Minimizing Energy and Maximizing Network Lifetime Multicasting in Wireless Ad Hoc Networks

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0. Overview

1. Introduction

1.1. Background

Most mobile nodes in a wireless ad hoc network are powered by energy limited batteries, the limited battery lifetime imposes a constraint on the network performance. Therefore, energy efficiency is paramount of importance in the design of routing protocols for the applications in such a network to enhance the network lifetime.

1.2. Problem statement

Given a wireless ad hoc network $M = (N,A)$, a source node s, and a destination set D ($\subset N$), the minimizing energy and maximizing network lifetime multicast problem is to construct a multicast tree rooted at the source and spanning the nodes in D such that the minimum residual battery energy among the nodes is maximized and at the same time the sum of transmission energies at non-leaf nodes is minimized.

1.2. Problem statement (cont.)

Given a constant $0 < \beta \leq 1$, we aim to find such a multicast tree that the total transmission energy consumption is minimized under the constraint that the minimum residual battery energy among the nodes is no less than β times of the optimum.

1.3. Our contributions

- **An approximation algorithm with an approximation ratio of $4 \ln K$, if the network is symmetric**
- **An approximation algorithm with an approximation ratio of $O(K^{\varepsilon})$ otherwise**

where K is the number of destination nodes, ε is constant with $0 < \varepsilon \leq 1$.

2. Preliminaries

2.1. Wireless communication model

Consider source-initiated multicast sessions. The wireless ad hoc network is modeled by a graph $M = (N, A)$, where N is the set of nodes with $|N| = n$, a directed edge $\langle u, v \rangle \in A$ if node v is within the transmission range of u. Assume the nodes in M are stationary, and each node is equipped with omnidirectional antennas.

2.1. Wireless communication model (cont.)

In this model each node has a number of power levels. For a transmission from node u to node v, separated by a distance $d_{u,v}$, to guarantee that v is within the transmission range of u, the transmission power at node u is modeled to be proportional to $d_{u,v}^{\alpha}$, where α is a parameter that typically takes on a value between 2 and 4.

2.1. Wireless communication model (cont.)

A wireless ad hoc network is *symmetric* **if there is always a corresponding power level with the same amount of power for two neighboring nodes** u **and** v**, i.e., there is a power level with power** $d_{u,v}^{\alpha}$ **at** u **and** v **respectively if** u **and** v **are the neighbors.**

Otherwise, the network is *asymmetric***.**

2.2. Related work

Most existing studies focused on either prolonging the network lifetime or minimizing the total energy consumption of a multicst (broadcast) tree.

A few studies have taken into account the above two conflicting objectives by proposing heuristics.

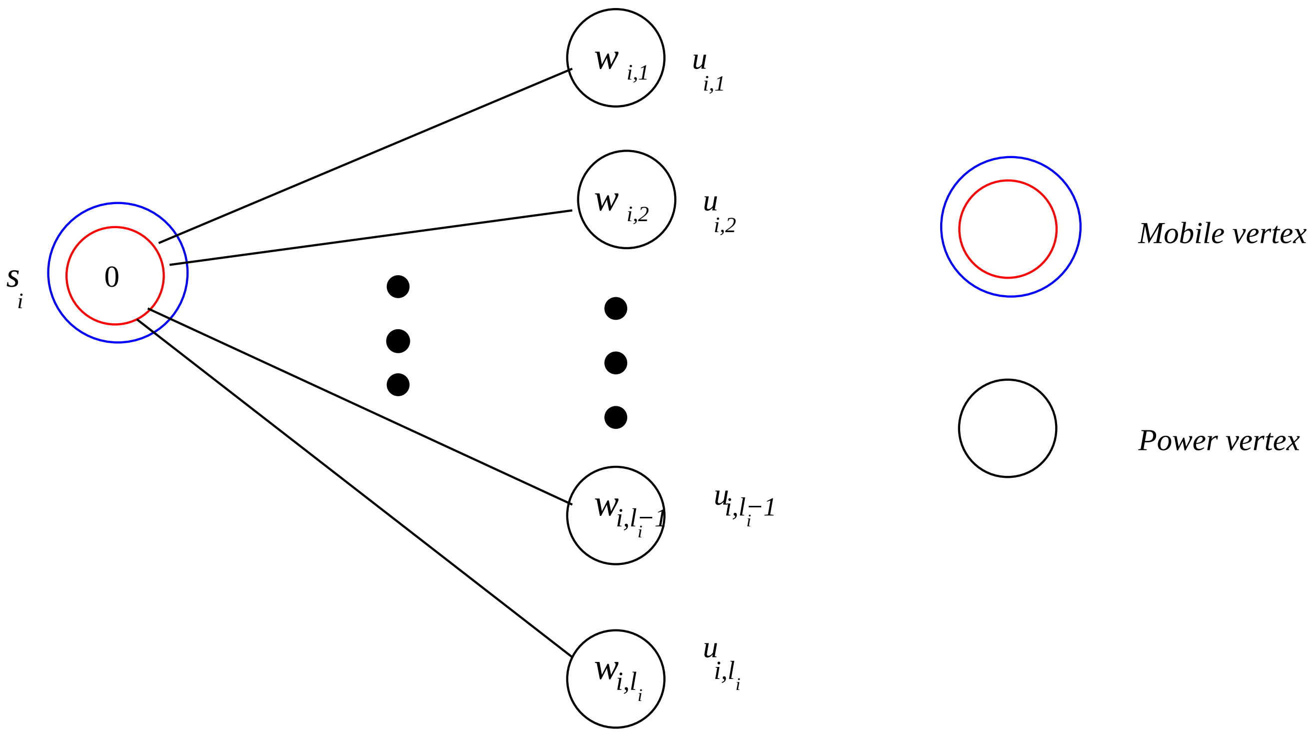
2.3. The Maximizing Network Lifetime Multicast Problem

The problem is to construct a multicast tree such that the network lifetime is maximized. We show that the maximizing network lifetime broadcast problem (MNLB for short), a special case of the *maximizing network lifetime multicast problem* **(MNLM for short), is polynomially solvable, So is MNLM.**

2.4. The Minimum Energy Multicast Problem

Symmetric case: An auxiliary, node-weighted, undirected graph $G = (V, E, \omega)$ **is constructed as follows.**

For each node $v_i \in N$**, let** $w_{i,1}, w_{i,2} \ldots, w_{i,l_i}$ **be adjustable power at its** l_i **power levels.**



2.4. The Minimum Energy Multicast Problem (cont.)

Algorithm for symmetric networks. It consists of two steps.

- **Find an approximate, minimum node-Steiner stree in G**
- **Transform the found tree into a multicast routing tree in M.**

2.4. The Minimum Energy Multicast Problem (cont.)

Asymmetric case: An auxiliary, edge-weighted, directed graph $G = (V, E, \omega_1)$ **is constructed. A widget** $G_i = (V_i, E_i)$ **for each node** $v_i \in N$ **is built, where** $V_i = \{s_i, v_{i,1}, v_{i,2}, \ldots, v_{i,l_i}\}$ **and** $E_i = \{\langle s_i, v_{i,l}\rangle \mid 1 \leq l \leq l_i\}$**,**

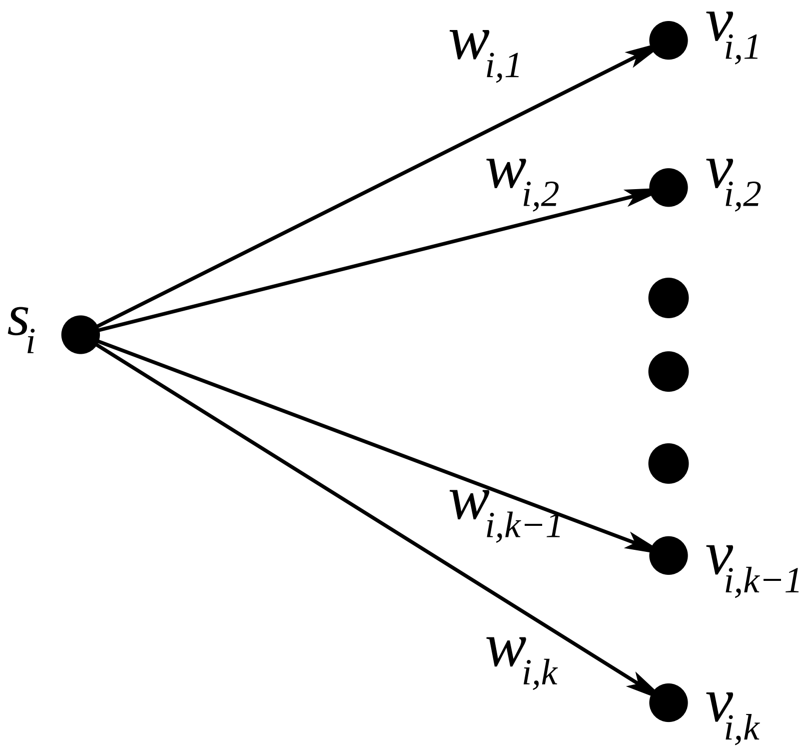


Figure 2: The widget $G_i = (V_i, E_i)$ for node v_i

2.4. The Minimum Energy Multicast Problem (cont.)

Algorithm for asymmetric networks, it consists of

- **Find an approximate, minimum directed Steiner tree in** G
- **Transform the rooted directed tree into a multicast routing tree.**

3. Approximation Algorithms

The algorithm for symmetric networks consists of two stages.

- **Stage 1 is to remove those potential links from G that result in the network lifetime less than β times of the optimum if they are used to transform the multicast message.**
- **Stage 2 is to find an approximate, minimum-energy multicast tree in the subnetwork.**

Algorithm Balan_Symm_Multicast_Tree **(N, s, D, β)**

Step 1. Find $N_{opt}(M)$ using the auxiliary directed graph $G' = (N, A', w)$.

Step 2. Construct a node-weighted, auxiliary graph $G = (V, E, \omega')$, where $\omega'(v) = rc(u) - d^{\alpha}_{u,v}$ for each power vertex v derived from a mobile vertex u,.

Step 3. An auxiliary graph $G_1 = (V, E', \omega')$ is induced from G by removing those power vertices v and the edges incident to them if $\omega'(v) < \beta N_{opt}(M)$.

Step 4. Another graph $G_2 = (V, E', \omega'')$ is constructed, and each power vertex $v \in V$ in G_2 derived from u is assigned $\omega''(v) = rc(u) - \omega'(v) = d^{\alpha}_{u,v}$.

Step 5. Find an approximate, minimum node-Steiner tree T_{app} in G_2.

Step 6. Transform T_{app} into a valid multicast tree.

3.1. Symmetric networks (cont.)

Theorem 1 ***Given a symmetric wireless ad hoc network*** $M = (N, A)$***, a source, a destination set*** D***, and a given constant*** β ***with*** $0 < \beta \leq 1$***, there is an approximation algorithm for the minimizing energy and maximizing network lifetime multicast problem, which delivers such a solution that the total energy consumption in the tree is within*** $4 \ln K$ ***times of the optimum, while the minimum residual battery energy among the nodes in*** M ***is no less than*** β ***times of the optimum.***

3.2. Asymmetric networks

The minimizing energy and maximizing network lifetime multicast problem in asymmetric networks can be dealt similarly. Instead of working in a *node-weighted, undirected* **auxiliary graph** G**, an** *edge-weighted, directed* **auxiliary graph** G **will be used, and each directed edge from a mobile vertex** u **to its power vertex** v **is assigned a weight** $\omega'(u,v) = rc(u) - d_{u,v}^{\alpha}$**.**

Algorithm Balan_Asymm_Multicast_Tree **(**N, s, D, β**)**

Step 1. Find $N_{opt}(M)$ **using** $G' = (N, A', w)$**;**

Step 2. Construct an edge-weighted, directed auxiliary graph $G = (V, E, \omega')$**, where** $\omega'(u, v) = rc(u) - d_{u,v}^{\alpha}$ **for each directed edge** $\langle v, u \rangle$ **derived from a mobile vertex** u**.**

Step 3. $G_1 = (V, E', \omega')$ **is induced from** G **by removing those directed edges** $\langle u, v \rangle$ **if** $\omega'(u, v) < \beta N_{opt}(M)$**.**

Algorithm Balan_Asymm_Multicast_Tree **(N, s, D, β)**

Step 4. Another auxiliary graph $G_2 = (V, E', \omega'')$ **whose topology is identical to** G_1 **is constructed. Assign each directed edge** $\langle u, v \rangle$ **in** G_2 **a new weight** $\omega''(u, v) = d_{u,v}^{\alpha}$**.**

Step 5. Find an approximate, minimum directed Steiner tree T_{app} **in** G_2 **rooted at the source.**

Step 6. Transform T_{app} **into a valid multicast tree.**

3.2 Asymmetric networks (cont.)

Theorem 2 ***Given an asymmetric ad hoc wireless network*** $M(N,A)$***, a destination set*** D***, and a constant*** β ***with*** $0 < \beta \leq 1$***, there is an approximation algorithm for finding a directed multicast tree rooted at the source and spanning the nodes in*** D***. The solution delivered is*** $O(|D|^{\varepsilon})$ ***times of the optimum under the constraint that the minimum residual battery energy energy among the nodes is no less than*** β ***times of the optimum, where*** ε ***is constant with*** $0 < \varepsilon \leq 1$.

5 Open Questions