Efficient Routing in Ad Hoc Networks with Directional Antennas

MILCOM’04

November 2004

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The Problem

Electrically Steerable Antenna

Network Links: Depend on antenna pointing!
Some Details – Pairwise States to Metrics

Edge metric = \{1, \infty\}

\infty = disconnected

Different Metrics & connectivity for each state

Node 6, State v6
Node 1, State v1

# antenna states squared

\# \text{ antenna states squared}

\begin{array}{cccc|cccc}
V_X & V_Y & \text{Metric} \\
E & W & N & S & E & W & N & S \\
1 & 1 & \infty & 1 & 1 & 1 & 1 & 1 \\
1 & 1 & \infty & 1 & 1 & 1 & 1 & 1 \\
1 & 1 & \infty & 1 & 1 & 1 & 1 & 1 \\
1 & 1 & \infty & 1 & 1 & 1 & 1 & 1 \\
1 & 1 & \infty & 1 & 1 & 1 & 1 & 1 \\
1 & 1 & \infty & 1 & 1 & 1 & 1 & 1 \\
1 & 1 & \infty & 1 & 1 & 1 & 1 & 1 \\
1 & 1 & \infty & 1 & 1 & 1 & 1 & 1 \\
1 & 1 & \infty & 1 & 1 & 1 & 1 & 1 \\
1 & 1 & \infty & 1 & 1 & 1 & 1 & 1 \\
1 & 1 & \infty & 1 & 1 & 1 & 1 & 1 \\
1 & 1 & \infty & 1 & 1 & 1 & 1 & 1 \\
\end{array}

\text{Antenna Gain Pattern}

\text{State 1} \quad \text{State 2} \quad \text{State 3} \quad \text{State 4}
How many antenna states are there?

For a pair of nodes, there are $m^2$ combinations of antenna states, there are $(n^2 - n)$ pairs in the network.

Errata in paper! $2^m$ should be $m^2$.

<table>
<thead>
<tr>
<th>Number of nodes $(n)$</th>
<th>Antenna Directions $(m)$</th>
<th>Directional Tx / Rx $m^2(n^2 - n)$</th>
<th>Directional Tx / Omni Rx $m(n^2 - n)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>4</td>
<td>32</td>
<td>8</td>
</tr>
<tr>
<td>3</td>
<td>3</td>
<td>54</td>
<td>18</td>
</tr>
<tr>
<td>20</td>
<td>4</td>
<td>6,080</td>
<td>1,520</td>
</tr>
<tr>
<td>40</td>
<td>8</td>
<td>99,840</td>
<td>12,480</td>
</tr>
</tbody>
</table>

$Larger\ Network$ $Tractable$
• **Step 1**: Analyze antenna states to form *multi-state network*
  – *Involves propagation and radio parameters, or sensing*
• **Step 2**: Find all routes in multi-state network efficiently
  – *Need efficient method to combat combinatorial explosion*
• **Step 3**: Map multi-state network routing solution back to antenna state settings
  – *With solution in hand, determine antenna direction settings*

*Multi-state networks are new*
The Multi-State, Dynamic Shortest Path Algorithm uses dynamic programming and only finds solutions for ‘dominant states’

- **Dominant State** - A particular setting of edge metrics, including don’t care settings, is called *dominant* if and only if altering any edge metric setting(s) will change the shortest reachable distance from $s$ to some vertex and where the state is not in turn dominated by another dominant state.

- **Dominant Set** - The dominant set of dominant states is the set of dominant states such that the associated graph is ‘covered,’ meaning that any possible graph state can be matched to a member in the dominant set.

This is a dominant set for the sample, $2^5 = 32$ states are covered with only 9 dominant states
2: Select $e_{\text{min}}$

4&5: If higher metric value for $e_{\text{min}}$ available, create copy of solution and use higher value, recurse in step 7

Otherwise step 8: select $e_{\text{min}}$ and set distances and nodes reached ($Q$)
Resulting Multistate Network

After analyzing antenna states to form connectivity or edge metrics – we get a multi-state graph

The ‘1, ∞’ comes from various $v_1$ and $v_5$ pairwise antenna settings. The 1 is for connected the ∞ is disconnected here, but actual quality metrics can be used as well.

Here, four directional antenna nodes give rise to thirteen bi-directional arcs that have two states $\{1, \infty\}$ each giving rise to $2^{26} = 67,108,864$ combinatorial states in the multistate graph.

$2^{26} = 67,108,864$ states are covered with only 836 dominant states for $v_8$ as source.
Final Steps

Use multi-state graph solution to find antenna direction settings

Step 1: Select one of three routes of cost ‘3’ found from $v_8$ to $v_3$ – dotted lines. *Suppose we pick the lower route*

Step 2: determine possible antenna states at each node that correspond to desired metrics
e.g. $v_4$ may be pointed ‘up’ for $v_6$ connectivity

Dotted lines will be the minimum length routes found by MSD-SPA

Three dotted lines are the all the minimum length routes.

Consider routing from node $v_8$ to $v_3$
Quality metrics above connectivity metrics

Multistates can include more than just \{1, \infty\} and reflect QoS of the link in various states
- For example, a high-rate connection may be available when Rx/Tx antennas are both pointed together, otherwise a medium rate might be achieved or no connection at all.
Summary and Future Work

• New and efficient means for determining network-wide antenna state settings for routing
  – Uses multiple link-states derived from propagation analysis or from real-time probing of the media
    • A node can use a control frame to switch through its antenna states while checking for connectivity or QoS level on the link
  – Method is ‘complete’ or optimal in that all multistate routes are efficient discovered in the form of a dominant set that covers the graph
    • Multiple solutions (antenna settings) can be found to satisfy a route

• Future:
  – Use the MSD-SPA computation method within the context of an ad hoc routing protocol
    • Perhaps tie in with DSR route responses or other protocols
    • Couple into actual antenna control
  – Further investigate final route selection process and complexity

Errata: goto www.OpCoast.com navigate to ‘Downloads’ then ‘Documents’ to find corrected paper

Don’t settle for sub-optimal solutions