Fair, Energy-aware Connectivity in Wireless Sensor Networks

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***Abstract*—The abstract is a substitution for the entire paper (about 250 words).**

I. Introduction

Over the past decade, Wireless Sensor Networks (WSN) have been employed in a variety of domains ranging from macroscopic applications such a weather monitoring and traffic control to microscopic applications in medical screening and biomedication. WSNs consist of a collection of independent devices (nodes) that are connected wirelessly in an ad hoc fashion. Individual nodes are equipped with sensors collecting information from the environment. The types of sensors employed by a node depend on the purpose of the WSN and may include active and passive sensors. The size of WSNs (i.e. the number of nodes in the network) also depends on the intended purpose of the network as well as other factors such as the networks resolution in terms of sampling frequency across space and transmission range, to name a few.

As wireless transmission ranges are limited, multi-hop networking plays an integral role in ensuring the connectivity of the network as a whole. Nodes transmit collected information to a centralized collection point, which in turn may distribute instructions or management data to nodes. Therefore, it is essential that segments of the network do not become disconnected due to wireless transmission range limitations. Section II reviews past and current research of connectivity in WSNs.

A second important criterion, which is one of the foci of this paper, concerns the energy efficiency of WSNs. Consider, for example, a remotely located earth quake sensing station or a patient with implanted heart rate and blood gas sensors. Due to geographical (non-availability of power line infrastructure), economic (prohibitive cost of expanding infrastructure) and/or medical (infeasibility of permanent power connections) reasons, among others, it often is impractical or impossible to power the nodes of a WSN using existing energy grids. For those reason, nodes are often battery powered, and as such, their lifetime is subject to the life of their batteries. Energy efficiency of nodes is therefore a primary concern for extending the lifetime of individual nodes and the network as a whole.

Furthermore, in this paper we introduce the notion of fairness with regard to power consumption. The aim of fair power consumption is to equalize the power consumption rates of nodes across an entire WSN. Fair power consumption has an immediate impact on economical and practical considerations for WSNs. Fair power consumption enables precise predictability of battery lifetimes of all the nodes in a network. Such predictability can be used to optimize node replacement schedules such that (1) all nodes fail (due to battery exhaustion) simultaneously, (2) groups of nodes fail simultaneously, or (3) nodes fail in a predetermined order. For example, it is desirable to replace implanted biomedical sensor nodes of a patient all at once at the largest possible intervals in order to minimize frequent multiple invasive procedures. Therefore, it is desirable to maximize the fair battery lifetime of all nodes in the WSN.

Wireless radio transmissions drop off at an exponential rate due to ground reflection of radio signals. Since the signal attenuation rate is exponential with distance, it requires a significant amount of energy to transmit a signal only a small distance further. As such, it is often desirable to introduce relay nodes. Relay nodes differ in that their primary task is not sensing their environment but to ensure connectivity of the network. For the purposes of this paper, relay nodes will also be utilized to approximately equalize power consumption rates. Relay nodes are introduced in areas (as long as resource limitations permit) where power consumption is highest.

In this work, we propose an algorithm with the aim to minimize overall power consumption of WSNs. While overall power consumption has been studied previously, our algorithm considers fairness in power consumption rates in the minimization process. As seen in Section III, our algorithm may introduce additional, limited resources (i.e. nodes) to a fixed network. These resources may be moved to achieve minimal overall power consumption and maximum fairness. Hence, we introduce an approximation algorithm for three dimensions in WSNs: (1) minimal power consumption, (2) maximum fairness in power consumption and (3) minimal additional resources.

In Section II we present previous work relevant to our research followed by a precise problem definition, our approach and resulting algorithm in Section III. Section IV gives a formal analysis of our algorithm. We conclude our discussion in Section VII.

II. Related Work

Connectivity is by far the most important criterion involved in WSN design decisions. Extensive research has been conducted to:

- identify ways to interconnect all nodes with a minimum number of links. The Minimum Spanning Tree (MST) adopted from graph theory and general networking addresses this issue.
- interconnect nodes by a network of shortest length when additional nodes (i.e. relay nodes) are introduced. This problem has been studied as the Steiner Tree problem.
- optimize a network of shortest length according to a restricting parameter. In WSN, the transmission range of a node may impose limits on the length of a link.

Cheng [1] proposed a relay node placement algorithm using the minimum number of relay nodes, so that the distance between each hop is less than or equal to the common transmission range. This problem is similar to the Steiner Minimum Tree with minimum number of Steiner Points and bounded edge-length (SMT-MSPBEL). They proposed a 3-approximation algorithm and a 2.5 approximation algorithm. The 2.5 approximation algorithm is a randomized algorithm whose performance is faster than 3-approximation algorithm.

Lloyd [2] discusses two strategies for ensuring a WSN is fully connected. The first is a single-tiered node placement strategy in which every node is connected via some path consisting of either sensor nodes or relay nodes. The length between a sensor node and any other node must be ¡= r, while the length between two relay nodes can be of distance R, where R is defined as R ¿= r. Node placement is achieved using Steiner Tree nodes.

The second strategy discussed is what they call a two-tiered node placement strategy, in which any two nodes of the WSN are fully connected by all relay nodes. That is, between any two sensor nodes in the WSN there exists a path by which every intermediary node is a relay node.

Recent research on relay node placement in Wireless Sensor Networks mostly focuses on connectivity establishment (Estrin et al. [3]). Connectivity is one of the most crucial issue, since most of the actions are taken collaboratively. In addition, sensors are small battery operated devices. Usually after the deployment of wireless sensor networks, it is impossible to access a sensor node and change the battery. Once the battery is depleted the node dies. The most important source of energy consumption in sensor networks is message transmission. The energy required to transmit data is directly proportional to r^4 where r is the distance between source and destination.

NEED TO REFER TO THIS PAPER [4].

III. Proposed Approach

A. Problem Formulation

Specifies the problem (i.e. fairness in WSN) we are addressing in this paper. Defines the key concepts, such a fairness in relation to power consumption and efficiency of power consumption as well as addresses pitfalls such as minimal power consumption which is not addressed by this paper.

B. System Model

The system model is explained. All assumptions required for the model are specified.

Important performance metrics, such as:

- `time to death of the first node`(TTFD)
- `average node lifetime` (ANL)
- `cut vertex lifetime` and its optimality
- additional resource requirements such as `number of Steiner points` and additional nodes
- L - maximum power consumption rate
- K - number of new Steiner Points
- α - minimum standard deviation of power consumption rates given K Steiner points

are defined in this section.

C. Algorithms for Fairness in WSNs

In this section we will explain our two step approach to solving the fairness problem in WSNs.

1) Connecting Nodes: This section explains how to connect and initially disconnected set of nodes using the Steiner Minimum Tree (SMT) algorithm.

2) Optimizing Node Location: In this section we explain an extension to the SMT problem to include a fairness measure across the network of nodes. The explanation will include the moving of Steiner Points to optimal locations as well as the introduction of additional resources (nodes) to achieve optimality. The discussion includes an overview of the trade-off between additional resources and fairness and illustrates results of the optimization operations across multiple dimensions (such as minimizing the deployment of additional resources, maximizing fairness while minimizing power consumption).

IV. Analysis

The section compares our approach the 3-approximation algorithm for minimal power consumption of WSNs.

V. Theoretical Analysis

Our approach will be compared to the 3-approximations time and space usages from a theoretical standpoint.

VI. Experimental Analysis

The theoretical analysis will be verified by an experimental analysis.

VII. Conclusion

Concluding remarks summarizing our approach and future work will be outlined in this section.

Acknowledgment

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