Efficient Routing in Ad Hoc Networks with Directional Antennas

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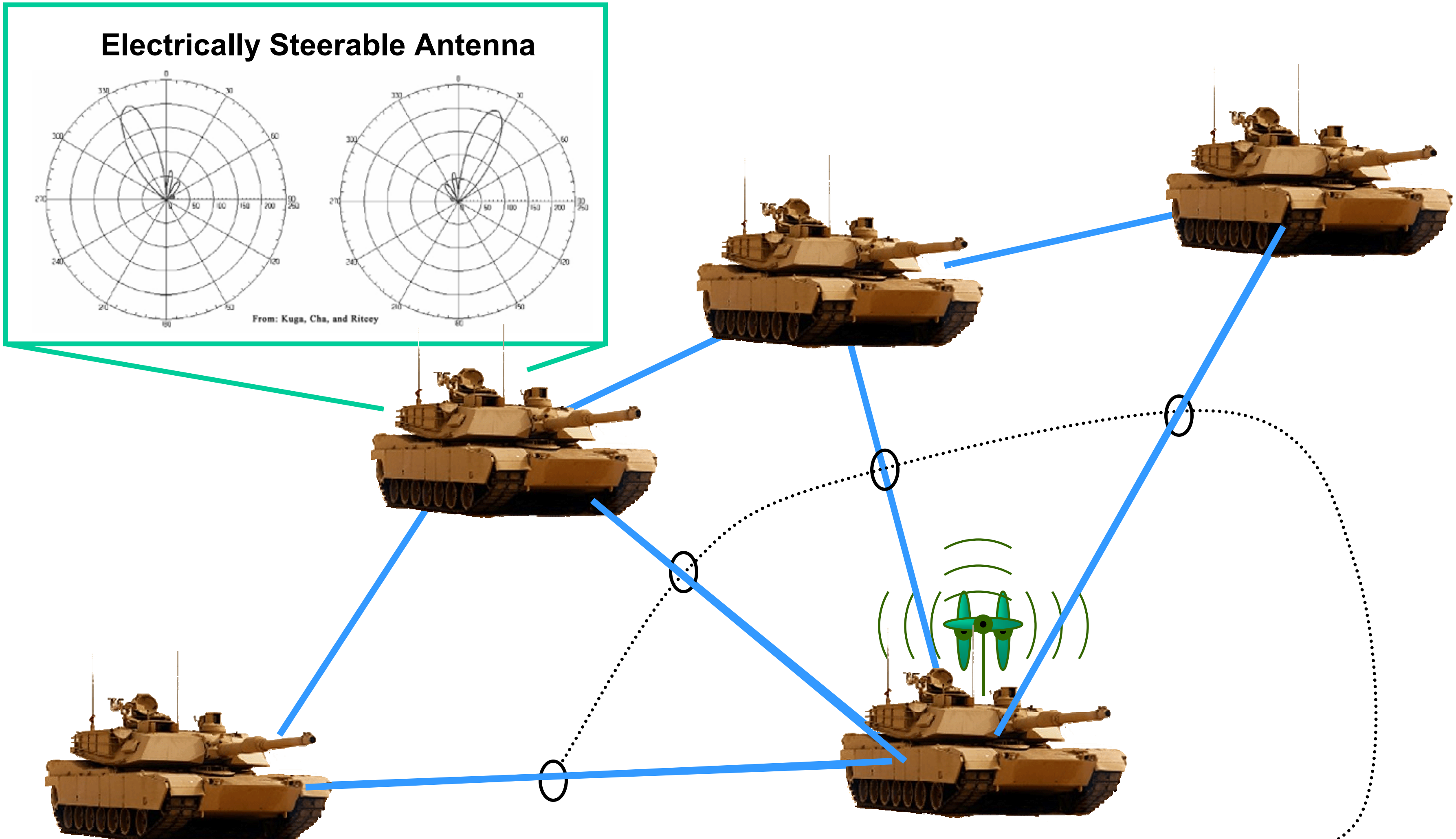
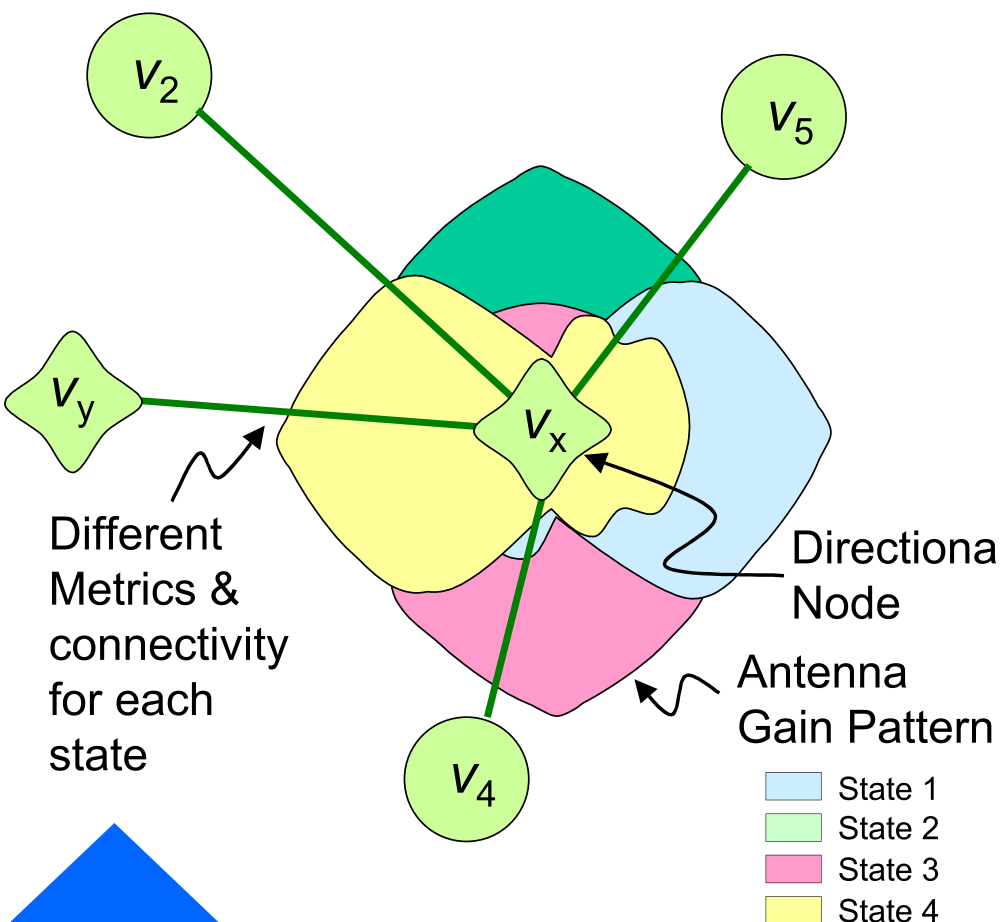
The Problem



Network Links:
Depend on antenna pointing !

Some Details – Pairwise States to Metrics



antenna states squared

v_X				v_Y				Metric
E	*W*	*N*	*S*	*E*	*W*	*N*	*S*	$v_X \rightarrow v_Y$
1				1				∞
	1			1				1
		1		1				1
			1	1				∞
1					1			∞
	1				1			∞
		1			1			∞
			1		1			∞
1						1		∞
	1					1		∞
		1				1		∞
			1			1		∞
1							1	∞
	1						1	∞
		1					1	∞
			1				1	∞

Edge metric = {1, ∞}

∞ = disconnected

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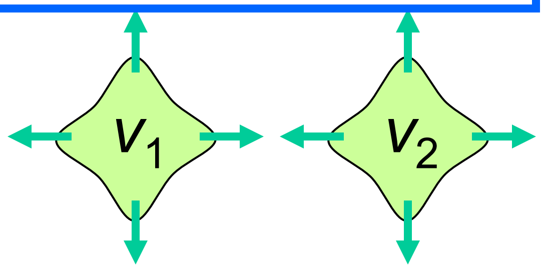
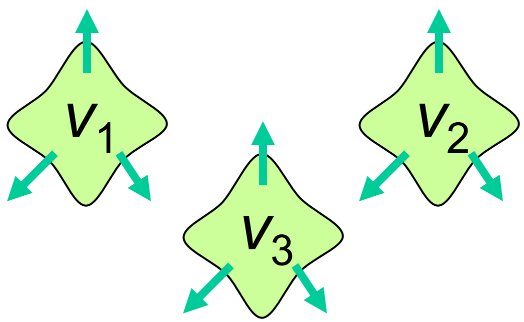
How many antenna states are there?

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

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





Larger Network

Tractable

Number nodes (*n*)	Antenna Directions (*m*)	Directional Tx / Rx $m^2(n^2\text{-}n)$	Directional Tx / Omni Rx $m(n^2\text{-}n)$
2	4	32	8
3	3	54	18
20	4	6,080	1,520
40	8	99,840	12,480

$m^2(n^2\text{-}n)/2$ if symmetric

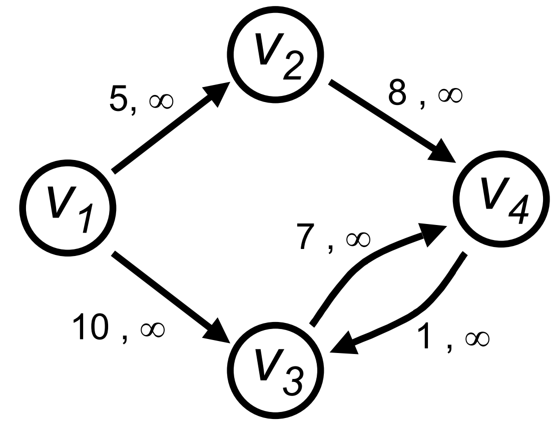
Overall Solution Steps

- **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

MSD-SPA Algorithm

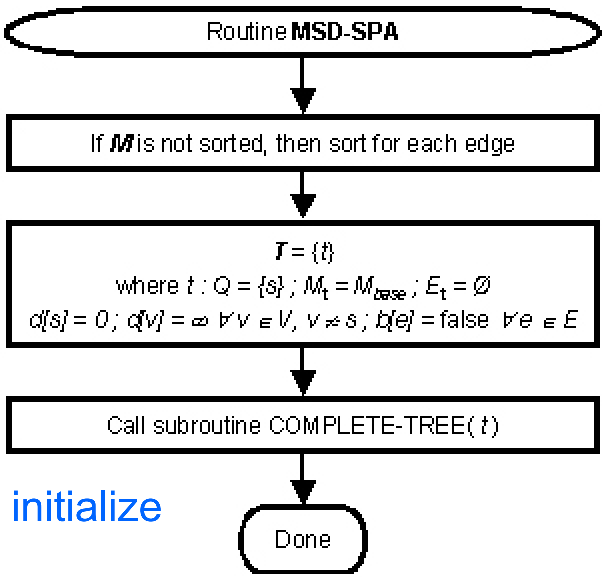
- The <u>M</u>ulti-<u>S</u>tate, <u>D</u>ynamic <u>S</u>hortest <u>P</u>ath <u>A</u>lgorithm uses dynamic programming and only finds solutions for ‘dominant states’
  - Dominant State - A particular setting of edge metrics, including <u>don’t care</u> settings, is called *dominant* if and only if altering 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.



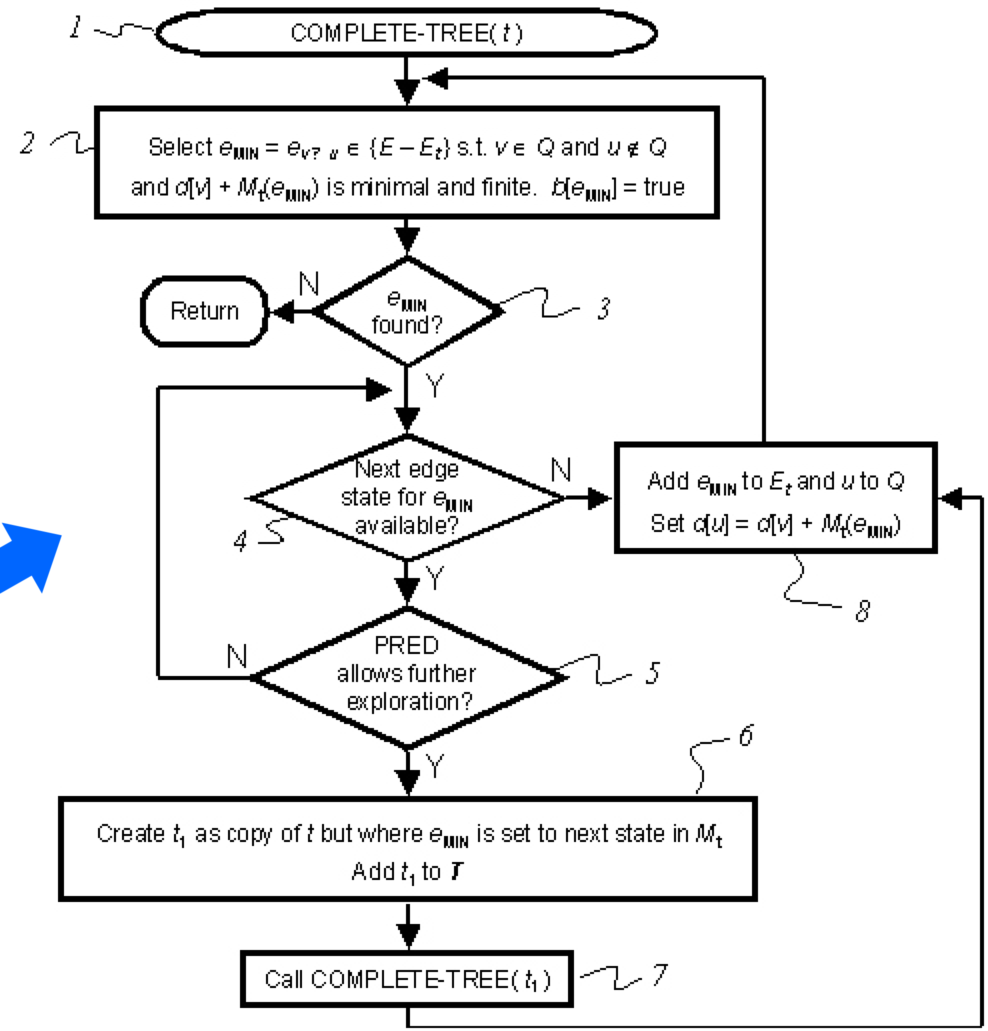
$e_{1\to 2}$	$e_{1\to 3}$	$e_{2\to 4}$	$e_{3\to 4}$	$e_{4\to 3}$	$d[v_2]$	$d[v_3]$	$d[v_4]$
∞	∞	—	—	—	∞	∞	∞
5	∞	∞	—	—	5	∞	∞
∞	10	—	∞	—	∞	10	∞
∞	10	—	7	—	∞	10	17
5	10	∞	∞	—	5	10	∞
5	∞	8	—	∞	5	∞	13
5	∞	8	—	1	5	14	13
5	10	8	—	—	5	10	13
5	10	∞	7	—	5	10	17

This is a dominant set for the sample, $2^5 = 32$ states are covered with only 9 dominant states

MSD-SPA Algorithm



initialize



2: Select e_{min}

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

Otherwise step 8: select e_{min} and set distances and nodes reached (Q)

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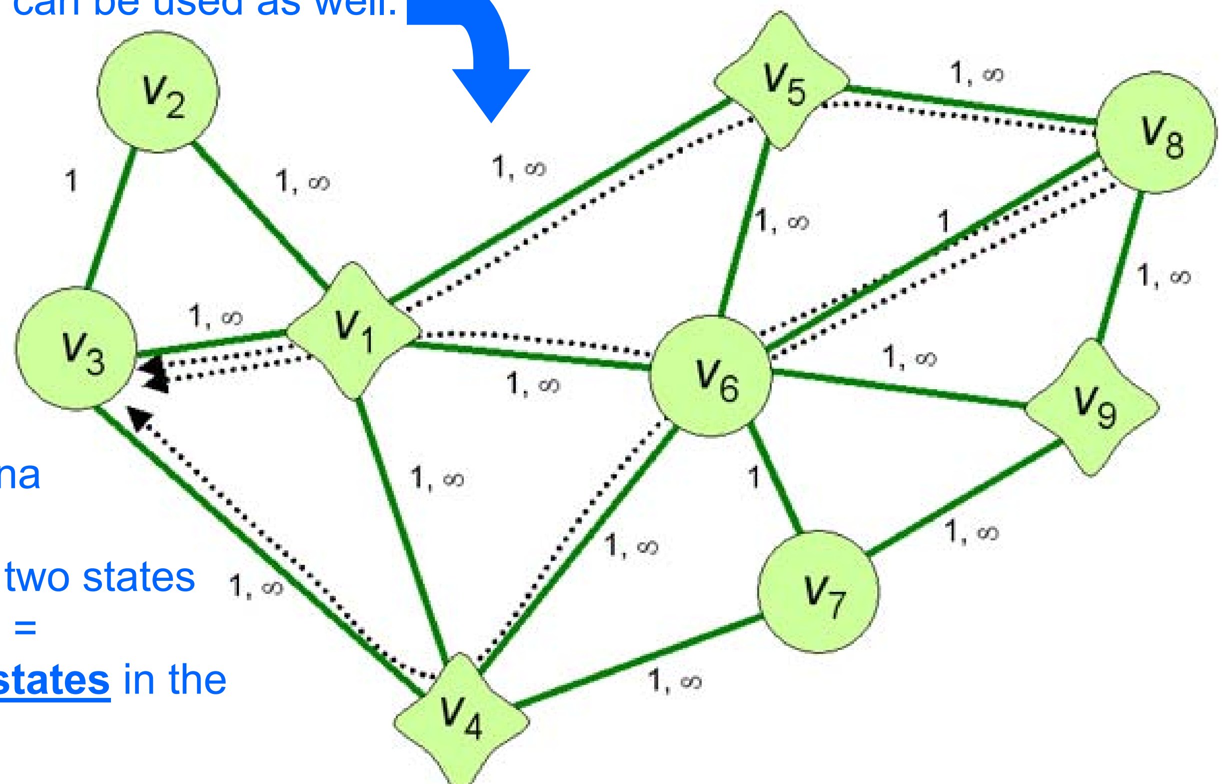
Resulting Multistate Network

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.



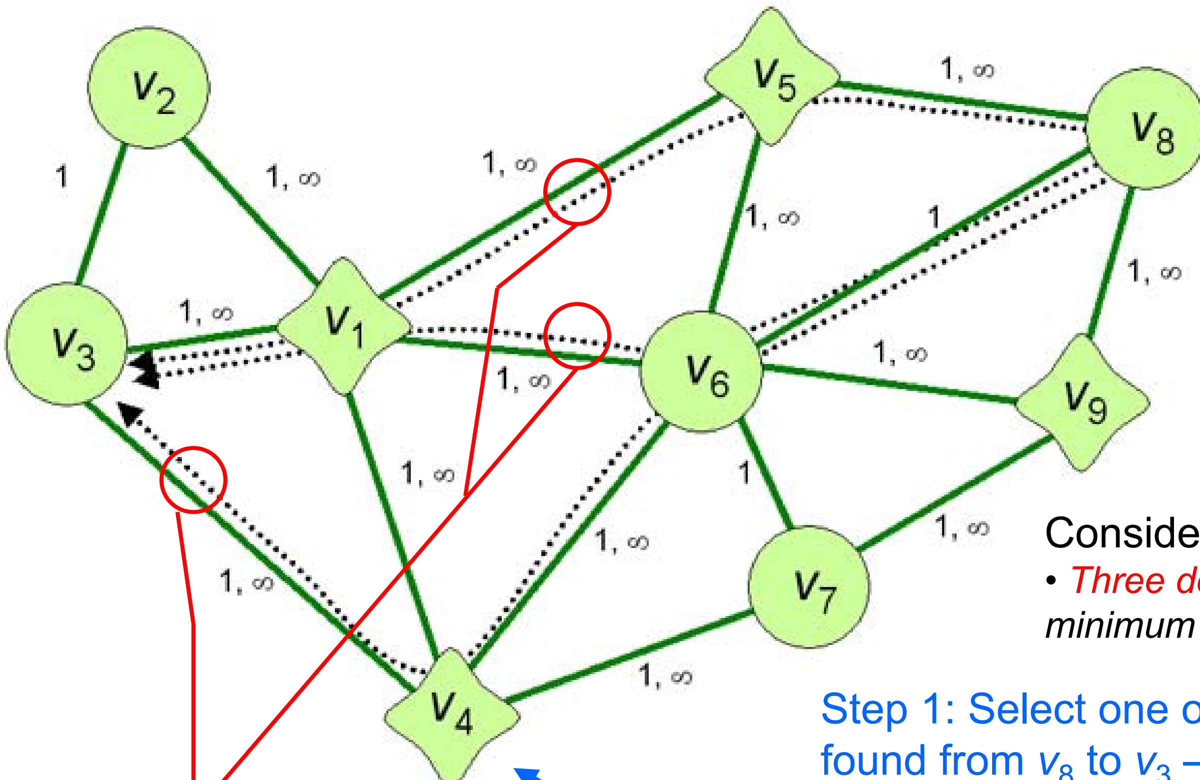
Here, **four** directional antenna nodes give rise to **thirteen** bi-directional arcs that have two states {1, ∞} each giving rise to 2^{26} = 67,108,864 **combinatorial states** in the multistate graph.

Untractable for brute force method, but …

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



Consider routing from node v_8 to v_3

- *Three dotted lines are the all the minimum length routes.*

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

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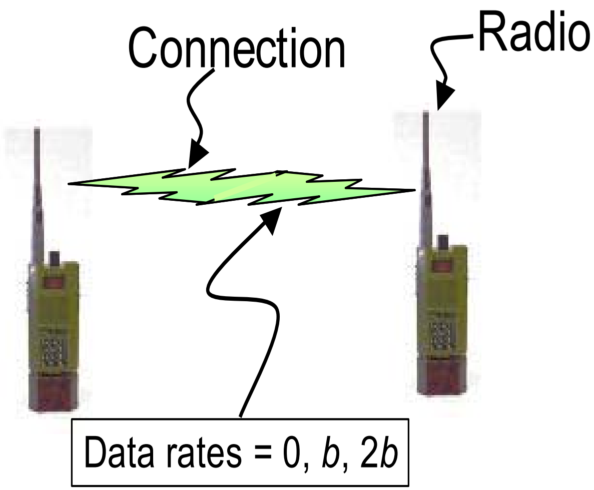
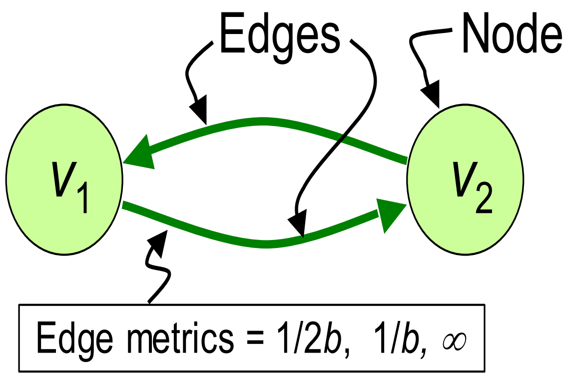
Quality metrics above connectivity metrics





Multistates can include more than just {1, ∞} 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.

Don't settle for sub-optimal solutions

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