Roofnet: An 802.11b Mesh Network

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Context: Mesh Networks

- **Ad hoc networking**
  - Mobile, highly dynamic topologies
  - Chief metrics: routing protocol overhead, packet delivery success rate, hop count
  - Largely evaluated in simulation

- **Sensornets**
  - Fixed, resource-impoverished nodes
  - Chief metric: energy consumption

- **Mesh networks**
  - Fixed, PC-class nodes
  - Motivation: shared Internet access in community
  - Chief metric: TCP throughput
  - Today: Roofnet, a real, deployed mesh network
Context: Mesh Networks

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**Why a multi-hop mesh vs. single-hop access points?**
Roofnet: Design Choices

• Volunteer users host nodes at home
  – Open participation without central planning
  – No central control over topology

• Omni antennas
  – Ease of installation by naïve user: no choice of neighbors or aiming
  – Links interfere, likely low quality

• Multi-hop routing (not 1-hop APs)
  – Potentially better coverage, path diversity
  – Routing more complex, end-to-end loss higher

• Goal: high TCP throughput
  – Reachability alone less challenging on (nearly) static network
Roofnet: Design Choices

- Volunteer users host nodes at home
  - Open participation without central planning
  - No central control over topology

Stated non-goals for paper:
- Throughput of multiple flows
- Scalability in number of nodes
- Design of routing protocols
- Performance change over time
- Topology change as users join / leave network
Roofnet Deployment

• Each node: PC, 802.11b card, roof-mounted omni antenna
Node Addresses

• Autoconfiguration of wireless interface IP address
  – High byte: private (e.g., net 10) prefix
  – Roofnet nodes not reachable from Internet
  – Low 3 bytes are low 3 bytes of Ethernet MAC address

• NAT between wired Ethernet and Roofnet
  – Private addresses (net 192.168.1) for wired hosts
  – No address allocation coordination across Roofnet nodes required
  – Roofnet hosts can’t connect to one another; only to Internet
Internet Gateways

• Roofnet node tries DHCP on wired Ethernet; then tries reaching Internet hosts; success indicates node is an Internet gateway

• NAT between wireless interface and wired Internet gateway interface
  – Why needed?

• Roofnet nodes track gateway used for each open TCP connection they originate
  – If best gateway changes, open connections continue to use gateway they already do
  – Why?
Routing Protocol

- Srcr: DSR-like protocol
- Each link has metric (not necessarily 1!)
- Data packets contain full source routes (robust against loops; metric may be dynamic)
- Nodes keep database of link metrics
  - Nodes write current link metric into source route of all packets they forward
  - Nodes flood route queries when cannot find route; queries accumulate link metrics
  - Nodes cache link metrics overheard in queries/responses
- Run Dijkstra’s algorithm over database to compute source routes
Link Characteristics

• Wired networks
  – Wired link offers bit error rate $10^{-12}$
  – Links “all” (connected) or “nothing” (cut)

• Wireless networks
  – Bit error rate depends on SNR at receiver
  – Dependent on distance, attenuation, &c.
  – Ideal: radio mimics “all or nothing” links; beyond threshold distance, bit error rate approaches 1
  – Reality: links at every bit error (packet loss) rate
  – Are all hops created equal?
Varying Link Loss Rates: Example

- A → C: 1 hop; high loss
- A → B → C: 2 hops; lower loss

But does this happen in practice?
Hop Count and Throughput

- [DeCouto et al., 2003]; indoor predecessor to Roofnet
- 134-byte packets; theoretical 1-hop max = 451 pkts/s
Hop Count and Throughput (cont’d)

- [DeCouto et al., 2003]
- Shortest path not highest throughput
- 3-hop paths span wide range of throughputs
Wireless Link Loss Rates

- [DeCouto et al., 2003]
- Vertical bar ends: loss rates in each direction on one link
- Large fraction of links very lossy in at least one direction
- Asymmetric loss rates
- Wide range of loss rates
Link Metric: Straw Men

- Discard links with loss rate above a threshold?
  - Risks disconnecting nodes!

- Product of link delivery ratios as probability of end-to-end delivery?
  - Ignores inter-hop interference: prefers 2-hop route with 0% loss over 1-hop with 10% loss, when latter is nearly double the throughput

- Throughput of highest-loss link on path?
  - Also ignores inter-hop interference
ETX: Expected Transmissions

- **Link ETX**: predicted number of transmissions
- **Path ETX**: sum of link ETX values on path
- Calculate link ETX using forward and reverse delivery ratios
- To avoid retry, data packet and ACK must succeed
- ETX = 1 / (d_f x d_r)
  - d_f = forward delivery ratio (data packet)
  - d_r = reverse delivery ratio (ACK packet)
ETX: Expected Transmissions

- **Link ETX**: predicted number of transmissions
- **Path ETX**: sum of link ETX values on path
- Calculate link ETX using *forward* and *reverse* delivery ratios

\[ ETX = \frac{1}{d_f \times d_r} \]

- \( d_f \) = forward delivery ratio (data packet)
- \( d_r \) = reverse delivery ratio (ACK packet)

**Does path ETX allow overlapping transmissions along a path?**

**Does path ETX offer equal accuracy for paths of all lengths?**
ETX: Measuring Loss Rates

- Periodically send broadcast probe packets of fixed size
- All nodes know sending rate of probes
- All nodes compute loss rate based on how many arrive per measurement interval
- Nodes enclose loss measurements in their probes (B tells A loss from A→B)
Multi-Rate Radios

- ETX assumes all radios run at same bit-rate
- 802.11b rates: \{1, 2, 5.5, 11\} Mbps
- Cannot compare 2 transmissions at 1 Mbps with 2 at 2 Mbps
- Solution: use time spent rather than transmission count
ETT: Expected Transmission Time

- ACKs always sent at 1 Mbps
- Data packets typically 1500 bytes
- Nodes send 1500-byte broadcast probes at every bit rate $b$ (delivery ratio: $d_{f,b}$)
- Nodes send 60-byte (min size) broadcast probes at 1 Mbps (delivery ratio: $d_r$)
- At each bit-rate $b$, $\text{ETX}_b = 1 / (d_{f,b} \times d_r)$
- For packet of length $S$, $\text{ETT}_b = (S/b) \times \text{ETX}$
- Link ETT = $\min_b (\text{ETT}_b)$
ETT: Assumptions

• Path throughput \( t \) given by:

\[
t = \frac{1}{\sum_i \frac{1}{t_i}}
\]

– where \( t_i = \) throughput of hop I

• Underestimates throughput for long paths
  – distant nodes can send simultaneously

• Overestimates throughput for paths with heavy “self-collisions”
Auto Bit-Rate Selection

- Radio firmware automatically chooses bit-rate among \{1, 2, 5.5, 11\} Mbps
  - avoids bit-rates with high loss rates
- Undesirable policy!
Auto Bit-Rate Selection

- Radio firmware automatically chooses bit-rate among \{1, 2, 5.5, 11\} Mbps
  - avoids bit-rates with high loss rates
- Undesirable policy!
Auto Bit-Rate Selection (cont’d)

• Ideally, could choose exact bit-rate that at given SNR, gives highest throughput and nearly zero loss

• Instead, 802.11b bit-rates quantized at roughly powers of two

• Result: over single hop, bit-rate $2R$ with up to 50% loss always higher-throughput than bit-rate $R$!
Auto Bit-Rate Selection in RoofNet: SampleRate

- Samples delivery rates of actual data packets using 802.11 retransmit indication
- Occasionally sends packets at rates other than current rate
- Sends most packets at rate predicted to offer best throughput (as with ETT)
- Adjusts per-packet bit-rate faster than ETT
  - only 1 hop of information required
  - delivery ratio estimates not periodic, but per-packet
RoofNet Evaluation

- TCP always single flow at a time
- Multi-hop: 15-second, 1-way bulk TCP transfers between all pairs of nodes
- Single-hop: same, direct link between all pairs of nodes
- Loss matrix: loss rate between all pairs for 1500-byte broadcasts at each bit-rate
- No RTS/CTS (more later!)
- Background traffic: users always active
End-to-End Throughput
End-to-End Throughput
End-to-End Throughput

- Mean: 627 kbps; median: 400 kbps
- Routing queries fail for 10% of pairs; link losses, retries fail
### Hop Count, Throughput, Latency

<table>
<thead>
<tr>
<th>Hops</th>
<th>Number of Pairs</th>
<th>Throughput (kbits/sec)</th>
<th>Latency (ms)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>158</td>
<td>2451</td>
<td>14</td>
</tr>
<tr>
<td>2</td>
<td>303</td>
<td>771</td>
<td>26</td>
</tr>
<tr>
<td>3</td>
<td>301</td>
<td>362</td>
<td>45</td>
</tr>
<tr>
<td>4</td>
<td>223</td>
<td>266</td>
<td>50</td>
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<tr>
<td>5</td>
<td>120</td>
<td>210</td>
<td>60</td>
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<tr>
<td>6</td>
<td>43</td>
<td>272</td>
<td>100</td>
</tr>
<tr>
<td>7</td>
<td>33</td>
<td>181</td>
<td>83</td>
</tr>
<tr>
<td>8</td>
<td>14</td>
<td>159</td>
<td>119</td>
</tr>
<tr>
<td>9</td>
<td>4</td>
<td>175</td>
<td>182</td>
</tr>
<tr>
<td>10</td>
<td>1</td>
<td>182</td>
<td>218</td>
</tr>
<tr>
<td>no route</td>
<td>132</td>
<td>0</td>
<td>–</td>
</tr>
<tr>
<td>Avg: 2.9</td>
<td>Total: 1332</td>
<td>Avg: 627</td>
<td>Avg: 39</td>
</tr>
</tbody>
</table>

- Neighboring nodes interfere with one another
## Theoretical Max Throughput (Lossless)

- Computed analytically, assuming hops don’t forward in parallel
- One-hop routes seem to use 5.5 Mbps
- Longer routes far slower than predicted

<table>
<thead>
<tr>
<th>Rate</th>
<th>1 Hop</th>
<th>2 Hops</th>
<th>3 Hops</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>890</td>
<td>445</td>
<td>297</td>
</tr>
<tr>
<td>2</td>
<td>1634</td>
<td>817</td>
<td>545</td>
</tr>
<tr>
<td>5.5</td>
<td>3435</td>
<td>1718</td>
<td>1145</td>
</tr>
<tr>
<td>11</td>
<td>5013</td>
<td>2506</td>
<td>1671</td>
</tr>
</tbody>
</table>
User Experience: Mean Throughput from Gateway

<table>
<thead>
<tr>
<th>Hops</th>
<th>Number of nodes</th>
<th>Throughput (kbits/sec)</th>
<th>Latency (ms)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>12</td>
<td>2752</td>
<td>9</td>
</tr>
<tr>
<td>2</td>
<td>8</td>
<td>940</td>
<td>19</td>
</tr>
<tr>
<td>3</td>
<td>5</td>
<td>552</td>
<td>27</td>
</tr>
<tr>
<td>4</td>
<td>7</td>
<td>379</td>
<td>43</td>
</tr>
<tr>
<td>5</td>
<td>1</td>
<td>89</td>
<td>37</td>
</tr>
<tr>
<td>Avg: 2.3</td>
<td>Total: 33</td>
<td>Avg: 1395</td>
<td>Avg: 22</td>
</tr>
</tbody>
</table>

- Latency: 84-byte ping; interactive use OK
- Acceptable throughput, even 4 hops out
Link Quality vs. Distance: All Links

- Single-hop TCP workload
- Many links ca. 500 kbps of varying lengths
- A few short, high-throughput links; a very few long, high-throughput links
Link Quality vs. Distance: Ssrc Links

- Multi-hop TCP workload
- Ssrc favors short, fast links
Sample Rate Bit-Rate Choice: Lossy Links Useful

- Median: 0.8; 20%+ loss links used half the time
Density Evaluation

- Want to evaluate Roofnet with varying numbers of nodes (== varying density)
- One-hop TCP throughput known by measurement
- Using path ETT formula, can estimate multi-hop TCP throughput for any path
- Choose random node subsets, compute estimated throughput using only subset member nodes in paths
Node Density and Connectivity

- 25th, 50th, 75th percentiles over 100 random subsets
- Connected = $\geq 1$ kbyte / s throughput
Node Density and Throughput

- Why does throughput increase?
Node Density and Path Length

- Increasing density increases diversity: adds short, low-loss links!
Diversity in Node Use: “Meshness”

- Most nodes route via a diverse set of neighbors
Mesh Robustness Evaluation: Sensitivity to Eliminated Links

- Know single-hop TCP throughputs for all node pairs
- Try eliminating links, compute multi-hop throughputs analytically (ETT path equation)
- Orders of link removal:
  - Most Effect: link that decreases average throughput most
  - Long x Fast: link with greatest product distance x tput
  - Fastest: link with greatest throughput
  - Random: mean of 40 simulations, deleted in random order
Link Elimination Sensitivity: Average Throughput

- Best few links matter a lot
- Over 50 links lost before throughput halved
• Long & fast links more essential to connectivity than fastest links
Node Elimination Sensitivity: Average Throughput

- Eliminate nodes that appear in the most all-pairs routes
- First two eliminations reduce throughput by 43%; thereafter more gradual
Why not Access Points?

• Mesh networking is far from perfect
  – Complexity of multi-hop routing and path selection, vs. single-hop access point choice
  – Interference between neighboring forwarding hops
  – Loss substantially increases with path length

• Could we do better with same hardware?
  – Place nodes as before
  – Same goal: Internet access for all nodes
  – Constrain topology to access point case: all nodes one hop from an Internet gateway
Evaluation Strategy: Multi-Hop vs. AP

• **Add gateways** to the network one by one
• “**Optimal**”: at each step, add gateway that maximizes number of nodes that becomes newly connected with non-zero throughput
• “**Random**”: use randomly selected set of gateways of designated size; repeat for 250 trials; take median set (by # of connected nodes)
• Break ties by **mean throughput**
### Optimal Gateway Placement

<table>
<thead>
<tr>
<th>GWs</th>
<th>Conn</th>
<th>Multi-Hop Throughput (kbits/sec)</th>
<th>Single-Hop Throughput (kbits/sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>37</td>
<td>781</td>
<td>23</td>
</tr>
<tr>
<td>2</td>
<td>37</td>
<td>1450</td>
<td>32</td>
</tr>
<tr>
<td>3</td>
<td>37</td>
<td>1871</td>
<td>34</td>
</tr>
<tr>
<td>4</td>
<td>37</td>
<td>2131</td>
<td>36</td>
</tr>
<tr>
<td>5</td>
<td>37</td>
<td>2355</td>
<td>37</td>
</tr>
<tr>
<td>6</td>
<td>37</td>
<td>2450</td>
<td>37</td>
</tr>
<tr>
<td>7</td>
<td>37</td>
<td>2529</td>
<td>37</td>
</tr>
<tr>
<td>8</td>
<td>37</td>
<td>2614</td>
<td>37</td>
</tr>
<tr>
<td>9</td>
<td>37</td>
<td>2702</td>
<td>37</td>
</tr>
<tr>
<td>10</td>
<td>37</td>
<td>2795</td>
<td>37</td>
</tr>
<tr>
<td>15</td>
<td>37</td>
<td>3197</td>
<td>37</td>
</tr>
<tr>
<td>20</td>
<td>37</td>
<td>3508</td>
<td>37</td>
</tr>
<tr>
<td>25</td>
<td>37</td>
<td>3721</td>
<td>37</td>
</tr>
</tbody>
</table>

- **Complete coverage:** 5 GWs in single-hop; 1 GW in multi-hop
- **Multi-hop** offers greater throughput at any number of gateways (**why?**)
Random Gateway Placement

<table>
<thead>
<tr>
<th>GWs</th>
<th>Multi-Hop Conn</th>
<th>Multi-Hop Throughput (kbits/sec)</th>
<th>Single-Hop Conn</th>
<th>Single-Hop Throughput (kbits/sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>34</td>
<td>760</td>
<td>10</td>
<td>535</td>
</tr>
<tr>
<td>2</td>
<td>35</td>
<td>1051</td>
<td>17</td>
<td>585</td>
</tr>
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<td>3</td>
<td>35</td>
<td>1485</td>
<td>22</td>
<td>900</td>
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<td>4</td>
<td>35</td>
<td>2021</td>
<td>25</td>
<td>1260</td>
</tr>
<tr>
<td>5</td>
<td>36</td>
<td>1565</td>
<td>28</td>
<td>1221</td>
</tr>
<tr>
<td>6</td>
<td>36</td>
<td>1954</td>
<td>30</td>
<td>1192</td>
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<td>7</td>
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<td>10</td>
<td>37</td>
<td>1945</td>
<td>34</td>
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<td>15</td>
<td>37</td>
<td>2305</td>
<td>36</td>
<td>1714</td>
</tr>
<tr>
<td>20</td>
<td>37</td>
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</tr>
<tr>
<td>25</td>
<td>37</td>
<td>2703</td>
<td>37</td>
<td>2317</td>
</tr>
</tbody>
</table>

- Complete coverage: 8 GWs for multi-hop; 25 for single-hop
### Random Gateway Placement

<table>
<thead>
<tr>
<th>GWs</th>
<th>Conn</th>
<th>Multi-Hop Throughput (kbits/sec)</th>
<th>Single-Hop Throughput (kbits/sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>34</td>
<td>769</td>
<td>25</td>
</tr>
</tbody>
</table>

For few gateways, random placement with multi-hop outperforms optimal placement with single-hop.

For many gateways, optimal placement with single-hop outperforms random placement with multi-hop.

<p>| | | | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
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<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>15</td>
<td>37</td>
<td>2305</td>
<td>36</td>
<td>1714</td>
<td></td>
</tr>
<tr>
<td>20</td>
<td>37</td>
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<td>2695</td>
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<tr>
<td>25</td>
<td>37</td>
<td>2703</td>
<td>37</td>
<td>2317</td>
<td></td>
</tr>
</tbody>
</table>

- Complete coverage: **8 GWs for multi-hop; 25 for single-hop**
Forwarding Creates Interference

- Multi-hop throughput **less than predicted**
- Reason: **interference between successive forwarding hops**
RTS/CTS Don’t Prevent Interference

<table>
<thead>
<tr>
<th>Hops</th>
<th>Pairs</th>
<th>Average Throughput without</th>
<th>Average Throughput with</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3</td>
<td>2094</td>
<td>1735</td>
</tr>
<tr>
<td>2</td>
<td>5</td>
<td>836</td>
<td>725</td>
</tr>
<tr>
<td>3</td>
<td>6</td>
<td>314</td>
<td>312</td>
</tr>
</tbody>
</table>

- Mean throughputs for node pairs separated by paths of various lengths
- Single-hop: RTS/CTS just overhead
- Multi-hop: RTS/CTS don’t improve throughput