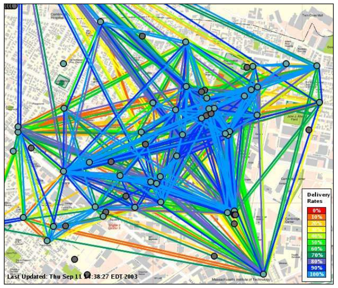
MIT Roofnet



Robert Morris

Daniel Aguayo, John Bicket, Sanjit Biswas, Douglas De Couto

MIT Computer Science and Artificial Intelligence Laboratory

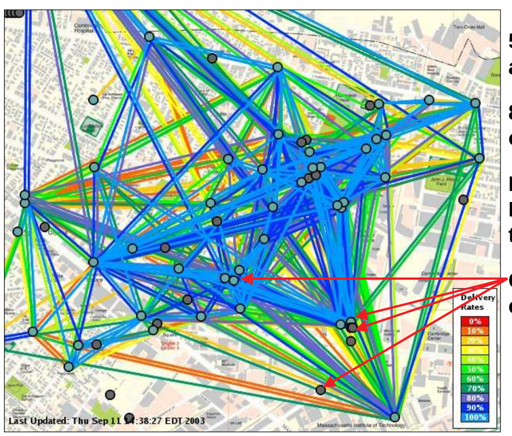
http://pdos.lcs.mit.edu/roofnet

Talk Outline

1. **Roofnet Overview**
2. **Link-Quality-Aware Routing (ETX)**
3. **Roofnet Performance and Status**
4. **Opportunistic Routing (ExOR)**

2

The Roofnet Network



2 km

54 nodes in students' apartments

802.11 radios, antennas on roofs

Multi-hop routing to MIT's campus net and the Internet

Gateways to DSL or campus net

3

Existing Community Networks

- Goal: inexpensive sharing of Internet access
- Multi-hop mesh to extend reach
- Two+ directional antennas/node
- Use Internet routing protocols (OSPF)

photograph courtesy of BARWN.org

4

Our Key Design Choice

Omni-directional antennas:
- Easy to install
- Inexpensive
- Can self-configure
- More choice of neighbors
- But no notion of a "link"…

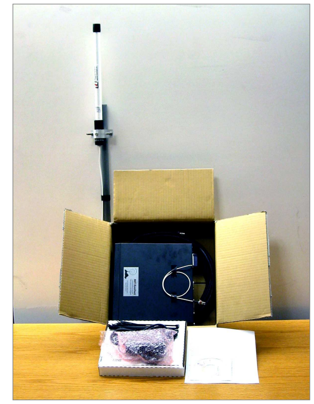
Goal: enable much larger mesh networks

Self-Installation Kits

Omni Antenna ($65)
8dBi, 20 degree vertical

Computer ($340)
533 Mhz PC, hard disk, CDROM

802.11b card ($155)
Engenius Prism 2.5, 200mW



50 ft. Cable ($40)
Low loss (3dB/100ft)

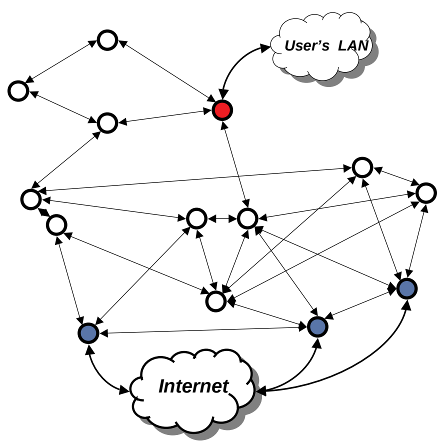
Miscellaneous ($75)
Chimney Mount, Lightning Arrestor, Wrench, etc.

Software ("free")
Our networking software

Total: $685

Takes about 45 minutes to install

Roofnet/Internet Connectivity

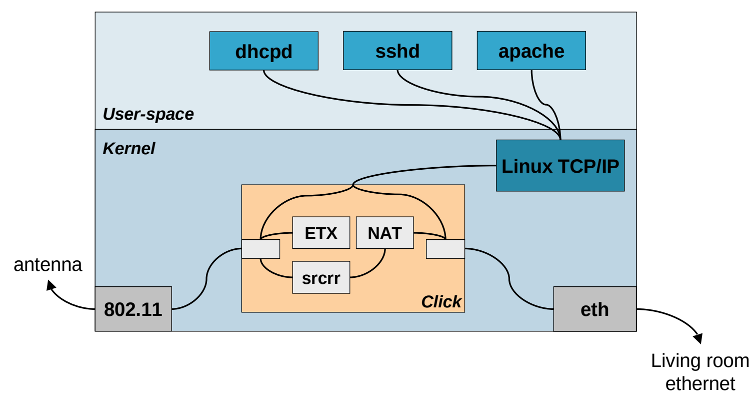


Living-room nets
192.168.x.x

Roofnet Nodes
5.x.x.x
(172.16.x.x)

Wired Gateways
MIT campus net, or users' DSL

Roofnet Node Software Structure

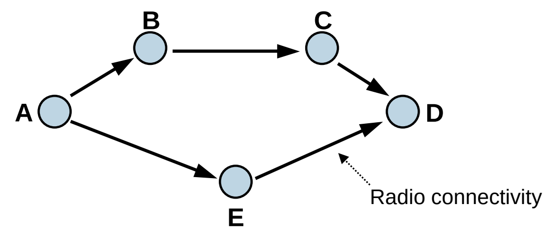


Talk Outline

1. Roofnet Overview
2. **Link-Quality-Aware Routing (ETX)**
3. Roofnet Performance and Status
4. Opportunistic Routing (ExOR)

9

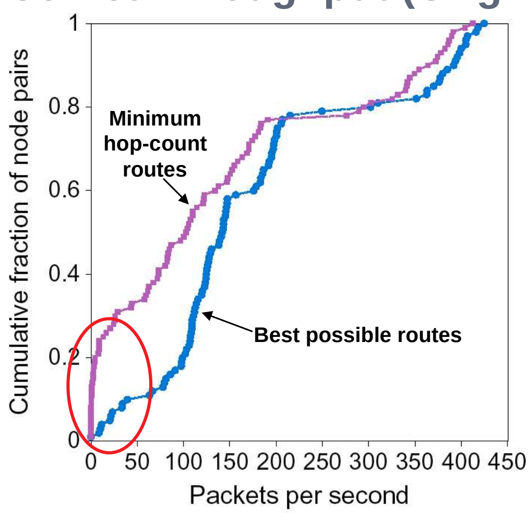
Routing: Best Path from A to D?



- Internet approach: minimize the hop count
- **A-E-D**

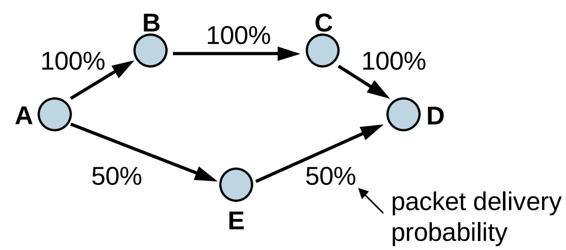
10

Roofnet Throughput (Original)



11

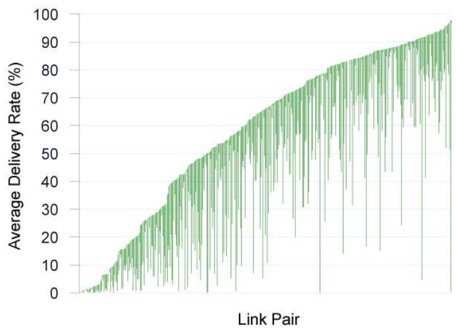
Problem 1: Long Links Work Badly



- Minimizing hop-count uses low-quality links
- But S/N vs. BER specs suggest this isn't important

12

Roofnet Link Quality Distribution

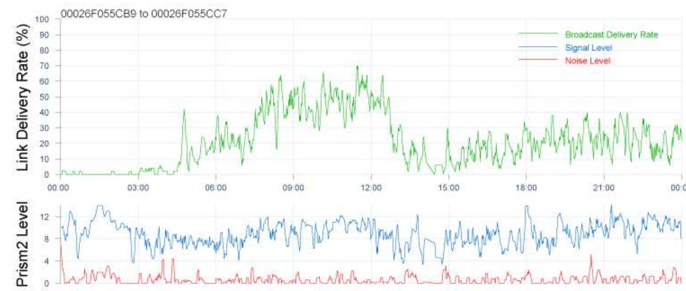


Wide range of delivery ratios

Hard to say a link is either good or bad

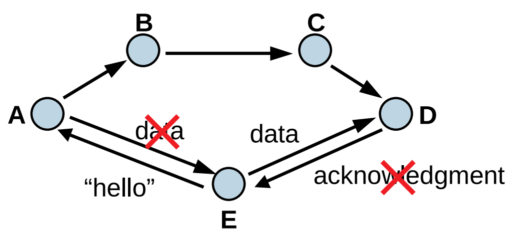
Forward and reverse rates are often different

One Link Over 24 Hours

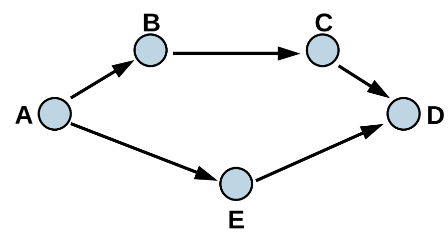


- Cannot use Prism S/N ratio to predict link quality

Problem 2: Asymmetric Links



Problem 3: Radios Share a Channel



- Nodes **A, B,** and **C** interfere
- **A-B-C-D**: throughput is 1/3
- **A-E-D**: throughput is 1/2

Solution: ETX Metric

- **Need to balance link quality, asymmetry, interference**
- **Idea: throughput ≈ 1 / (number of transmissions)**
  - One transmission for each hop
  - One for each lost data packet (since 802.11 re-sends)
  - One for each lost acknowledgment
- **ETX: "Expected Transmission Count"**
- **Routing protocol chooses route w/ minimum ETX**

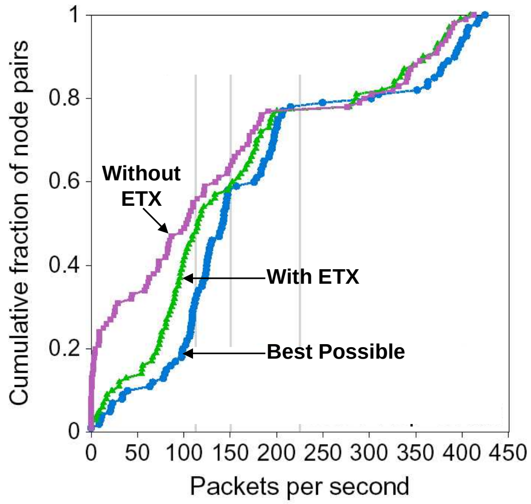
17

Calculating Per-Link ETX

- **ETX = 1 / P(delivery)**
- **P(delivery) = P(data OK) * P(ACK OK)**
- **So, ETX = 1 / (d_f * d_r)**
- **Each node periodically broadcasts a probe**
- **Neighbors measure d_f from probes**
- **Neighbors exchange d_f to get d_r**
- **Problems: packet size, bit rate**

18

ETX Improves Roofnet Throughput



19

SrcRR Routing Protocol

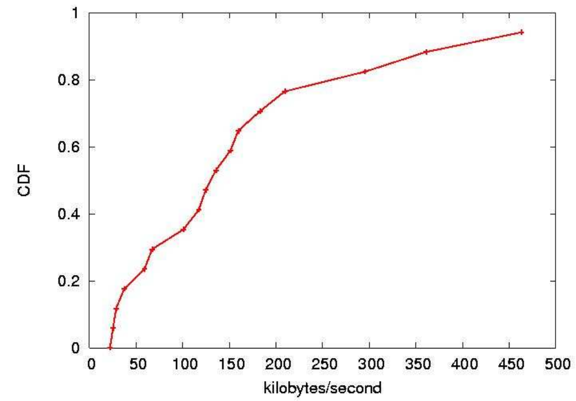
- **Source routing, link-state database**
  - DSDV isn't stable when network is busy
- **DSR-like queries to populate link-state database**
- **Keeping the source's ETX values up to date:**
  - Data packets accumulate latest per-hop ETX
  - Data packets carry random sample of nearby link ETXs
  - Ten 802.11 transmit failures: send link's ETX back to source
  - One-way traffic: periodically send link's ETX back to source
- **Source only re-floods if half as good as original**

20

Talk Outline

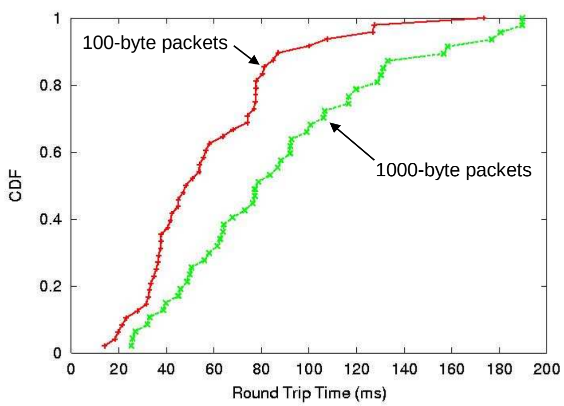
1. Roofnet Overview
2. Link-Quality-Aware Routing (ETX)
3. **Roofnet Performance and Status**
4. Opportunistic Routing (ExOR)

End-to-end TCP Throughput

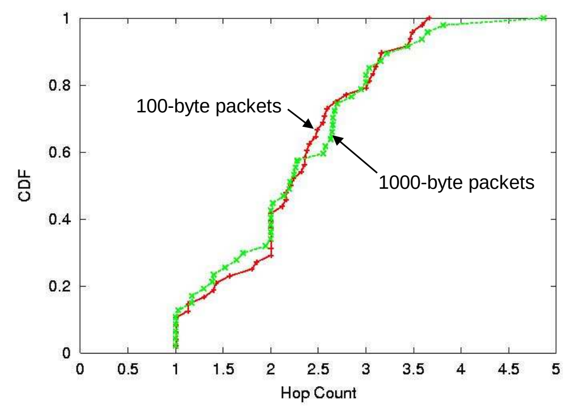


• Median about 1 mbit/s, max about 3.6 mbit/s

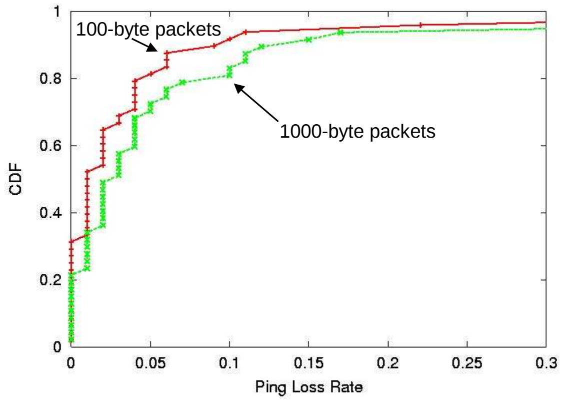
End-to-end Ping Times



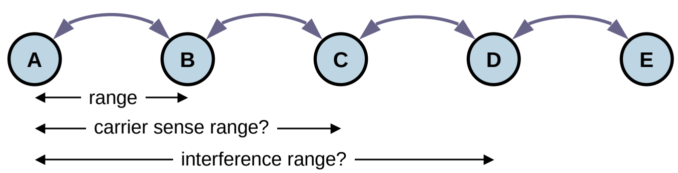
One-way Hop Counts



End-to-end Ping Loss Rates



Path Self-Interference?



- **A** sends RTS, **B** sends CTS, **A** sends long packet
- **C** heard the CTS and won't send
- What if **D** forwards a packet to **E**?
- Will that repeatedly waste **A**'s entire transmission?

Token-Passing

- **Goal: eliminate path self-interference**
- **Send a token back and forth along active DSR path**
- **Holder can forward 10 packets, then forwards token**
- **Increases throughput a lot:**
  - Avoids interference loss?
  - Helps 802.11 firmware stay at high bit rates?
- **Problems:**
  - Doesn't help much if two paths are active
  - Lost token? Duplicate token? Idling and re-creating the token?
- **This is a major focus for us right now**

Other Current Roofnet Problems

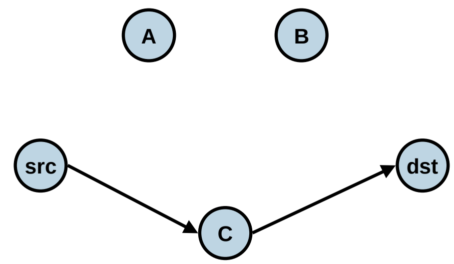
1. **Prism 2.5 MAC carrier sense ignores many packets**
   - Declares "carrier" if signal strength above threshold
   - Threshold is too high, cannot be set lower
   - Result: two nodes transmit at the same time and interfere
2. **Fix ETX to guess which links will run at 11 mbps**
3. **Prism 2.5 firmware is too timid about high rates**
4. **Only security problem: users running viruses/DDoS**
5. **We've lost one node to lightning**

Talk Outline

1. Roofnet Overview
2. Link-Quality-Aware Routing (ETX)
3. Roofnet Performance and Status
4. **Opportunistic Routing (ExOR)**

29

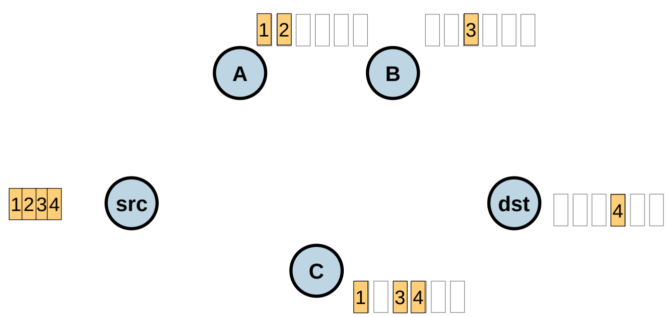
Routing: The Traditional View



- **Measure all link qualities**
- **Pick the best route**
- **Forward data along that route's links**
- **This strategy is optimal for wired networks**

30

How Radios Actually Work

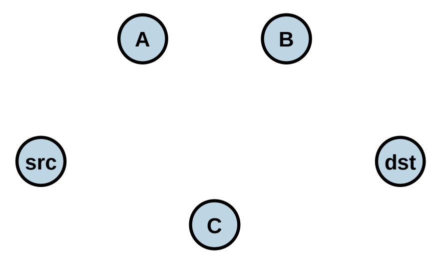


- **Every packet is a radio broadcast…**

31

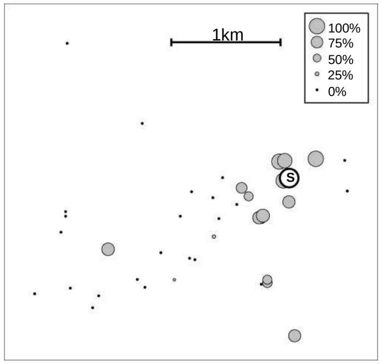
Assumptions

1. **Many receivers hear every broadcast**
2. **Gradual distance-vs-reception tradeoff**
3. **Receiver losses are uncorrelated**



32

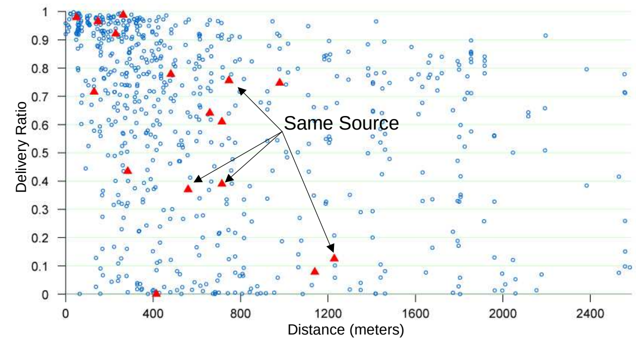
1. Multiple Receivers per Transmission



- **Broadcast tests on rooftop network**
  - Source sends packets at max rate
  - Receivers record delivery ratios
- **Omni-directional antennas**
- **Multiple nodes in “radio range”**

33

2. Gradual Distance vs. Reception Tradeoff

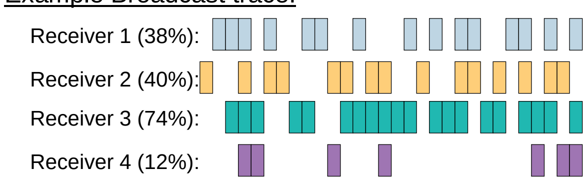


- **Wide spread of ranges, delivery ratios**
- **Transmissions may “get lucky” and travel long distances**

34

3. Receiver Losses are Uncorrelated

<u>Example Broadcast trace:</u>



- **Two 50% links don’t lose the same 50% of packets**
- **Losses not due to common source of interference**

35

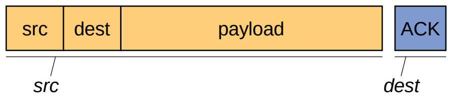
Extremely Opportunistic Routing (ExOR) Design Goals

- **Ensure only one receiver forwards the packet**
- **Receiver “closest” to the destination should forward**
- **Lost agreement messages may be common**
- **Let’s not get eaten alive by overheads**

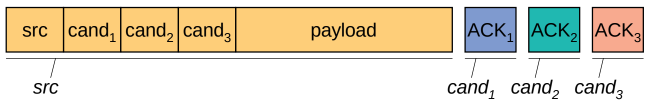
36

Who Received the Packet?

Standard unicast 802.11 frame with ACK:

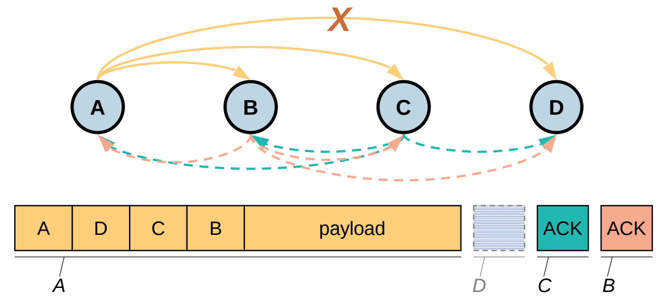


ExOR frame with slotted ACKs:



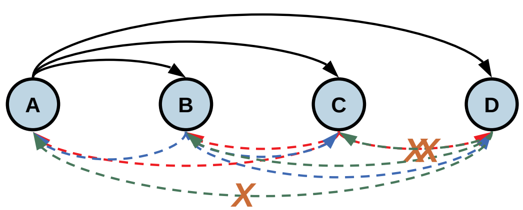
- **Slotting prevents collisions (802.11 ACKs are synchronous)**
- **Only 2% overhead per candidate, assuming 1500 byte frames**

Slotted ACK Example



- **Packet to be forwarded by Node C**
- **But if ACKs are lost, causes confusion**

Agreeing on the Best Candidate



A: **Sends frame with (D, C, B) as candidate set**

D: **Broadcasts ACK “D” in first slot (not rx’d by C, A)**

C: **Broadcasts ACK “C” in second slot (not rx’d by D)**

B: **Broadcasts ACK “D” in third slot**

Node D is now responsible for forwarding the packet

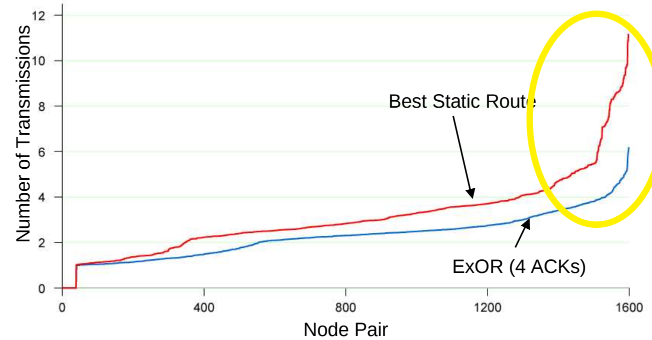
Putting it all Together

- **ExOR Protocol in a nutshell:**
  - Forwarder picks candidate set (using n^2 matrix of loss rates)
  - Forwarder broadcasts packet
  - Candidates send slotted ACKs
  - Single candidate responsible for forwarding
- **Backup Duplicate Detection**

Protocol Simulation

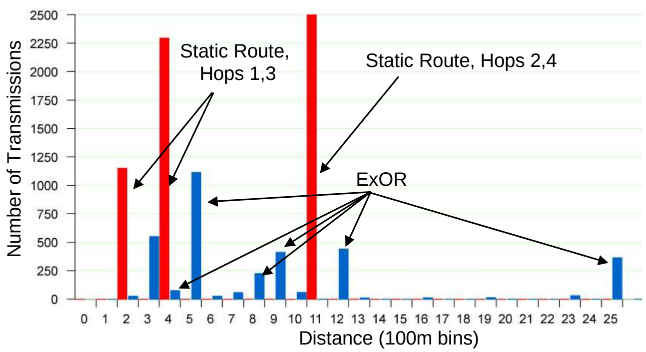
- **Methodology**
  - Use Roofnet delivery ratios and topology
  - Every node has full matrix of inter-node loss rates
  - Loss rates constant over time
- **Performance Measure: Total Transmissions**
  - Simulator cannot compute throughput properly
  - Total transmission count is probably inverse of throughput

ExOR Outperforms Best Static Route



- **Performance of all 40^2 possible routes (sorted)**
- **Gains up to 2x on longer routes**

Transmission Distance

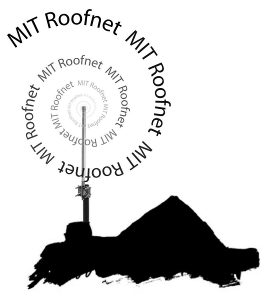


- **Best static route: 5.94tx, ExOR: 3.3tx**
- **ExOR moves packets farther using a variety of links**

Roofnet Summary

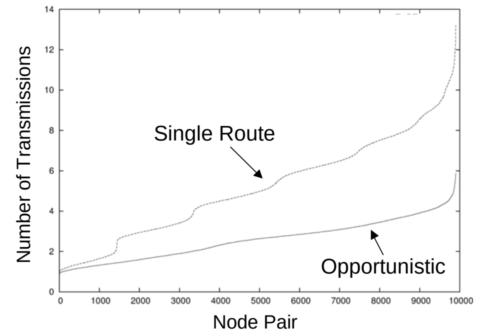
- **Roofnet provides useful broadband Internet access**
- **Wireless breaks standard routing assumptions**
- **Current areas of research:**
  - **Scheduling to avoid inter-hop interference**
  - **ExOR**
- **Future areas of research:**
  - **Transmit power control**
  - **Routing-aware carrier sense**

http://pdos.lcs.mit.edu/roofnet



http://pdos.lcs.mit.edu/roofnet/

Simulated ExOR Performance



Simulation of 50 nodes using loss rates from UCLA sensor network
Reduces transmissions by nearly 2x over best predetermined path

RSSI vs. Delivery Ratio