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Cooperative Topology Control with Adaptation for improved lifetime in wireless sensor networks

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ABSTRACT

Topology control algorithms allow each node in a wireless multi-hop network to adjust the power at which it makes its transmissions and choose the set of neighbors with which it communicates directly, while preserving global goals such as connectivity or coverage. This allows each node to conserve energy and contribute to increasing the lifetime of the network. In this paper, we consider (i) both the energy costs of communication as well as the amount of available energy at each node, (ii) the realistic situation of varying rates of energy consumption at different nodes, and (iii) the fact that co-operation between nodes, where some nodes make a sacrifice by increasing energy consumption to help other nodes reduce their consumption, can be used to extend network lifetime. This paper introduces a new distributed topology control algorithm, called the *Cooperative Topology Control with Adaptation (CTCA)*, based on a game-theoretic approach that maps the problem of maximizing the network's lifetime into an ordinal potential game. We prove the existence of a Nash equilibrium for the game. Our simulation results indicate that the CTCA algorithm extends the life of a network by more than 50% compared to other algorithms. We also study the performance of the distributed CTCA algorithm in comparison to an optimal centralized algorithm as a function of the communication ranges of nodes and node density.

1. Introduction

In wireless ad hoc networks, especially sensor networks, the battery life of each node plays a critical role in determining the functional lifetime of the entire network. When a node exhausts its limited energy supply, it may fail to reach nearby nodes leading to a disconnected network and disabling some essential communications. Without energy, the node will also fail to continue the environmental monitoring activities essential to the functional operation of the system. Adding redundant nodes in the network may extend the functional lifetime but it is ultimately not a cost-effective approach. In this paper, we consider the problem of extending the lifetime of a network using a new adaptive game-theoretic approach.

Topology control is among the better-known approaches to conserving energy and prolonging a network's functional life. In a topology control algorithm, each node adjusts the power at which it makes its transmissions to reduce the energy consumption to only what is needed to ensure topological goals such as connectivity or coverage [1]. Examples of topology control algorithms include Directed Relative Neighborhood Graph (DRNG) [2], Directed Local Spanning Subgraph (DLSS) [2], Step Topology Control (STC) [3] and Routing Assisted Topology Control (RATC) [4]. In most traditional algorithms, the topology of the network is determined at the very beginning of the life of the network where the only

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consideration for each node is to reduce its transmission power while keeping the graph connected. After the execution of one of these algorithms, each node will transmit at the selected power level until it eventually runs out of energy. However, depending on the location of a node in relation to others, some nodes may end up with a much larger communication radius, and therefore a much larger transmission power, than some others. This uneven distribution of the assigned transmission powers may result in an unbalanced energy consumption at the nodes, leading to some nodes exhausting their energy far sooner than some others. Such a scenario can end the functional life of the network earlier than necessary. This highlights two weaknesses of these algorithms: they are not adaptive to different rates of energy consumption on different nodes and they do not allow cooperation between nodes to extend the network lifetime. Each of these weaknesses is addressed by the algorithm proposed in this paper: *Cooperative Topology Control with Adaptation (CTCA)*.

We illustrate the principle of cooperative topology control with a simple toy example shown in Fig. 1. Suppose Fig. 1(a) illustrates the result of a topology control algorithm, where no node can reduce its transmission power unilaterally without disconnecting the graph. In this figure, the presence of an edge from one node, say *A*, to another node, say *B*, implies that *A* can transmit at a power level sufficient to reach node *B*. The communication radius of each node is shown by the dashed arcs. Assuming all nodes start out with the same energy supply and make transmissions at the same rate, we note that node *A* has the largest energy cost and thus has the shortest lifetime. Node *C*, on the other hand, has the smallest transmission power, and therefore, has the longest lifetime. Traditional topology control algorithms discussed above will lead to the situation in Fig. 1(a) ending the functional life of the network when node *A*'s energy is exhausted even though node *C* would have plenty of remaining energy. Fig. 1(b) illustrates a topology where node *C* increases its transmission power so that it can now reach node *B* directly. Now, node *A* is able to reduce its transmission power to only be directly connected to node *C*, as shown in Fig. 1(c). This involves node *C* making a sacrifice by increasing the power at which it makes its transmissions in order to allow node *A* to reduce its transmission power, thus extending the life of node *A* and of the network.

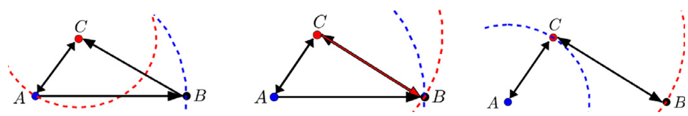
In this paper, we employ game theory to facilitate such topology control that allows cooperation between nodes as illustrated in Fig. 1. Our approach is through developing an ordinal potential game [5,4] into which our problem can be mapped, so that all nodes pursue a localized strategy that can be expressed through a single global function, or the global potential function. Our approach also allows an adaptive strategy so that a node does not end up with the same power level through its entire lifetime. This is significant to extending the network lifetime because it is almost always the case that different nodes consume energy at different rates. Our approach to allowing adaptation is through incorporating the energy remaining on the nodes in the neighborhood into the decisions made by each node. Since this remaining energy changes over the life of a network, our topology control algorithm adaptively adjusts the power levels at each node. This constantly keeps shifting energy consumption from nodes with less energy reserves to those with more energy reserves, thus extending the life of the network.

1.1. Problem statement

Given a wireless sensor network, let graph $G(t) = (N, E(t))$ represent its topology at time t, where $N_i \in N$ represents a node within the network, and $(N_i, N_j) \in E(t)$ represents the fact that node N_j is within node N_i's communication radius and can hear from N_i directly at time t. Topology control algorithms have traditionally emphasized preserving connectivity as a constraint while pursuing the goal of reduced energy consumption at each node. In the same tradition, we consider the functional life of the network to have ended when one of the following two cases occurs:

- Case 1: A node reduces its current transmission power in order to save energy, but becomes unable to reach certain nodes and, consequently, loses connection from part of the network.
- Case 2: A node runs out of energy, thus getting disconnected from the rest of the network.

If Case 1 happens, the communication links whose removal caused the network to become disconnected can be restored back into the network to restore the functional life of the network. On the other hand, if Case 2 happens, the network's functional lifetime cannot be extended in any way. Therefore, to improve the lifetime of the network, (i) Case 1 should be avoided by always ensuring connectivity in the assignment of power levels to the nodes, and (ii) Case 2 should be pushed as far into the future as possible by reducing the rate of energy consumption at the node



(a) The initial topology of the network where no node can reduce its transmission power.

(b) Node C choosesto increase its transmission power so as to directly connect to B.

(c) Node A can now reduce its transmission power to directly connect only to C.

Fig. 1. An example illustrating cooperative topology control.