Maintenance Awareness in Wireless Sensor Networks

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***Abstract* - In wireless sensor networks where deployment is expected to surpass the lifetime of batteries, a major part of the operation costs is expected to be consumed by maintenance costs. It is important, therefore, to identify sources of maintenance related costs and to reduce them.**

In this paper we propose a maintenance model to explain sources of maintenance costs in wireless sensor networks. We also introduce the concept of maintenance awareness in such networks and describe a new technique to reduce maintenance costs. Our first experimental results shows that substantial cost reduction can be achieved.

***Keywords* - Sensor networks, maintenance, routing, GPSR.**

I. Introduction and Motivation

Wireless sensor networks are collections of autonomous devices with computational, sensing and wireless communication capabilities. Research in these networks has been growing steadily in the past few years given the wide range of applications that can benefit from such a technology.

It is expected that in the near future, the price of a sensor node will drop to a few cents of Euro. At this price, the hardware value of a sensor field will be a small fraction of its cost. The dominating cost factors associated with a sensor field will be deployment and operation cost. Deployment will generally involve trained personal and specialized equipment that may include airplanes to drop sensors over areas that cannot be accessed otherwise. Some sensor units may instead require careful placement in the field thus consuming many hours of qualified labour. Furthermore, in long lived systems it is necessary to keep the network operational for a period of time that surpasses the lifetime provided by the batteries when the network was first deployed. Maintenance will thus be required and will involve periodic replacement of batteries/nodes in the sensor field. Given the potential high costs, we believe that an appropriate design of sensor networks must take deployment and maintenance needs into consideration.

In this paper, we focus on the problem of identifying a maintenance model from which we will be able to derive metrics for designing low-maintenance wireless sensor networks. The paper contains the following original contributions:

(i) A generic *maintenance model* for wireless sensor networks.

(ii) The concept of *maintenance-aware sensor networks*, designed to take into consideration the costs of maintaining long-lived networks.

(iii) A concrete example and performance assessment of a maintenance-aware sensor network.

The rest of the paper is organized as follows. Section II gives a brief overview of related work. Section III presents a maintenance model for wireless sensor networks and describes the concept of maintenance awareness. Section IV discusses design metrics for maintenance-aware sensor networks and presents a example of such a network. In this network, a modified version of a known geographical routing protocol (GPSR) is used to achieve maintenance awareness. Section V evaluates the design of the proposed network. The paper ends with a summary of our findings and describes our future research work.

II. Related Work

The problem of designing sensor networks has been generally restricted to the development of energy-efficient hardware and software. In recent years, several data dissemination protocols were proposed to deal with power awareness with two main focus areas: extension of network lifetime (e.g. [1]) and reduction of total power consumed (e.g. [2]). Research in energy efficient MAC layers includes the development of S-MAC [3]. At the operating system level, Berkeley's TinyOS is a well-known system designed to be deployed in a hardware platform that has small physical size and is energy constrained.

To our knowledge, this is the first work in the literature to propose a deeper analysis on the costs of deploying and operating a wireless sensor networks with means of improving their design. As we show in this work, the design of maintenance-aware systems must go beyond energy-efficiency.

III. Maintenance-Aware Sensor Networks

Within a wireless sensor network, the periodic replacement of node batteries is necessary to ensure continuous functionality of the system over a long period of time. We name the replacement of one or more batteries in the field a *maintenance operation*. Each maintenance operation has an associated *maintenance cost* C_m. The point in time and the structure of a maintenance operation is defined by a *maintenance policy* P. During the lifetime of a sensor field, several maintenance operations are performed. The sum of all maintenance costs associated with the maintenance operations is the *total maintenance cost* C_t.

In the following paragraphs we describe the cost structure (the *cost model*) and policies for the maintenance of wireless sensor networks. The cost model and a maintenance policy define a *maintenance model* for the network. Later, we show how the maintenance model is used in the design of maintenance-aware sensor networks.

A. Cost Model

Sensor fields may contain nodes underneath water, on the top of hills or spread over a large flat area. In each of these situations, the equipment, the personnel and the effort necessary to perform a maintenance operation have different characteristics that will affect the maintenance cost.

The cost of servicing a sensor s in a sensor field S can be divided into four components:

- *Cross-operation cost ($c_c(s)$)*: Cost associated with the infrastructure necessary to service nodes. The cross-operation cost of a node can be obtained by dividing the infrastructure cost during the lifetime of the network by the number of sensors in the field.
- *Pre-operation cost ($c_p(s)$)*: Cost associated with organizing a maintenance operation. The pre-operation cost of a node may vary with each operation and is obtained by dividing the total organization cost by the number of nodes serviced in the operation.
- *Access cost ($c_a(s)$)*: cost associated with one-time resources spent while accessing the sensor to be serviced. The access cost of a node may vary in each operation.
- *In-situ cost ($c_s(s)$)*: Cost associated with one-time resources spent while servicing an individual sensor in its current location in the sensor field. In situ-costs includes the battery and hardware replaced.

The cost components just described can be added to produce the maintenance cost $C_m(s)$ of servicing a single node s in the sensor field:

$$C_m(s) = c_c(s) + c_p(s) + c_a(s) + c_s(s) \quad (1)$$

B. Maintenance Policy

The maintenance operations and their frequency are defined by the maintenance policy. A simple policy might have the following structure:

> *A maintenance operation is triggered every time a node has less than 10% of its initial battery charge remaining. During the maintenance operation, the battery of the node is recharged/replaced.*

Every maintenance operation incurs a maintenance cost C_m defined by equation (1). During the lifetime of a sensor field I maintenance operations will take place. The total maintenance cost C_t of the sensor field is then given by:

$$C_t(P) = \sum_{i=0}^{I} C_{m_i} \quad (2)$$

The goal of a maintenance policy is to reduce the total maintenance cost of the sensor field. This can be achieved by minimizing the following parameters:

(i) C_m, the maintenance operation cost

(ii) I, the number of maintenance operations

The reduction of the maintenance operation cost C_m is primarily a managerial problem and therefore out of the scope of this paper. The number of maintenance operations I is influenced by:

(i) the structure of the maintenance policy.

(ii) the design and operation of the sensor field.

In Section III.C we discuss how maintenance policy, design and operation of sensor networks may concur to reduce the number of maintenance operations.

Maintenance Zones. Some of the cost factors comprising C_m may be dominant over others. As previously stated (Section I), in the future it is likely that access costs $c_a(s)$ will dominate over in-situ costs $c_s(s)$ in many applications. In such scenario, the maintenance cost for replacing one sensor will be approximately the same as the maintenance cost for replacing all sensors in the vicinity. We refer to a group of nodes in the same vicinity as a *maintenance zone*. More formally:

> *A maintenance zone is a set of sensor nodes $Z \subseteq S$ such that for every pair of sensors $s_1, s_2 \in Z$, $c_a(s_1) \cong 0$ once s_2 was accessed in the same maintenance operation.*

Sensors in a field S are grouped into maintenance zones according to the cost model. Therefore, the exact aspect of a maintenance zone is very dependent on the sensor field under consideration. As a practical example, consider the deployment of wireless sensor nodes for environmental monitoring in redwood trees at University of California Botanical Garden's Mather Redwood Grove [4]. In this deployment, several sensor nodes are attached in different positions of trees that can be hundreds of feet tall. Climbing equipment is used to deploy such sensors and a maintenance zone can be clearly defined as the set of nodes in a common tree.

C. Maintenance Awareness

By assuming that access costs are dominant over in-situ costs we are able to add battery energy to one or more sensors in the same zone at a constant maintenance cost. This additional energy, injected according to the maintenance policy, can be used to extend the time intervals between maintenance operations. Nevertheless, in order to effectively achieve a reduction on the number of maintenance operations I and therefore improve maintenance cost C_t, the sensor field must be able to take advantage of the additional energy injected. A sensor network able to take advantage of the additional energy introduced in the system through periodic maintenance is referred as *maintenance-aware*.

In general, there are two possible ways of adding maintenance awareness to a wireless sensor network:

(i) **Design:** sensor nodes can be designed with the specific purpose of benefiting from the usage of additional energy (e.g., the MAC-Layer or routing protocols).

(ii) **Operation:** The application must access the field in a way that the additional energy is properly used.

Obviously, network operation tuning is very application specific. The more generic approach, and the one we adopt in our work, is to add maintenance awareness through changes in the internal design of the sensor network.

IV. Maintenance-Aware Sensor Networks by Routing Protocol Modification

In the remaining of the paper we focus on the modification of routing protocols to achieve maintenance awareness in wireless sensor networks. As we show in Section V, routing protocols hold a great potential for reducing maintenance costs. In this section we discuss metrics to rate the efficiency of routing protocols according to maintenance costs. We also show how an existing routing protocol, the Greedy Perimeter Stateless Routing (GPSR) protocol, can be modified to become maintenance-aware.

A. Routing Protocol Design Metrics

The design of maintenance-aware routing protocols requires the existence of appropriate metrics for their evaluation. Research in sensor networks has focussed on *energy efficiency* as the main design goal of data dissemination protocols. Besides total energy consumption, another metric commonly used is *network lifetime*, defined as the time for the first node in the network to deplete. These metrics alone, however, are inappropriate for the design of sensor networks since they oversimplify deployment and operation costs. As we have shown in [5], the following statements regarding these metrics are true:

(i) Maintenance efficiency is not energy efficiency.

(ii) Maximizing network lifetime does not mean maximizing maintenance costs.

In the maintenance model presented in Section III, we assume that access costs are dominant over in-situ costs. Therefore, in applications where pre-operation costs can be neglected, a suitable metric for the design of maintenance efficient protocols is the number of zone accesses during the lifetime of the system. This metric will be used throughout the remainder of this paper.

B. Maintenance in GPSR based Sensor Networks

As an example of adding maintenance awareness to wireless sensor networks, we have chosen to modify the Greedy Perimeter Stateless Routing (GPSR) protocol. GPSR is a well known geographic routing protocol described in [6].

GPSR. All nodes in GPSR must be aware of their position within a sensor field. Each node communicates its current position periodically to its neighbors through beacon packets. Upon receiving a data packet, a node analyzes its geographic destination. If possible, the node always forwards the packet to the neighbor geographically closest to the packet destination. If there is no neighbour geographically closer to the destination, the protocol tries to route around the “hole” in the sensor field.

Modified GPSR (GPSR-M). In order to take advantage of the extra energy injected in the field through periodic maintenance operations (see Section III), the behavior of GPSR is slightly changed. A message is *NOT* necessarily delivered to the neighbor geographically closest to the packets destination. Instead, the message is randomly delivered to any node closer to the packet destination.

As pointed out previously, the resulting protocol will not be necessarily more energy efficient or be able to improve network lifetime. We show in the next section, however, that this protocol can achieve better maintenance efficiency.

V. Evaluation of the Maintenance-Aware GPSR

To study the impact of GPSR-M on the maintenance costs of wireless sensor networks, we have conducted comparative simulation experiments between GPSR and the modified GPSR version. The following paragraphs describe our simulation environment, the experiment setup and results.

A. Simulation Environment

We have chosen to build our own lightweight simulator in order to able to scale our experiments to hundreds of nodes. Our simulator places each node of the sensor field into a maintenance zone. Sensors have an energy model that tracks the energy spent in each message sent. This mac layer is chosen for simplicity in this stage of our work.

B. Experiment Setup

The experiment setup selected reflects a common class of real-world applications but it is still simple enough to be able to understand the influence of various parameters on the maintenance cost. Our experiment is characterized by the following parameters: *field structure, maintenance-zone structure, operation model* and *routing protocol.*

Field Structure. A grid-layout is assumed for the sensor field and a base-station in a field’s corner is used to collect all data generated. The field contains 420 nodes spread over an area of $100x100m^2$. All sensors have the same specification and are equally spaced from each other. The radio range of each node is 7.1m and a full battery allows for 1000 packet transmissions.

Maintenance-Zone Structure. In our experiments, we use a grid layout for the maintenance zones. The sensor field is partitioned into 25 zones, each covering an area of $20x20m^2$. A node belongs to only one zone. The cost model has the following structure: $c_c(s) = 0$, $c_p(s) = 0$, $c_a(s) = 1$, $c_s(s) = 0$. The maintenance policy replaces the batteries of *all nodes* in a zone that contain at least one sensor with less that 10% of its full charge energy.

Operation Model. We assume that, at any time, exactly one sensor is actively sending data to the base-station. This sensor is selected randomly within the sensor field. A node sends n messages before a new node is selected. The number n is randomly chosen between 1 and n_{max}. Each message sent is separated from the previous one by an interval of $T = 30s$.

Routing Protocol. Both GPSR and GPSR-M is used in our simulations.

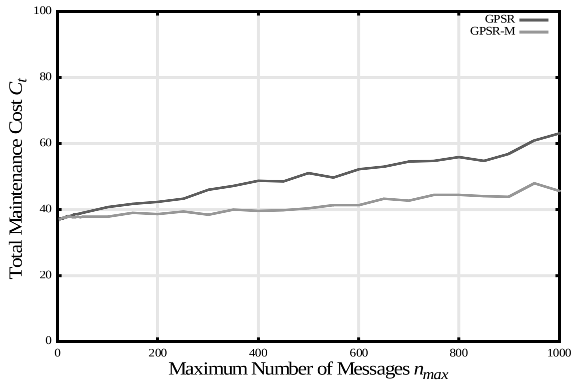

Figure 1 - Average total maintenance cost C_t

C. Comparative Evaluation.

We simulate the operation of a sensor field over the period of two weeks. The value n_{max} (see operation model) is used as a parameter for the experiment, reflecting slightly different operation conditions of the sensor field. Each point in the graphs shown in Fig. 1 and Fig. 2 is obtained by averaging the result of 20 simulation runs.

Maintenance Cost. Fig. 1 shows how the total maintenance cost C_t varies with parameter n_{max} for both GPSR and GPSR-M. With GPSR-M, the sensor field always incurs lower maintenance costs. For low values of n_{max}, the randomization achieved with periodic selecting a different node to report a small amount of data to the sink provide good energy consumption balance in the field. In this case, the additional randomization offered by the GPSR-M does not help much. The difference between both protocols, however, becomes increasingly pronounced as the value of n_{max} increases. This result shows that operation conditions have an important influence on maintenance efficiency as discussed in Section III.C. Nonetheless, proper designed protocols can go a long way in improving maintenance costs.

The coefficient of variation of the measurements shown in Fig. 1 is less then 11.8% for GPSR and less then 11.8% for GPSR-M at all measurement points.

Energy Consumption and Latency. Fig. 2 shows the average consumed energy for transmissions during the experiment. It shows that the GPSR-M protocol is less energy efficient then the standard GPSR. In our experiments we also observe, that a message delivered using GPSR-M travels a longer path (increased hop count). This result shows that gains in maintenance efficiency imply a price in terms of increased latency.

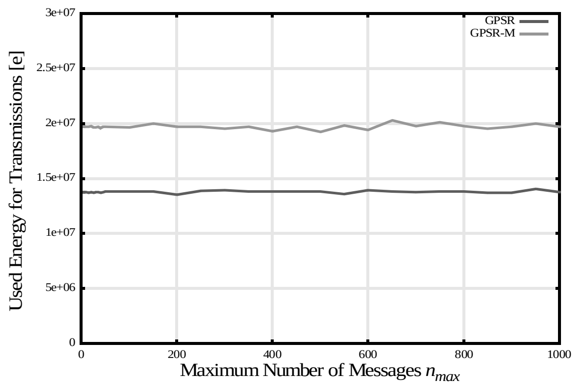

Figure 2 - Average used transmission energy

The coefficient of variation of the measurements shown in Fig. 2 is less then 6.7% for GPSR and less then 7.2% for GPSR-M at all measurement points.

VI. Conclusions and Future Work

In this paper, we discussed the need for incorporating to the design of long-lived wireless sensor networks, metrics that take into consideration their maintenance costs. In order to derive suitable metrics, we introduced a generic maintenance model that explains the cost structure and defines policies for maintenance operations in such networks. We modified a well-known geographical routing protocol (GPSR) to improve the maintenance costs of sensor fields. The theory developed allowed us to compare the maintenance efficiency of the original and modified versions of the routing protocol. Our first results indicate a considerable potential for maintenance savings of the modified protocol, despite the fact that it is less energy efficient. This observation supports our claim that maintenance-efficiency cannot be equated with energy-efficiency. Besides being less energy-efficient, the modified GPSR also incurs more latency in the delivery of packets.

In the future we plan to extend our investigation to include heterogeneous sensor fields where nodes may have different access costs. In this scenario, the depletion rate of nodes with higher access costs must be minimized. Furthermore, research must be carried out in maintenance-aware MAC protocols, since routing will not affect considerably how fields are maintained in networks where the energy depletion is dominated by the MAC layer.

VII. References

[1] J. Chang and L. Tassiulas, "Energy Conserving Routing in Wireless Ad-hoc Networks," in *Proc. INFOCOM*, 2000, pp. 22-31.

[2] D. Ganesan , R. Govindan , S. Shenker and D. Estrin, “Highly-resilient, energy-efficient multipath routing in wireless sensor networks,” in *Proc. MobiHoc*, 2001, pp. 11-25.

[3] W. Ye, J. Heidemann and D. Estrin, “An energy-efficient MAC protocol for wireless sensor networks,” in *Proc. INFOCOM*, 2002, pp. 1567-1576.

[4] S. Yang. (2003, July). Redwoods go high tech: Researchers use wireless sensors to study California's state tree. *UC Berkekey News* [Online]. Available: http://www.berkeley.edu/news/media/releases/2003/07/28_redwood.shtml.

[5] A. Barroso, U. Roedig and C. Sreenan. (2003, Nov.). On the Relation Between Energy Efficiency, Network Lifetime Span and Maintenance Costs in Wireless Sensor Networks. Dept. of Computer Science, University College Cork, Ireland. [Online]. Available: http://student.cs.ucc.ie/~ab6/

[6] B. Karp and H. T. Kung, “GPSR: greedy perimeter stateless routing for wireless networks,” in *Proc. MOBICOM*, 2000, pp. 243-254.