Fair, Energy-aware Connectivity in Wireless Sensor Networks

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***Abstract*—Wireless Sensor Networks (WSN) consist of a collection of independent devices (nodes) that are connected wirelessly in an ad hoc fashion. Generally, each node is equipped with sensors collecting information from and monitoring its environment. Information gathered from WSN has had an enormous impact in the private and public sectors such as traffic monitoring and biomedication.**

Reliable connectivity in WSN has been an extensive research focus followed by energy conservation measures. As devices (nodes) in a WSN are often battery powered, battery lifetimes dictate node lifespans. The more energy can be conserved, the longer the WSN can operate without interruption.

Previous work focuses on power optimization of the overall sensor network. The drawback of such a strategy comes from the unequal power consumption rates of different nodes. Since nodes require more energy in order to cover greater transmission distances, it follows that replacement schedules according to battery lifetimes differ and are harder to predict for individual nodes. Equalized replacement schedules are essential for biomedication application. In such a setting, it is preferable to replace all nodes in one procedure with minimal patient discomfort.

We introduce the notion of *fairness* of power consumption in WSN. We propose a two-fold optimization problem where the fairness of a measure F_n for each node n across a wireless sensor network is to be minimized. In addition, a WSN is to be connected in a way such that, after the addition of a minimal number of relay nodes, the spanning tree connecting the network is of minimum length and the distances between nodes are approximately equal.

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.

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) simultaniously, (2) groups of nodes fail simultaniously, 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

. The further a signal should travel to more energy must be utilized. Since the signal attenuation rate is exponential with distance, a significant amount of energy must be used to transmit a signal only a small distance further. Chang et. al [1] investigated WSN power consumption optimization by imposing a global maximum transmission range and employing Steiner Points in the resulting Steiner Minimum Tree as relay nodes to ensure connectivity. Using this technique, [1] were able to conserve a significant amount of energy in the overall WSN topology.

This idea differs from previous work in that power consumption of the network as a whole is equalized and optimized as opposed to only optimizing the power consumption which may leave individual nodes with differing power consumption rates. Hence, we introduce the notion of *fairness* of power consumption in WSN. We, therefore, propose a two-fold optimization problem as follows:

Optimize the fairness of a measure F_n for each node n across a wireless sensor network, given that F_n is exponentially related to a distance measure between neighboring nodes. Thus, F_n is to be minimized. Furthermore, the network is to be connected in a way such that, after the addition of a minimal number of relay nodes, the spanning tree connecting the network is of minimum length and the distances between nodes are approximately equal.

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.

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. 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.

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