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).**

***Index Terms*—Wireless Sensor Network, Energy Conservation, Fairness, Energy Consumption**

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 V.

II. Related Work

Construction and design of wireless sensor networks often heavily relies on common graph algorithms such as Prim and Kruskal's *Minimum Spanning Tree (MST)* [1] to ensure connectivity while minimizing the total length of all edges (i.e. wireless connections). The *Steiner Tree* problem extends this notion by introducing additional vertices to a graph in order to reduce the length of the spanning tree. The Steiner Tree problem is of particular interest to WSNs, in that additional vertices called relay nodes are often introduced to ensure connectivity. Estrin et al. [2] focus on connectivity establishment and maintainability using relay nodes in WSNs. They note that WSNs are subject to wireless transmission range constraints which in turn affect the interconnections between nodes. As the energy required to transmit data on wireless links is directly proportional to the distance between source and destination nodes, a significant amount of additional energy is required to establish and maintain a connection with more distant nodes. Hence, the most prominent source of energy consumption in wireless sensor networks is message transmission. Estrin et al. utilize relay node placement to combat increased energy requirements by placing nodes along wireless links of maximum distance in the network.

Lloyd [3] 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 $\leq r$, while the length between two relay nodes can be of distance R, where R is defined as $R \geq r$. 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.

Gao et al. [4] introduce the notion of reducing the radio range of nodes and employing a collaborating scheme between nodes to forward data to a base station or sink in order to conserve energy.

Song et al. [5] address the *energy hole* problem - the problem of depleting the energy reserves of high load nodes faster than non-high load nodes - by proposing an NP hard multi-objective optimization problem (MOP). They propose a centralized algorithm as well as a distributed algorithm for assigning the transmission ranges of sensors in order to maximize the network lifetime. Notice that increasing the network lifetime also increases the lifetime the shortest lived nodes. We differ in our work in that we aim to equalized the power consumption rates of all nodes while simultaneously increasing the network lifetime.

Cheng [6] proposes 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 propose a 3-approximation algorithm as well as a 2.5 approximation algorithm. The 2.5 approximation algorithm follows a randomized strategy whose performance is faster than 3-approximation algorithm.

Gandham et al. [7] investigate energy efficiency in wireless sensor networks using multiple base stations. In order to prolong the lifetime of the sensor network, multiple base stations are employed that cover the entire network area. The lifetime of the sensor network is separated into equal periods of time called *rounds* and base stations are relocated at the start of a round. They propose an algorithm for base station placement at the beginning of each round which maximizes network lifetime.

Tang et al. [8] study relay node placement problem in large scale wireless sensor networks such that sensor nodes are connected to at least one relay node and all relay nodes are connected amongst each other. To provide relay node fault tolerance they define the *2-Connected Relay Node Double Cover* (2CRNDC) problem and present a polynomial time approximation algorithms to solve the 2CRNSC.

Nguyen et al. [9] address the problem of unbalanced energy consumption among sensor nodes. This paper touches on concepts directly related to our work. They notice that unbalanced energy consumption among sensor nodes in home network domains is the result of employing only a single base station to collect sensor data. As sensor nodes further from the base station have to utilize more energy to transmit data across further distances, they propose a sensor network architecture with 2 base stations (and their corresponding communication protocol). While this solution approximately equalizes power consumption in relatively small networks, we are interested in a more general network topology.

III. Proposed Approach

A. System Model

The model and algorithms described in this paper make the following assumptions:

- Each sensor/node sends an equal amount of data per time unit.
- Each node can receive an arbitrary amount of data per time unit.
- Each node can store an arbitrary amount of data without energy penalties. This assumption enables this model to ignore data transmission bottlenecks.
- The transmission range of each sensor node does not exceed the maximum transmission range T.
- Only nodes within transmission range of each other are connected (i.e. have an edge between each other in the network).
- A node's energy dissipation per bit transmitted (according to the first order radio model [10]).
- Transmitting a bit over distance d requires energy d^2.
- Sensor nodes have a fixed location. Their location may not change during the lifetime of the network.
- Relay nodes are movable. Their location is flexible during the lifetime of the network.
- Relay nodes can be added to the original network.

B. Problem Formulation

In the Minimal Fair Energy Consumption with Minimal Additional Resources (MFEC-MAR) problem the goal, given a wireless sensor network represented as a graph $G = (V \cup S, E)$, is to equalize the power consumption rate PCR of all nodes in G. That is $PCR(v_1) = PCR(v_2) = PCR(v_3) = ... = PCR(v_n)$ where $n = |V \cup S|$ denotes the number of vertices/nodes in G. The set of vertices in G is composed of a set of fixed vertices V (i.e. sensor nodes) and a set of moveable vertices S (i.e. relay nodes). The edges E in G are subject to the maximum transmission range T of the nodes. It is furthermore the goal of MFEC-MAR to minimize overall power consumption of the network such that $\sum_{i=1}^{n} PCR(v_i)$ is minimal. The set of moveable vertices S is adjustable in $|S|$ and is minimized as well. Hence, MFEC-MAR is a multi-objective optimization problem (MOP). Formally, MFEC-MAR is defined as follows:

- **Input:** A sensor network $G = (V, E)$, where V is a set of fixed vertices and E is the set of edges between vertices if they are within transmission range T, a fairness measure α, a maximum power consumption rate P
- **Output:** A non-disconnected network $G' = (V \cup S, E')$ such that:
  - $STDEV(PCR_{v \in |V \cup S|} v) \leq \alpha$
  - $\forall_{v \in |V \cup S|} PCR(v) \leq P$
  - $\sum_{v \in |V \cup S|} PCR(v)$ is minimal
  - $|S|$ is minimal

For the remainder of this paper, whenever we refer to fairness of power consumption rates (PCR), we denote this fairness measure α as the maximum allowable standard deviation of power consumption rates.

IV. Algorithm and Analysis

A. Algorithms for MFEC-MAR (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).

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

B. Theoretical Analysis

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

C. Experimental Analysis

The theoretical analysis will be verified by an experimental analysis.

V. Conclusion

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

Acknowledgment

The authors would like to thank Dr. Alan Sherman for his valuable feedback and suggestions related to the design and analysis of the algorithms presented herein and his guidance while writing this manuscript. We are grateful for Neelofer Tamboli for her supporting work regarding this project.

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MakeFair(*T,S*)
Input: $G = (X, U)$ such that G^{tc} is an order.
Output: $G = (X, V)$ with $V \subseteq U$ such that G^{tc} is an interval order.
begin
  $V \longleftarrow U$
  $S \longleftarrow \emptyset$
  for $x \in X$ **do**
    $NbSuccInS(x) \longleftarrow 0$
    $NbPredInMin(x) \longleftarrow 0$
    $NbPredNotInMin(x) \longleftarrow |ImPred(x)|$
  end
  for $x \in X$ **do**
    if $NbPredInMin(x) = 0$ **and** $NbPredNotInMin(x) = 0$ **then**
      $AppendToMin(x)$
    end
  end
  while $S \neq \emptyset$ **do**
    remove x from the list of T of maximal index
    while $|S \cap ImSucc(x)| \neq |S|$ **do**
      for $y \in S - ImSucc(x)$ **do**
        { remove from V all the arcs zy : }
        for $z \in ImPred(y) \cap Min$ **do**
          remove the arc zy from V
          $NbSuccInS(z) \longleftarrow NbSuccInS(z) - 1$
          move z in T to the list preceding its present list
          {i.e. If $z \in T[k]$, move z from $T[k]$ to $T[k-1]$}
        end
        $NbPredInMin(y) \longleftarrow 0$
        $NbPredNotInMin(y) \longleftarrow 0$
        $S \longleftarrow S - \{y\}$
        $AppendToMin(y)$
      end
    end
    $RemoveFromMin(x)$
  end
end

Algorithm 1: IntervalRestriction

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