A New MILP Formulation and Distributed Protocols for Wireless Sensor Networks Lifetime Maximization

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Abstract— **This paper concerns the definition of an analytical model and distributed 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, different sink mobility rates, as well as the costs to support and perform data routing. Solutions to the model provide the route of the sink as a sequence of sites and the sojourn times at those sites that induce the maximum network lifetime. We then propose the *Greedy Maximum Residual Energy* (GMRE) protocol for sink mobility. GMRE 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 that GMRE leads to improvements in network lifetime that are four times as much as the lifetime when the sink is kept static, while balancing energy consumption throughout the network. At the same time, we show how the expected increases in data latency are reasonably contained.**

I. INTRODUCTION

In this paper we consider the problem of prolonging the time of operations (i.e., the *lifetime*) of a wireless sensor network (WSN). In particular, we are concerned with WSNs where a large number of energy constrained, irreplaceable wireless sensor nodes are deployed in a given geographic area. Sensed data are delivered to a collection point, often referred to as *the sink*, which is considered resource-rich, i.e., energy, processing power and memory are not limited resources.

Our work stems from the observation that when a sink is statically placed the sensor nodes that can directly communicate with it (the sink's *neighbors*) tend to deplete their energy faster than other nodes. They consume energy for transmitting their own data to the sink and also for relaying packets from any other node. This problem, here termed the "sink neighborhood problem," leads to a premature disconnection of the network. The sink gets isolated from the rest of the network due to the "death" by energy depletion of its neighbors while most of the sensors still have a good part of their initial energy.

One way of alleviating the sink neighborhood problem is by exploiting the mobility of some of the network components. The idea is changing the neighbors of the sinks so that the energy consumption for packet relaying is balanced throughout the network. Since moving the nodes would require extra power from the already limited energy of a node, the most promising way of changing the sink's neighbors is to have the sink itself move to different parts of the deployment area, while keeping the sensors static.

In this paper, we consider the problem of how to move the sink so that the network lifetime is maximized. Our aim is defining both an analytical formulation of this problem and distributed and localized heuristics that provide suitable sink movement patterns that lead to prolonged network lifetime.

The problem of controlling the mobility of the sink for reducing nodes energy consumption and hence obtaining extended network lifetimes has been previously tackled with in [1] and, more recently, in [2], [3] and [4]. In these works, centralized algorithms are presented based on Linear Programming (LP) formulations [1]–[3] and on a geographic traffic load model [4]. The sink moves among the (static) sensor nodes and, while sojourning at given locations, collects data that are sent to it via multi-hop routes.

The first work is mostly concerned with energy minimization. The authors present an ILP (Integer LP) model to determine the locations of multiple sinks and the routes from the sensors to the sinks. Time is divided into rounds. At the beginning of each round information on the nodes residual energy is centrally gathered and the ILP problem is solved to determine new, feasible locations the sinks should travel to for minimizing the maximum energy consumption spent at the nodes during that round. Minimizing the energy consumption results in increased network longevity. No constraints are enforced on the sink movements, and there is no relation between the number of the sinks and their position in subsequent rounds.

We first considered the problem of network lifetime max-

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imization through controlled sink mobility in [2]. Sink locations (in this case the sensor sites) and sink sojourn times at those locations are determined that maximize the network lifetime via a new LP formulation of the problem: Maximizing the network lifetime equals maximizing the combined sojourn times of the sink at the visited locations (referred to as *sink sites* in the following). The sink has no limitation on the time $t_k \geq 0$ it can spend at sensor k and can move (instantaneously, and at no cost) from any location to any other location in the network. Improvements on network longevity are obtained that are almost five-fold when the sink sojourns at the nodes located at the four corner areas and in the central area of the grid.

By combining the model presented in [2] and the LP formulation for maximum lifetime routing described in [5], Papadimitriou and Georgiadis [3] present another centralized solution for the problem of maximizing network lifetime. By turning a constant of the model in [2] into a variable, the model presented in [3] jointly solves the problem of determining the sink sojourn times at the given sites, and the routing of the packets to the current position of the sink. This (data) routing-dependent solution achieves improvements with respect to the lifetime values of [2] that are twofold.

The problem of lifetime maximization has been formulated as a min-max problem by Luo and Hubaux [4]. By considering together sink mobility and data routing, a load balancing solution is 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.

All these solutions are centralized, in the sense that either via an LP formulation or via an alternative min-max description of the problem, optimal sink routes and sojourn times are obtained as the output of a computation that needs as input global network parameters.

This paper contributes in multiple ways to the investigation about using controlled sink mobility for extending WSN lifetime.

First of all, we present a new Mixed Integer Linear Programming (MILP) model that determines sink route and sojourn times at the sink sites. Differently from previous solutions, we include parameters and constraints that model realistic requirements of a WSN. For instance, we consider the cost of moving the sink from a sink site to another, both from a data latency point of view (as packets need to be buffered during the sink movement) and from an energy consumption point of view (we consider the cost of building and releasing data routes from the sensors to the current position of the sink explicitly). Constrained movements of the sink are explicitly taken into account by introducing in the model the parameter d_{MAX} that limits the maximum distance the sink can travel while moving from a sink site to the following one. We also introduce constraints for considering the mobility rate of the sink, imposing a minimum sojourn time for the sink at the different sites. This allows an in-depth investigation on how lower or higher sink mobility affects network lifetime.

Our MILP model provides a *centralized solution* to the problem of finding sink routes and sojourn times that maximize network lifetime. Centralized solutions, however, are not suitable for most WSNs applications, since gathering the necessary input for the model (i.e., the whole network topology and the routing costs) would be unbearably time and energy consuming. The second contribution of this paper is the introduction of a completely distributed and localized protocol for sink mobility. Throughout the network lifetime the sink keeps moving as drawn by sink sites in energy-rich areas of the network. More specifically, the sink keeps monitoring the sites it is allowed to travel to (i.e., those sites whose distance from the current site is $\leq d_{MAX}$) with respect to the energy of the nodes around them. When one of these sites is in an area with higher energy, the sink greedily moves at that new site. Each time the sink travels to a new site, the network nodes are instructed to buffer both new packets and packets that are in transit toward the sink until the sink reaches the new position. Once at the new site, new routes are established from every node to the sink for packet delivery. To the best of our knowledge, this heuristic, that we term the *Greedy Maximum Residual Energy* (GMRE) protocol, is the first completely distributed and localized solution for sink mobility in WSNs.

Extensive ns2-based simulation experiments have been performed to demonstrate the effectiveness of GMRE in maximizing network lifetime. In particular, GMRE-induced lifetime has been compared with the lifetime obtained by three other sink mobility schemes. These schemes are the centralized MILP solution, a simple heuristic that has the sink roaming randomly through the sensor nodes (the *Random Movement*, or just RM, protocol), and the case where the sink is placed at the center of the deployment area. We have observed that up to fourfold improvements on network lifetime are obtained when the sink moves according to the GMRE protocol. Longer network lifetime is paid with longer data latency. This is a necessary trade-off, since when the sink is moving between sites data packets, whether new or in transit, are buffered until routes to the new position of the sink are established. Also, sink mobility might result in the sink sojourning at the border of the network (to drain energy there) leading to longer route lengths (which imply higher latencies) with respect to the case where the sink stays static at the center of the deployment area. Our simulations show, however, that the average end-to-end data latency in GMRE is always way below twice the case when the sink is static, which is the best case for this metric.

The rest of the paper is organized as follows. Section II defines the problem of controlled sink mobility and the scenarios we consider. The following Section III introduces the MILP formulation with its novelty, generality and strengths. The new distributed heuristics are described in Section IV. Simulation results are presented and explained in Section V. Section VI concludes the paper.

II. PROBLEM DEFINITION

We consider a scenario where a large number $|N|$ of resource constrained, static nodes with sensing and wireless communication capabilities are scattered in a given geographic area. (In the following these nodes are referred to as *sensor nodes*, or often, simply, nodes.) We assume periodic generation of packets at the sensor nodes: Node $i \in N$ transmits at a given data rate r_i packets that are "convergecasted" to the sink for processing. While the nodes are static, the sink can be mobile. More specifically, we consider a set $S = \{1, \ldots, q\}$ of q *sink sites* which are the locations within the geographic area the sink can visit. For instance, Fig. 1 shows a typical scenario where 32 nodes (represented by circles) are scattered randomly and uniformly on a bidimensional area, and 16 sink sites (squares) are organized in a 4×4 grid. A (solid) link between two nodes indicates that those two nodes are neighbors (i.e., they can hear each other's transmissions). A (dotted) link between two sites indicates that the sink can move from one site to the other and vice-versa.

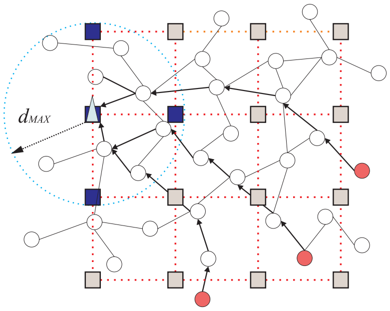


Fig. 1. Sensor nodes, sink sites, routes and sink movements

Because of the sink neighborhood problem the sink moves throughout the network in the attempt to balance the energy consumption among the nodes. Every time the sink reaches a new site, it floods a packet f to all the network nodes making them aware of its current location. A node that receives f starts sending/relaying its packets toward the new site of the sink. Every routing scheme that works with the topological information provided by f, such as geographic or shortest paths-based routing, is a viable routing for data delivery to the sink. We observe that the independence from the particular routing protocol yields a twofold advantage. First of all, it guarantees the longest possible network lifetime given the specific routing. Furthermore, it allows the network users to design or choose the routing algorithm that best meets the WSN applications requirements in terms of a host of different metrics of interest (not just the lifetime). 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 (packets in transit are buffered), and waits for the reception of 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 these delays, we introduce the 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 $\leq d_{MAX}$. Fig. 1 shows the three sites (darker squares) the sink (the triangle) can reach from its current position. (Routes from selected sensors to the current site of the sink are also shown.)

We observe that in case of fast sink mobility and low data traffic the energy cost for route construction and release can be significant, which imposes that this cost should be explicitly taken into account. In order to evaluate the impact of different (higher or lower) sink mobility rates, we introduce the parameter t_{min} to represent a mandatory minimum time the sink has to sojourn at a site.

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 *of the sink at each visited site* $k \in S$ *so that network lifetime is maximized.*

III. MATHEMATICAL MODEL

In this section we present a Mixed Integer Linear Programming (MILP) formulation of the problem described above.

Sets, parameters and variables

- S is the set of sink's sites, i.e., the locations at which the sink may sojourn: $S = \{1, \ldots, q\}$.
- N is the set of the network nodes: $N = \{1, \ldots, n\}$.
- e_0: Initial energy (Joules) of each node.
- f_{ik}: Energy consumption (Joules) at node $i \in N$ for setting up/releasing routes when the sink moves to/from site $k \in S$.
- c_{ik}: Power consumption (Watts) for receiving and transmitting packets at node $i \in N$ when the sink sojourns at site k.
- t_{min}: Mandatory minimum time (secs) for which the sink is required to stay at site $k \in S$.
- d_{jk}: Euclidean distance (meters) between any two sink sites $j, k \in S$.
- d_{MAX}: Maximum distance (meters) the sink is allowed to travel each time it moves.
- A: The set of directed edges joining sink sites whose distance is less than or equal to d_{MAX}, i.e., $A = \{(j, k) \in S \times S : j \neq k, d_{jk} \leq d_{MAX}\}$.
- O: The set of directed edges $(0, k)$, $k \in S$, joining a fictitious site 0 (origin) with the sites in S.
- D: The set of directed edges $(k, q+1)$, $k \in S$, joining the sites in S with a fictitious site $q+1$ (final destination).
- X: The union of A, O and D.
- t_k: Sojourning time (secs) of the sink at site $k \in S$.
- y_k: Binary variable taking the value 1 if the sink sojourns at site $k \in S$ ($t_k > 0$); 0 otherwise ($t_k = 0$).
- x_{jk}: Binary variable indicating the status of $(j, k) \in X$. $x_{jk} = 1$ if and only if arc (j, k) is on the sink movement route; $x_{jk} = 0$ otherwise.
- u_k: Auxiliary variable used to enforce a unique sink path.

MILP formulation

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

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

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

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

$$\sum_{k \in S} x_{k,q+1} = 1 \tag{5}$$

$$\sum_{\substack{j \in S \cup \{0\} \\ (j,k) \in O \cup A}} x_{jk} = \sum_{\substack{j \in S \cup \{q+1\} \\ (k,j) \in A \cup D}} x_{kj} \quad (k \in S) \tag{6}$$

$$\sum_{\substack{j \in S \cup \{0\} \\ (j,k) \in O \cup A}} x_{jk} = y_k \quad (k \in S) \tag{7}$$

$$u_j - u_k + q x_{jk} \leq q - 1 \quad ((j,k) \in A) \tag{8}$$

$$t_k, u_k \geq 0 \quad (k \in S) \tag{9}$$

$$y_k \in \{0,1\} \quad (k \in S) \tag{10}$$

$$x_{jk} \in \{0,1\} \quad ((j,k) \in X) \tag{11}$$

The objective function (1) maximizes the sink's total time at sojourning sites, which is the effective network lifetime.

Constraint (2) states that the combined energy spent for data delivery and data route construction and release should not exceed the node's initial energy. The right part of double inequality (3) forces y_k to take the value 1 if the sink sojourns at site k ($t_k > 0$), thus linking the binary variable y_k with the continuous variable t_k. M is a significantly large number. The left part of double inequality (3) restricts the sojourn time t_k to be at least equal to the mandatory minimum sojourn time t_{min} if the sink sojourns at site k ($y_k = 1$) and at the same time forces y_k to take the value 0 if the sink does not sojourn at site k ($t_k = 0$).

The first sojourning site in the sink's movement path is allowed to be any site in S. To implement this, we introduce a fictitious fixed initial site 0 (origin). At the beginning of the sensor network's lifetime, the sink moves in zero time (and cost) from the origin to some site $k \in S$. Then, it sojourns at that first site and at subsequent other sites in S to be determined by the model. Finally, from the last sojourning site the sink moves to a second fictitious site "q+1" (destination), again in zero time, thus completing a path from the origin to the destination that marks the end of the sensor network's lifetime. The arcs $(j,k) \in X$ on that path are associated with binary variables x_{jk} equal to 1. The variable x_{jk} is equal to 0 for all the $(j,k) \in X$ that do no belong to the path. Equivalently, one can think of a unit of flow moving from the origin to the destination. Constraint (4) induces a unit of flow from the origin to some node $k \in S$, while constraint (5) causes the destination to absorb a unit of flow coming from some node $k \in S$. Constraint (6) forces flow conservation at all sites $k \in S$, thus ensuring the generation of a path. Constraint (7) ensures that the nodes $k \in S$ on the generated path are sites at which the sink sojourns ($k | y_k = 1$). To elaborate, if y_k in constraint (7) equals 1, then the sink sojourns at site k, and therefore there must be one and only one arc on the sink's movement path reaching site k. On the other hand, if y_k equals 0, then there will not be any incoming arc in that site. We notice that flow conservation constraint (6) and constraint (7) do not prevent the formation of cycles disjoint from the path from the origin to the destination. Constraint (8) ensures that no such cycles are formed. A similar constraint has been used in the integer programming formulation of the Traveling Salesman Problem (TSP) to avoid sub-tours [6]. Constraint (9) requires that decision variables t_k and auxiliary variables u_k be non-negative. Constraints (10) and (11) restrict variables y_k and x_{jk} to values in $\{0, 1\}$.

Some comments are in order. The parameter t_{min} has been introduced to assess the effect of different (higher or lower) sink mobility rates on network performance. For a given t_{min} the model will produce the sink route and sojourn time $t_k \geq t_{min}$ at site k that maximize network lifetime. By varying the t_{min} we can explore a number of trade-offs. For instance, at higher t_{min}s we expect to have lower overhead (e.g., for route construction and release). Shorter t_{min}s result in better choices of sojourn times at different sites (which imply a longer network lifetime) at the price of increasing overhead.

The model leaves degrees of freedom for what concerns determining the power consumption rate c_{ik} of each node $i \in N$ when the sink sojourns at site $k \in S$. This cost depends on both node i's transmission rate r_i and on the particular protocol for routing the packet to the sink sojourning at site k. The costs c_{ik}s could be computed analytically [2], or they can be provided as input to the model from simulations or from real-data traffic traces, i.e., the model can be customized to find the optimum lifetime for different routing protocols (by computing the corresponding values of f_{ik} and c_{ik}).

Constraint (8) renders infeasible all cycles formed by the nodes in S, thus allowing only a unique simple path. We notice, however, that the model can be easily extended to allow the sink to sojourn at the same site multiple times. A single "physical" site can be represented by h "logical" sites, where h is the number of times we want the sink to be able to pass through that site. The logical sites have no arcs between them, and are connected to all the (logical) sites of adjacent (physical) sites. With this simple modification we obtain the optimal lifetime given that the sink is allowed to visit each site at most h times. The global optimum is achieved by progressively running the solver of the model on increasing h values until the lifetime stabilizes.

Our MILP formulation improves over previously proposed models in multiple ways. The model is independent of a number of factors such as the specific sensor node deployment and sensor density; the sink site topology; the size and shape of the geographic area of deployment, and the sensor node technical features (e.g., transmission radius, energy model, etc.). Moreover, the model includes a number of realistic constraints, such as the non-instantaneous movement of sink between sites potentially far apart from each other. Finally, differently from all previously proposed LP solutions, our formulation explicitly includes the costs for changing sink sites.

IV. DISTRIBUTED PROTOCOLS

In this section we describe the details of the two new distributed protocols for sink mobility that we are going to compare with the optimal routing strategy provided by the MILP model.

The two protocols differ in the strategy with which the sink sojourning at a site chooses the next one.

In the Greedy Maximum Residual Energy (GMRE) protocol the sink greedily selects the site within d_{MAX} surrounded by nodes that have the most energy left. The idea is that in time, this should most likely result into a balanced energy consumption throughout the network, and hence into a longer network lifetime. After spending a time t_{min} at a site, a sink evaluates whether to move toward one of the adjacent sites or to stay where it is. Two sites are adjacent if their distance is $\leq d_{MAX}$. In order to decide whether to move or not, the sink gathers information about the minimum 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 protocol we assume that a node that is in the "transmission vicinity" of a site (i.e., whose Euclidean distance from a site is less than or equal to the nodes transmission range) is aware of that. This can be obtained by endowing the nodes with a suitable localization mechanism, or by providing this information to the nodes themselves 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 sites 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 minimum of the obtained values (or any suitable function that can express how critical for the network lifetime is to place the sink in that area).

The second, simple protocol for sink mobility that we propose here captures the case of uncontrolled, random mobility of the sink. Every t_{min} 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, the sink moves to that site. This simple scheme, referred to in the following as the Random Movement heuristic (*RM*), generalizes data gathering protocols previously proposed in the literature (e.g., the data mules approach [7]) to the case of multi-hop data routing. We use RM mainly as a benchmark for assessing the effectiveness of GMRE in prolonging network lifetime.

V. SIMULATION RESULTS

In this section we discuss the results of a thorough ns2-based performance evaluation of the presented protocols. In particular, we have compared the following four sink mobility schemes. (1) The sink is static. This is a degenerate mobility scheme. So degenerate, in fact, that the sink does not move. In this case, that we name STATIC, the sink is placed at the geographical center of the deployment area, which is the position that maximizes the network lifetime. (2) The sink moves along the optimum route derived by the MILP model presented in Section III (OPT mobility in the following). (3) The sink moves according to the RM scheme. (4) The sink moves as specified by the GMRE heuristic.

The performance of the four schemes have been compared with respect to the average network lifetime (defined as the time until the first node dies having fully depleted its energy), and with respect to the average end-to-end latency experienced by the data packets, i.e., the time that goes from packet generation at a sensor node to the successful delivery of that packet at the sink.

Our simulations refer to scenarios in which $N = 400$ sensor nodes are deployed in a grid-like topology over a square area of side $L = 400$m. The sensor nodes transmission range is fixed and equal to 25m. This means that all nodes which are not on the perimeter of the area have a "cross-like visibility" of their neighbors (i.e., they have four neighbors). A single sink moves through $|S|$ possible sites. Sink sites are arranged into a 4×4, 6×6, 8×8 matrix-like structure. The model parameter d_{MAX} has been set to 190m.

We consider the sensor nodes to be all alike and equipped with 50 Jules of initial energy. The transmission radius is set to 25m. The energy model used in our experiments follows the specifications of the TR 1000 radio transceiver from RF Monolithics, i.e., the energy consumption corresponding to transmission and reception is 14.8mW and 12.5mW, respectively. Sensor nodes generate data at the fixed rate of $r = 0.5$bps. Channel capacity and MAC settings are typical of sensor networking (250Kbps and CSMA/CA, respectively). Data delivery to the sink is performed by using the simple routing protocol presented in [8], which is representative of a wide class of routing schemes for WSNs. The route construction process is sink initiated. The sink floods a packet via which the nodes calculate their hop distance from the sink. Routing happens based on this simple (and unchanging) information: A node that is i hops away from the sink will send data packets to one of its neighbors whose distance is $i - 1$. The specific neighbor can be different each time, and it is chosen among all possible neighbors randomly and uniformly. Finally, in order to assess the advantages of sink mobility independently of the particular awake/asleep scheduling used for energy conservation we did not consider the energy consumed by the node while being idle or asleep.

All the presented results achieve a 95% confidence level within a 5% precision.

Fig. 2 shows the sensor network lifetime in networks with different numbers of sink sites and for values of t_{min} that vary between $50,000$s and $1,000,000$s. Each figure compares the lifetime obtained by OPT, GMRE, RM and STATIC. The lifetime in the static case is equal to $7,013,801$s (of course independently of t_{min}). This is the time when one of the four sink's neighbors (i.e., the nodes that relay all the network data to the sink) dies because of energy depletion. The other three nodes remain with negligible amount of energy, dying immediately after the first. This leaves the sink isolated from the rest of the network.

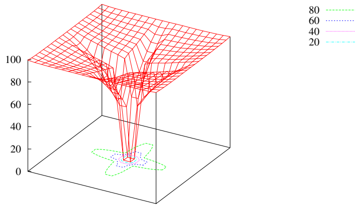


Fig. 3. Average residual energy at lifetime (STATIC, 16 sink sites)

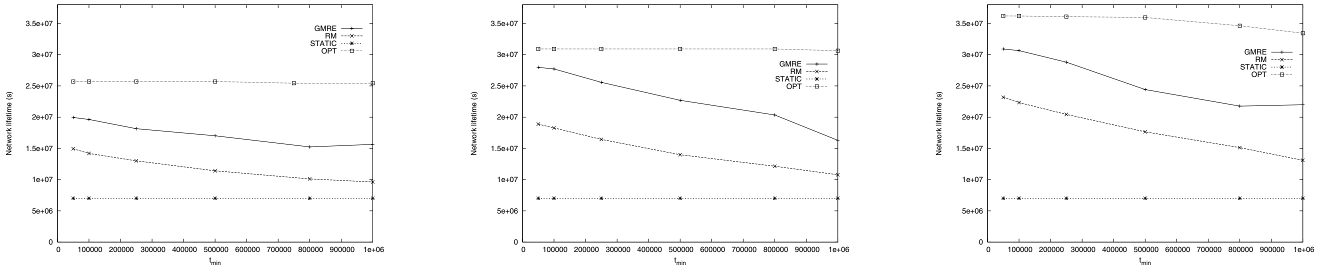
The uneven energy consumption of STATIC is shown in Fig. 3, where we depict the distribution of the sensor nodes average residual energy at network lifetime (expressed as a percentage of the initial energy.) The remarkably high variance among the residual energies is due to the different distance of each node from the sink and, in general, to the different number of sensor-to-sink paths to which a node belongs, which implies different number of packets to relay. Nodes along the "cross" centered at the sink tend to be the preferred data relays. The closer these nodes are to the sink, the higher the number of packets they receive and transmit, and consequently the higher their energy consumption. This implies that these are the nodes with the lower residual energy at network lifetime. In particular, when the first node dies the other sink's neighbors have a very low residual energy ($\leq 0.03\%$), the energy at the nodes along the cross arms averages at 71.07%, while 42.75% of the network nodes have more than 95% of their initial energy available! This incapacity of balancing node energy consumption results in short network lifetime and inefficient use of available resources: The network is soon unable to be fully operational while a large number of the deployed nodes still are.

The idea of moving the sink stems from the attempt of obviating to the sink's neighborhood problem demonstrated by the experiments above. If the sink can move, the nodes which consume the most energy for data relaying vary over time, thus balancing energy depletion and resulting in increased network lifetime. Improvements with respect to the static case can be as high as 200% (350%) when the sink moves according to GMRE in scenarios with 16 (64) sink sites. In this case the GMRE lifetime is only from 16 to 28% shorter than the OPT lifetime when t_{min} is kept below $\leq 250K$s.

Improvements on network lifetime are obtained even when the sink moves randomly (RM heuristic). We have observed improvements short of 100% in case the sink can travel to 16 different sites, while longer lifetimes ($\leq 220\%$) are obtained in scenarios with 64 sink sites.

In general, for both GMRE and RM, the lower the t_{min}, the higher the network lifetime. This is due to the fact that at higher t_{min}s the sink cannot finely decide the time to spend at each site, which implies a less uniform energy consumption at the nodes. For very high t_{min}s it is not even possible for the sink to sojourn at all network sites: Lifetime is reached before the sink can visit them all.

Even in the case of OPT mobility, lower t_{min}s correspond to longer lifetimes. In this case, however, the decrease in the network lifetime when t_{min} grows is not as evident as for GMRE and RM. It is interesting to point out the reasons for which this is the case. First of all, in the OPT case t_{min} is simply a lower bound on the sojourn time: The sink has to stay there for that time, but does not have to move after it, and can stay an (optimum) amount of time after t_{min} and then move. In case of GMRE and RM dictated sink mobility, the decision about whether to move or not is due every t_{min} (after which the sink often moves). This has a twofold consequence. On one side, increasing t_{min} is more imposing for GMRE and RM than for OPT in terms of fine tuning the sojourn time at a site. Moreover, being able of deciding optimum sojourn times implies much lower sink mobility in the OPT case, which corresponds to lower overhead for route management and hence to lower energy consumption with respect to that incurred by GMRE and RM. Secondly, GMRE and RM do not have a global view of the network topology and do not know the network traffic, i.e., how the nodes energy consumption evolves over time, resulting in decreased performance with respect to OPT. The RM heuristic does not enforce any energy-based criterion for sink movement, resulting in the worst



(a) 4 × 4 sink sites

(b) 6 × 6 sink sites

(c) 8 × 8 sink sites

Fig. 2. Average network lifetimes for increasing t_{min}s

performance among all the mobility schemes. Even if GMRE takes into account nodes residual energy, the decision about whether to move or not, and where, is based on the current status of the network and on a local view of the residual energy. According to the best "greedy" tradition, this could lead to a bad move with respect to global network lifetime maximization. The impact of such bad move is clearly higher for high t_{min}s: The wrong toll is paid for a longer time.

The OPT mobility performance also degrades for higher values of t_{min}. In this case it converges to values that are typical of when the sink is kept static. For instance, for values of t_{min} approaching 7.013.801s the MILP model positions the sink at one of the sites in the center of the deployment area and leaves it there (static). However, for what explained above, increasing values of t_{min} are less critical in case of OPT mobility than in case of GMRE and RM, and OPT network lifetime values start to decrease steeply at very high t_{min}s (not shown in the figures). Considering that OPT needs global information for deriving optimum sink mobility and sojourn times, and considering also the more "philosophical," algorithmic differences between OPT and GMRE mobility, the fact that our heuristic never obtains network lifetimes more than 28% lower than OPT's, for relatively low sink mobility rate (small t_{min}s), can really be considered an excellent result.

Increases in network lifetime obtained because of the sink traveling from site to site are paid in term of increased data packet latency. The reasons are quite clear. First of all, packets that are generated while the sink is moving and those in transit toward the sink, have to wait until routes to the new position of the sink are established. Furthermore, in order to balance energy depletion, the sink will spend time not only at the center of the deployment area but also along borders. This imposes longer average routes and hence a higher packet latency than the latency experienced when the sink is statically placed at the center. The latter is actually the dominant reason for increased latency in low sink mobility scenarios.

To better understand the average end-to-end latency experienced by a data packet, we started by investigating the sojourn times of the sink in different parts of the deployment area according to the considered mobility schemes. We observe that the two sink mobility schemes that achieve the highest network lifetimes, i.e., OPT and GMRE, tend to make the sink sojourning at sites on the corners and along the perimeter. This depends on the energy consumption at the nodes when the sink stays at the different sites. More precisely, when the sink sojourns at a corner (say, in the lower left part of the deployment area) the highest energy consumption happens close to the sink site, for nodes at the lower and left sides of the area. When the sink is on the perimeter (e.g., on the lower side) the highest energy consumption occurs on the perpendicular line intersecting the lower side at the sink location, and less evidently on the lower side itself. When the sink is located close to the center of the deployment area nodes along the cross centered at the sink site are the most stressed in terms of energy consumption (Fig. 4). In the latter case as there are more nodes within transmission range from the sink they better load balance the energy consumption for delivering to the sink the packets generated by the other nodes. This translates into a lower energy consumption experienced at the nodes close to the sink. However, nodes in the central areas always consume energy, independently of where the sink is located. The energy consumption for center nodes can be very high not only when the sink is located at the center but also when it is on the perimeter. Locating the sink at the center thus drains energy from critical nodes whose energy will be continuously depleted over the network lifetime. Locating the sink at the corners for long times instead appears to be a very promising strategy, as it depletes the energy of nodes which experience very little energy consumption when the sink is at any of the other sites. This motivates the behavior of the GMRE and OPT schemes. OPT leads to further improvements over GMRE as it exploits the available global information on the energy consumption per node when the sink stays at a site and on the traffic to better select the sink sojourn times. For example, if placing the sink at two sites stresses the same nodes, the OPT scheme will tend to avoid spending long sojourn times in both the two sites. Overall, the finer tuning of the sojourn times leads OPT to better load balance the energy consumption among the nodes, and hence to longer lifetimes. At network lifetime around 20% (60%) of the nodes have consumed more than 80% of the initial energy in GMRE (OPT). This was the case for only the 1% of the nodes in STATIC.

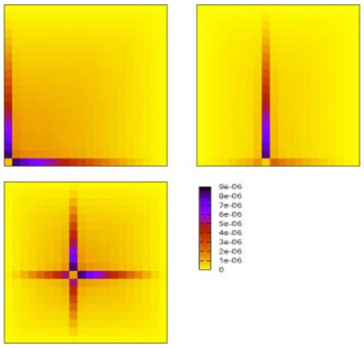


Fig. 4. Nodes energy consumption for sink at different sites

Given its stochastic nature, the RM heuristic positions the sink mostly at the center of the deployment area, resulting in worse load balancing and lower network lifetime. This is clearly shown in Fig. 5 which depicts the average sojourn times per site in the case of networks with 64 sites, for OPT, GMRE and RM.

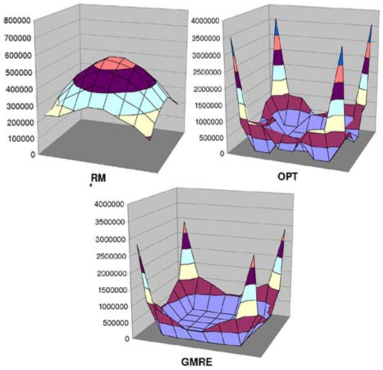


Fig. 5. Average sojourn times ($t_{min} = 50$K)

TABLE I

AVERAGE PACKET LATENCY (SEC)

	4×4 sink sites		8×8 sink sites	
t_{min}	50K	1M	50K	1M
OPT	.31	.31	.315	.315
GMRE	.32	.30	.32	.29
RM	.27	.28	.25	.26
STATIC	.19	.19	.19	.19

It is now possible to fully understand the latency performance of the different schemes. Table I reports the average data latency incurred by packets in OPT, GMRE, RM and STATIC for scenarios with 16 to 64 sink sites. We considered values $t_{min} = 50,000$s and $= 1,000,000$s. (Intermediate values are consistent with these ones.) We observe that no packet ever generated is lost, and hence that all packets are successfully delivered to the sink. When the sink sojourns at perimeter or at corner sites (which is typical of GMRE and OPT) we know that the lifetime increases. However, these are also the cases when the average length of the routes to the sink increases, which implies, in turn, a higher packet latency. It is thus reasonable to expect that lower latencies are experienced when the sink is statically placed at the center of the sensor deployment area. The RM heuristic, which tends to move the sink to sites located centrally, is the second best mobility scheme in terms of latency. The increase with respect to STATIC is expectedly lower when the number of sink sites increases, since in this case central sites are closer to the geographical center of the deployment area. This increase never tops 40%. As t_{min} increases the sink tends to stay less at central sites, leading to higher average latencies experienced by RM packets. The opposite trend is observed for GMRE. For small t_{min}s the sink stays at sites on the corners and on the perimeter, which leads to average latencies up to 30% higher than those experienced in the RM case. When t_{min} increases the sink sojourns less at corner sites, which implies a decrease of the average latency. Finally, optimum sink mobility is not significantly affected by varying t_{min} in the selected range, and the latency values are similar to those observed for GMRE.

VI. CONCLUSIONS

In this paper we considered the problem of prolonging network lifetime for wireless sensor networks comprised of energy constrained nodes. We propose solutions for which energy consumption is balanced among the network nodes by having the sink moving throughout the network. Network lifetime maximization is achieved by solving a new MILP formulation that takes into account key parameters of sensor networking. Distributed solutions are also presented and evaluated via extensive simulations. By just using locally available information such distributed schemes obtain remarkable improvements on network lifetime with respect to the case of a static sink optimally placed.

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