Energy-efficient Broadcast Routing and Topology Control in Wireless Ad Hoc Networks

Presented by Yingshu Li
yili@cs.umn.edu
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Outline

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Introduction

Introduction --- Wireless networks
A wireless ad hoc network consists of a collection of mobile hosts dynamically forming a temporary network without the use of any existing network infrastructure.
Introduction --- Wireless networks

Characteristics of Ad Hoc Networks

- Instantly deployable and re-configurable
- Node mobility
- Shared, scarce wireless channel
- Multihop routing
- Broadcast advantage
- Limited battery power

Introduction --- Broadcast routing

The broadcasting problem consists of finding a transmission radius for each node so that the source node can broadcast to all nodes either directly or indirectly through the relay nodes.

Introduction --- Broadcast routing

A broadcast tree is a spanning tree for the network in which the root is the source node and each path from the root to a node corresponds to the sequence of transmissions by which the source node communicates its message to that node.
**Introduction --- Broadcast routing**

Current research work
- Proved to be NP-hard.
- Exhaustive search of minimum energy broadcast tree.
- Broadcast least-unicast-cost algorithm.
- Broadcast incremental power algorithm.

**Introduction --- Topology control**

A topology, consisting of a set of nodes and a set of communication links between node pairs, describes the connectivity information of a network.

**Strongly Connected topology ---**
If there is a communication path between any ordered pair of nodes, then the topology is strongly connected.

**Topology too sparse ---** There is a danger of network partitioning and high end-to-end delays.
**Topology too dense ---** The limited spatial reuse reduces network capacity and cause more interference.
Introduction --- Topology control

Current research work
The main purpose of topology control is to assign transmission powers to nodes so that the resulting graph satisfies some specified properties:
- Minimizing total energy consumption
- Connectivity or bi-connectivity
- Reducing interference
- Small diameter
- Increasing effective capacity

Introduction
Considerations of the the energy-efficiency issue in broadcast routing and topology control:
- Minimize the total energy consumption of the whole network
- Balance the energy consumption at each node

Wireless Communication Model

Network lifetime --- The earliest time that a node is depleted of energy

Goal --- To maximize the network lifetime and to balance the energy consumption at each node
Wireless Communication Model

Assumptions:

- The nodes are static or they move slowly
- All nodes are located in the 2-dimensional plane
- $P_{ij} = C r^\alpha$, $r$ is the distance between $i$ and $j$, $\alpha \in [2, 4]$, $C = 1$
- Omni-directional antennas
- Each node can adjust its transmission power

Weights of nodes and edges

$M =$ the maximum energy at each node
$E_i =$ the remaining energy of node $i$
$W_i = M / E_i$ (weight of node $i$)
$P_{ij} =$ power needed to transmit from $i$ to $j$
$W_{ij} = P_{ij} \cdot W_i$ (weight of edge $(i, j)$)
Energy-efficient Broadcast Routing

Problem definition:
Given an edge-weighted complete directed graph $G$ and a root node $r$, an arborescence is a tree with root $r$ and paths from $r$ to every other node of $G$. Find an arborescence rooted at $r$ to minimize the weight of the heaviest edge.

Energy-efficient Broadcast Routing

Minimum Weight Incremental Arborescence (MWIA)

Grow an arborescence from the root $r$
Energy-efficient Broadcast Routing

Add nodes to the arborescence one at a time on the minimum weight basis. This process continues until all the nodes are included.

Theorem 1: Every MWIA is an optimal solution.
Energy-efficient Broadcast Routing

Simulation results

Compared with the Broadcast Incremental Power algorithm (BIP) by Wieselthier et al.

In BIP, node $v$ is added to the tree by edge $(u, v)$ if $P_{uv} = \min_{i \in T, j \notin T} \{ P_{ij} - P_j \}$

Energy-efficient Broadcast Routing

The lifetime of a network using MWIA algorithm is almost 3 times longer than that of the network using the BIP algorithm.

Energy-efficient Topology Control

Problem definition:
Given an edge-weighted complete directed graph $G$, find a sub-graph $H$ with minimum largest edge-weight such that for every ordered pair of nodes $(u, v)$ in $G$, $H$ contains a path from $u$ to $v$. 
Energy-efficient Topology Control

Minimum Weight Incremental Arborescence based Topology Control (MWIA - TC)

Model the network as an edge-weighted directed graph.

Let $G'$ be the edge-weighted directed graph obtained from $G$ by exchanging weight of edge $(x, y)$ and weight of edge $(y, x)$.

Find an MWIA rooted at $r$ in $G'$.

Change the direction of each edge in the MWIA just found to its reverse direction. We call such a tree-like sub-graph as a reverse-MWIA $T'$ rooted at $r$ in $G$. 
Theorem 2: Find an MWIA $T$ rooted at $r$ and a reverse-MWIA $T'$ rooted at $r$ in $G$. The union $T \cup T'$ is an optimal solution to the topology control problem.

Simulation results

Compared with Minimum Incremental Power algorithm (MIP) by Cheng et. al.

$$P_{uv} = \min_{i \in T', j \notin T} \{ P_{ij} - P_i + P_{ji} \}$$

Simulation 1 --- Evaluate the effect of MWIA-TC on the energy consumption of a network when nodes have different remaining energy.

$$W_i = P_i \times \frac{M}{E_i} = K \cdot \epsilon^\alpha, \quad \alpha = 2, \quad K \in [1, 10]$$

Mean power consumption of MWIA-TC is 10.1% lower
Maximum power consumption is 14.9% lower
Standard deviation is 15.6% smaller than that of MIP.
Simulation 2 --- Evaluate the effect of MWIA-TC on the energy consumption of a network when nodes have different variances of remaining power.

\[ W_{ij} = P_{ij} \cdot \left( \frac{M}{E_i} \right) = K \cdot r^n, \quad K \in [1, \ max_K] \]

As \( max_K \) increases, the improvement of MWIA-TC over MIP is also increased.
Simulation 3 --- Evaluate the effect of MWIA-TC on the network lifetime.

Network lifetime = \( \min_{\forall i} \{ \text{remaining energy of node } i / \text{transmission power of node } i \} \)

\( X = \text{maximum energy reserve} / \text{minimum energy reserve} \)

The lifetime improvement by use of MWIA-TC increases when the variance of the remaining energy increases.
Energy-efficient Topology Control

![Graph 1](image1)

![Graph 2](image2)

Conclusion and Future Work

**Broadcast routing and topology control**
- How frequently to update the broadcast tree and the topology.
- Evaluate the performance of the proposed solutions in terms of the throughput, message complexity, transmission delay and etc.
- Study the problem in mobile environment where node mobility is highly concerned.
- Develop distributed algorithms.

Conclusions and Future Work

**Minimum connected dominating set (MCDS)**
A dominating set of a graph is a subset of all the nodes such that each node is either in the dominating set or adjacent to some node in the dominating set. A connected dominating set of a graph is a dominating set and the subgraph induced is connected.
Conclusions and Future Work

Sensor networks
- Sensors are densely deployed in large numbers
- Sensor networks’ topology changes very frequently
- Sensors are very limited in power, computational capacities and memory
- Sensors are very prone to failures
- Sensors may not have global identification (ID) because of the large amount of overhead
- Building an intelligent data collecting system

Data communication in mobile ad-hoc network

Current research issues:
- Client power consumption
- Connectivity of the network
- Reachability of mobile clients from a server
- Power consumption and mobility of the servers

Future research issues:

Ways in which data communication may take place
a). Data broadcast (data push)
b). Data-on-demand (data pull)
c). Peer-to-peer communication