each DS/SS

How to choose MIMO mode (roughly)
- Low SNR – use Single-Stream
- High SNR – use Dual-Stream

(b) SFER monotonicity in DS mode.
(c) SFER monotonicity in SS mode.
MIMO Rate Adaptation
Applying RA in 802.11n

Observation
- Limiting aggregation improves throughput
- Higher aggregation at bad rate means more data lost

<table>
<thead>
<tr>
<th>Rates (Mbps)</th>
<th>RRA (%)</th>
<th>RRA-Limited (%)</th>
<th>Aggregation Bound</th>
</tr>
</thead>
<tbody>
<tr>
<td>13.5SS</td>
<td>2</td>
<td>1</td>
<td>4</td>
</tr>
<tr>
<td>2TSS</td>
<td>3</td>
<td>0.5</td>
<td>8</td>
</tr>
<tr>
<td>2TDS</td>
<td>1</td>
<td>0.5</td>
<td>8</td>
</tr>
<tr>
<td>40.65SS</td>
<td>8</td>
<td>14</td>
<td>13</td>
</tr>
<tr>
<td>54SS</td>
<td>23</td>
<td>42</td>
<td>17</td>
</tr>
<tr>
<td>54DS</td>
<td>29</td>
<td>26</td>
<td>17</td>
</tr>
<tr>
<td>81SS</td>
<td>11</td>
<td>1</td>
<td>26</td>
</tr>
<tr>
<td>81DS</td>
<td>23</td>
<td>15</td>
<td>26</td>
</tr>
<tr>
<td>108SS</td>
<td>33</td>
<td>35</td>
<td>35</td>
</tr>
<tr>
<td>108DS</td>
<td>33</td>
<td>35</td>
<td>35</td>
</tr>
<tr>
<td>Goodput (Mbps)</td>
<td>24.22</td>
<td>35.60</td>
<td></td>
</tr>
<tr>
<td>SFER (%)</td>
<td>46.61</td>
<td>24.83</td>
<td></td>
</tr>
<tr>
<td>Avg. Aggr. level</td>
<td>19.36</td>
<td>13.81</td>
<td></td>
</tr>
</tbody>
</table>

MIMO Rate Adaptation
Design
ZigZag Scheme
- Switches between inter-mode (DS->SS) and intra-mode
- First intra-mode – finds the best rate
- Then goes to inter-mode, and picks best rate
- Then goes back to intra-mode
- Uses probe packets

Detects collisions (Hidden Terminals)
- Only use RTS/CTS if the overhead is not too costly
MIMO Rate Adaptation Implementation

Tested:
- Static
  - UDP/3x3 Antennas/5GHz/40MHz
  - UDP/2x2 Antennas/5GHz/40MHz
  - TCP/3x3 Antennas/5GHz/40MHz
  - UDP/3x3 Antennas/2.4GHz/40MHz
  - UDP/3x3 Antennas/2.4GHz/20MHz
- Mobile
- Hidden Terminals
  - Various interference levels
- Field Test

MIMO Rate Adaptation Results – Static Test

Observation:
- MiRA is better when further from AP
- More antennas is better
- 5GHz ≠ 2.4 GHz

Figure 8: 3 x 3 /5GHz/UDP static setting.
Figure 9: 3 x 3 /5GHz/TCP static setting.
Figure 10: 3 x 3 /2.4GHz/UDP static setting.
MIMO Rate Adaptation Results – Mobility and Hidden Terminals

Mobility:
- MiRA can adapt quickly, so can adapt to mobile

Hidden Terminals:
- Similar performance to RRAA

![Figure 12: Goodput in hidden terminal.](image)

MIMO Rate Adaptation Results – Field Trial

MiRA performs better

![Figure 13: MiRA performance in field trials.](image)
MIMO Rate Adaptation

Conclusions

MIMO has differences from 802.11a/b/g

Need to consider DS vs SS

Questions?