

Energy-Aware Broadcasting and Multicasting in Wireless Ad Hoc Networks: A cross-layering approach

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Abstract

The wireless networking environment presents formidable challenges to the study of broadcasting (one-to-all) and multicasting (one-to-many) problems, especially when energy-aware operation is required. To address the specific problem of **energy-aware tree construction in wireless ad hoc networks**, we have developed the Broadcast Incremental Power (BIP) and Multicast Incremental Power (MIP) algorithms. Our algorithms are based on a **cross-layering** approach in which tree structure and communication range are chosen jointly.

We describe the similarities and differences between **energy-limited** and **energy-efficient** modes of operation, and we illustrate the impact of these overlapping (and sometimes conflicting) considerations on network operation. Examples of energy-limited applications include sensor networks and military networks in which soldiers' batteries cannot be recharged during a mission. When such constraints are present, fundamental objectives include the **maximization of a network's useful lifetime** and the **maximization of traffic volume** that is delivered during this lifetime. Additionally, we extend our model to **exploit the properties of directional antennas** to obtain further performance improvement.

Energy-Aware Networking

Energy-Efficient vs Energy-Constrained

◆ Energy-Efficient

- * Energy is a **cost** (e.g., to replace batteries)
 - Minimize energy to achieve given communication goals

☞ Energy-Constrained

- * Energy is a **constraint**
 - A node dies when its energy is depleted
 - ◆ Sensor networks
 - ◆ Ad hoc networks in which batteries can't be recharged or replaced

* Goals:

- Maximize network's useful lifetime
- Maximize quantity of data delivered to destinations

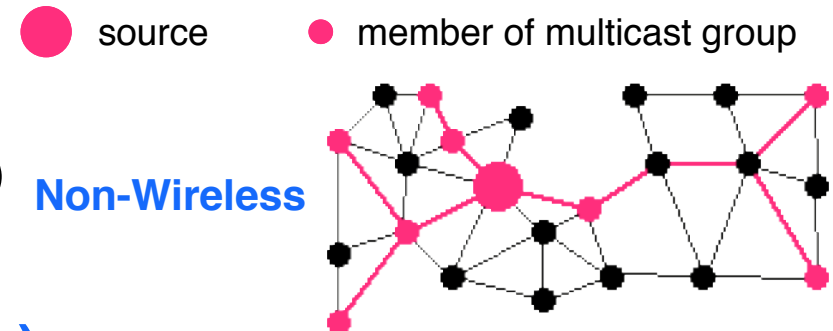
Optimizing energy efficiency does NOT guarantee good performance in energy-constrained applications!

A networking problem:

Energy-Efficient Multicasting in Ad Hoc Wireless Networks

Non-Wireless

- * Find **trees** to minimize number of transmissions (or other cost function) in a **fixed graph**



Wireless Ad Hoc (Infrastructureless)

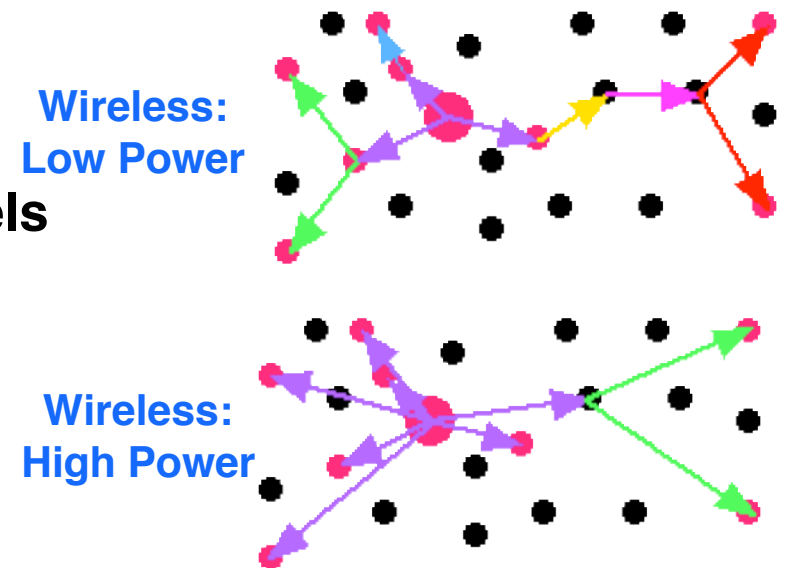
- ☞ **Fundamental trade-offs**
 - Reach vs interference
 - Reach vs energy expenditure
- * Connectivity depends on RF power levels

$$p = r^\alpha \quad (p < p_{max})$$

we assume that RF power is continuously adjustable

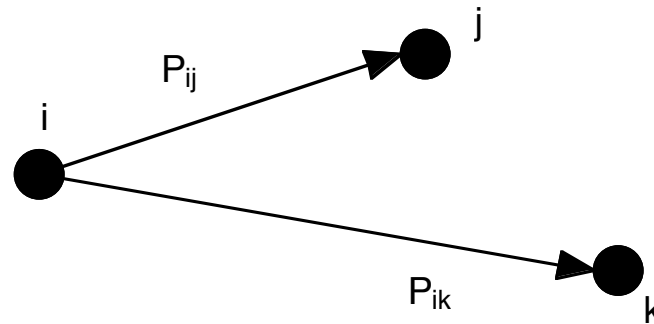
Broadcasting

- * A special case of multicasting in which all nodes are members of multicast group



An Important Energy-Related Property of Wireless Networks

The “Wireless Multicast Advantage”



➤ A wireless transmission reaches all of its neighbors

➤ (Assuming use of **omnidirectional** antennas)

❖ $P_{i,(j,k)} = \max \{ P_{ij}, P_{ik} \}$ — “Node-based” costs: **Max**

➤ Cost in wired networks

❖ $D_{i,(j,k)} = D_{ij} + D_{ik}$ — “Link-based” costs: **Additive**

Wireless vs Wired Networks

Wired Networks	Wireless Networks
Well-defined graph	Connectivity determined by transmitted power
Well-defined link capacities	A node's capacity can be allocated to form links with its neighbors
Well-defined link costs	Costs are node-based
No interference between links	Frequencies must be coordinated
Link-Centric	Node-Centric

❖ Wireless networks are different!

👉 Novel approaches must be developed

➤ Can't simply apply techniques developed for wired networks

Energy-Related Issues Create a Dependence Among Network Functions

- * Media access control (MAC)
- * Routing
- * Network self-organization
- * Network performance

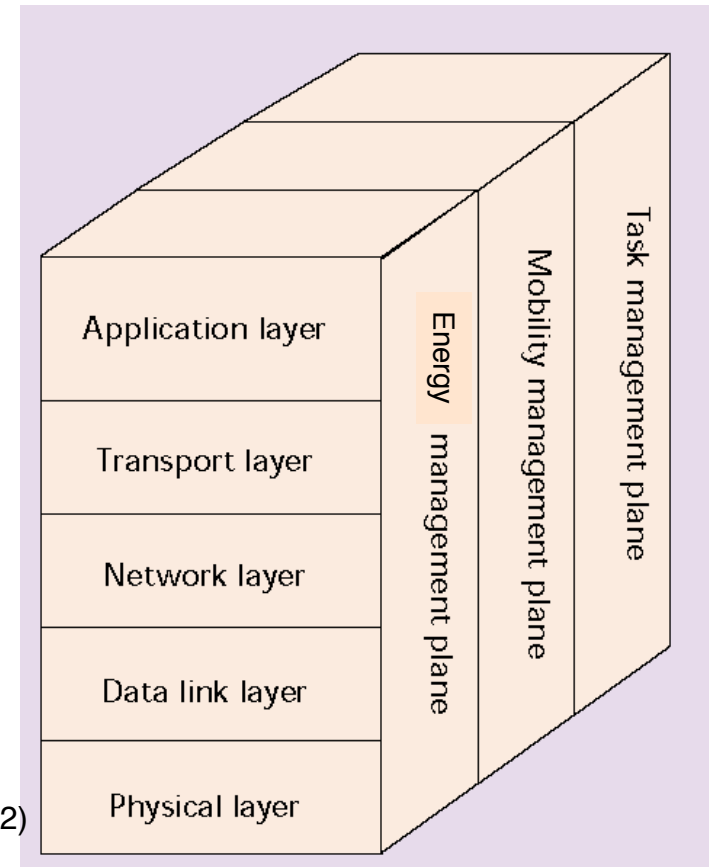
Energy-aware operation

🔑 Cross-Layer Design

- **A major cross-layer issue:**

- **How to allocate the available energy among sensing, signal processing, and communication**

- ❑ **both for network longevity and mission performance**



(Ref: Akyildiz et al, 2002)

Optimal Broadcast and Multicast Trees (Energy-Efficient Case)

What to optimize?

- ❖ Minimize energy expenditure of tree for each request
 - ❖ Source node becomes root of tree

What's new?

- ❖ Properties of ad hoc wireless networking environment

➤ Complexity

❖ Wired Networks

- * Broadcasting: **Minimum-Cost Spanning Tree** (Polynomial $O(N^2)$)
- * Multicasting: **Steiner Tree** (NP-Complete)

❖ Wireless Networks

- * Broadcasting: **No polynomial algorithms available**
 - NP-Complete $\Rightarrow$ heuristics are needed
- * Multicasting: **Certainly at least as difficult as broadcasting**

Our Approach

1) Find minimum-power broadcast tree

👉 **Broadcast Incremental Power (BIP) Algorithm**
— suboptimal

❖ Similar to Minimum-cost Spanning Tree (MST) Problem

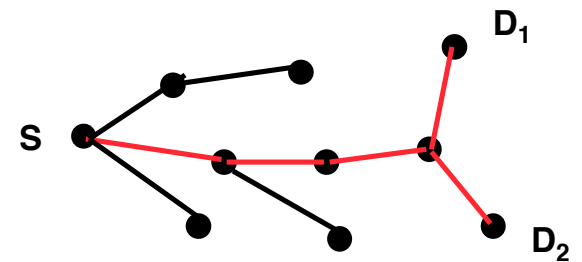
- * Finding MST is easy for link-based (wired) networks
- * Difficult (NP-complete) for node-based (wireless) networks

❖ BIP is similar to Prim's algorithm

- * But uses **incremental cost** when new nodes are added
- * BIP is **node-based**

2) “Prune” the tree produced by BIP

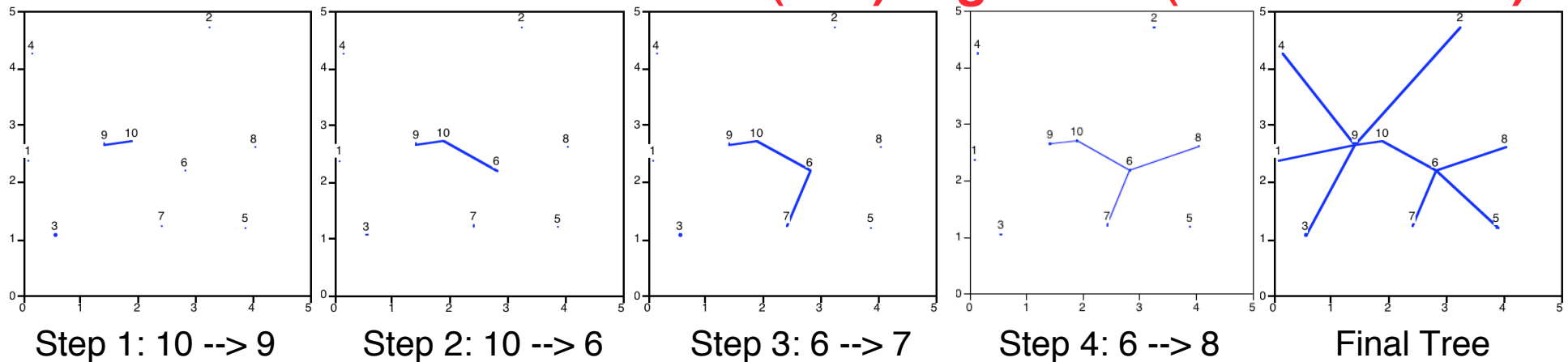
👉 **Multicast Incremental Power (MIP)**



3) “Sweep” to eliminate unnecessary transmissions

The Incremental Cost Principle for Energy-Efficient Broadcast Trees

Broadcast Incremental Power (BIP) Algorithm (Infocom 2000)



A node-based minimum-cost spanning tree algorithm

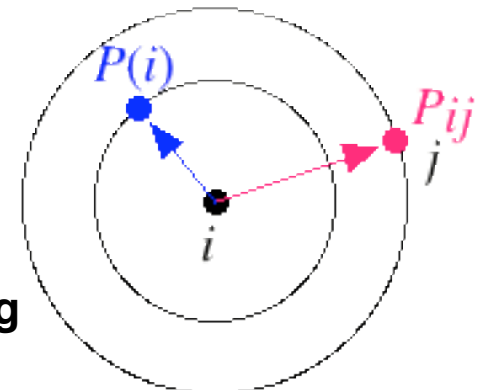
- Start with only the Source node (10) in the tree
- At each step, add the node that can be added using the smallest **incremental** power

✳ Additional power for Node i to reach new Node j

➤ $P'_{ij} = P_{ij} - P(i)$

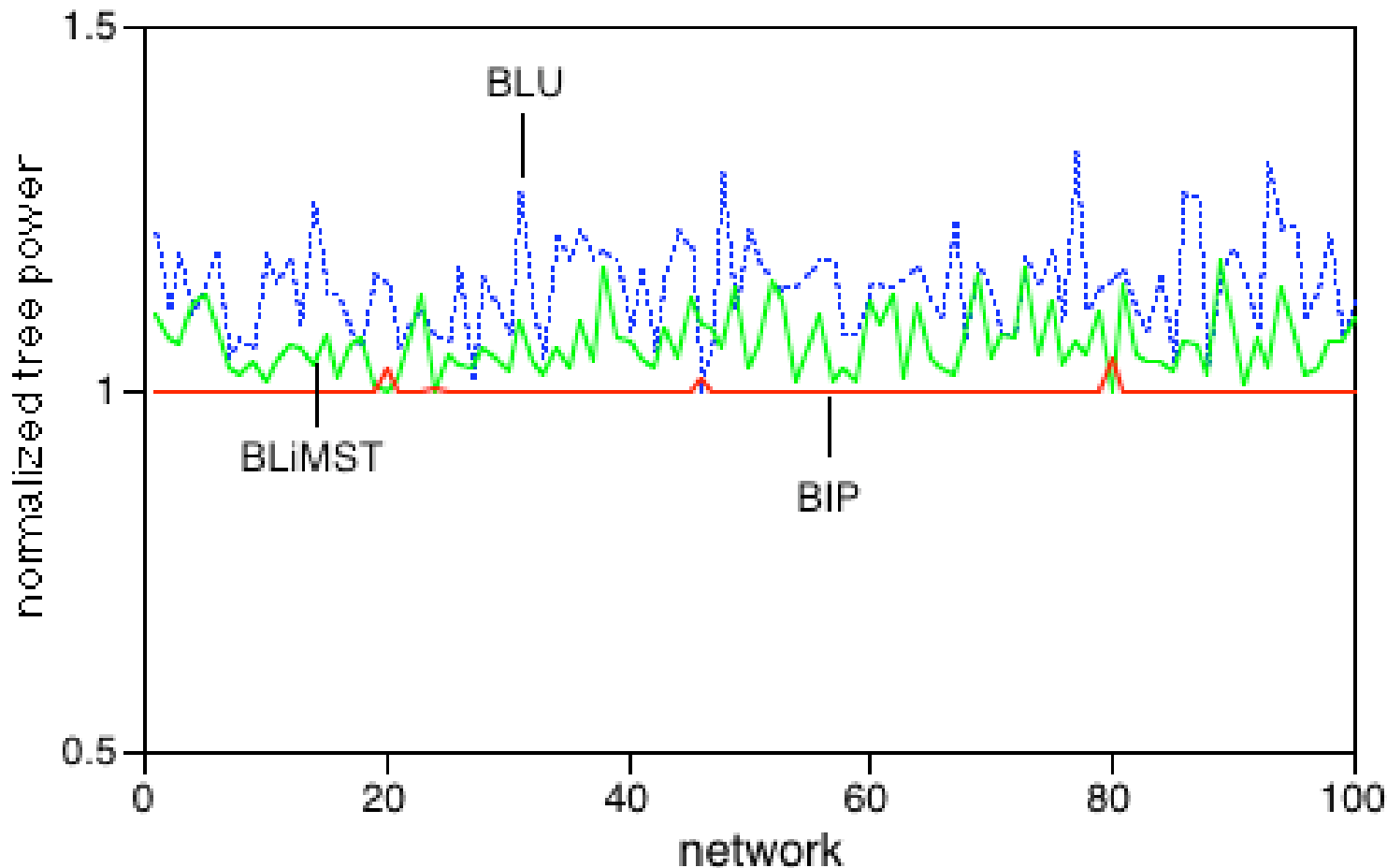
♦ P_{ij} = Power required for Node i to reach Node j

♦ $P(i)$ = Power at which Node i is already transmitting



BIP Provides Improved Energy Efficiency

Example: 100 different 100-node networks; Group size = 100



BIP is best for almost all network examples

BLU and BLiMST are “conventional” algorithms that do not incorporate the properties of the wireless channel

Hard Constraints on Energy

- A node “dies” when its battery is fully depleted
- ☞ How can we extend the network’s useful lifetime?
 - ❑ e.g., time that first node dies

Re-define link costs:

$$C_{ij} = P_{ij} \left(\frac{E_i(0)}{E_i(t)} \right)^\beta$$

✱ P_{ij} = link power, $E_i(t)$ = residual energy at Node i at time t

- ☞ Choose value of β to discourage use of nodes with little residual energy

Note: We use a simplified model, under which each node initially has energy $E_i(0)$. We neglect the fact that the total energy that a battery can deliver is based on its discharge/recovery pattern.

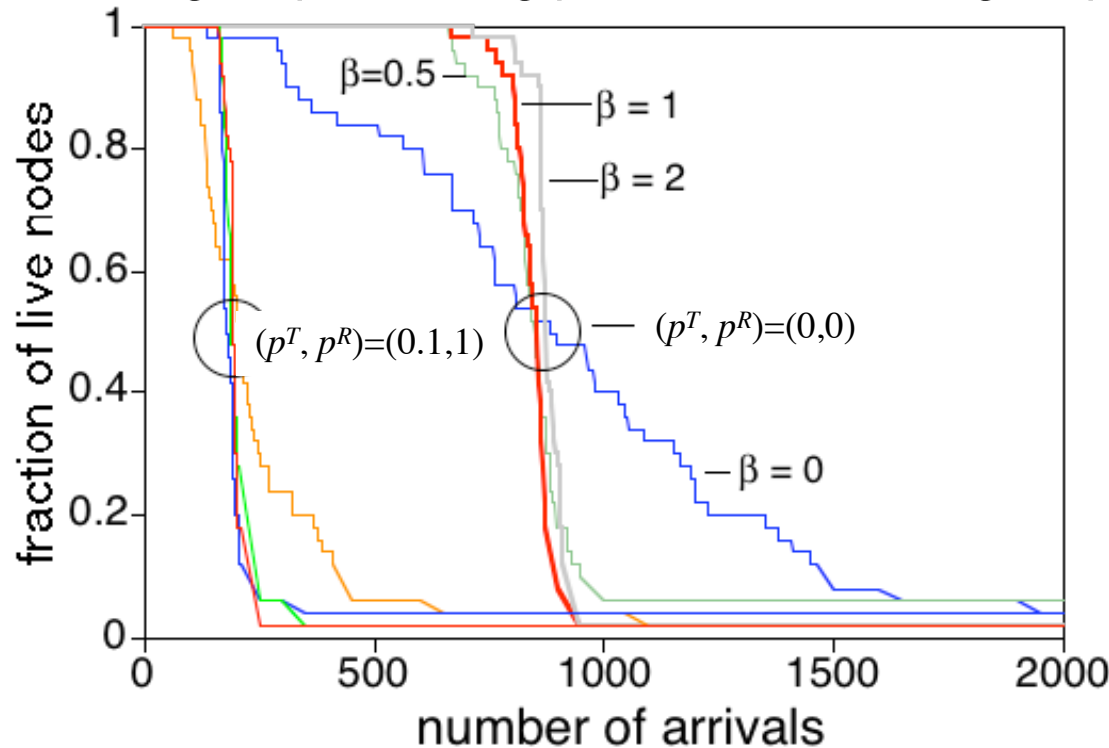
Extend Network Lifetime (MIP)

via choice of β

50-node network;

Multicast groups randomly chosen with between 1 and 49 destinations;

(p^T, p^R) = (Transmitter signal-processing power, Receiver signal-processing power)



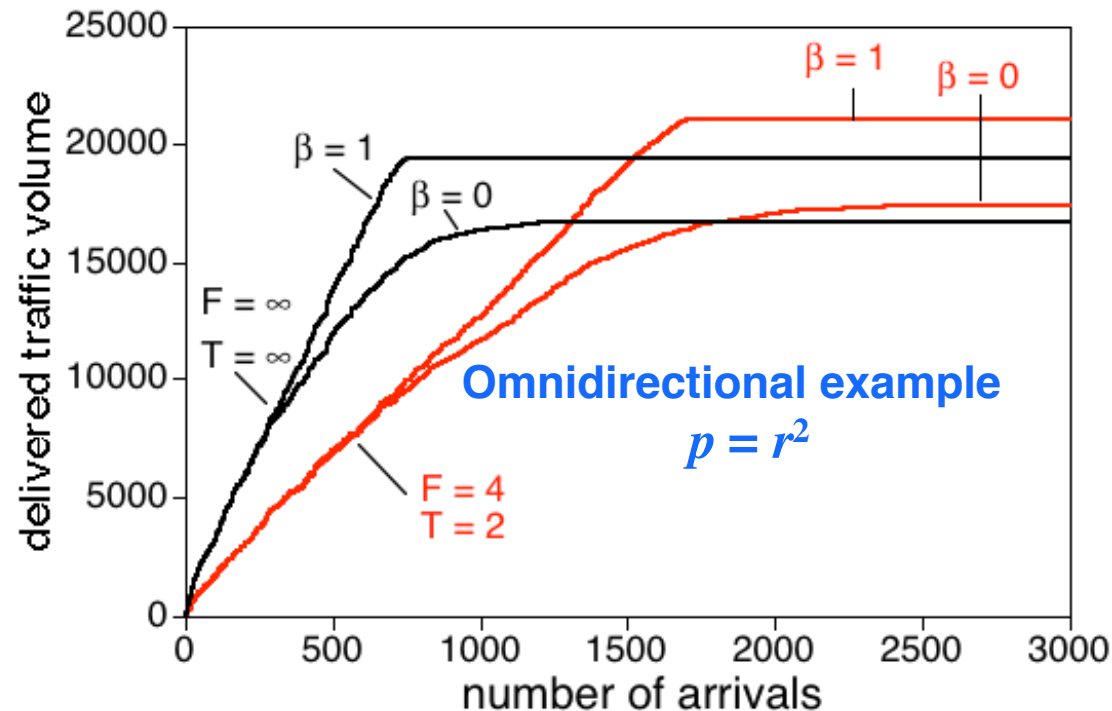
- $0.5 \leq \beta \leq 2$

- * Delays death of first node significantly
- * Keeps most (80% to 90%) nodes alive longer

- Impact of high levels of signal-processing power ($(p^T, p^R) = (0.1, 1.0)$)

- * Nodes die much sooner, but same qualitative behavior

Impact of $\beta > 0$ and Finite Resources (MIP)



$\beta > 0$

- * Significantly delays death of first node
- * Keeps 80–90% of nodes alive much longer
- * Increases overall traffic volume
- * Near-constant rate of traffic delivery until network dies

Finite Resources

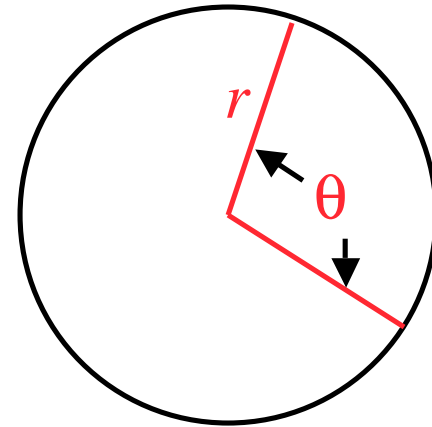
- * Lowers rate of traffic delivery
- * But may result in greater overall delivered traffic volume

Why Directional Antennas?

Concentrate energy where needed

$$p^{RF}(r, \theta) \propto \frac{\theta}{360} r^\alpha \quad 2 \leq \alpha \leq 4$$

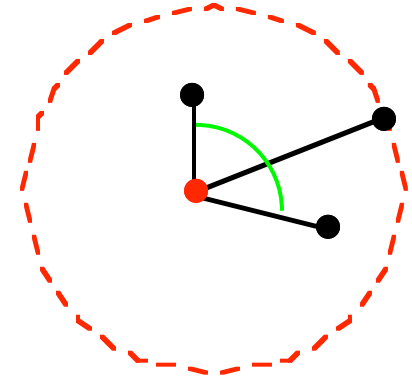
- **Reduce energy expenditure**
or
Extend communication range
- **Reduce interference**



Algorithms for Directional Antennas

DA1: Reduced-Beam BIP (RB-BIP)

- Construct broadcast tree using BIP
- Reduce the beamwidth at each transmitting node



DA2: Directional BIP (D-BIP)

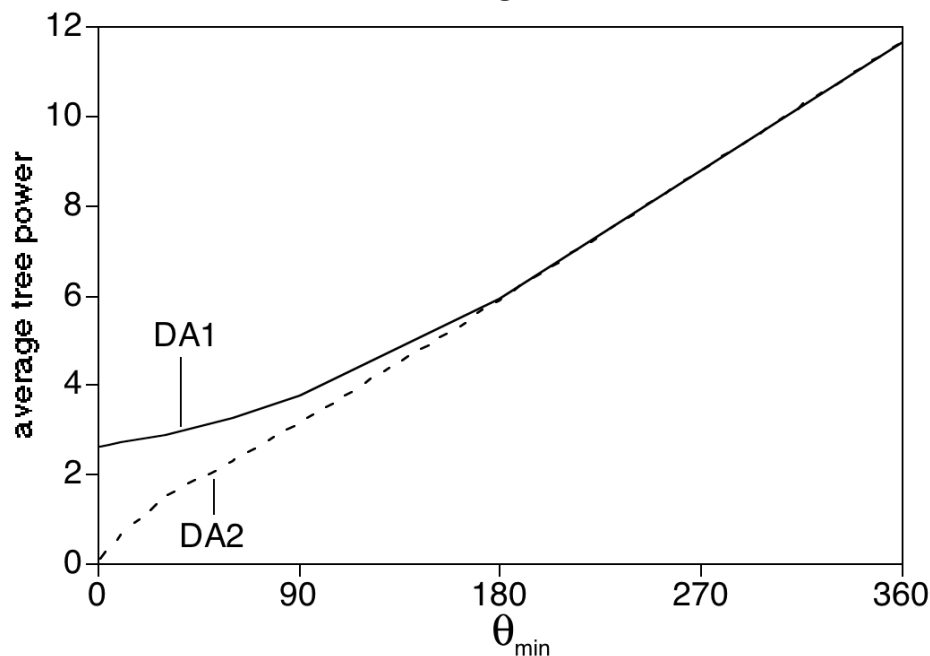
- At each step, find the pair (θ, r) that minimizes the incremental cost
 - Two basic possibilities:
 - * Former leaf node will transmit
 - * An already transmitting node will do one or more of the following:
 - Increase its power (r)
 - Increase its angle (θ)
 - Shift the beam
 - DA2 is more complex than DA1
- Multicasting:
 - First find broadcast trees using RB-BIP or D-BIP
 - Then prune, resulting in RB-MIP or D-MIP

Networking Techniques That Exploit Directional Antennas Provide Improved Energy Efficiency

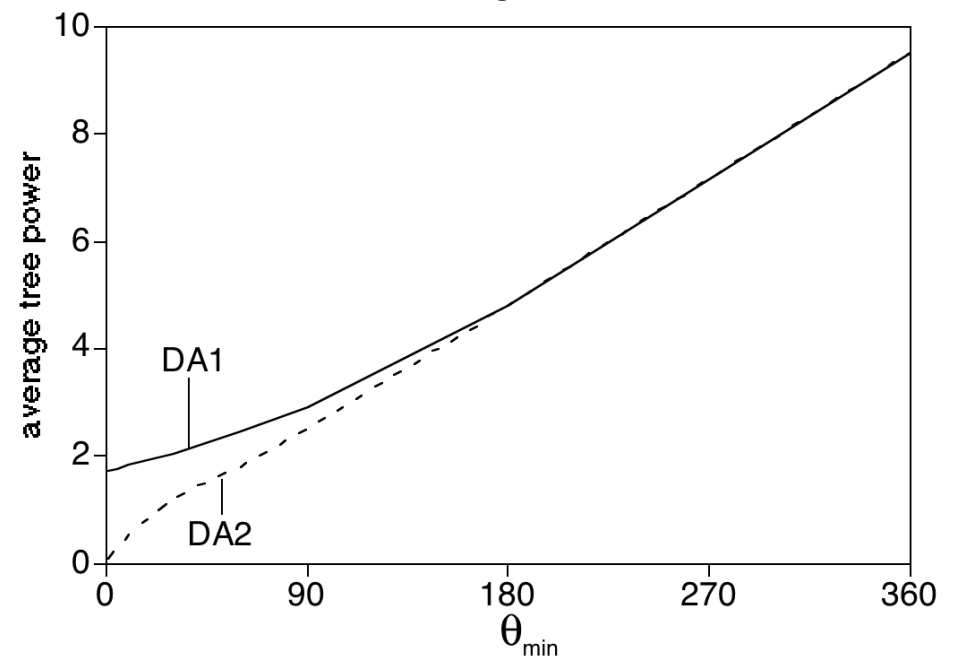
DA1: RB-BIP; DA2: D-BIP

50-node network; $\alpha = 2$; $p^T = p^R = 0$

Broadcasting RB-BIP & D-BIP



Multicasting RB-MIP & D-MIP

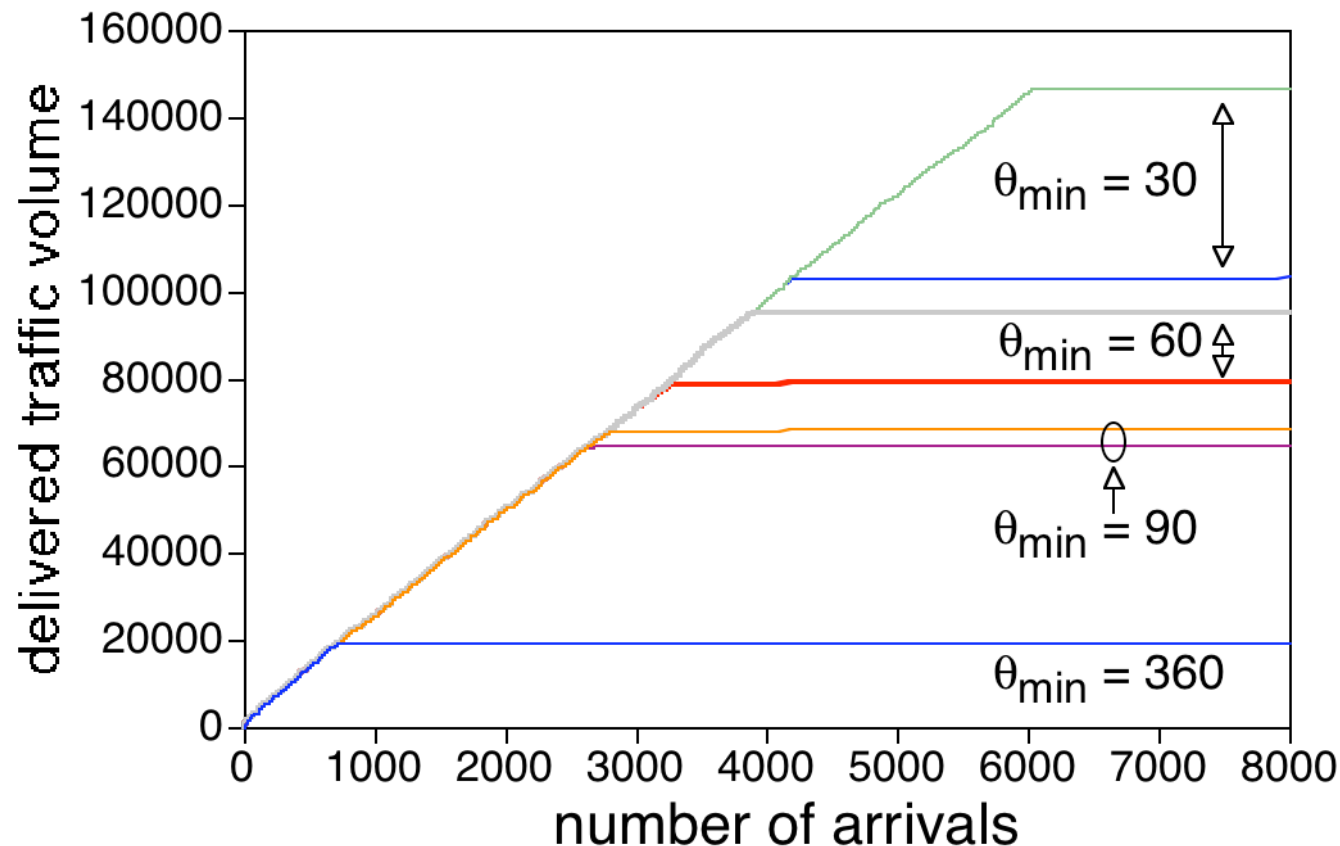


Size of multicast groups is uniformly distributed between 2 and 50

- Use of directional antennas provides considerable power reduction
- Especially D-BIP when $\theta_{\min} < 90$

Networking Techniques & Directional Antennas Increase Network Lifetime and Traffic Volume

50-node network; finite energy at each node; $\alpha = 2$; $\beta = 1$



For each value of θ :
 Lower curve: **RB-MIP**
 Upper curve: **D-MIP**

Curves stop increasing
 when network dies

- **Delivered traffic volume increases as $\theta_{\min}$ decreases**
- **Advantage of D-MIP increases as $\theta_{\min}$ decreases**

Summary and Conclusions

❖ Two modes of energy-aware networking

- Energy efficient
- Energy constrained

❖ Properties of wireless medium should be exploited in network design

- **Vertical coupling of protocol layer functions**
 - ❑ e.g., how to allocate energy among sensing, signal processing, and communication

❖ BIP and MIP algorithms provide improved energy-aware performance

- Developed for energy-efficient operation
- Adapted for energy-constrained operation

❖ Directional antennas

- Provide further improvement in energy-aware performance
- Can be exploited in design of networking algorithms

☞ **Networking techniques can greatly improve energy efficiency and/or network lifetime**

- ❖ Improved energy sources are NOT the only way to address energy issues

Journal Articles on Energy-Aware Networking

- [1] J. E. Wieselthier, G. D. Nguyen, and A. Ephremides, “Algorithms for Energy-Efficient Multicasting in Static Ad Hoc Wireless Networks,” *Mobile Networks and Applications (MONET)*, **6**-3, pp. 251-263, June 2001.
- [2] J. E. Wieselthier, G. D. Nguyen, and A. Ephremides, “Energy-Efficient Broadcast and Multicast Trees in Wireless Networks,” *Mobile Networks and Applications (MONET)*, **7**-6, pp. 481-492, December 2002.
- [3] J. E. Wieselthier, G. D. Nguyen, and A. Ephremides, “Energy-Efficient Multicasting of Session Traffic in Bandwidth- and Transceiver-Limited Wireless Networks,” *Journal of Cluster Computing*, **5**-2, pp. 179-192, April 2002.
- [4] J. E. Wieselthier, G. D. Nguyen, and A. Ephremides, “Resource Management in Energy-Limited, Bandwidth-Limited, Transceiver Limited Wireless Networks for Session-Based Multicasting,” *Computer Networks*, **39**-2, pp. 113-131, June 2002.
- [5] J. E. Wieselthier, G. D. Nguyen, and A. Ephremides, “Energy-Aware Wireless Networking with Directional Antennas: The Case of Session-Based Broadcasting and Multicasting,” *IEEE Transactions on Mobile Computing*, **1**-3, pp. 176-191, July-Sept. 2002.