Controlling Sink Mobility in Wireless Sensor Networks: A New Model and Protocols

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***Abstract*— This research concerns the definition of an analytical model and protocols for determining the routes of a mobile data collector (*sink*) traveling through the nodes of a wireless sensor network (WSN). The routes are determined with the overall aim of maximizing the network lifetime. The contribution of our work is twofold. First, we introduce a novel mixed integer linear programming formulation for determining the sink's route and the sojourn time at the different “sink sites.” The model takes into account realistic parameters such as the maximum distance the sink can travel between sites as well as constraints on the sojourn time at a site. Solutions to the model provide the route of the sink as a sequence of sites and the sojourns time at those sites that induce the maximum network lifetime.**

We then propose the *Greedy Maximum Residual Energy* (GMRE) protocol for sink mobility. Such protocol is distributed and localized, thus being suitable for wireless sensor networking. In GMRE the sink greedily keeps moving toward those areas in the network where there is the most residual energy, as if “drawn” to them. This heuristic is then compared with a very simple and energy-unaware protocol where the next site in the sink route is chosen randomly and uniformly each time the sink moves.

Simulation results show remarkable improvements both for network lifetime and for balancing energy consumptions throughout the network in case GMRE is adopted.

I. INTRODUCTION

Wireless sensor networks (WSN) are networks comprised of a large number of wireless nodes with sensing capabilities. Routing of the sensed data to a collection point (called *sink*) happens as in ad hoc networks, i.e., in a multi-hop fashion. Given the nodes energy constraints, particular attention has been given to the definition of data dissemination protocols that aim at minimizing energy consumption. In particular, mechanisms have been proposed for easing the burden of data collection that exploit the mobility of network components such as sensor nodes, mobile agents and the sink itself. This research concerns the analytical study and the definition of protocols for controlling the mobility of the sink. That sink mobility is effective for prolonging network lifetime has been proven clearly, independently and with different techniques in [1] and [2] (where further references to works on the use of mobility for efficient data gathering in WSNs can be found). A linear programming (LP) formulation of the problem of maximizing network lifetime is given in [1]. Values for network lifetime in networks with the static sink optimally placed are compared to those obtained by having the sink moving according to the LP model: The improvements are fivefold. Luo and Hubaux [2] formulate the problem of lifetime maximization as a min-max problem. By considering together sink mobility and data routing, load balancing can be obtained that, while keeping the sink moving along the external perimeter of the network, achieves lifetimes 500% higher than when the sink stays in the center of the network.

In this work, we want to determine the actual routes that a mobile sink must travel for achieving optimal network lifetime (here defined as the time till the first node “dies” because of energy depletion). To this purpose, we consider the general setting of a WSN where a set $S = \{1, \ldots, q\}$ of q sink's *sites* is given that are the points within the geographic area the sink can sojourn at. The given set S captures the fact that parts of the sensor nodes deployment area might be inaccessible to the sink. Every time the sink reaches a new site, it floods a packet f to all the network nodes making them aware of its current site. A node that receives f starts sending/relaying its packets towards the new site of the sink. Packet generation at a node happens according to a fixed data rate. Every routing scheme that works with the topological information provided by f is a viable routing for data delivery to the sink. Every time the sink leaves a site, it again floods a packet to all nodes to communicate that it is no longer reachable at that site. Upon receiving this second packet, a node stops forwarding data (remaining packets may be either discarded or buffered), and wait to receive a new packet f from the sink, carrying its whereabouts.

There is virtually no bound on how far the sink can travel between two sites. However, we note that while the sink is traveling, the sensors do not transmit. Therefore, if new data are sensed, these are buffered. This implies the possibility of high delays for data packets. In order to contain this delay, we introduce a new parameter d_{max} which represents an upper bound on the distance that the sink can travel from a site to the following one. Thus, the pair (S, d_{max}) uniquely defines a graph of sink's sites where there is a link between two sites if and only if their (Euclidean) distance is $\leq d_{max}$.

Finally, we observe that the floodings to set up and release routes between the current site and all sensor nodes can be tough on nodes that are energy constrained, and on network performance in general. In order to contain the effect of these floodings, we introduce the parameter t_{min}, which is the time that the sink *has to* stay at a site. In this way we limit the number of route management packets: The higher t_{min}, the lower the number of times the sink has to flood the network.

What we will solve via mathematical modeling and the design of distributed protocols is the following problem: *Determine the starting site and the route for the mobile sink over the graph (S, d_{max}), together with the sojourn times $t_k \geq t_{min}$ of the sink at each visited site $k \in S$ so that network performance is optimized.*

II. A NEW MILP ANALYTICAL MODEL

The first contribution of this work concerns the definition of a new mixed integer linear programming (MILP) analytical model that takes into account all the realistic constraints mentioned above. In the following, N is the set of the network nodes, $N = \{1, \ldots, n\}$. We also consider the following parameters and variables. e_0: Initial energy (Joule) of each node. f_{ik}: Power consumption (Joule) at sensor node $i \in N$ to set up/release routes when the sink moves to a new sojourning site $k \in S$. c_{ik}: Power consumption (Joule/sec) for receiving and transmitting packets at node $i \in N$ when the sink sojourns at site $k \in S$. d_{ij}: Euclidean distance (meter) between any two candidate sojourning sites $j, k \in S$. t_k: Sojourn time (sec) of the sink at site $k \in S$. y_k: Binary variable taking the value of 1 if the sink sojourns at $k \in S$ ($t_k > 0$); 0, otherwise ($t_k = 0$). x_{jk}: Binary variable signifying the status of arc (j, k), $j, k \in S \cup \{0\}$, where site "0" is a fictitious site. $x_{jk} = 1$ if the arc joining sites j and k, (j, k), is on the sink's movement path; 0, otherwise. u_k: Auxiliary variable used to enforce a unique sink path.

The MILP is the following.

$$\text{Max} \sum_{k \in S} t_k \tag{1}$$

$$\text{subject to:} \quad \sum_{k \in S} c_{ik} t_k + \sum_{k \in S} f_{ik} y_k \leq e_0 \quad i \in N \tag{2}$$

$$t_{min} y_k \leq t_k \leq M y_k \quad k \in S \tag{3}$$

$$\sum_{k \in S} x_{0k} = 1 \tag{4}$$

$$\sum_{k \in S} x_{k0} = 1 \tag{5}$$

$$\sum_{\substack{k \in S \cup \{0\} \\ k \neq j}} x_{jk} = y_j \quad j \in S \tag{6}$$

$$\sum_{\substack{j \in S \cup \{0\} \\ j \neq k}} x_{jk} = y_k \quad k \in S \tag{7}$$

$$u_j - u_k + q x_{jk} \leq q - 1 j \neq k, j, k \in S \tag{8}$$

$$d_{jk} x_{jk} \leq d_{max} j \neq k, j, k \in S \tag{9}$$

$$t_k, u_k \geq 0 \quad k \in S \tag{10}$$

$$y_k \in \{0, 1\} \quad k \in S \tag{11}$$

$$x_{jk} \in \{0, 1\} \quad j, k \in S \tag{12}$$

III. DISTRIBUTED HEURISTICS FOR SINK MOBILITY

Our investigation of the models shows a clear dependence of a node energy consumption on its vicinity to the sink. We observed that this relation is independent of the routing protocol and of the particular node deployment (i.e., random or grid-based). This observation suggests a general strategy for the selection of the next site the sink should be moving to: The next location of the sink will be in the area with the highest current residual energy. Namely, the sink will greedily select the site within d_{max} surrounded by nodes that have the most energy left. In time, this should most likely result into a balanced energy consumption throughout the network, and hence into a longer network lifetime.

Based on this intuition we describe here the *GMRE* heuristic (GMRE stands for Greedy Maximum Residual Energy). After spending a time t_{min} at a site, a sink evaluates whether to move toward one of the adjacent sites (two sites are adjacent if their distance is $\leq d_{max}$) or to stay where it is. In order to make this decision it gathers information about the residual energy at the nodes around each of the potential future sites (we call this energy value the residual energy at the site), and compare it with the residual energy at the current site. If there are adjacent sites with a residual energy higher than that at the current site, the sink moves to the site with the highest residual energy (selecting randomly among sites with the same residual energies in case of ties). Otherwise the sink stays at the current location.

Key to the definition and implementation of GMRE is the communication to the sink of the residual energies at the adjacent sites. This communication proceeds in two phases. First, for each of the adjacent sites, the sink identifies one *sentinel* sensor node that will be in charge of measuring and reporting the residual energy at the site when requested by the sink. The second phase concerns the sink interrogation of the sentinels. This is performed whenever the sink has to decide whether to move or not.

To implement the first phase we take advantage of the flooding performed by the sink when it makes the nodes aware of its new location. For this heuristic we assume that a node that is in the "transmission vicinity" of a site (i.e., whose distance from a site is $\leq R$) is aware of that. This can be obtained by endowing the nodes with a suitable localization mechanism, or by providing this information to them at network initialization. The flooding message contains the coordinates of the current location of the sink. Upon receiving the flooding packet, a node knows if it is in the vicinity of a possible future sink site. In this case, it sends to the sink a (small) packet for its candidacy as sentinel. Upon receiving such packets the sink decides which is the sentinel for a given site. This mechanism also allows the sink to identify those site that are isolated (no packet is received from nodes around that site). In this case, the sink will not consider that site as a possible future one.

The second phase starts when the sink has to decide whether to move to a new site or not. At this time, the sink interrogates the selected sentinels about the residual energy at their sites. This is accomplished by sending a (small) packet to the sentinels. When interrogated, the sentinels query their neighboring sensor nodes about their residual energy and communicate back to the sink the average of the obtained values (or any suitable function that can express the energy of the areas).

Another simple heuristic which captures the uncontrolled, random mobility of the sink as often described in the literature, is the following. Every t_{min} time the sink selects randomly and uniformly the new location among all the sites within distance d_{max} from the current. In case a site different from the current is selected, it moves to that site. This heuristic, termed the Random Movement heuristic (*RM*), is here introduced mainly as a benchmark for assessing the effectiveness of GMRE in prolonging network lifetime.

IV. SIMULATION RESULTS

The GMRE protocol has been evaluated by means of extensive, ns2-based simulations. Its performance has been compared to the performance of data dissemination in case of WSN with static sink (placed at the center of the deployment area) and in case the sink moves according to RM.

The simulations refer to scenarios in which $n = 400$ static wireless nodes with a maximum transmission radius of 25 meters are placed on a grid in a geographic square area of side $L = 400$m. We make the assumption that two nodes are neighbors if and only if their Euclidean distance is ≤ 25m. We consider sets of sink's sites of different size q. The sites are distributed on a grid. In our experiments we have set q equal to a value which ranges from 16 to 64. The parameter d_{max} has been set to 190m, while t_{min} ranges between $50,000$s and $1,000,000$s. Each device has an initial (residual) energy of 50J. The power consumed while transmitting, receiving are equal to 14mW and 12.5mW, respectively (as from the data sheet of the IST Energy Efficient Sensor Networks, EYES, project nodes). Nodes have a fixed data rate, equal to 0.5bit/s. A shortest path routing protocol is adopted. All our results achieve a 95% statistical confidence with 5% precision.

We have considered several metrics of interest to sensor networking, which include (all averages): network lifetime, data packet latency, and the node residual energy over time.

We have observed that, in the case of GMRE and RM, the network lifetime decreases with increasing values of t_{min}, reflecting the fact that at high t_{min} the sink cannot freely move to all possible sites. Furthermore, the higher t_{min}, the coarser the granularity of sojourn times and hence the less balanced is the energy depletion throughout the network.

The GMRE solution leads to up to a 100% increase on network lifetime over the RM heuristic. With respect to the case with a non-mobile sink the improvement is fourfold (networks with 64 sink sites). In GMRE (and in the optimal MILP solution) the sink tends to sojourn at the perimeter of the deployment area, with higher sojourn times spent at the corners (Fig. 1). In case of the RM heuristic, the sink tends to gravitate around the center of the area. As a consequence, since the routes to the sink are on average shorter, the average data packet latency is smaller for RM (GMRE has delivery times that are up to 29% higher, on average).

The energy-aware movement strategy adopted by GMRE also results in a more balanced energy consumption. This is clearly shown in figures 2 and 3 which depict the average residual energy per node (as a fraction of the initial energy) at network lifetime for GMRE and RM, respectively.(The figures refer to networks with 64 sink sites.)

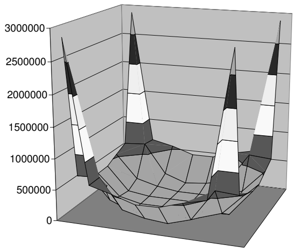

Fig. 1. GMRE: Sojourn times for 64 sink sites, $t_min = 100000$s

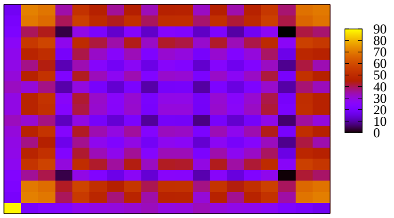

Fig. 2. GMRE: Node residual energy

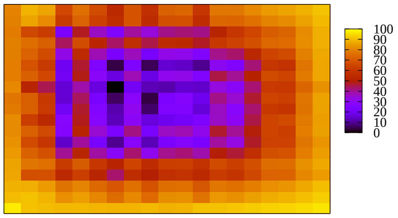

Fig. 3. RM: Node residual energy

V. ACKNOWLEDGMENTS

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