# On the Use of Transmission Power Control for Energy-Efficient MANET Services

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Work with Tommy Chu and Fulu Li.

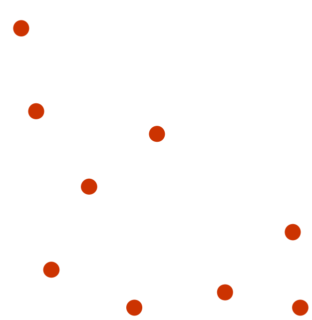
# Outline

- Motivation
- Problem Structure
- Previously Proposed Schemes
- A New Scheme
- The Impact of Mobility
- Towards Addressing Mobility
- Conclusions

## Motivation

- An old(er) problem.
  - Provide distribution of TV/radio broadcasts using relay stations on mountaintops.
- The new twist.
  - Provide broadcast/multicast services in collections of mobile ad hoc networks (MANETs).

## An Example



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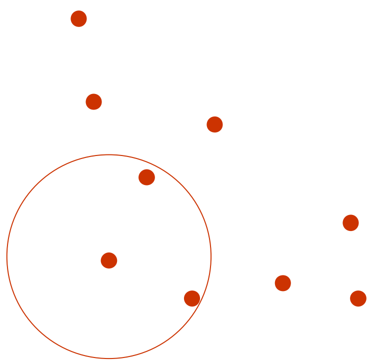

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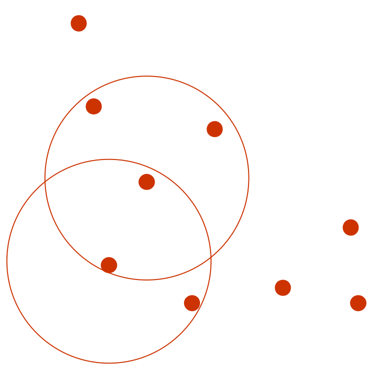

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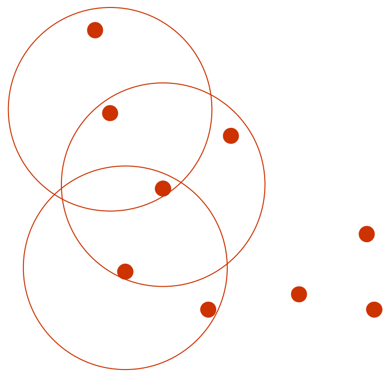

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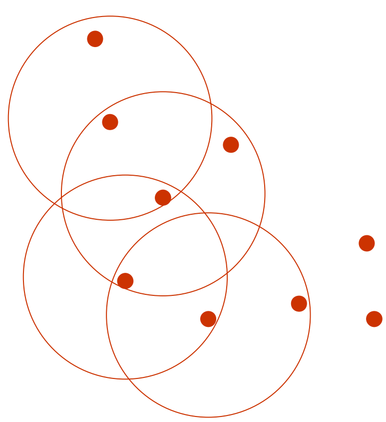

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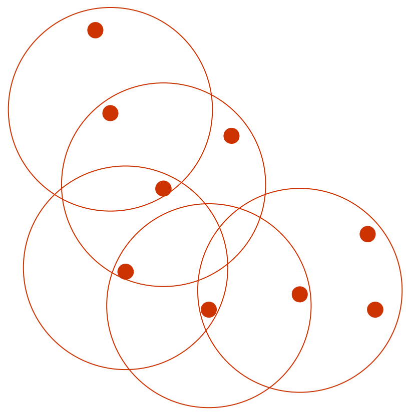

# Mobile Ad-Hoc Networks (MANETs)

- Infrastructure-less wireless communication.
- Multi-hop routing.
- Equal properties/responsibilities of nodes.
- *Why MANETs?*

## Broadcast (Multicast) Service

- Deliver data to all (some) of the nodes.
  - Multicast treated as a sub-case of broadcast.
- Why Broadcast/Multicast?
  - It is an *elementary* service, i.e., many applications require broadcast:
    - Resource Discovery
    - Paging/Registration
    - Certain Unicast Routing Algorithms

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## Control of Transmission Power

- Four Possible Objectives
  - Minimization of Interference
  - Minimization of Energy Consumption
  - Localization (Reduction) of Congestion
  - Maintenance of Connectivity

## Energy-Efficiency Objective

- Form a minimum-energy broadcast tree.
  - Rooted at a specific source.
- *The wireless "advantage"*
  - A single transmission received by many nodes.

## Wired vs. Wireless Broadcast

Wired Broadcast Cost: $\sum_{i} c_i$

## Wired vs. Wireless Broadcast

Wireless Broadcast Cost: $\sum_{j} \max_{i} (c_i)$

## Transmission Energy Cost

$$c_i = c_{XY} \approx d_{XY}^{\lambda}$$

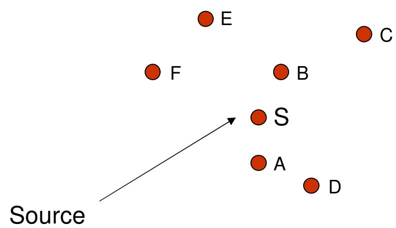
$$(2 \leq \lambda \leq 5)$$

## Technicalities & Assumptions

- Quasi-Static Topology
- Acquisition of Cost/Distance Information
  - Passive
    - Measurement of Signal Strength +
    - Transmission Power Info
  - Active
    - Neighborhood Discovery +
    - Quantized Emission Power Levels

(Sufficient to establish emission power vs. reachable subset association.)

## Wireless Broadcast Example

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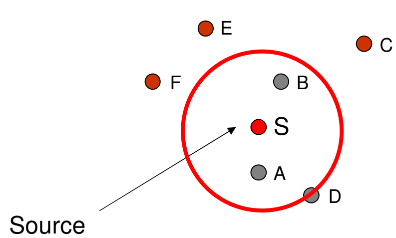
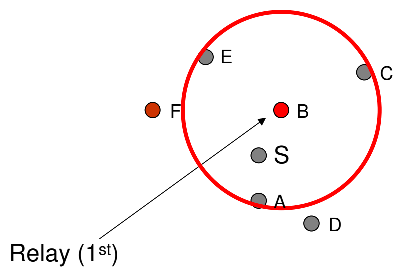


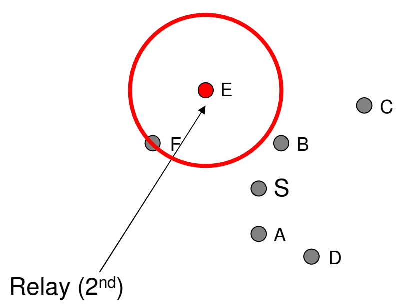

**Cost:** $\max(d_{SA}^{\lambda}, d_{SB}^{\lambda}, d_{SD}^{\lambda})$

## Wireless Broadcast Example




**Cost:** $\max(d_{SA}^{\lambda}, d_{SB}^{\lambda}, d_{SD}^{\lambda}) + \max(d_{BE}^{\lambda}, d_{BC}^{\lambda})$

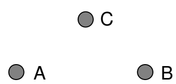
## Wireless Broadcast Example




**Cost:** $\max(d_{SA}^{\lambda}, d_{SB}^{\lambda}, d_{SD}^{\lambda}) + \max(d_{BE}^{\lambda}, d_{BC}^{\lambda}) + \max(d_{EF}^{\lambda})$

$= d_{SD}^{\lambda} + d_{BE}^{\lambda} + d_{EF}^{\lambda}$

## Complication: Lack of Triangle Inequality

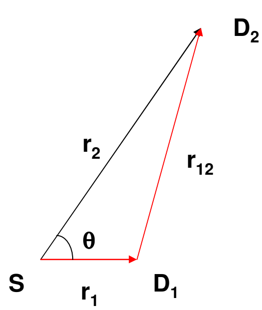



$$d_{AB} \le d_{AC} + d_{CB}$$

$$(\lambda = 1)$$

**Observation: It is generally better (less cost) to use multiple relays.**

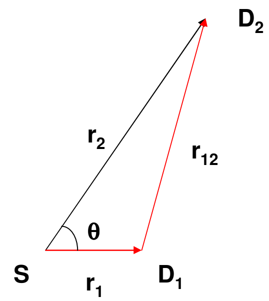
## The Triangle




**Inverse square of distance cost:**

1. **Transmit directly to $D_2$**
   - **If $r_1 > r_2 \cos \theta$**
2. **Transmit to $D_1$, then $D_1$ to $D_2$**
   - **otherwise**

## The Triangle (cont.)

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**Inverse $\lambda$-power ($\lambda > 2$) of distance cost:**

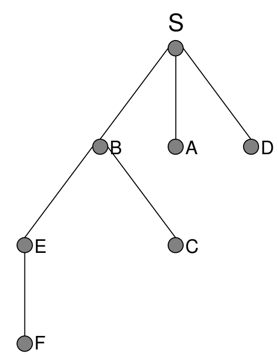
1. **Transmit directly to $D_2$**
   - **$x^{\lambda} - 1 < (1 + x^2 - 2x \cos \theta)^{\lambda/2}$**
   - **$x = r_2/r_1$**
2. **Transmit to $D_1$, then $D_1$ to $D_2$**
   - **otherwise**

## Minimum Energy Broadcast (MEB)

- An NP-hard problem in both its general form and "geometric" form.
- A quick-and-dirty search space upper bound:

$$N^{N-2}$$

## The Implicit Tree

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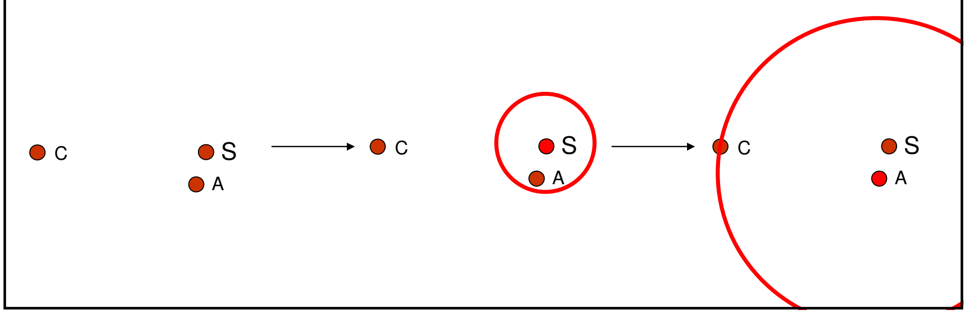
# A (Not Surprising) Fact

**Greedy Link-based Algorithms Can Fail Miserably**

**e.g. Minimum Spanning Tree (no wireless “advantage” exploited)**

**In general, local optimality is a trap.**

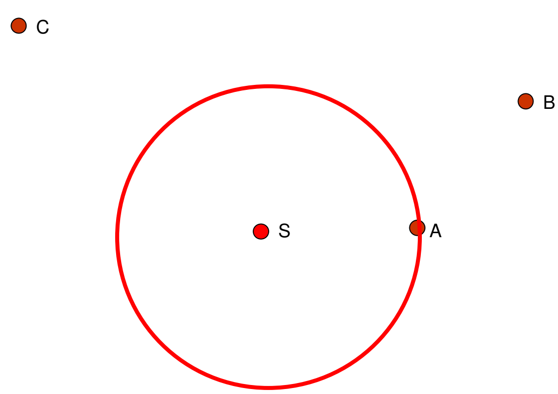


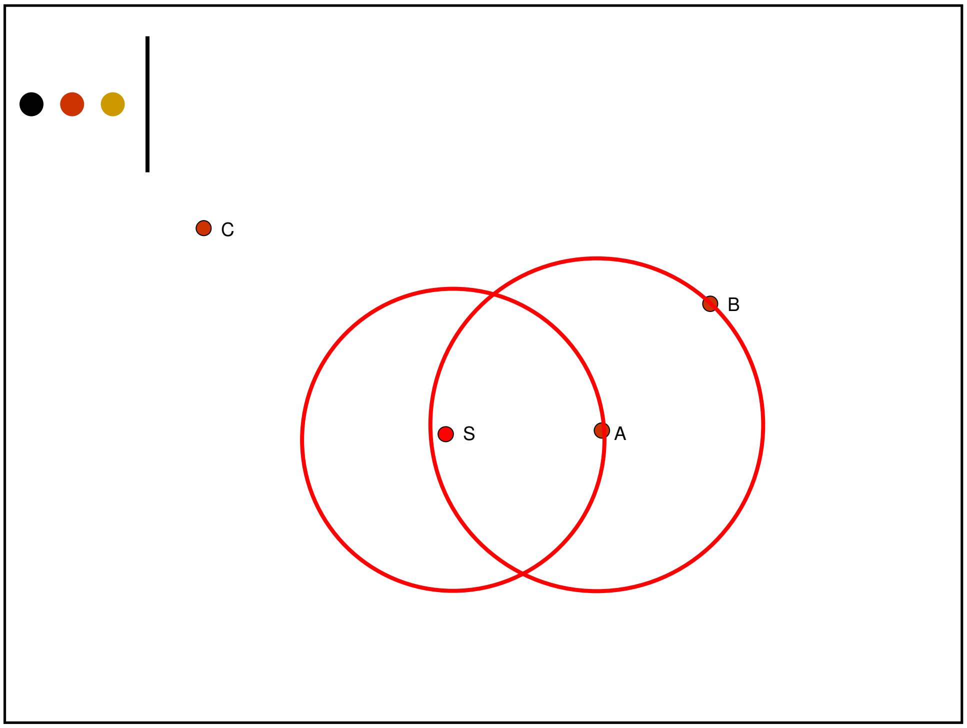

# BIP: Broadcast Incremental Power [WNE01]

- A modification to Prim’s algorithm.
  - Vertices instead of edges.
  - Add vertex (node) that requires the *least additional power*.
    - Additional power = either extension of the range of an already admitted vertex, or relay of a station already reachable but not yet relaying.
- An incremental algorithm
  - Start with single vertex (source).
  - Add vertices until all are added.

# A Pathology of BIP

- By adding vertices (hence adjusting transmission ranges), it is possible that a set of nodes becomes reachable by more than one relay transmission.
  - Perform a "sweep" operation to reduce unnecessary transmissions.

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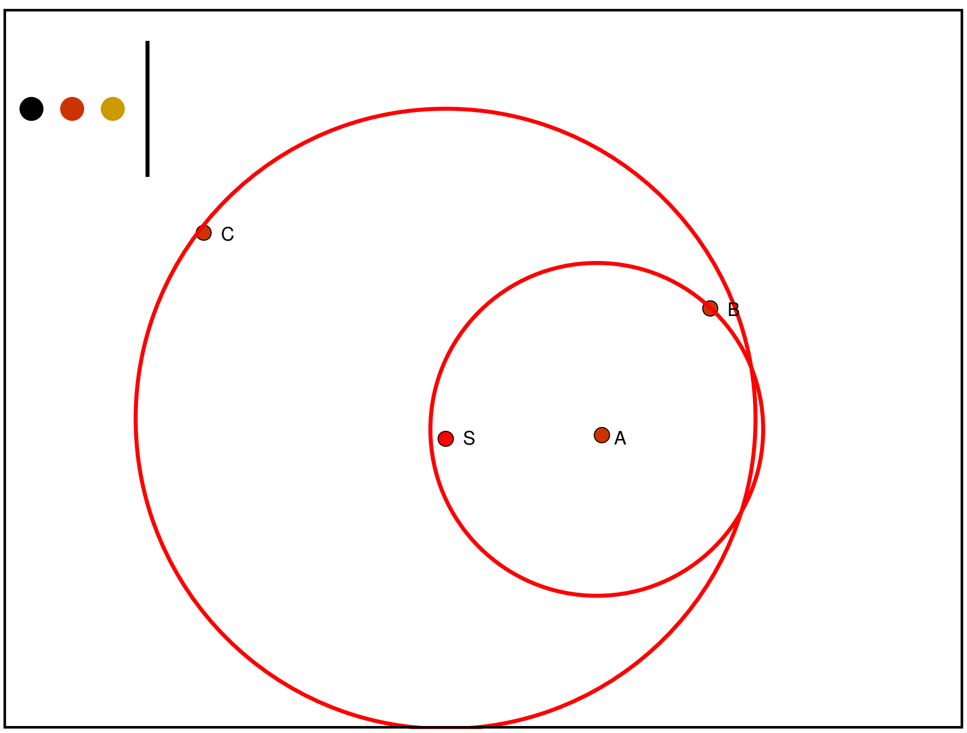
C
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S
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## Except for BIP

MST (BLiMST)

Prim's algorithm (edge-wise).

SPT (BLU)

Single source shortest path union.

## Previous Results

- In increasing performance:
  - SPT (BLU)
  - MST (BLiMST)
  - BIP

# BIP vs BLU vs BLiMST

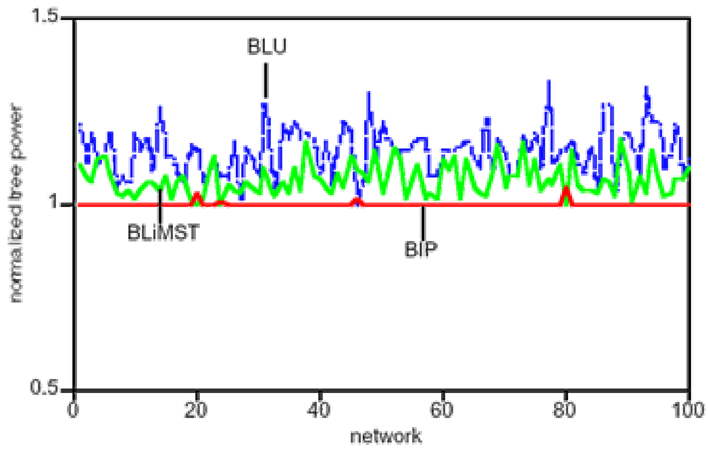


Fig. 11 — Normalized tree power for 100 network instances; 100-node networks, broadcast case (i.e., group size = 100), a = 2.From **On the Construction of Energy-Efficient Broadcast and Multicast Trees in Wireless Networks** by Jeffrey E. Wieselthier, Gam D. Nguyen, Anthony Ephremides.

# Sidebar: Multicasting

- Same as broadcasting.
  - Eliminate nodes (leaves and interior) that do not participate in the multicast group.
  - Rather simple-minded approach.
    - The fixed-network alternative is at least a Steiner tree problem – not much hope on that side either.

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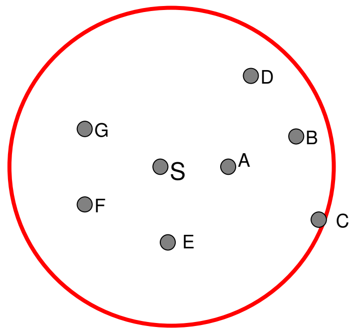
## Iterative Maximum-Branch Minimization (IMBM)

1. Form initial (trivial) tree.
2. *Pick* a relay X, and the node Y with max. cost (on the edge of X's transmission) such that:
   1. Possible to replace the direct XY path with an intermediate relay node (e.g, Z).
   2. Exploit the existence of the new intermediate relay, Z, to reduce costs of other relays even further.
3. Stop when not possible to improve total cost.

(*Pick*: randomly between all XZ pairs where the combined 2.1+2.2 reduces the overall tree cost).

## IMBM Example

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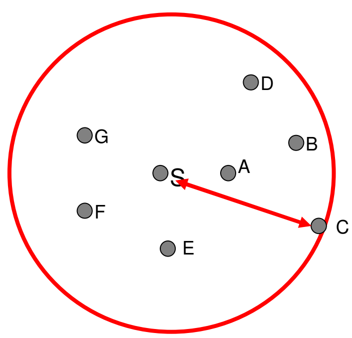

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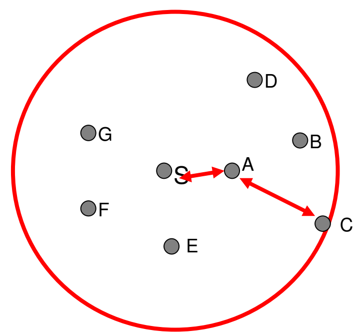


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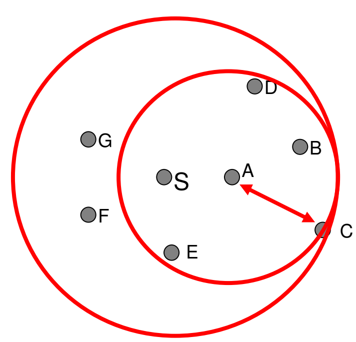

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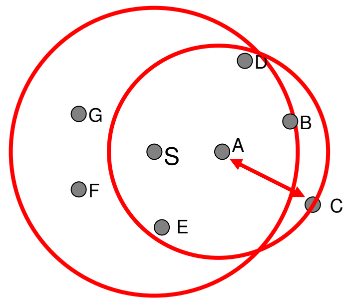


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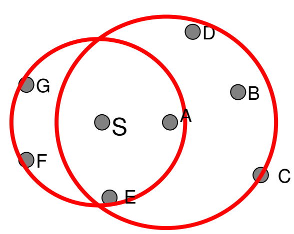
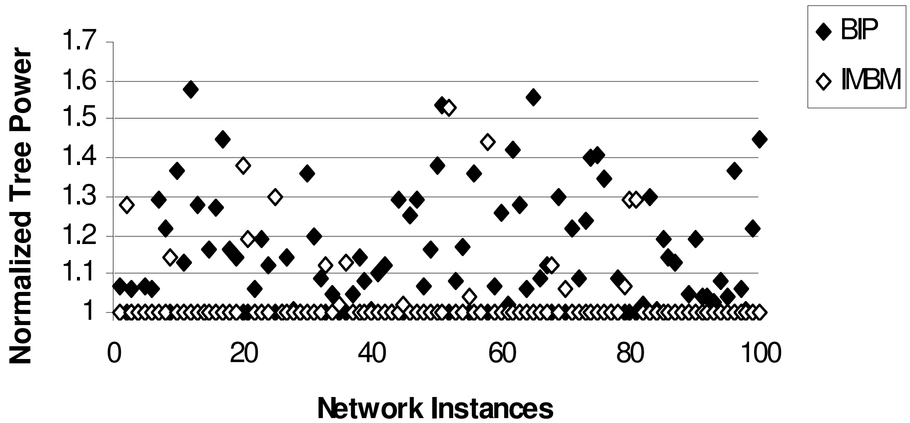
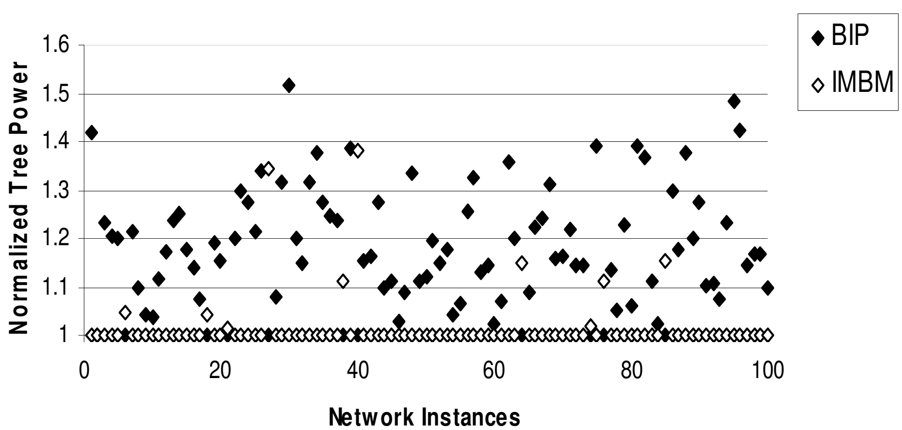


# Experimental Results - 10 nodes



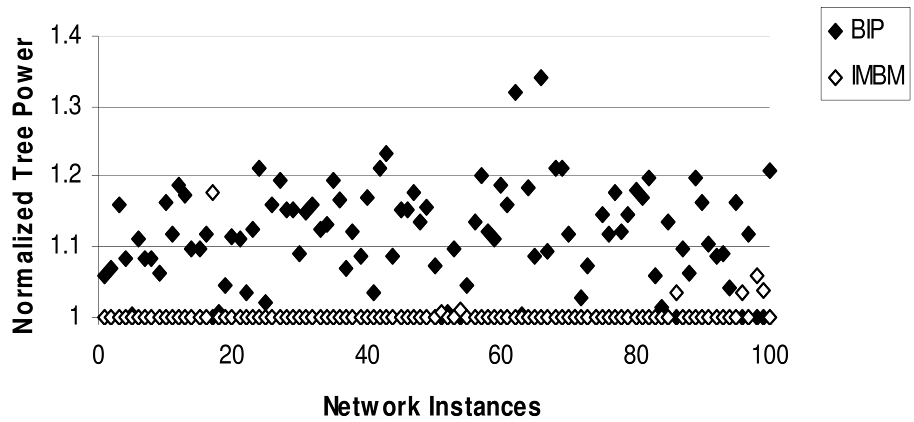

Normalized power of the broadcast trees generated by IMBM and BIP for a variety of network instances (100), the number of randomly-distributed nodes for each network is 10 and the propagation loss exponent is 2.

# Experimental Results - 30 nodes




Normalized power of the broadcast trees generated by IMBM and BIP for a variety of network instances (100), the number of randomly-distributed nodes for each network is 30 and the propagation loss exponent is 2.

# Experimental Results - 100 nodes




Normalized power of the broadcast trees generated by IMBM and BIP for a variety of network instances (100), the number of randomly-distributed nodes for each network is 100 and the propagation loss exponent is 2.

# Current State of Affairs

- BLiMST
  - Between 6 and 12 times the optimal.
- BIP
  - Between 13/3 and 12 times the optimal.
- BLU
  - At least n/2.
- IMBM
  - Not known,
    - but not would not be surprising if it is also bad.

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# The Impact of Mobility

- The quasi-static assumption:
  - The network nodes move only occasionally.
- The “true” mobility assumption:
  - Nodes move, then pause, then move, etc.
- A mobility model:
  - Random Waypoint Model (RWP)

## RWP (for one node)

- Pick a point (waypoint) within a rectangle.
  - Uniform random on X and Y.
- Select a certain velocity.
  - Uniform random between 0 and Vm.
- Move from current point to waypoint.
- Pause at the waypoint.
  - Exponentially distributed.
- Repeat

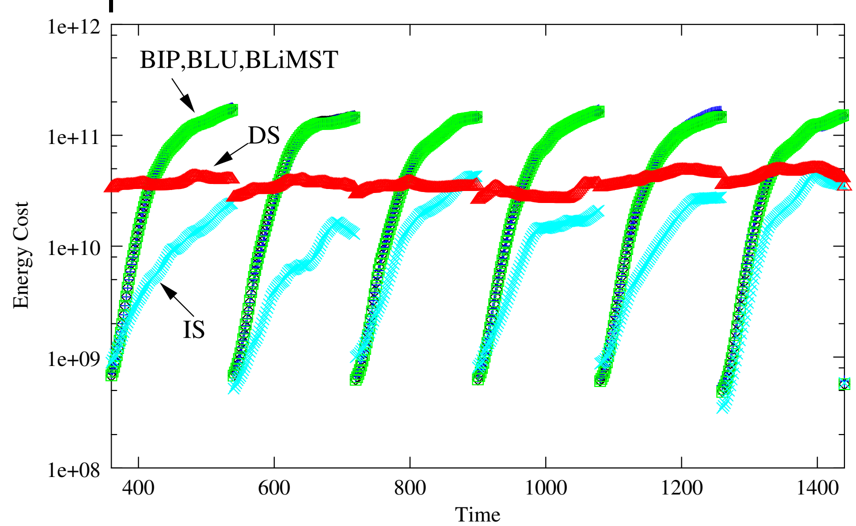
## Naïve Mobility-Support Scheme

- Construct tree as per BIP/BLU/BLiMST
  - IMBM is similar.
- When mobile, adjust power level to maintain the originally constructed tree.

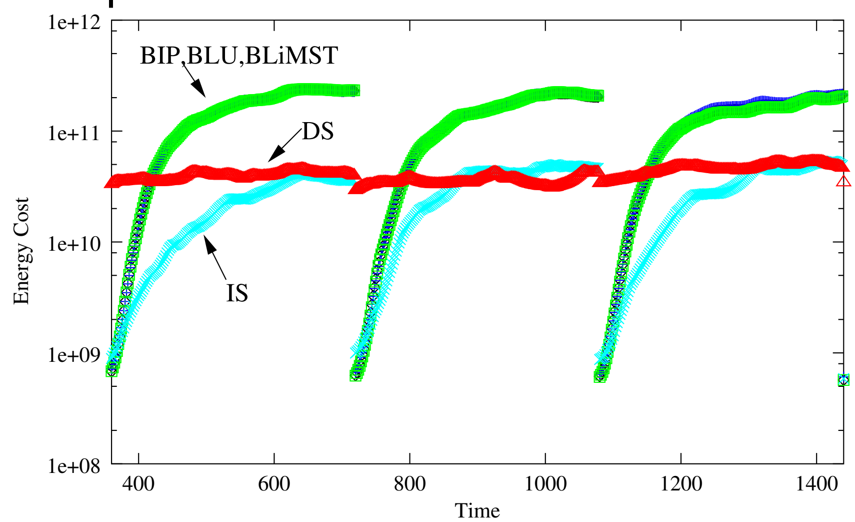
## Additional Simplistic Broadcast Tree Construction Schemes

- IS: Incremental Search.
  - Assume initially all nodes are relays with radius 0.
  - Edge list is admitted in minimum additional cost order.
    - Minimum additional cost to expand radius of a relay.
  - Terminate when all vertices reached.
    - A-la Kruskal MST but cycles are allowed.
- DS: Decremental Search.
  - Assume initially all nodes are relays with maximum radius.
  - Edges are *eliminated* in order of maximum cost reduction.
    - Maximum cost reduction by shrinking radius.
  - Terminate when edge removal would disconnect the graph.
    - We start from completely connected graph, but don't go far.

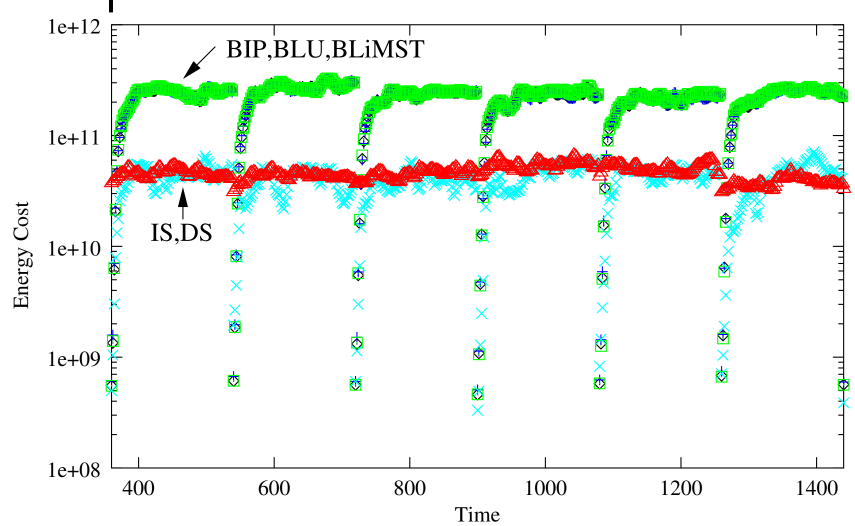
## Naïve Scheme Results



## Naïve Scheme Results – Long




## Naïve Scheme Results - Fast



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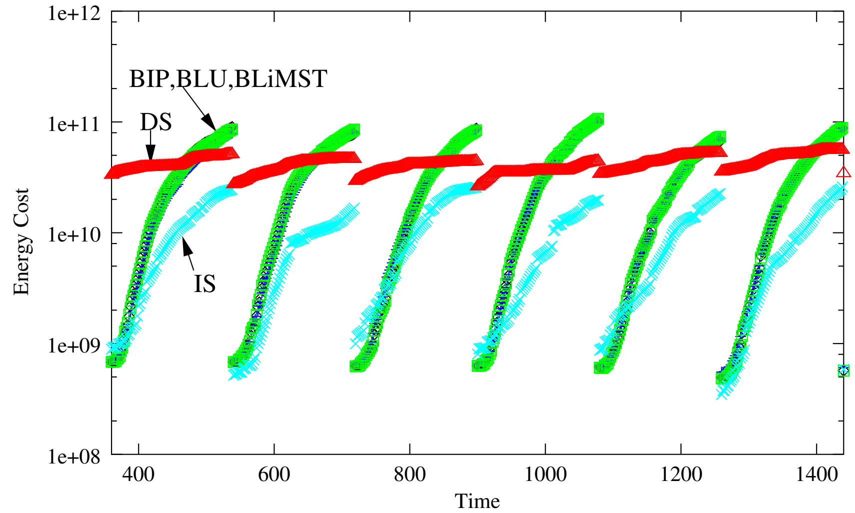
## Towards Addressing Mobility

- Tradeoff of continuously re-running the tree construction and a simple algorithm to *maintain* the tree despite mobility.

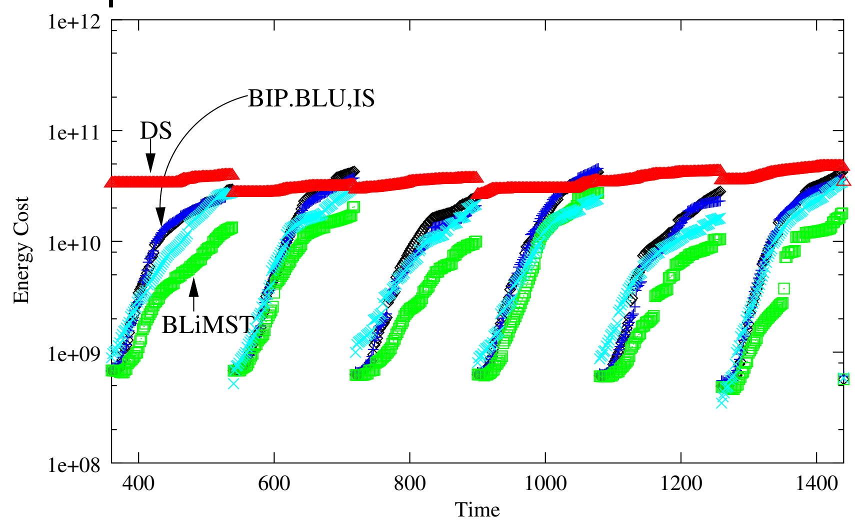
- Two simple tree *maintenance* options:
  - Re-parenting
    - Allow movement up one level of a node or a relay node.
  - Roaming Leaf:
    - Leaf nodes: find nearest relay. Relay nodes: re-parenting.

  - Two desirable properties:
    - (a) *Localized Search* and
    - (b) *Invariant Relay Set*

## Re-Parenting

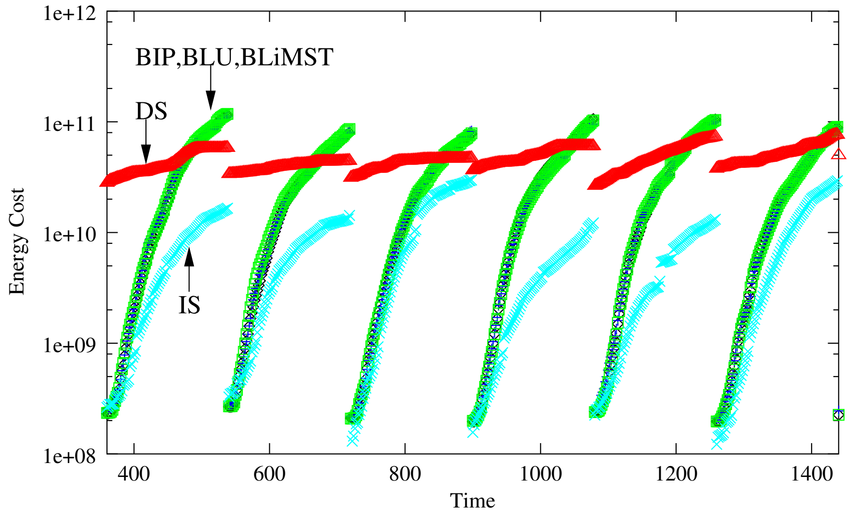



## Roaming Leaf

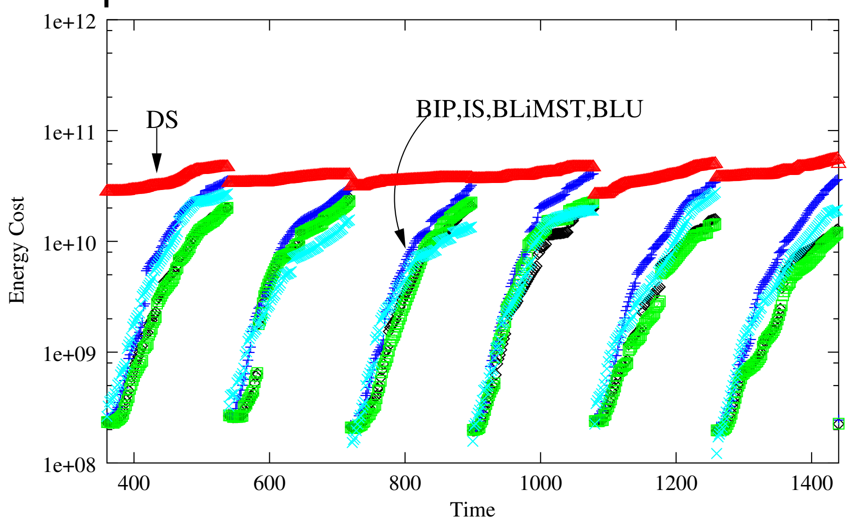



Relay Nodes: BLU < BIP < BLiMST

# Re-Parenting - Biased




# Roaming Leaf - Biased



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## Conclusions

- Greed and local optimality are obstacles in solving the Minimum Energy Broadcast Tree.
- Iterative Maximum-Branch Minimization (IMBM) is a top-down algorithm performing better than the bottom-up Broadcast Incremental Power (BIP).
  - The benefit is reduced for increased $\lambda$.
  - Selection of initial tree may have impact.

## Future Work

- Improve IMBM.
  - Calibrate initial tree based on $\lambda$.
- Cost "Discovery" Protocols
  - The costs can be asymmetric.
  - Possibly unrelated to geometric properties.
- Identify instances that are exactly solvable.
  - In polynomial time.
    - A couple of interesting cases: line topology, line with given distance distribution between points, etc.

## Some Observations

- Constraints
  - Limit on per-node capacity (vertex-wise)
  - Transmit power constraints.
- *We know* $\theta$ IS important.
  - Directional antennas & inference about $\theta$
    - Recent work of Wieselthier et al.
  - Do exact coordinates simplify the problem?

## Mobility

- Protocols for tree maintenance algorithms.
- Establish control over the "depth" and "breadth" of trees.
  - Depth – higher chance that at least an edge needs to be adjusted (cost-wise).
  - Breadth – higher chance that a relay possesses a non-zero number of children after a number of nodes move.

## Questions?