Predictable 802.11 Packet Delivery from Wireless Channel Measurements

Daniel Halperin
Wenjun Hu, Anmol Sheth, David Wetherall
802.11 Wi-Fi technology

- **Fast** - 600 Mbps in 802.11n represents a 300x speedup in 12 years
- **Reliable** - vehicular speeds, extended range, stable hardware and software
- **Ubiquitous** - few dollars per chip allows integration everywhere
802.11 Wi-Fi technology

- **Fast** - 600 Mbps in 802.11n represents a 300x speedup in 12 years
- **Reliable** - vehicular speeds, extended range, stable hardware and software
- **Ubiquitous** - few dollars per chip allows integration everywhere

New, exciting apps on the horizon
New apps stress network

Wireless Display

Mobile Wireless

Wireless Input
New apps stress network
New apps stress network

All-wireless
Home

Performance really matters
Performance – *in theory*

Channel Measurements

Rate Selection

Textbook Algorithms

39 Mbps
Performance – *in theory*

Channel Measurements

*In practice, this has never worked!*

Rate Selection

Mbps
Performance – *In practice*

Statistics-based Adaptation

Problem: Convergence time

- Dynamic environments
- Large search spaces
  - >300 tx configs in 802.11n
  - Combined rate & power

*Both are trends*
Goals: Bridging Theory and Practice

• Accurately predict performance over real channels
• Agile response to changing channels
• Leverage measurements available in real NICs
• Extend to 802.11n and more applications

Key: an accurate channel metric
Goals: Bridging Theory and Practice

- Accurately predict performance over real channels
- Agile response to changing channels
- Leverage measurements available in real NICs
- Extend to 802.11n and more applications

Key: an accurate channel metric
Today’s talk

• Why it’s hard to predict performance with RF measurements today

• Our solution: an accurate channel metric using Effective SNR

• Evaluation of Effective SNR in Wi-Fi Networks
Today’s talk

• Why it’s hard to predict performance with RF measurements today

• Our solution: an accurate channel metric using Effective SNR

• Evaluation of Effective SNR in Wi-Fi Networks
SNR based on RSSI

- **Received Signal Strength Indicator**
  - Measures total power received in packet
  - With Noise, gives SNR for packet

- *Treated as if directly reflects performance*
  E.g., NIC manufacturers list per-rate ‘sensitivity’

- In practice, **SNR** at which a rate starts to work can **vary more than 10 dB** for real links
802.11: OFDM and MIMO

Orthogonal Frequency Division Multiplexing

Multiple-Input Multiple-Output

Frequency-selective fading

Spatial diversity
802.11: OFDM and MIMO

Orthogonal Frequency Division Multiplexing

Multiple-Input Multiple-Output

Key: Different subchannels have different SNRs
Packet SNR for 4 faded links

SNR (dB)

Subcarrier index

SNR (dB)

Subcarrier index

Daniel Halperin, SIGCOMM 2010, dhalper@cs.washington.edu
Packet SNR for 4 faded links

30 dB

SNR (dB)

Subcarrier index

Packet SNR for 4 faded links

30 dB
Packet SNR for 4 faded links

SNR (dB) vs. Subcarrier index

30 dB

17 dB
Packet SNR for 4 faded links

30 dB

17 dB
Packet SNR for 4 faded links

SNR (dB)

30 dB

17 dB

Errors

Subcarrier index

Packet SNR

35

25

15

5

-28

-14

0

14

28
Packet SNR for 4 faded links

Fundamental SNR mismatch

Errors

17 dB

Subcarrier index

SNR (dB)

Packet SNR

35

25

15

5

-28

-14

0

14

28
An 802.11n opportunity

- **802.11n provides detailed channel measurements**
  Used for advanced MIMO techniques

- **Channel State Information (CSI) measures MIMO and OFDM!**
  - Matrix captures per-antenna paths
  - One matrix per subcarrier

- **Can we use it to predict packet delivery?**
  In theory? In practice?
Today’s talk

- Why it’s hard to predict performance with RF measurements today

- Our solution: an accurate channel metric using Effective SNR

- Evaluation of Effective SNR in Wi-Fi Networks
Effective SNR

- Introduced by Nanda and Rege in 1998
- **Packet SNR**: total power in the link
- **Effective SNR**: useful power in the link

![Graph showing SNR (dB) vs. Subcarrier index]
Effective SNR

- Introduced by Nanda and Rege in 1998
- **Packet SNR:** total power in the link
- **Effective SNR:** useful power in the link
Using Effective SNR

Channel Measurements

39 Mbps

Rate Selection

Textbook Algorithms
Using Effective SNR

Channel State Information (MIMO & OFDM)

Rate Selection

39 Mbps

Textbook Algorithms

Wireless Communications

Ananth Padmanabhan
Using Effective SNR

Channel State Information (MIMO & OFDM)

Effective SNR Model

Rate Selection

39 Mbps
Using Effective SNR

Channel State Information (MIMO & OFDM)

1x65  ❌
1x52  ❌
2x26  ✔
3x13  ✔

Working Configurations; Application Decision

Effective SNR Model
Using Effective SNR

Channel State Information (MIMO & OFDM)

Working Configurations; Application Decision

1x65 ✗
1x52 ✗
2x26 ✔
3x13 ✔

Effective SNR Model
Obtaining CSI

- **RX measures CSI** from packet preamble
  NICs do this for MIMO/OFDM operation

- **For every received frame**
  Measures all antennas + subcarriers used

3-antenna Link

3x3 Matrix

One matrix per Subcarrier
Using Effective SNR

Channel State Information (MIMO & OFDM)

Working Configurations; Application Decision

- 1x65: ✗
- 1x52: ✗
- 2x26: ✔
- 3x13: ✔

Effective SNR Model
Computing Effective SNR

- **Single antenna link** (1x1)
  - CSI gives the per-symbol SNR

- **Multiple RX antennas** (1xN)
  - Maximal-ratio combining

- **MIMO link** (MxN)
  - Minimum mean-square error (**MMSE**)

CSI → Compute SNRs per symbol → SNRs
Computing Effective SNR

CSI → SNRs

<table>
<thead>
<tr>
<th>Modulation</th>
<th>BER((\rho))</th>
</tr>
</thead>
<tbody>
<tr>
<td>BPSK</td>
<td>(Q\left(\sqrt{2\rho}\right))</td>
</tr>
<tr>
<td>QPSK</td>
<td>(Q\left(\sqrt{\rho}\right))</td>
</tr>
<tr>
<td>QAM-16</td>
<td>(Q\left(\sqrt{\rho/5}\right))</td>
</tr>
<tr>
<td>QAM-64</td>
<td>(Q\left(\sqrt{\rho/21}\right))</td>
</tr>
</tbody>
</table>

Compute BERs per symbol

Textbook formulas
Computing Effective SNR

CSI \Rightarrow\text{SNRs} \Rightarrow \text{BERs} \Rightarrow \text{BER}_{\text{eff}}\Rightarrow \text{Average: Effective BER}
Computing Effective SNR

CSI → SNRs

Convert back to SNR

SNR_{eff} → BER_{eff}

BERs
Using Effective SNR

Channel State Information (MIMO & OFDM)

Effective SNR Model

Working Configurations; Application Decision

1x65  X
1x52  X
2x26  ✔
3x13  ✔
Predicting Packet Delivery

- **Effective SNR thresholds** for each rate
  - Threshold per **NIC implementation**, not per NIC or per channel
- Adds **flexibility** to handle real NICs
  - **Hard vs soft decoding**
- **Other special techniques**
  - e.g., use optimal Maximum Likelihood receiver only for small modulations
Example Applications

- **Rate/MIMO/Channel width selection:** What is the fastest configuration for this link?

3x3, 40 MHz
Example Applications

• **Rate/MIMO/Channel width selection:**
  What is the fastest configuration for this link?

![Diagram showing 1x3 and 3x3, 40 MHz configurations]
Example Applications

- **Rate/MIMO/Channel width selection:** What is the fastest configuration for this link?

![Diagram of antenna configurations]

- 3x3, 40 MHz
Example Applications

- **Rate/MIMO/Channel width selection:**
  What is the fastest configuration for this link?

![Diagram showing 3x3 configuration and 3x3, 40 MHz options]
Example Applications

- Rate/MIMO/Channel width selection:
  What is the fastest configuration for this link?

- 3x3, 40 MHz

Example Applications

- **Power Consumption:**
  Which receive antenna is best to disable to save power?

![RX Antenna Selection](image)

3x3, 40 MHz
Example Applications

- **Spatial Reuse:**
  What is the lowest transmit power at which I can support 100 Mbps bitrate?

\[ \text{Power} \times 3x3, 40 \text{ MHz} \]
Today’s talk

• Why it’s hard to predict performance with RF measurements

• Our solution building a better metric using Effective SNR

• Evaluation of Effective SNR in Wi-Fi Networks
Implemented in Intel NIC

• Intel Wi-Fi Link 5300 NIC (3x3, 450 Mbps)
• Two testbeds with > 200 widely varying links
• Linux (2.6.35-rc3) open source `iwlwifi` driver
• Firmware `debug mode`: send CSI to RX host
• Real-time computation: \(~4 \mu s\) per 3x3 CSI
Evaluation Questions

• Does Effective SNR accurately predict packet delivery?

• Does an Effective SNR rate selection algorithm perform well?

• More results in the paper
  • Wireless link transition region
  • Transmit power control
  • Collisions
Predicting Optimal 3x3 Rate
Predicting Optimal 3x3 Rate

Rate / stream (Mbps) vs. Packet SNR (dB).

Daniel Halperin, SIGCOMM 2010, dhalperi@cs.washington.edu
Predicting Optimal 3x3 Rate

![Graph showing the relationship between Packet SNR (dB) and Rate (Mbps). The graph displays a stepwise increase in rate as the Packet SNR increases.]
Predicting Optimal 3x3 Rate
Rate control evaluation

• **802.11a:** Does Effective SNR match related work? ESNR versus SampleRate, SoftRate, OPT

• **802.11n:** Does Effective SNR extend to 802.11n? ESNR versus OPT

• **Channel simulation over mobile trace**
  to compare against related work & vary speed
  - MATLAB simulation + SoftRate GNU Radio
  - Effective SNR algorithm gets corrupted CSI
Matches or beats 802.11a algorithms

All within 15% of OPT
Effective SNR for 802.11a

- Matches or beats 802.11a algorithms
- All within 15% of OPT

No rate fallback on retries: 50% performance gap
ESNR extends to MIMO

- 80% accuracy, 10% overselection
- 24 rates vs 8, larger gap vs Previous-OPT
Related work
## Related work

<table>
<thead>
<tr>
<th>SoftRate (2009)</th>
<th>✔</th>
</tr>
</thead>
<tbody>
<tr>
<td>AccuRate (2010)</td>
<td>✔</td>
</tr>
<tr>
<td>Error Estim. Codes (2010)</td>
<td>✔</td>
</tr>
<tr>
<td>Effective SNR</td>
<td>✔</td>
</tr>
</tbody>
</table>
## Related work

<table>
<thead>
<tr>
<th></th>
<th>802.11a</th>
<th>MIMO &amp; Ant Sel.</th>
<th>TX Power</th>
<th>Channel Width</th>
<th>Real NICs</th>
</tr>
</thead>
<tbody>
<tr>
<td>SoftRate (2009)</td>
<td>✔</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>AccuRate (2010)</td>
<td>✔</td>
<td></td>
<td></td>
<td></td>
<td>✔</td>
</tr>
<tr>
<td>Error Estim. Codes (2010)</td>
<td>✔</td>
<td></td>
<td>✔</td>
<td></td>
<td>✔</td>
</tr>
<tr>
<td>Effective SNR</td>
<td>✔</td>
<td>✔</td>
<td>✔</td>
<td>✔</td>
<td>✔</td>
</tr>
</tbody>
</table>
Conclusions

• For the first time, we can use measurements available in real NICs to predict packet delivery over real channels

• **Matches good performance** of existing rate adaptation algorithms and **extends to 802.11n**

• Applies to a **broad problem space** and provides a **simple, practical API** for protocols

• **Lots more in the paper!**
Thanks! Questions?
dhalperi@cs.washington.edu