Architecture and Evaluation of an Unplanned 802.11b Mesh Network

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Overview

• Introduction
• Design of Roofnet
• Evaluation of Roofnet
• Network Use
• Related Work
• Conclusions
Introduction

• Purpose:
  – determine the effectiveness of an unplanned wireless mesh network in providing high performance internet access

• What is an unplanned wireless mesh network?
  – little planning needed in the network topology
  – setup based on convenience more than the network topology requirements
Introduction (cont.)

• Paper is a case study of the Roofnet 802.11b mesh network

• Characterized by:
  – Unplanned node placement
  – Use of omni-directional antennas
  – Multi-hop routing
Introduction (cont.)

• Risks of unplanned network?
  – Nearly unusable network performance
  – Connectivity problems due to proximity of nodes
  – Omni-directional antennas may not provide enough coverage area
  – Multi-hop forwarding might leave users effectively disconnected
Introduction (cont.)

• What advantages could such a network provide?
  – Less effort spent on deployment planning and maintenance
  – Reduced cost and setup time resulting from the use of omni-directional antennas
    • e.g. directional antennas must be aligned and take into account side lobe issues (not a problem for omni-directional antennas)
  – Networks can grow and shrink according to demand of users without network re-plan
Introduction (cont.)

• Community wireless networks are usually built to allow many users to share few wired internet connections.
• These networks are usually spread out over urban geographic area.
Introduction (cont.)

Common approaches:

- Carefully constructed multi-hop network
  - Nodes carefully placed in the network
  - Directional antennas used and aimed to create high quality radio links
  - Require technical expertise to design the network

- Hot-spot access points
  - Clients directly connect
  - Access points usually independently operated, can be loosely connected or not at all
  - Don’t require much coordination to deploy/operate
  - Coverage area usually less than the multi-hop networks
Introduction (cont.)

• Roofnet is made up of best characteristics of common wireless network approaches:
  – Node placement is unconstrained
  – Omni-directional Antennas
  – Multi-hop routing can improve network coverage/performance
  – Network routing is tuned for throughput in slowly changing network with many intermediate quality links
Introduction (cont.)

• Risks of Roofnet implementation?
  – Radio ranges could be too short to connect some nodes
  – Many links may be low quality due to range
  – Interference from other Nodes or ISM band transmitters in area may cause persistent packet loss
  – Standard TCP may interact poorly with low performance radio links
Introduction (cont.)

- Previous studies focused on routing metrics and packet loss caused by radio level issues
  - Some focused on the network being mobile which requires the network to cope with rapid topology changes
  - Others focused on increasing throughput in static mesh networks
  - Former not a concern of Roofnet as the non-mobile network is expected to change infrequently
Design of Roofnet

- Made up of 37 nodes deployed over approx 4 sq. km. in Cambridge, MA
- Nodes hosted by volunteers living near network’s coverage area
- Each user set up own node using roof-mounted antennas
- Buildings varied in heights and line of sight signal propagation often obstructed due to other buildings

Figure 1: A map of Roofnet. Each dot represents a wireless node. The map covers the south-east portion of Cambridge, Massachusetts. The Charles River curves along the lower boundary of the map, MIT is at the lower right, and Harvard is at the upper left.
Design of Roofnet
* Hardware *

- Node consists of a PC with 802.11b card, ethernet card, CD drive, and roof mounted antenna
- Separate computer used by user to access Internet service provided by Roofnet node via the node’s Ethernet interface
- Roofnet Antennas:
  - Most nodes have 8dBi Omni-directional antennas, providing 3-dB of vertical beam and a 20 degree width. This sacrifices gain but means antenna doesn’t have to be perfectly vertical
  - Three nodes use 12dBi Yagi directional antennas with 45 degree horizontal and vertical Beam widths located on the roof of 3 tall buildings.
Design of Roofnet (cont.)

* Hardware *

- 802.11b wireless cards
  - Based on Intersil Prism 2.5 chipset
  - Transmit at 200 Milliwatts
  - RTS/CTS disabled
  - All share same 802.11b channel
  - User non-standard IBSS (ad hoc) mode
Design of Roofnet (cont.)

* Software and Auto-Configuration *

- Each node runs identical software
- Routing software implemented in Linux using Click, a DHCP Server and Web Server allowing users to monitor network

**Software goal:**
- allow nodes to act as a cable or DSL modem.
  i.e. user plugs their computer or access point into the Ethernet port and it automatically configures the connection using DHCP
- Roofnet node would be user’s IP Router
**Design of Roofnet (cont.)**

* * Software and Auto-Configuration *

- Software allows user to self-configure via:
  - Allocating addresses to user nodes by providing Roofnet layer to allocate own Roofnet and IP addresses and using DHCP for its users. NAT is used to reserve 192.168.1.x IP addresses.
  - Finding gateways between Roofnet and Internet by:
    - Each Roofnet node determining if it is connected to the internet through its Ethernet port. If so, it advertises itself as a gateway
    - Each gateway acts as NAT for other connections from Roofnet nodes to the Internet
    - If Roofnet node determines it is not a gateway, acts as DHCP Server and default router for user equipment connected via Ethernet
  - Choosing good multi-hop route to gateway by determining if there is a more optimal route through another gateway. It uses that gateway for future connections and continues using the current gateway for the previously setup connections.
Design of Roofnet (cont.)

* Routing Protocol *

- Uses its own routing protocol named Srcr which tries to find the highest throughput route between any pair of Roofnet nodes.
- Maintains a database of link metrics and uses Dijkstra’s Algorithm to find the optimal routes.
Design of Roofnet (cont.)

* Routing Metric *

- **Srcr** chooses the route with the lowest Estimated Transmission Time (ETT)
  - the predicted total packet transmission time on a particular route.
- Each node transmits broadcast packets periodically keeping statistics on each neighbor.
- Statistics are transmitted to each neighbor.
Design of Roofnet (cont.)

* Bit Rate Selection *

- Roofnet has its own algorithm to choose the bit-rate (1, 2, 5.5, 11 megabits/second).
- Roofnet prefers links with highest throughput rate. This often means high link-level loss rates. For example
  - Single hop high loss could be better than 2 hop route with perfect links
  - bit-rates are nearly a power of 2 apart so 50% loss at higher bit rate is more desirable than better performance at a slower bit rate.
Evaluation of Roofnet

* Method *

• Results were derived from four data-sets of measurements on the Roofnet:
  – “Multi-hop” TCP - gathered from results of 15-second one way bulk TCP data transfers between each roofnet node pair
  – “Single-hop” TCP - measured the TCP throughput between each pair of nodes over radio link
  – “Loss Matrix” - measured the loss rate between each pair of nodes by sending 1500-byte broadcast packets for each 802.11 Tx rate
  – “Multi-hop density” - measured multi-hop TCP throughput between a fixed set of four nodes, while varying the number of Roofnet nodes participating in routing.
Evaluation of Roofnet

* Basic Performance *

- Average TCP throughput among all pairs of Roofnet Nodes was 627 Kbps.
- The median was 400 kpbs.
Evaluation of Roofnet
* Basic Performance *

Table 1 compared to theoretical data in table 2 shows single hop’s throughput is consistent with the 5.5 megabit Tx rate. However, the other throughputs for the multi-hop cases are inconsistent with the theoretical data.

Discrepancy could be due to inter-hop collisions not accounted in the equation used to derive the theoretical data.

As Roofnet users mainly talk to the Internet gateway with the best metric, so routes with fewer than average hops will be used.

Table 1: Average TCP throughput and round-trip ping latency between each pair in the network, arranged by the number of hops in a typical path between the pair. (multi-hop TCP)

<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>168</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>56</td>
</tr>
<tr>
<td>5</td>
<td>120</td>
<td>210</td>
<td>60</td>
</tr>
<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>44</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>
</tbody>
</table>

Avg: 2.9 Total: 1332 Avg: 627 Avg: 39

Table 2. Theoretical loss-free maximum throughput over one, two, and three hops for each 802.11b transmit bit-rate, with 1500-byte packets.

<table>
<thead>
<tr>
<th>Rate</th>
<th>Max Throughput (kbits/sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>599 443 297</td>
</tr>
<tr>
<td>2</td>
<td>164 817 536</td>
</tr>
<tr>
<td>5.5</td>
<td>323 1718 1341</td>
</tr>
<tr>
<td>11</td>
<td>5073 2538 1671</td>
</tr>
</tbody>
</table>
Table 3: Average TCP throughput and round-trip ping latency to the 38 non-gateway nodes from each node's chosen gateway, arranged by hop count. Even at four hops, the average throughput is comparable to many DSL links. (multi-hop TCP)

<table>
<thead>
<tr>
<th>Hops</th>
<th>Number of nodes</th>
<th>Throughput (kbit/sec)</th>
<th>Latency (ms)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>72</td>
<td>2752</td>
<td>9</td>
</tr>
<tr>
<td>2</td>
<td>8</td>
<td>949</td>
<td>18</td>
</tr>
<tr>
<td>3</td>
<td>5</td>
<td>379</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>
</tbody>
</table>

Avg: 2.3 | Total: 38 | Avg: 1395 | Avg: 22

- Table 3 shows the throughput arranged by hop count to each node from its gateway
- There are only 5 hops because all nodes are not very far from the nearest gateway
- The authors make indicates throughput for DSL is comparable to 379 kpbs as obtained over 4 hops.
- Avg latency to the gateways is 22 ms (not very noticeable in an interactive session)
Majority of avail links are between 500 and 1300 meters long and at best-bit rate transfer approx 500 kbps.

It should be noted that there are a few longer and faster throughput links.

Lower graph shows Srer favors short links with higher throughput.

It also shows it ignores the majority which are the slower links.
Evaluation of Roofnet
* Link Quality and Distance *

- Link’s throughput is determined by its best Tx rate and probability that its data will get delivered at that bit-rate
- It is important to point out that links with a significant loss and a higher bit-rate are more desirable. The higher bit-rate can be more effective than a slower bit rate with no loss.

![Cumulative Fraction of Loss vs Delivery Probability](image)

Figure 3: The distribution of delivery probabilities of links used in 802.11 routes, at the bit-rates chosen by SampleRate. The median is 0.8, meaning that 80% often uses links with loss rates of 20% or more. (multi-hop TCP, loss matrix)
Evaluation of Roofnet
* Effect of Density *

• The more nodes, the more effectiveness effective the mesh network

• The authors simulated different size subsets to examine the effects of density.
Evaluation of Roofnet
* Effect of Density *

- The diagrams show increasing the number of nodes results in:
  - increased connectivity
  - increased average throughput
Evaluation of Roofnet

* Effect of Density *

- Number of nodes increases with the hop count. Denser networks offer more choices of short high quality links resulting in more hops in the routes.
- Links are deemed to be high quality if throughput goes up with the node density (see previous slide)

Figure 5: The simulated effects of node density on connectivity and throughput. The $x$ axes show the number of nodes in the network. From top to bottom, the $y$ axes show the fraction of node pairs that achieve throughput of more than one kilobyte per second; the average throughput over all pairs; and the average hop-count. Each bar shows the 25th, 50th, and 75th percentile over 100 random subsets. Increasing density causes the network to be more highly connected, and increases the average throughput; higher density allows routes to be constructed from shorter, higher-quality hops. (Simulated from single-hop TCP)
Evaluation of Roofnet
* Mesh Robustness *

• Mesh robustness measures benefits of routing choices resulting from using a mesh architecture and omni-directional antennas

• How to measure mesh robustness?
  – Determine how many potentially useable neighbors each node has
  – Determine the extent the network is vulnerable to the loss of its most valuable links
Evaluation of Roofnet  
* Mesh Robustness *

• Regarding fig. 6
  – Most nodes have many neighbors.
  – Few are poorly connected.

• Regarding fig. 7
  – Neighbors are only of value if they are used.
  – Some nodes don’t use all of their neighbors but a majority use more than 2 neighbors.
Evaluation of Roofnet
* Mesh Robustness *

- Impact of losing valuable links (4 methods to compare)
  - Most Effect = delete links that effect avg throughput the most.
  - Long X Fast = delete links with highest product of distance and throughput.
  - Fastest = delete links with highest throughput.
  - Random = average of 40 simulations where links were deleted randomly.

Figure 8: Simulated average throughput and connectivity among all pairs versus the number of links eliminated. Each curve shows the result of eliminating links in a particular order. (Simulated from single-hop TCP)
Evaluation of Roofnet * Mesh Robustness *

• Results:
  – Deleting more effective links considerably reduces throughput and connectivity over random deletion.
  – Removing a few of the best connected nodes had greatest impact on throughput after they were deleted, the effect of deleting others after was less dramatic.
Evaluation of Roofnet
* Architecture Alternatives *

- Analyzed choosing gateway locations vs. randomly choosing them

- Results
  - Careful choosing results in greater throughput for multi-hop and single hop
  - For a smaller number of gateways random multi-hop performs better than carefully chosen single hop gateways.
  - For large number of gateways carefully chosen single hops are better than the random multi-hop gateways.
Evaluation of Roofnet
* Inter-hop Interference *

- Multi-hop links slower than expected when compared to single-hop
- Most likely due to packet loss due to concurrent transmissions on different hops colliding
- Delaying sending gives packets time to reach the destination and increased throughput.
- TRTS/CTS didn’t improve performance. 802.11 networks use it to prevent collisions.

![Figure 10: Comparison of multi-hop throughput and throughput predicted from individual hop throughputs. Each point represents one node pair. The expected throughputs for single-hop routes (most of the points above 2000 kbps/second) differ from the measurements, but the errors are not biased, since the predictions are themselves a separate set of measurements. The expected multi-hop throughputs are mostly higher than the measured throughputs. Multi-hop TCP and simulations from single-hop TCP)](image-url)
Roofnet Network Use

- User activity measured by monitoring TX/RX packets on one of 4 Roofnet gateways between Roofnet and the Internet
- Statistics:
  - 24 hour period – speed was 160 kbps between Roofnet and Internet. 94% were wireless data traffic and 5% were protocol control packets
  - 48% of data traffic was sent from nodes 1 hop from gateway; 36% for two hops; 16% for three hops or more
  - Gateway radio busy about 70% of 24 hour monitoring period
  - More than 99% of the packets were TCP
  - Biggest bandwidth consumer (30%) during this time frame was BitTorrent peer to peer file sharing program
  - 68% of connections through the gateway were web connections although requests only comprised 7% of the bytes transmitted
Related work

• Several evaluations of deployed multi-hop wireless networks.
  – Focused on improving routing in static mesh networks or route repair due to mobility issues.

• Roofnet unique because:
  – evaluates a deployed mesh with active users
  – considers effects of arch. decisions and not protocol design.

• Roofnet expanded on existing protocols and technology

• Community mesh wireless networks exist:
  – Seattle Wireless, San Francisco’s BAWUG, the Southamton Open Wireless Network, among others.

• Commercial mesh Internet access technologies exist.
Conclusions

• The network architecture described in this paper favors:
  – Ease of deployment due to omni-directional antennas
  – Self-configuring software
  – Link-quality-aware multi-hop routing

• Volunteer participation grew network to 37 nodes in the course of a year.

• Performance of the network shows that it works well:
  – Average throughput between nodes is 627 kbps.
  – Only a few internet gateways needed
  – Position of nodes is based on convenience not by network design.

• Roofnet’s Multi-hop mesh network increases connectivity and throughput over a hypothetical single-hop network.

• For more information on Roofnet see http://pdos.csail.mit.edu/roofnet/doku.php.
Conclusions

• Roofnet is being used by several communities
  – Roofnet Cambridge, MA
  – TentCity in Boston, MA
  – NetEquality, Portland, OR

• Questions?