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5th International Workshop, WEA 2006
Cala Galdana, Menorca, Spain, May 2006
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Preface

The Workshop on Experimental Algorithms, WEA 2006, is intended to be an international forum for research on the design, analysis and especially the implementation, evaluation and engineering of algorithms, as well as on combinatorial optimization and its applications. WEA 2006, held at Hotel Cala Galdana on Menorca, Spain, May 24–27, is the fifth of the series after Riga (2001), Monte Verita (2003), Rio de Janeiro (2004), and Santorini (2005).

This volume contains all contributed papers accepted for presentation, together with invited lectures by Ricardo Baeza-Yates (Yahoo! Research), Jon Bentley (Avaya Labs Research), and Sotiris Nikoletseas (University of Patras and Computer Technology Institute). The 26 contributed papers were selected out of 92 submissions received in response to the call for papers. All the papers published in the proceedings were selected by the Program Committee on the basis of at least three referee reports, with the help of trusted external referees.

We would like to thank all of the authors who responded to the call for papers, our invited speakers, and the members of the Program Committee, as well as the external referees, and the Organizing Committee members.

We gratefully acknowledge support from the Ministry of Education of Spain and the Technical University of Catalonia.

March 2006

Carme Àlvarez
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Algorithms for Wireless Sensor Networks: Design, Analysis and Experimental Evaluation*

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Abstract. The efficient and robust realization of wireless sensor networks is a challenging technological and algorithmic task, because of the unique characteristics and severe limitations of these devices. This talk presents representative algorithms for important problems in wireless sensor networks, such as data propagation and energy balance. The protocol design uses key algorithmic techniques like randomization and local optimization. Crucial performance properties of the protocols (correctness, fault-tolerance, scalability) and their trade-offs are investigated through both analytic means and large scale simulation. The experimental evaluation of algorithms for such networks is very beneficial, not only towards validating and fine-tuning algorithmic design and analysis, but also because of the ability to study the accurate impact of several important network parameters and technological details.

1 Introduction

Recent dramatic developments in micro-electro-mechanical (MEMS) systems, wireless communications and digital electronics have already led to the development of small in size, low-power, low-cost sensor devices. Such extremely small devices integrate sensing, data processing and wireless communication capabilities. Current devices have a size at the cubic centimeter scale, a CPU running at 4 MHz, some memory and a wireless communication capability at a 4Kbps rate. Also, they are equipped with a small but effective operating system and are able to switch between "sleeping" and "awake" modes to save energy.

Their wide range of applications is based on the possible use of various sensor types (i.e. thermal, visual, seismic, acoustic, radar, magnetic, etc.) to monitor a wide variety of conditions (e.g. temperature, object presence and movement, humidity, pressure, noise levels etc.). Thus, sensor networks can be used for continuous sensing, event detection, location sensing as well as micro-sensing. Hence, sensor networks have important applications, including (a) environmental (such as fire detection, flood detection, precision agriculture), (b) health applications

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(like telemonitoring of human physiological data), (c) home applications (e.g. smart environments and home automation) and (d) military/security applications. For a survey of wireless sensor networks see [1].

Because of their rather unique characteristics, efficient and robust distributed protocols and algorithms should exhibit the following critical properties: **a) Scalability.** Distributed protocols for sensor networks should be highly scalable, in the sense that they should operate efficiently in extremely large networks composed of huge numbers of nodes. **b) Efficiency.** Because of the severe energy limitations of sensor networks and also because of their time-critical application scenaria, protocols for sensor networks should be efficient, with respect to both energy and time. **c) Fault-tolerance.** Sensor particles are prone to several types of faults and unavailabilities, and may become inoperative (permanently or temporarily). The sensor network should be able to continue its proper operation for as long as possible despite the fact that certain nodes in it may fail.

Since one of the most severe limitations of sensor devices is their limited energy supply, one of the most crucial goals in designing efficient protocols for wireless sensor networks is minimizing the energy consumption in the network. This goal has various aspects, including: (a) minimizing the total energy spent in the network (b) minimizing the number (or the range) of data transmissions (c) combining energy efficiency and fault-tolerance, by allowing redundant data transmissions which however should be optimized to not spend too much energy (d) maximizing the number of "alive" particles over time, thus prolonging the system's lifetime and (e) balancing the energy dissipation among the sensors in the network, in order to avoid the early depletion of certain sensors and thus the breakdown of the network.

We note that it is very difficult to achieve all the above goals at the same time. There even exist trade-offs between some of the goals above. Furthermore, the importance and priority of each of these goals may depend on the particular application. Thus, it is important to have a variety of protocols (and hybrid combinations of protocols), each of which may possibly focus at some of the energy efficiency goals above (while still performing well with respect to the rest goals). Furthermore, there exist fundamental, inherent trade-offs between important performance measures, most notably between energy dissipation and latency (i.e. time for information to get to the control center).

In the light of the above, we present and evaluate several data propagation protocols: a) *The Directed Diffusion (DD) Protocol*, that creates and maintains some global structure (e.g. a set of paths) to collect data. b) *The Low Energy Adaptive Clustering Hierarchy (LEACH) Protocol*, that uses clustering to handle data collectively and reduce energy. c) *The Local Target Protocol (LTP)*, that performs a local optimization trying to minimize the number of data transmissions. d) *The Probabilistic Forwarding Protocol (PFR)*, that creates redundant data transmissions that are probabilistically optimized, to trade-off energy efficiency with fault-tolerance. e) *The Energy Balanced Protocol (EBP)*, that focuses on guaranteeing the same per sensor energy dissipation, in order to prolong the lifetime of the network.

Through both rigorous mathematical means and performance evaluation of implemented protocols, we demonstrate the strengths, weaknesses and trade-offs of the protocols and indicate the network conditions and dynamics for which each protocol is best suitable. We believe that a complementary use of rigorous analysis and large scale simulations is needed to fully investigate the performance of protocols in wireless sensor networks. In particular, asymptotic analysis may lead to provable efficiency and robustness guarantees towards the desired scalability of protocols for sensor networks that have extremely large size. On the other hand, protocol implementation allows to investigate the detailed effect of a great number of technical specifications of real devices, a task that is difficult (if possible at all) for analytic techniques which, by their nature, use abstraction and model simplicity.

The definition of abstract (yet realistic) models for wireless sensor networks is very important, since it enables rigorous mathematical analysis of protocol performance. Such models include: a) random geometric graphs [8, 17], where a random plane network is constructed by picking points (that abstract sensors) in the plane by a Poisson process, with density d points per unit area, and then joining each pair of points by a line if they are at distance less than r (this captures transmission range). Interesting properties under this model are investigated in [5]. b) Another interesting model is that of random sector graphs, where each randomly chosen point (sensor) in the plane chooses an angle and a euclidean distance (that together define a cyclic sector corresponding to the sensor's transmission area [6]). Interesting properties (connectivity, chromatic number) are investigated in [18]. c) Stochastic models (such as Markov Chains, dynamic systems) like the ones in [12, 13] are particularly useful for capturing energy dissipation and data propagation. A new relevant model is that of random intersection graphs, where each vertex randomly picks elements from a universe, and two vertices are adjacent when they pick at least one element in common ([11]). Independence properties and algorithms are proposed in [15].

2 Representative Protocols

Directed Diffusion: Maintaining Sets of Paths. Directed Diffusion (DD) [10] is a data-centric communication paradigm, a suite of several protocols. In general, it requires some coordination between sensors to create and maintain a somewhat global structure (e.g. a set of paths) for propagating data. DD uses four elements: a) interest messages, issued by the control center, containing attribute-value pairs, specifying data matching the attributes. b) Gradients towards the control center, created when receiving interest messages, storing a direction towards the sink and a value (data rate) for "pulling down" data. c) Data messages, created by the relevant sensors to the task description (as contained in the interest messages). d) Reinforcements of gradients (i.e. favoring one or more neighbors at each level of the tree) to select "best" paths (wrt some criteria) for "drawing down" real data. Reinforcement can be positive (i.e. reinforce the neighbor that first reported a new event or the one with the higher data rate) or negative (i.e. when a gradient does not deliver any new messages for some time or when its data rate is low).

Since DD reinforces certain "good" paths for getting data, it improves over flooding a lot. Especially in the case where the network conditions do not change a lot, it incurs significant energy savings. In networks of high dynamics however (where many changes happen in the network) its performance drops, since established paths may now become inefficient (or even break down), since path maintenance and update may be too slow wrt the changes in the network.

LEACH: A Clustering Protocol. LEACH [9] partitions the network into clusters of sensors, with a single sensor in each cluster being a cluster-head. Non cluster-heads transmit data to their cluster-head; cluster-heads gather received data, compress it and send it directly to the sink. To avoid energy depletion of cluster-head sensors, clusters are created in a dynamic way over time, and cluster-heads rotate in a randomized way.

Because of compression and aggregation of data at cluster-heads and collective transmission to the sink, LEACH manages to reduce energy dissipation, especially in small area networks. In large networks however, directed transmissions are distant and expensive. Also when the network traffic is high (i.e. many agents are sensed and reported) the performance of LEACH drops, since rotation of cluster-heads may be slow and not avoid energy depletion of cluster-heads.

LTP: A Hop-by-Hop Data Propagation Protocol. The LTP Protocol was introduced in [2]. The authors adopt a two-dimensional (plane) framework: A *smart dust cloud* (a set of particles) is spread in an area. Let d (usually measured in numbers of $particles/m^2$) be the *density* of particles in the area. Let $\mathcal{R}$ be the maximum (radio/laser) transmission range of each grain particle. A *receiving wall* $\mathcal{W}$ is defined to be an infinite line in the smart-dust plane. Any particle transmission within range $\mathcal{R}$ from the wall $\mathcal{W}$ is received by $\mathcal{W}$. The wall represents in fact the authorities (the fixed control center) who the realization of a crucial event should be reported to. The wall notion generalizes that of the sink and may correspond to multiple (and/or moving) sinks. Each smart-dust particle is aware of the general location of $\mathcal{W}$.

Let $d(p_i, p_j)$ the distance (along the corresponding vertical lines towards $\mathcal{W}$) of particles p_i, p_j and $d(p_i, \mathcal{W})$ the (vertical) distance of p_i from $\mathcal{W}$. Let $info(\mathcal{E})$ the information about the realization of the crucial event $\mathcal{E}$ to be propagated. Let p the particle sensing the event and starting the execution of the protocol. In this protocol, each particle p' that has received $info(\mathcal{E})$, does the following:

- *Search Phase*: It uses a periodic low energy directional broadcast in order to discover a particle nearer to $\mathcal{W}$ than itself. (i.e. a particle p'' where $d(p'', \mathcal{W}) < d(p', \mathcal{W})$).
- *Direct Transmission Phase*: Then, p' sends $info(\mathcal{E})$ to p''.
- *Backtrack Phase*: If consecutive repetitions of the *search phase* fail to discover a particle nearer to $\mathcal{W}$, then p' sends $info(\mathcal{E})$ to the particle that it originally received the information from.

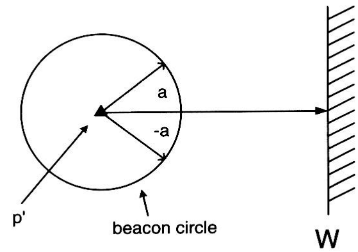

Fig. 1. Example of the Search Phase

Definition 1. Let h_{opt} be the (optimal) number of "hops" (direct, vertical to $\mathcal{W}$ transmissions) needed to reach the wall, in the *ideal* case in which particles always exist in pair-wise distances $\mathcal{R}$ on the vertical line from p to $\mathcal{W}$. Let h be the actual number of hops (transmissions) taken to reach $\mathcal{W}$. The *"hops" efficiency* of the protocol is the ratio $C_h = \frac{h}{h_{opt}}$.

Clearly, the number of hops (transmissions) needed characterizes the energy consumption and the time needed to propagate the information $\mathcal{E}$ to the wall. Remark that $h_{opt} = \left\lceil \frac{d(p,\mathcal{W})}{\mathcal{R}} \right\rceil$, where $d(p,\mathcal{W})$ is the (vertical) distance of p from the wall $\mathcal{W}$. In the case where the protocol is randomized, or in the case where the distribution of the particles in the cloud is a random distribution, the number of hops h and the efficiency ratio C_h are random variables and one wishes to study their expected values.

Towards a rigorous analysis of the protocol, [2] makes the following simplifying assumption: *The search phase always finds a* p'' (of sufficiently high battery) in the semicircle of center the particle p' currently possessing the information about the event and radius R, in the direction towards $\mathcal{W}$. Note that this assumption on always finding a particle can be relaxed in many ways. [2] also assumes that the position of p'' is uniform in the arc of angle $2a$ around the direct line from p' vertical to $\mathcal{W}$. It is also assumed that each target selection is stochastically *independent* of the others, in the sense that it is always drawn uniformly randomly in the arc $(-\alpha, \alpha)$. By analysing the stochastic process of data propagation, the following can be obtained:

Lemma 1 ([2]). *The expected "hops efficiency" of the local target protocol in the a-uniform case is*

$$E(C_h) \simeq \frac{\alpha}{\sin\alpha}$$

for large h_{opt}. *Also, for* $0 \leq \alpha \leq \frac{\pi}{2}$, *it is* $1 \leq E(C_h) \leq \frac{\pi}{2} \simeq 1.57$.

PFR: A Probabilistic Forwarding Protocol. To combine energy efficiency and fault-tolerance, the Probabilistic Forwarding Protocol (PFR) has been introduced in [3]. The modeling assumptions made can be found in [3]. Notice that GPS information is not needed for this protocol. Also, there is no need to know the global structure of the network.