Bringing Life to Dead Spots

Grace Woo

Pouya Kheradpour, Dawei Shen, and Dina Katabi
Many APs But Still Poor Coverage

Problem increases with mobility and low power devices
Poor Coverage Is Not No Coverage!

Can recover a correct packet if we combine the correct bits from these receptions.
But Which AP Got the Right Bit?

- Clearly can’t have per bit checksum
- Prior work (MRD) tries all block combinations to satisfy checksum

- Exponential Complexity
- Works for a few bit errors **But not dead spots**
SOFT

• Recovers a correct packet from its faulty receptions at APs

• Leverages physical layer hints to identify correct bits

• SOFT’s delivery rate is up to 10x higher than current WLANs and MRD
SOFT Architecture

APs leverage high-speed Ethernet to combine their receptions.

But which bits are correct?
Physical Layer Knows More!

PHY already estimates a confidence in its 0-1 decision \( \Rightarrow \) Soft Value

<table>
<thead>
<tr>
<th>0.0</th>
<th>0.2</th>
<th>0.4</th>
<th>0.6</th>
<th>0.8</th>
<th>1.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>-1.0</td>
<td>-0.5</td>
<td>0.0</td>
<td>0.5</td>
<td>1.0</td>
<td></td>
</tr>
</tbody>
</table>

**PDF of per bit soft values**

- Soft Value < 0 \( \Rightarrow \) “0”
- Soft Value > 0 \( \Rightarrow \) “1”

Larger absolute soft values \( \Rightarrow \) More confidence in bit
We Use the Soft Values

- SOFT changes the PHY interface to expose the soft values to higher layers
- SOFT combines the soft values of a bit to decode it correctly
- The combiner forwards the decoded packet if it satisfies the 802.11 checksum
How Do We Combine Soft Values?

Say for a particular bit, we got

- 0.4
- 0.1
- 0.2

How do we decode the bit?

- Maximum soft value $\rightarrow$ Bit is “1”
- Majority vote $\rightarrow$ Bit is “0”
- Average $\rightarrow$ Bit is “1”

Different Combining Methods $\rightarrow$ Different Answers!
SOFT Combining Algorithm

Intuitively, we want to favor less noisy channels.

Let \( \sigma_i^2 \) be the noise variance on the channel to AP\(_i\).

Let \( S_{ij} \) be the soft value of bit \( j \) reported by AP\(_i\).

**SOFT decision rule:**

\[
\sum_i \frac{S_{ij}}{\sigma_i^2} \geq 0 \implies \text{Bit } j \text{ is "1" else "0"}
\]

For AWGN and dead spots rule is proven optimal.
But, How Does SOFT Get the Noise Variance?
Randomness in soft values is caused by channel noise

Estimate $\sigma_i^2$ from the PDF of the soft values in packet
How About Overhead?

• PHY soft values can be 32-bit float
  → Excessive Ethernet traffic

Solution

• Invoke SOFT only when associated AP can’t decode
• Quantize soft values (we used 3 bits)
What About the Downlink?

Use Time Diversity
Combine a packet with its retransmission
Performance
SOFT Implementation

- Software – GNURadio codebase
- Hardware – USRP frontend
- GMSK and DBPSK modulations
- Soft values are inputs to the slicer

- Poor Coverage:
  - SNR 5 – 12 dB
  - BER about $10^{-3}$
Experimental Setup

• 13 GNURadio nodes

• Compared
  – Current 802.11 WLAN (user associates with best AP)
  – MRD
  – SOFT

• Each Experiment
  – 3 random APs
  – Random source
  – Transmit 500 packets
Does SOFT Help?

CDF of 100 experiments

Packet Delivery Rate

0.00 0.20 0.40 0.60 0.80 1.00

0.00 0.20 0.40 0.60 0.80 1.00

CDF of 100 experiments

Packet Delivery Rate
Does SOFT Help?

Current Approach
Does SOFT Help?

CDF of 100 experiments

Packet Delivery Rate

Current Approach
MRD
Does SOFT Help?

CDF of 100 experiments

Current Approach
MRD
SOFT

SOFT’s delivery rate can be 10x higher
Performance with Increasingly Poor Coverage

Packet Delivery Rate

Bit Error Rate
Performance with Increasingly Poor Coverage

Packet Delivery Rate

Bit Error Rate

Current Approach
Performance with Increasingly Poor Coverage

Packet Delivery Rate vs. Bit Error Rate

- Current Approach
- MRD
Performance with Increasingly Poor Coverage

Packet Delivery Rate vs. Bit Error Rate

Current Approach
SOFT Addresses Dead Spots
SOFT on Downlink

CDF over 50,000 packets

Number of Retransmissions Until Correct Packet

Current Approach
SOFT on Downlink

CDF over 50,000 packets

17 ReTx

SOFT
Current Approach

Much Higher Throughput!
Combining Method Is Important

CDF of 100 experiments

SOFT Outperforms MAX and MAJORITY
Effect of Quantization

SOFT Average Delivery Rate

Overhead on Wired Ethernet is Acceptable

- 3 Bits
- 32 Bits

All presented results are for 3-bit quantization!
Conclusion

• WLAN can have better coverage if the interface to the PHY exposes soft values

• Delivery rate can be up to 10x higher

• The new architecture, SOFT, can co-exist with unmodified 802.11 cards and APs
Comments

• Combine spatial diversity and temporal diversity with PHY-layer information

• Combining algorithm is provably optimal

• Room for improvement
Comparison: MRD, PPR, SOFT

• MRD
  – Leverage multiple receivers spaced apart to recover losses
  – Exhaustive search + ARQ

• PPR
  – Leverage physical-layer hints
  – Post-ample
  – Use partial ARQ to recover the incorrect pkts

• SOFT
  – Leverage multiple receivers spaced apart to recover losses
  – Leverage physical-layer hints
  – Direct combine + ARQ
analog signal → demodulation → bits before FEC → FEC → bits after FEC

MIMO

MRD
PPR
SOFT
<table>
<thead>
<tr>
<th></th>
<th>MRD</th>
<th>PPR</th>
<th>SOFT</th>
<th>MIMO</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spatial diversity</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Temporal</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Partial retransmission</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PHY layer support</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Coop./comm. between APs</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Inherent loss vs. collision</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Implication on MAC protocol</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Room for Improvement

- Partial retransmission + combining
- Combining before FEC
- Rate adaptation
- MAC scheduling
- Reduce ethernet overhead
- Spatial reuse
Impacts on Other Layers

- **MAC auto-rate**
  - Should adjust according to the final loss rate (not individual link loss rates)

- **Routing**
  - A group of receivers should cooperatively help to move pkts forward

- **TCP**
  - Longer delay and more reorders ➔ receivers need to buffer out-of-order packets