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# An integer linear programming-based tool for wireless sensor networks[☆]

I. Kadayif*, M. Kandemir, N. Vijaykrishnan, M.J. Irwin

*Microsystems Design Laboratory, The Pennsylvania State University, University Park, PA 16802, USA*

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**Abstract**

Wireless sensor networks will be widely deployed in the future for monitoring important environmental conditions, security, and health care. One of the most important challenges in the implementation of such networks is minimizing energy dissipation. Given that many of the energy optimization problems defined for sensor networks are very hard, heuristics are commonly employed. Evaluating the effectiveness of these heuristics, i.e., how close do they come to the optimal solutions, is a challenge. While algorithms that give optimal solutions cannot be on-line (since they are expensive), if they are used off-line, they can provide invaluable insight to improve existing heuristics and to derive new ones. In this paper, we present an integer linear programming (ILP)-based tool that can be used to evaluate optimal solutions for communication energy optimization in sensor networks under specific constraints. This tool, which is based on the required sensing and communication schedules, determines optimal sensor movement and communication strategies to minimize energy consumption due to inter-sensor communication. The tool can also accommodate several constraints related to movement capabilities of sensor nodes, their battery capacities, and their communication ranges since all these can be expressed in a linear form. In addition, it can also work with objective functions other than minimizing communication energy. Our experience with the tool indicates that it is very useful for studying different scenarios under which an objective function needs to be optimized.

## 1. Introduction and motivation

Continued technology improvements have made it possible for sensors to be deployed in various applications ranging from large military to simple home security applications [2,3,23,28,29,33,37]. Many of the applications employ several wireless sensors, which are collectively referred to as *distributed sensor networks*, that coordinate and communicate with each other in sensing and detecting events of importance. There are several key issues that need to be addressed to enable cost-effective, robust, and long-lived wireless sensor networks. These include optimal methodologies for sensor placement/movement, fault-tolerant signal integration, sensor information fusion, and inter-sensor communication. Major constraints influencing the design decisions in addressing these issues include the size and weight of the sensors, their energy-capacities, the communication bandwidth and channel conditions, and the cost of the sensors.

Energy optimization is an important goal to improve the longevity of the distributed sensor network. Due to constraints on physical size/weight, the energy capacity of the battery in sensor nodes is typically limited. Hence, energy optimization can either increase the lifetime of the node or enable more powerful operations at a sensor node. In order to tackle the limited battery capacities, many sensors scavenge energy from the external environment in addition to using batteries. However, the amount of power that can be harnessed this way is very limited (typically, in the range of 100 $\mu$W). Therefore, energy optimizations are important even in such environments where energy scavenging is possible.

The sources of energy consumption in a sensor network are due to the computations at the individual nodes, the

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[*] Corresponding author.

*E-mail addresses:* kadayif@cse.psu.edu (I. Kadayif), kandemir@cse.psu.edu (M. Kandemir), vijay@cse.psu.edu (N. Vijaykrishnan), mji@cse.psu.edu (M.J. Irwin).

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communications across the different nodes, and the energy expended when nodes are idling but active (awake). In addition to these sources, in a mobile sensor, energy is also expended due to locomotion when moving the sensor from one location to another. There have been several efforts focused on reducing the energy consumed due to the various sources. However, given that many of the optimization problems are difficult, heuristics are commonly employed. A main problem is in evaluating the effectiveness of these heuristics, i.e., how much more can these solutions be improved upon. This problem can be addressed by developing formal methods and mathematical frameworks that provide optimal solutions against which these heuristics can be compared.

In this paper, we present an *integer linear programming* (*ILP*)-based tool that can be used to evaluate optimal solutions for energy optimization under specific constraints. This tool takes as input the initial placement of a network of sensors based on a two-dimensional grid topology. The tool, which is based on the required sensing and communication schedules, determines an optimal movement and communication strategy to minimize energy consumption during inter-sensor communication. The user can also specify constraints such as sensor movement capability, battery capacity and communication range, and specify respective costs for movement and communication. This tool is useful in exploring various scenarios of interest that include (but not limited to):

- determining the optimal sensor movements and communications to minimize weighted energy consumption (defined later) under a given communication schedule,
- determining the optimal sensor movements and communications to improve network survivability under battery constraints, and
- determining the type of sensors to deploy based on their relative costs under a given budget and communication/sensing requirements.

The rest of this paper is organized as follows. Section 2 describes the sensor environment, specifying the underlying assumptions and their modeling using the ILP formulations. Section 3 illustrates the flexibility of this tool in modeling various constraints and scenarios. Section 4 shows how new objective functions for optimization can be incorporated in the tool. Section 5 discusses related work. Finally, conclusions are provided in Section 6.

## 2. Modeling the sensor network

### 2.1. Basic problem and assumptions

We assume that the sensor nodes can be placed within an $N1 \times N2$ two-dimensional grid.[1] Note that while some grid locations have sensors placed on them, some of them are empty; that is, in general, the total number of sensor nodes is less than $N1 \times N2$. In this paper, we denote grid locations using $p_{i,j}$, where $0 \leqslant i \leqslant N1-1$ and $0 \leqslant j \leqslant N2-1$. Each grid location can have at most one sensor node. Fig. 1 shows an example two-dimensional grid (10 × 10) with 28 sensor nodes in it. We assume that a communication schedule is given and has *M* entries. Each entry in this schedule is a pair of sensor nodes that need to communicate (i.e., one of them is the sender and the other is the receiver). For a given entry in the communication schedule, the sender node is called the source and the receiver node as the sink. We also assume that we are given two tables: (1) one that gives the energy spent when a sensor node at a given grid location communicates with a sensor in some other grid location, and (2) one that gives the energy expended when a sensor moves from one grid location to another. Therefore, in theory, our framework can operate with any communication/movement energy model (as long as table entries are filled appropriately). In our examples, unless stated otherwise, the movement/communication energy from $p_{i,j}$ to $p_{k,l}$ is modeled as $abs(i-k) + abs(j-l)$ units, where *abs* is the absolute value function. Consequently, for a 4 × 4 grid, with this linear model, the movement energy can be captured as a table as shown in Table 1. A similar table can be created for the communication energy modeled as a function of the distances between the communicating nodes. The presence of two different tables provides flexibility in adopting different weights for communication and movement energies. As this tool is intended as an experimental tool, we also provide two parameters ($\alpha$ and $\beta$) to quickly change and experiment with different relative weights for communication and movement energies. These parameters reduce the effort to completely populate the tables when new energy cost functions are to be employed.

Unless stated otherwise, the objective function optimized by our tool is minimizing the weighted energy consumption, i.e., sum of the weighted communication and movement energies consumed by all sensor nodes. In our context, mobile sensors move to reduce the subsequent communication energy. In other words, to satisfy a given communication schedule, the sensors first move to optimal grid locations and then communicate. Consequently, we can define our basic energy optimization problem as one of *determining optimal movements for sensors to satisfy a given communication schedule such that the weighted energy consumption is minimized.* As will be discussed later in detail, our tool is also capable of solving this problem under multiple (and potentially complex) constraints. Such additions to the basic energy optimization problem are detailed in Section 3.

In the rest of this paper, we show how our tool formulates the basic problem and additional constraints using ILP. A mathematical programming problem is one in which there is a particular function to be maximized or minimized subject to several constraints. For instance, a typical mathematical programming problem, can be formulated as “minimize

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[1] Our ILP-based tool can also work with three-dimensional grids; however, in this paper, our focus is on two-dimensional grids.