Routing in
Wireless Mesh Networks
# Multi-hop Wireless Networks

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<th>Mobile Nodes</th>
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<td>Community wireless networks (Mesh Networks)</td>
<td>Improving Network Capacity</td>
<td>Battlefield networks</td>
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<td>Key challenge</td>
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<td>Handling mobility, limited power.</td>
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Wireless Mesh Networks
What do you think are good routing metrics?
Potential Ideas (and their cons)

- Product of per-link delivery ratios
- Throughput of a path’s bottleneck link
- End-to-end delay
Potential Ideas (and their cons)

- Product of per-link delivery ratios
  - A perfect 2-hop route is viewed as better than a 1-hop route with 10% loss ratio
- Throughput of a path’s bottleneck link
  - Same as above
- End-to-end delay
  - Changes with network load as queue lengths vary ... can cause oscillations
A High-Throughput Path Metric for Multi-Hop Wireless Routing

D. S.J. Couto, D. Aguayo, J. Bicket, R. Morris

MIT
Hop Count Metric
Hop Count Metric

- Maximizes the distance traveled by each hop
  - Minimizes signal strength -> Maximizes the loss ratio
  - Uses a higher TxPower -> Interference
- Possibly many shortest routes
- Avoid lossy links?
Hop Count vs. “Optimal”

x axis: throughput

y axis: fraction of pairs with less throughput

Run R1: 1 mW, 134-byte packets
Hop Count Route Selection

Run R1: 1 mW, 134-byte packets

Max 3-hop throughput

Max 4-hop

Packets per second delivered

23-19-24-36
23-37-24-36
23-37-19-36
23-12-19-36
23-19-11-36
23-19-36
23-19-20-36
23-19-7-36
Motivation for a Better Routing Metric

(a) Pairwise delivery ratios at 1 mW

Bidirectional loss rates

Fine-grained choices

(b) Pairwise delivery ratios at 30 mW

Intermediate loss rates

Link number
What metrics would you suggest to account for different link loss rates?
**ETX**

- The predicted number of data transmissions required to send a packet over a link
- The ETX of a path is the sum of the ETX values of the links over that path
- **Examples:**
  - ETX of a 3-hop route with perfect links is 3
  - ETX of a 1-hop route with 50% loss is 2
ETX continued...

- Expected probability that a transmission is successfully received and acknowledged is \( d_f \times d_r \)
  - \( d_f \) is forward delivery ratio
  - \( d_r \) is reverse delivery ratio

- Each attempt to transmit a packet is a Bernoulli trial, so...

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

- Based on delivery ratios, which affect throughput
- Detects and handles asymmetry by incorporating loss ratios in each direction
- Uses precise link loss measurements to make fine-grained decisions between routes
  - Assumes you can measure these ratios precisely
- Penalizes routes with more hops, which have lower throughput due to inter-hop interference
  - Assumes loss rates are equal over links
- Tends to minimize spectrum use, which should maximize overall system capacity (reduce power too)
  - Each node spends less time retransmitting data
Acquiring ETX values

- Measured by broadcasting dedicated link probe packets with an average period \( \tau \) (jittered by \( \pm 0.1\tau \))

- Delivery ratio:

  \[
  r(t) = \frac{\text{count}(t-w, t)}{w/\tau}
  \]

  - \( \text{count}(t-w, t) \) is the # of probes received during window \( w \)
  - \( w/\tau \) is the # of probes that should have been received

- Each probe contains this information
Implementation and such...

- Modified DSDV and DSR
- $\tau = 1$ packet per second, $w = 10$ sec
- Multiple queues (different priorities)
  - Loss-ratio probes, protocol packets, data packets
DSDV Performance

One hop
Asymmetric
ETX inaccurate
DSDV and High Transmit Power
Less throughput advantage than when probe packets are smaller (134 bytes)

Why?
Packet sizes continued

ETX underestimates ACK delivery ratios -> overestimates total number of transmissions per packet

ACK’s smaller than probe packets
Pros and cons?
Conclusions

- **Pros**
  - ETX performs better or comparable to Hop Count Metric
    - Accounts for bi-directional loss rates
  - Can easily be incorporated into routing protocols

- **Cons**
  - Only considers link loss rates
  - May not be best metric for all networks
    - Mobility
    - Power-limited
    - Adaptive rate (multi-rate)
    - Interference
  - Predictions of loss ratios not always accurate and incur overhead
  - Does not explicitly incorporate the interaction between routing changes and ETX change \(\Rightarrow\) oscillation and select sub-optimal paths
Routing in Multi-Radio, Multi-Hop Wireless Mesh Networks

Richard Draves, Jitendra Padhye, and Brian Zill

Microsoft Research
Multi-Hop Networks with Single Radio

With a single radio, a node cannot transmit and receive simultaneously.
Multi-Hop Networks with Multiple Radios

With two radios tuned to non-interfering channels, a node can transmit and receive simultaneously.
Other Advantages of Multiple Radios

- Increased robustness due to frequency diversity
  - e.g. 2.4GHz (802.11b) and 5GHz (802.11a) have different fading characteristics

- Possible tradeoff between range and data rate
  - Can be helpful during early deployment
Existing Routing Metrics are Inadequate

Source → Mesh Router: 12 Mbps
Mesh Router → Destination: 12 Mbps
Source → Destination: 11 Mbps

Shortest path: 2 Mbps
Path with fastest links: 6 Mbps
Best path: 11 Mbps
Contributions

- New routing metric for multi-radio mesh networks
  - Weighted Cumulative Expected Transmission Time (WCETT)

- Implementation of the metric in a link-state routing protocol
  - Multi-Radio Link-Quality source routing (MR-LQSR)

- Experimental evaluation of WCETT:
  - 24-node, multi-radio mesh testbed
  - 2 radios per node, 11a and 11g
  - Side-by-side comparison with:
    - Shortest path (HOP)
    - ETX (De Couto et. al. MOBICOM 2003)
Summary of Results

- WCETT makes judicious use of two radios
  - Over 250% better than HOP
  - Over 80% better than ETX

- Gains more prominent over shorter paths and in lightly-loaded scenarios
Outline of the talk

- Design of WCETT
- Experimental results
- Conclusion
Design of Routing Metric: Assumptions

- No power constraints

- Little or no node mobility
  - Relatively stable links

- Nodes have one or more 802.11 radios

- Multiple radios on a node are tuned to non-interfering channels
  - Channel assignment is fixed
Implementation Framework

- Implemented in a source-routed, link-state protocol
  - Multi-Radio Link Quality Source Routing (MR-LQSR)

- Nodes discovers links to its neighbors

- Measure quality of those links

- Link information floods through the network
  - Each node has “full knowledge” of the topology

- Sender selects “best path”
  - Packets are source routed using this path
Goal for Multi-Radio Routing Metric
Goal for Multi-Radio Routing Metric

Maximize throughput of a given flow:

- Prefer high-bandwidth, low-loss links
- When possible, select channel diverse paths
- Prefer shorter paths
Components of a Routing Metric

- **Link Metric**: Assign a weight to each link
  - WCETT: Prefer high-bandwidth, low-loss links

- **Path Metric**: Combine metrics of links on path
  - WCETT: Prefer short, channel-diverse paths
Is ETX a good enough link metric?
Link Metric: Expected Transmission Time (ETT)

- Link loss rate = $p$
  - Expected number of transmissions
    \[ \text{ETX} = \frac{1}{1-p} \]

- Packet size = $S$, Link bandwidth = $B$
  - Each transmission lasts for $S/B$
    \[ \text{ETT} = \left( \frac{S}{B} \right) \times \text{ETX} \]

- Lower ETT implies better link
ETT: Illustration

1000 Byte Packet

ETT : 0.77 ms

ETT : 0.89 ms
Any limitations with ETT as link metric?
How to design ETT-based path metric?
Combining Link Metric into Path Metric

Proposal 1

- Add ETTs of all links on the path
- Use the sum as path metric

\[
\text{SETT} = \text{Sum of ETTs of links on path}
\]

(Lower SETT implies better path)

Pro: Favors short paths

Con: Does not favor channel diversity
SETT does not favor channel diversity

<table>
<thead>
<tr>
<th>Path</th>
<th>Throughput</th>
<th>SETT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Red-Blue</td>
<td>6 Mbps</td>
<td>2.66 ms</td>
</tr>
<tr>
<td>Red-Red</td>
<td>3 Mbps</td>
<td>2.66 ms</td>
</tr>
</tbody>
</table>
Impact of Interference

- Interference reduces throughput

- Throughput of a path is lower if many links are on the same channel
  - Path metric should be worse for non-diverse paths

- Assumption: All links that are on the same channel interfere with one another
  - Pessimistic for long paths
Combining Link Metric into Path Metric
Proposal 2

☐ Group links on a path according to channel
  ☐ Links on same channel interfere

☐ Add ETTs of links in each group

☐ Find the group with largest sum.
  ☐ This is the “bottleneck” group
  ☐ Too many links, or links with high ETT (“poor quality” links)

☐ Use this largest sum as the path metric
  ☐ Lower value implies better path

“Bottleneck Group ETT” (BG-ETT)
BG-ETT Example

<table>
<thead>
<tr>
<th>Path</th>
<th>Throughput</th>
<th>Blue Sum</th>
<th>Red Sum</th>
<th>BG-ETT</th>
</tr>
</thead>
<tbody>
<tr>
<td>All Red</td>
<td>1.5 Mbps</td>
<td>0</td>
<td>5.33 ms</td>
<td>5.33 ms</td>
</tr>
<tr>
<td>1 Blue</td>
<td>2 Mbps</td>
<td>1.33 ms</td>
<td>4 ms</td>
<td>4 ms</td>
</tr>
<tr>
<td>Red-Blue</td>
<td>3 Mbps</td>
<td>2.66 ms</td>
<td>2.66 ms</td>
<td>2.66 ms</td>
</tr>
</tbody>
</table>

BG-ETT favors high-throughput, channel-diverse paths.
BG-ETT does not favor short paths

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<tr>
<th>Path</th>
<th>Throughput</th>
<th>Blue Sum</th>
<th>Red Sum</th>
<th>BG-ETT</th>
</tr>
</thead>
<tbody>
<tr>
<td>3-Hop</td>
<td>2 Mbps</td>
<td>0</td>
<td>4 ms</td>
<td>4 ms</td>
</tr>
<tr>
<td>4-Hop</td>
<td>2 Mbps</td>
<td>4 ms</td>
<td>4 ms</td>
<td>4 ms</td>
</tr>
</tbody>
</table>
Path Metric: Putting it all together

- SETT favors short paths
- BG-ETT favors channel diverse paths

Weighted Cumulative ETT (WCETT)

\[ WCETT = (1-\beta) \times SETT + \beta \times BG-ETT \]

\( \beta \) is a tunable parameter

Higher value: More preference to channel diversity
Lower value: More preference to shorter paths
Any limitation on WCETT as path metric?
How to measure loss rate and bandwidth?

- Loss rate measured using broadcast probes
  - Similar to ETX
  - Updated every second

- Bandwidth estimated using periodic packet-pairs
  - Updated every 5 minutes
Outline of the talk

- Design of WCETT
- Experimental results
- Conclusion
Mesh Testbed

23 nodes running Windows XP.
Two 802.11a/b/g cards per node: Proxim and NetGear (Autorate)
Diameter: 6-7 hops.
Experiment Setting

- 2-Minute TCP transfer between 100 randomly selected node pairs (Out of 23x22 = 506)
- Only one transfer active at a time
- Performance metric:
  - Median throughput of 100 transfers

Baseline (Single Radio)
NetGear on 802.11a (Channel 36), Proxim OFF

Two Radio
NetGear on 802.11a (Chan 36), Proxim on 802.11g (Chan 10)

(802.11g radios have longer range, lower bandwidth)
**Median Throughput**
*(Baseline, single radio)*

WCETT provides performance gain even with one radio.
Median Throughput
(Two radios)

WCETT makes judicious use of 2nd radio: 86% gain over baseline.

Throughput (Kbps)

- Single Radio
- Two Radios

WCETT (β = 0.5) ETX HOP

Performance of HOP worsens with 2nd radio!

WCETT

Performance of HOP worsens with 2nd radio! Y baseline
Do all paths benefit equally with WCETT?

**Improvement in Median Throughput over Baseline (1 radio)**

WCETT gains are more prominent for shorter paths.
Impact of $\beta$ value

Channel diversity is important; especially for shorter paths
Performance of Two Simultaneous Flows

- 2-Minute TCP transfer between 100 randomly selected node pairs
- Two transfers active at a time
- Two radios: Netgear: 36-a, Proxim: 10-g
- Performance metric: 2 x Median throughput
- Repeat for ETX and WCETT ($\beta = 0, 0.5, 0.9$)
Two simultaneous flows

β = 0: No weight to diversity
β = 0.9: High weight to diversity

Throughput better for lower values of β
Conclusions

- Previously proposed routing metrics are inadequate in multi-radio scenario

- WCETT improves performance by judicious use of 2\textsuperscript{nd} radio
  - Benefits are more prominent for shorter paths

- Optimal value of $\beta$ depends on load

- Passive inference of loss rate and channel bandwidth