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

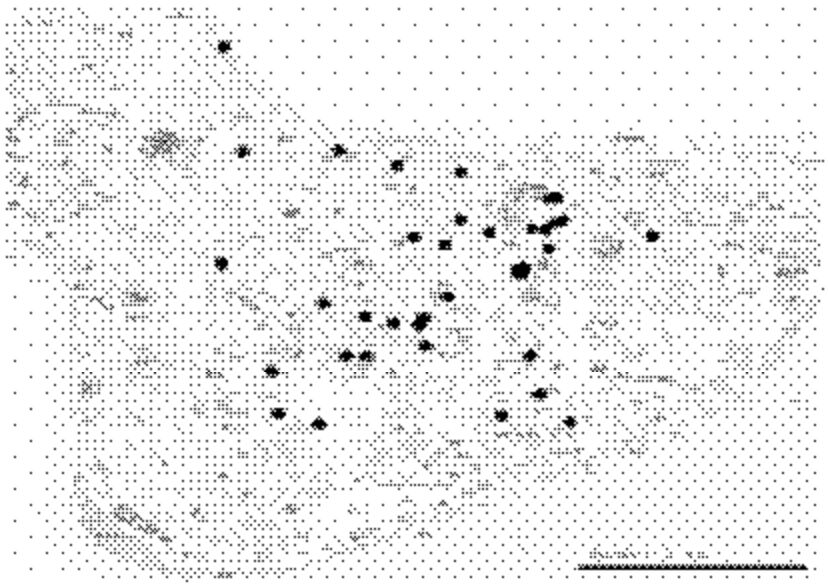


Figure 1: A map of Roofnet. Each dot represents a wireless node. The map covers the south-east portion of Cambridge, Massachusetts. The Charles River curves along the lower boundary of the map. MIT is at the lower right, and Harvard is at the upper left.

- 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

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 *

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

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)

	Max Throughput (kbits/sec)		
Rate	1 Hop	2 Hops	3 Hops
1	590	446	297
2	1634	817	545
5.5	3486	1718	1146
11	5072	2536	1671

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 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.**

Evaluation of Roofnet
* Basic Performance *

Hops	Number of nodes	Throughput (kbits/sec)	Latency (ms)
1	12	2752	9
2	8	940	19
3	5	652	27
4	7	379	43
5	1	89	37
Avg: 2.3	Total: 33	Avg: 1395	Avg: 22

Table 3: Average TCP throughput and round-trip ping latency to the 33 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 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)**

Evaluation of Roofnet
* Link Quality and Distance *

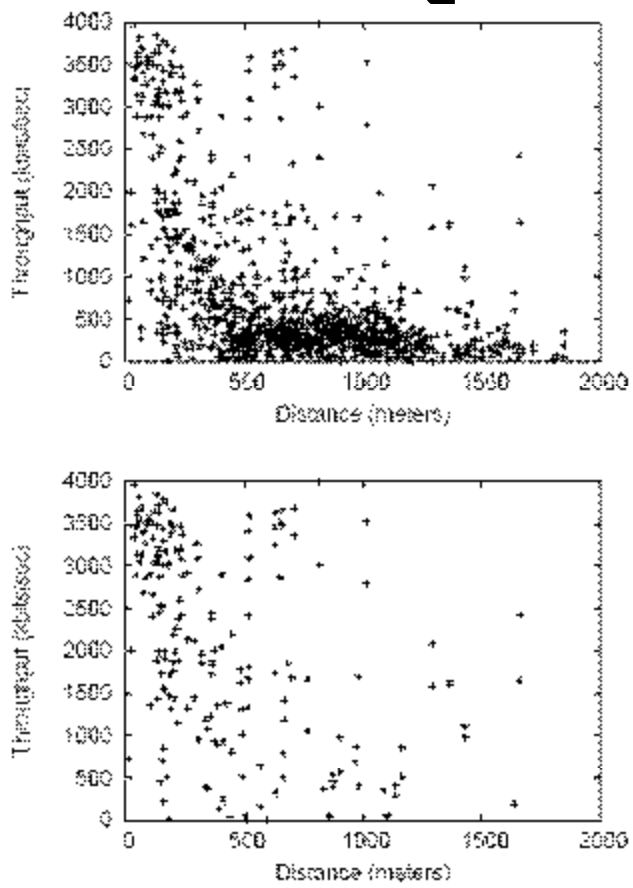


Figure 3: Link throughput versus distance for all links (top) and for the links used by Srcr (bottom). Srcr makes the most use of short high-throughput links. (single-hop TCP, multi-hop TCP)

- **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 Srcr 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 *

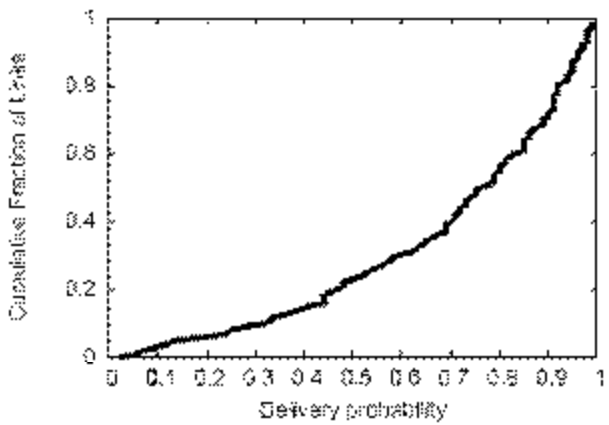


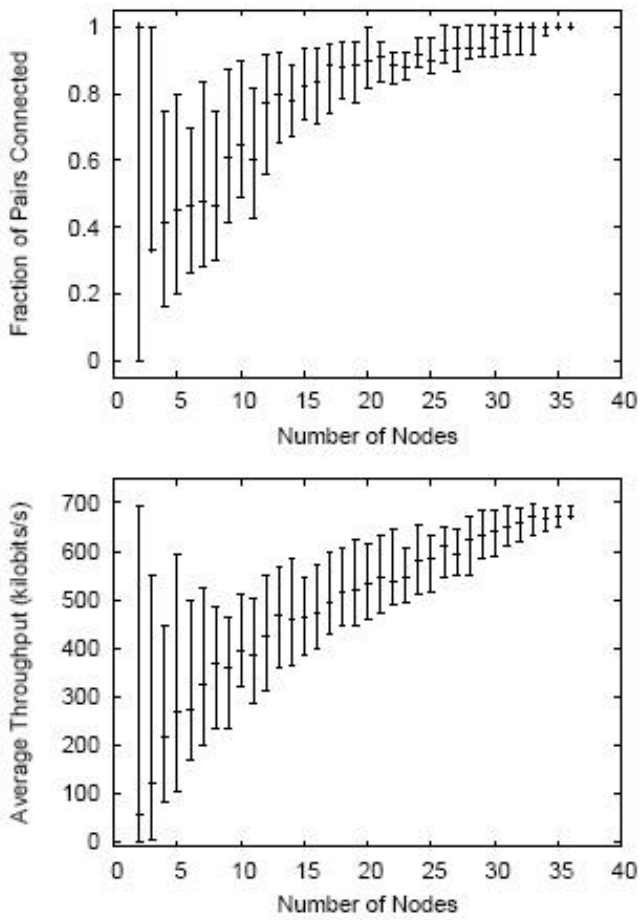
Figure 4: The distribution of delivery probabilities of links used in Srcr routes, at the bit-rates chosen by SampleRate. The median is 0.8, meaning that Srcr often uses links with loss rates of 20% or more. (multi-hop TCP, loss matrix)

- **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.**

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 shows 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)

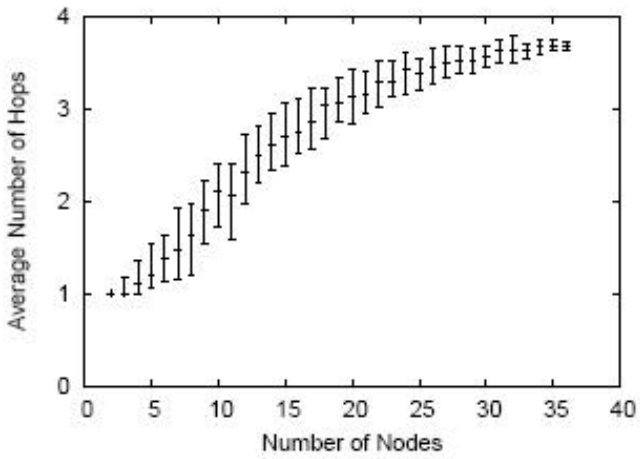


Figure 5: The simulated effects of node density on connectivity and throughput. The x axes show the number of nodes in the network. From top to bottom, the y axes show the fraction of node pairs that achieve throughput of more than one kilobyte per second; the average throughput over all pairs; and the 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.**

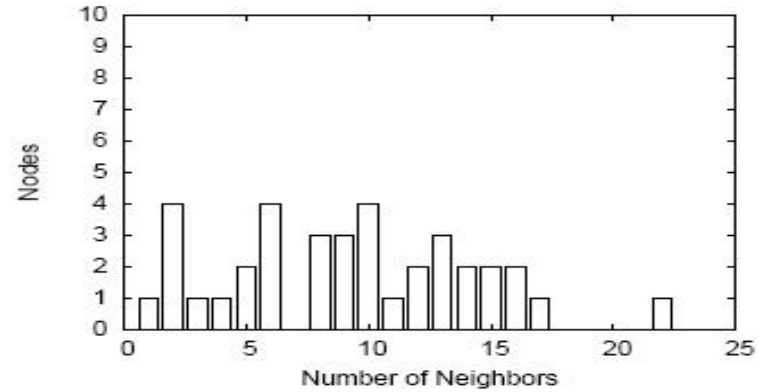


Figure 6: Histogram of the number of neighbors per node. A node counts as a "neighbor" if it has greater than 40% delivery probability for 1 megabit per second packets. (loss matrix)

- **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.**

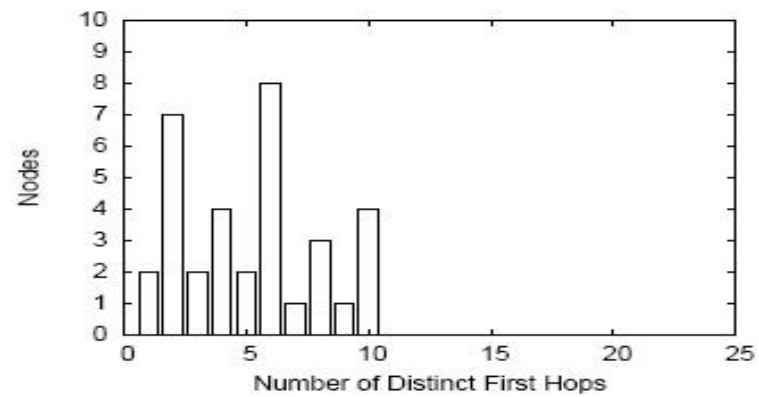


Figure 7: Histogram of the number of different first hops that Roofnet nodes use in all-pairs routes. (multi-hop TCP)

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.**

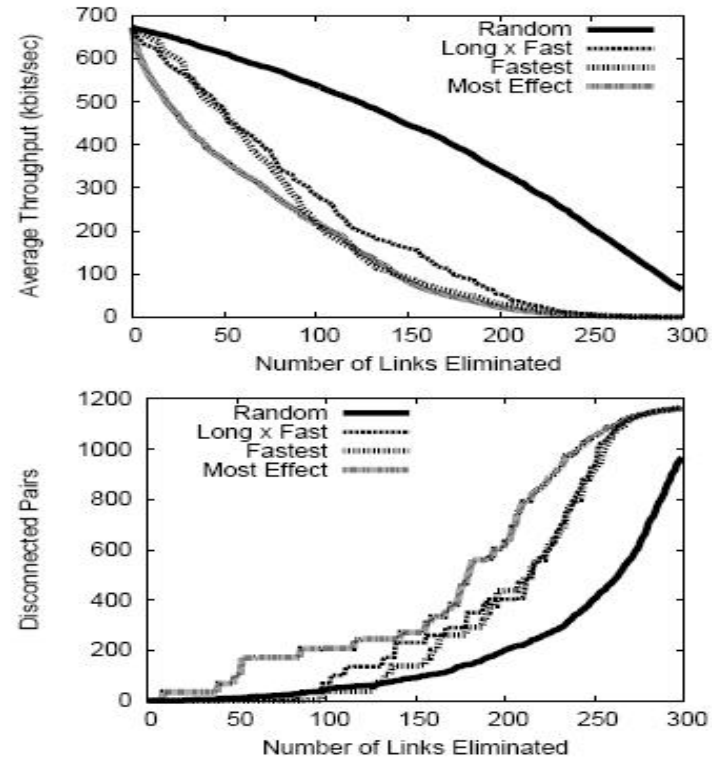


Figure 8: Simulated average throughput and connectivity among all pairs versus the number of links eliminated. Each curve shows the result of eliminating links in a particular order. (Simulated from single-hop TCP)

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 give packets time to reach the destination and increased throughput.**
- **TRTS/CTS didn't improve performance. 802.11 networks uses it to prevent collisions.**

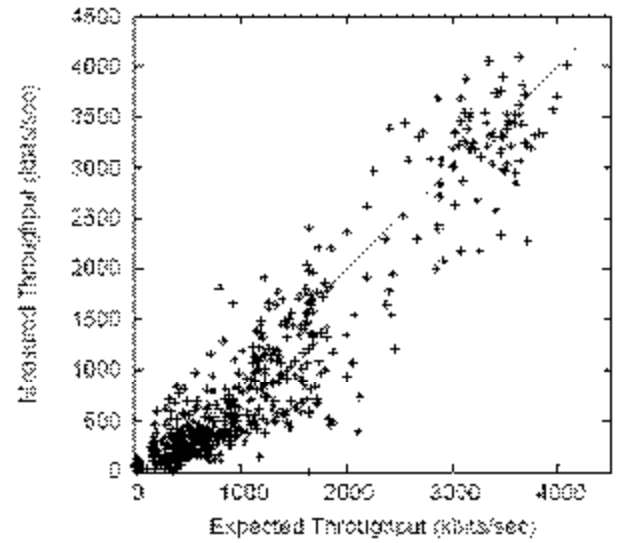


Figure 10: Comparison of multi-hop throughput and throughput predicted from individual hop throughputs. Each point represents one node pair. The expected throughputs for single-hop routes (most of the points above 2000 kbits/second) differ from the measurements, but the errors are not biased, since the 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)

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.
  - Eg. MeshNetworks Inc., Ricochet, and Tropos networks.

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?