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Reducing the Hot Spot Effect in Wireless Sensor Networks with the Use of Mobile Data Sink

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REDUCING THE HOT SPOT EFFECT IN WIRELESS SENSOR
NETWORKS WITH THE USE OF MOBILE DATA SINK

A Thesis

Submitted to the Graduate Faculty of the
University of New Orleans
in partial fulfillment of the
requirements for the degree of

Master of Science
in
Computer Science

by

Yacine Chikhi

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Abstract

The Hot Spot effect is an issue that reduces the network lifetime considerably. The network on the field forms a tree structure in which the sink represents the root and the furthest nodes in the perimeter represent the leaves. Each node collects information from the environment and transmits data packets to a “reachable” node towards the sink in a multi-hop fashion. The closest nodes to the sink not only transmit their own packets but also the packets that they receive from “lower” nodes and therefore exhaust their energy reserves and die faster than the rest of the network sensors.

We propose a technique to allow the data sink to identify nodes severely suffering from the Hot Spot effect and to move beyond these nodes. We will explore the best trajectory that the data sink should follow. Performance results are presented to support our claim of superiority for our scheme.

I Introduction:

I.1 Background:

Recent researches in wireless communications and digital electronics have allowed the development of low-cost and low-power multifunctional sensor nodes. Those devices are small in size and communicate in short distances.

The sensors, which role consists of sensing, processing data partially, and communicating components, leverage the idea of sensor networks based on collaborative effort of a large number of nodes to collect and process data.

Sensor networks represent a significant improvement over traditional sensors, which are deployed in the following two ways:

Firstly, sensors can be positioned far from the actual phenomenon, i.e., something known by sense perception. In this approach, large sensors that use some complex techniques to distinguish the targets from environmental noise are required.

Secondly, several sensors that perform only sensing can be deployed. The positions of the sensors and communications topology are carefully engineered. They transmit time series of the sensed phenomenon to the central nodes where computations are performed and data are fused.

A sensor network is composed of a large number of sensor nodes, which are densely deployed either inside the phenomenon or very close to it.

The position of sensor nodes does not need to be engineered or pre-determined. This allows random deployment in inaccessible terrains or disaster relief operations. Sensors can be literally dropped within the targeted field. On the other hand, this also means that sensor network protocols and algorithms must possess self-organizing capabilities.

Another unique feature of sensor networks is the cooperative effort of sensor nodes. Sensor nodes are fitted with an on-board processor. Instead of sending the raw data to the nodes responsible for the fusion, sensor nodes use their processing abilities to locally carry out simple computations and transmit only the required and partially processed data.

The above described features ensure a wide range of applications for sensor networks. Some of the application areas are health, military, and security.

Sensor networks can also be used to detect foreign chemical agents in the air and the water. They can help to identify the type, concentration, and location of pollutants. In essence, sensor networks will provide the end user with intelligence and a better understanding of the environment.

We envision that, in future, wireless sensor networks will be an integral part of our lives, more so than the present-day personal computers.

Realization of these and other sensor network applications require wireless ad hoc networking techniques. Although many protocols and algorithms have been proposed for traditional wireless ad hoc networks, they are not well suited for the unique features and application requirements of sensor networks. To illustrate this point, the differences between sensor networks and ad hoc networks are outlined below:

- The number of sensor nodes in a sensor network can be several orders of magnitude higher than the nodes in an ad hoc network.
- Sensor nodes are densely deployed.
- Sensor nodes are prone to failures.
- The topology of a sensor network changes very frequently.

- Sensor nodes mainly use broadcast communication paradigm whereas most ad hoc networks are based on point-to-point communications.

- Sensor nodes are limited in power, computational capacities, and memory.

- Sensor nodes may not have global identification (ID) because of the large amount of overhead and large number of sensors.

Since a large number of sensor nodes are densely deployed, neighbor nodes may be very close to each other. Hence, multi hop communication in sensor networks is expected to consume less power than the traditional single hop communication. Furthermore, the transmission power levels can be kept low, which is highly desired in covert operations.

Multi hop communication can also effectively overcome some of the signal propagation effects experienced in long-distance wireless communication.

Sensor networks may consist of many different types of sensors such as seismic, low sampling rate magnetic, thermal, visual, infrared, acoustic and radar, which are able to monitor a wide variety of ambient conditions that include the following: temperature, humidity, vehicular movement, lightning condition, pressure, soil makeup, noise levels, the presence or absence of certain kinds of objects, mechanical stress levels on attached objects, and the current characteristics such as speed, direction, and size of an object.

Sensor nodes can be used for continuous sensing, event detection, event ID, location sensing, and local control of actuators. The concept of micro-sensing and wireless connection of these nodes promises many new application areas. We categorize the applications into military, environment, health, home and other commercial areas. It is possible to expand this classification with more categories such as space exploration, chemical processing and disaster relief.

One of the most important constraints on sensor nodes is the low power consumption requirement.

Sensor nodes carry limited, generally irreplaceable, power sources. Therefore, while traditional networks aim to achieve high quality of service provisions, sensor network protocols must focus primarily on power conservation. They must have inbuilt trade-off mechanisms that give the end user the option of prolonging network lifetime at the cost of lower throughput or higher transmission delay.

I.2 The Hot Spot Effect:

Many researchers are currently engaged in developing schemes that fulfill these requirements.

Actually, most of the latest studies mainly focus on different algorithms, transmission protocols and aggregation techniques to save power and extend the network lifetime.

This work falls under the same purpose, treating specifically a critical aspect of a multi-hop network lifetime: *the Hot Spot effect*.

The Hot Spot effect is a major issue affecting network lifetime, often causing the collapse of the system when there are still energy resources within a large group of its nodes.

The network topology varies depending on the purpose it serves and the field dispositions it needs to adapt to. Sometimes many data sinks are needed to collect information from sensors that are widely spread, but most wireless sensor networks are composed of sensing nodes and a unique, fixed, central data sink that collects the information from those nodes in a multi-hop transmission fashion.

The Hot Spot effect is created by the traffic pattern established among the network nodes. Each node in the network will transmit to the closest node to its position towards the data sink.

Once that node receives those information packets, it forms new packets that include both received data and information sensed and pre-processed by the node itself. Then, using the same transmission pattern it transmits to the next node.

Based on this transmission pattern, the closest nodes to the data sink will generally have more packets to (re)transmit to that sink, and will run out of energy earliest. When these nodes run out of energy, holes may be created in the network in critical areas of the system: the node layer the surrounds the sink and forwards network data to it. These holes may lead to collapse of network functionalities since farther sensors might not be able to transmit to the data sink anymore.

Intermediate sensors are not only needed to sense and process field information but fulfilling their “router” role is as much crucial.

A major trade-off in a tree-based transmission structure is the uneven energy consumption among sensors. The Hot Spot nodes (the ones in the Hot Spot region) exhaust their resources faster and cause the collapse of the system while other, farther nodes might still have enough energy to sense, process and transmit information. Optimizing the energy consumption distribution is a major key in extending the network lifetime.

In this work, we try to mitigate the adverse impact of the Hot Spot effect on the network lifetime. Since this effect is based on the fact that a node has many packets from “lower” nodes to transmit, we propose a technique to move the data sink in order to reduce the transmission load of these nodes. Our goal is to balance the energy consumption among nodes to a certain level and prolong the network lifetime.

Talking about a mobile data sink involves naturally changing the transmission tree structure of the system, feature that we base our approach on to balance the energy consumption within the network.

In this work, we demonstrate the performance gain of allowing the data sink to move to certain locations. In that matter it is important to build a realistic 2-D model with a widely used data transmission scheme. For that model we must determine the optimal lifetime when using a fixed sink and then apply our scheme for performance evaluation.

The modeling process is first implemented through a simplified 1-D model. Our 1-dimensional network is not meant to represent any real-life application but serves the purpose of modeling the energy consumption pattern and establishing an energy consumption formula, used throughout this work.

The determination of the optimal fixed sink position is necessary, not only to allow the estimation of the optimal network lifetime, but to determine the path of our mobile data sink as well. A general formula to estimate the sink's optimal position will be presented in this work in that matter.

In our discussions, we consider several real-world applications: some regions of the network might have a higher node density than others and that might (should) affect the optimal position of the sink. Some regions might also collect more information and therefore will have a higher traffic rate towards the sink, and we shall see that it affects the optimal position of the data sink as well.

We will demonstrate that the challenges of designing a mobile data sink technique lie in establishing the path that the data sink shall take and determining the time period that needs to be spent in each position. Such time spans should be estimated according to the traffic pattern sensed and the geographical position of the surrounding nodes.

The sink needs to move towards the regions that have a high traffic rate to relief them from their load without “neglecting” regions of lower priority. The time span in each region is a key in determining the degree of assistance that the data sink motion provides to each area.

Plus, the sink should be able to give a “directional importance” to the traffic rate that it receives, and that should help it to evolve within the network. Data sink being larger devices than the regular sensors, they might be equipped with a GPS system, allowing them to identify and transmit their exact position, along with a directional antenna that is used not only to collect information but also recognize the direction of the transmitting source. With these two important features, the data sink has a precise knowledge of the traffic pattern surrounding it.

This work proposes a mobile data sink scheme that relieves the Hot Spot nodes from their transmission load, balances to a certain extent the energy consumption among sensors in order to extend the network lifetime.

I.3 Thesis Organization:

The remainder of this thesis is structured as follows: in Chapter II, we review the related work: what has been proposed in a matter of extending the network lifetime in general. We present our technique and discussions in Chapter III. Performance evaluations are presented in Chapter IV, stressing the enhancement that a mobile data sink brings compared to a fixed data sink. In Chapter V, we summarize the work. Finally, Chapter VI proposes ideas, possible future researches related to our scheme.

II Related Work:

Energy saving is a major research topic for Wireless Sensor Networks and many interesting studies have been proposed over the years to extend those networks' lifetime. Several latest studies focused on actual transmission protocols, information aggregation techniques, and transmission tree restructuring to increase the network lifetime [1,3,5,9]. Nevertheless, the concept of a mobile data sink has not been widely considered.

The reason is related to the difficulty of controlling a mobile data sink. As mentioned in our introduction, sensors are often placed in inhospitable environment with geographical topologies that do not allow easy access to the network devices. We argue that our mobile scheme determination is computable by a sensor device and therefore doesn't require any human assistance while evolving around the studied field.

Nevertheless, few researches based their work on networks with mobile data sinks, although not stressing the importance of the sink mobility in reducing the Hot Spot Effect.

The SEAD protocol [6] for instance has been established to take advantage of the mobile data sink technique to reduce the energy consumption while restructuring the transmission tree. It considers low-density networks with multiple data sinks without taking advantage of those devices' motion to reduce the Hot Spot Effect. Instead, it emphasizes efficient transmission path establishment.

SEAD proves that multiple transmission tree restructuring can be less expensive energy-wise than direct diffusion and multicast transmission protocols, both very used in Wireless Sensor Networks. This remark concerns our work directly since our Mobile Data sink involves renewing

the system topology constantly. We will demonstrate that the trade-off of that process confirms what SEAD indicated in that matter in IV.3.

The relatively short average lifetime of a sensor is a major concern in this type of networks. Efficient energy-saving dissemination protocols, such as SEAD, are crucial since the transmission-tree of the system needs to be constantly rebuilt.

Thus, research [5] considers a shortest path transmission scheme that increases significantly the network lifetime compared to a basic multi-hop transmission scheme with a fixed data sink. We shall see in Chapter IV that we propose a variant of that multi-hop approach based on an important assumption: all nodes are informed of the data sink position at all time.

As seen in [5,7,8], the data sink can be a powerful device equipped with a GPS, a directional transmission/reception antenna and a powerful energy reserve; in our case the data sink is able to broadcast its position to all its sub-nodes in order for them to forward their packets to it.

Broadcasting packets in a Wireless Sensor network is a common procedure, but our scheme only requires this operation from the sink.

Research [4] proposes an energy balanced propagation scheme to normalize the consumption among all nodes, which reduces significantly the Hot Spot effect. The scheme is based on a probabilistic approach determining if a sensor node should transmit to the next 1-hop away sensor towards the sink or increase its transmission range instead and transmit directly to the sink. The decision is made based on the energy level of the transmitting node's neighbors.

In our performance evaluation, we will compare our scheme's throughput to the one obtained in [4] and discuss trade-offs of both techniques.

Our transmission pattern is based on a multi-hop transmission as it has been assessed in several other research projects [1,3,10] and is detailed in Chapter IV.

Unlike conventional wireless ad hoc networks, a wireless sensor network potentially comprises of hundreds to thousands of nodes [8]. The sensors have to operate in noisy environments and, in order to achieve good sensing resolution, higher densities are required. Therefore, in a sensor network, scalability and optimal energy usage are crucial factors.

Energy maps have been proposed in that matter. Sensors keep track of the energy level of all their 1-hop away neighbors and decide what the most appropriate node to transmit to is, based on that knowledge.

The energy map technique is widely used [11] and allows a considerable network lifetime extension compared to a “basic” scheme where the sensor only transmits to the closest node in range towards the sink.

Our scheme uses a hybrid energy-map technique since each sensor has knowledge of the energy level of all 1-hop away neighbors but transmits to the closest in range towards the sink persistently until that node fails (see III).

This approach keeps the number of tree restructuring down compared to a regular technique where each node tries to balance its packet distribution among its neighbors.

We will explore trade-offs between the two energy map variants as well in Chapter IV.

III Details of the Mobile Data Sink scheme:

III.1 Assumptions:

Wireless sensor networks vary in their topology, density, and transmission protocols depending on the field that they are sensing and the level of data generation that is expected from them.

We present our assumptions of the network that we studied as followed:

- The number of sensors in a network can easily reach hundreds to thousands. Our work maintains a reasonable node density within the proposed network: average of 1 node per meter square.

- Our network relies on a unique data sink to collect data from all sensors in the network. Transmissions towards the sink are made in a multi-hop fashion unless the data sink is in the range of the transmitting node;

- Depending on the studied phenomenon, nodes can either generate data when sensing an important event, or sending updates periodically towards the sink. In this work, every sensor node generates a fixed rate sensing results and these results need to be delivered to the unique data sink of the network;

- We assume that the data sink has certain mobility capability while all other nodes are fixed. In common sensor networks, the sensors might have a very restrained mobility due to independent field factors, but their mobility is often neglected since it has no effect on the system transmission structure and the energy dissipation caused by the displacement is minimal compared to the cost of a single packet transmission. Therefore, we will not consider mobile sensors in our application;

- The data sink is the only device equipped with a GPS and a powerful transmitting antenna. Therefore, it is responsible for partially processing all sensed data and forwarding it to a satellite/user for final analysis. Regular sensor nodes only have limited knowledge of the network. They only have directional information of the location of their 1-hop away neighbors [8]. They do not use multicast in that matter but node-to-node transmission.

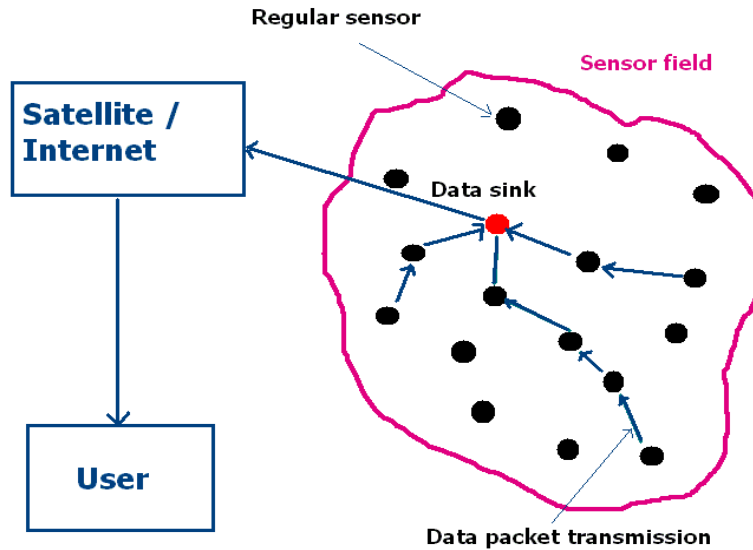


Figure 1: Data transmission pattern in a Wireless Sensor Network

III.2 Path Establishment for Data Sink Motion:

III.2.1 Motivation:

If the sink wants to move and break the tree structure of the network to reduce the Hot Spot effect, it should pass the position of the overloaded node and sit between its position and the rest of the lower nodes in that high density region. Nevertheless, doing so will only extend the problem to the very next node down the path.

The data sink needs to go in a position deep enough within the region itself to change the sub-tree transmission structure and balance the energy consumption within its nodes.

Figure 2 shows an illustration of how the sink's mobility changes the transmission tree structure and balances the energy consumption among nodes in a simple network.

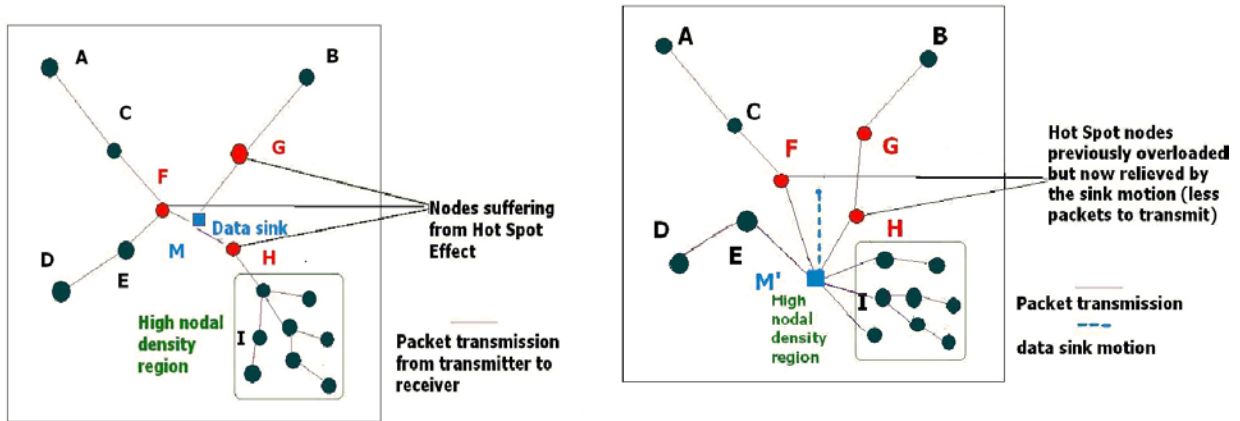


Figure 2: Importance of sink mobility in breaking the transmission tree structure and relieving the Hot Spot nodes in a simplified network

Table I illustrates the redistribution of transmission loads among the nodes, before and after the sink motion. The numbers have been normalized against the traffic rate of each sensor. Here we assume that all nodes transmit 1 data packet per second. The load is then given in packets received from lower nodes per second plus one packet transmitted by the node itself.

Nodes	A	B	C	D	E	F	G	H	I
Load before motion	1	1	2	1	2	5	2	9	2
Load after motion	1	1	2	1	2	3	2	3	5

Table 1

The three Hot Spot nodes in this case (F, G, H) receive respectively packets from (4, 1, 8) sub-nodes. After the sink motion, the load is brought down to (2, 1, 2) for those same nodes while the most “loaded” node within the new structure (I) only has to carry information from four sub-nodes.

In this simple model we underline clearly the double challenge of the sink mobility: relieving the Hot Spot nodes and balancing the average energy consumption among network sensors.

The average number of packet transmission for 3 Hot Spot Nodes goes from 4.33 packet/second to 1.66 packet/second while that same average for 13 sub-nodes from 1.69 packet/second to 1.92 packet/second. The difference might not seem significant for a single transmission but can increase the system throughput consequently on a network lifetime basis.

This redistribution of the retransmission load among network nodes is responsible for extending the network lifetime.

III.2.2 Methodology:

The above scheme works only in networks where one node suffers from the hot-spot issue. In a real-world application, having the sink moving towards the Hot Spot node position to “relief” it and break the Hot Spot structure might overlook the other regions of the network and ends up harming the network lifetime more than extending it.

Therefore, we made the following observation: **the sink must not stay still in a single location to relief a region but must keep moving from region to region in a round-robin fashion balancing the energy consumption among all regions.**

That will force a constant transmission tree reconstruction and the overload in this case needs to be considered (see III.3).

The challenge consists in building an efficient timed path determination algorithm to optimize the balancing of energy consumption among regions. Thus, the data sink finds its trajectory with the help of the following two pieces of information:

- *the traffic rate received from each Hot Spot node*, reflecting to a certain extent the number of sub-nodes transmitting through this sensor. The following deduction is acceptable for the sink when all nodes transmit periodically with a similar transmission rate. In that case the data sink can associate a priority level to each traffic rate that it gets from the nodes surrounding it ; and

- *the geographical location* of the nodes in the neighborhood that suffer from the hot-spot problem. As mentioned earlier, the data sink is equipped with a directional reception/transmission antenna that allows it to determine the exact geographical location from where the traffic rate is generated.

Our scheme consists in three major steps: Observation time and TRV assignment, positioning assessment, and time spans assessment.

Step 1: The data sink associates a region with each node transmitting to it directly (Hot Spot node). It assigns the packet rate that it receives from this node as that node's "**Traffic Rate Value**" or **TRV**. When deciding its motion trajectory, the data sink give priority to those nodes with high TRV, since the TRV represents the node density of the sub-region transmitting through the Hot Spot node.

Note that the data sink should only move after the network traffic pattern can be observed clearly. In the first instants of the network lifetime, the nodes surrounding the data sink might not

have received data packets from the sensors located at the very extremity of their transmission sub-tree. Those data packets need to be forwarded from lower to upper node towards the Hot Spot node, and finally to the sink. Thus, it takes a time period for all Hot Spot nodes to transmit at their full traffic rate capacity. If the sink needs to assign TRV based on those traffic rates it has to wait a certain time before doing so. This is called **Observation Period (T_{obs})**.

In a network where all nodes transmit data packets periodically as the one we are studying, the determination of T_{obs} becomes trivial: the data sink must keep track of traffic rates received from each 1-hop away node. Then, it considers T_{obs} as over when all those nodes transmit at a regular rate for consecutive instances. To avoid any discrepancy due to the noise/packet collision in the field, the data sink can impose a threshold to reach for consecutive transmission rates per Hot Spot node before considering T_{obs} over.

Once T_{obs} passed, the data sink assigns TRV to all Hot Spot nodes based on the last traffic rate recorded.

In our model, we set the TRV of a Hot Spot node to the traffic rate that it transmits to the data sink. (Note that other criteria are also possible, such as residual energy, a combination of traffic rate and residual energy. In this work, however, we focus on traffic rate.)

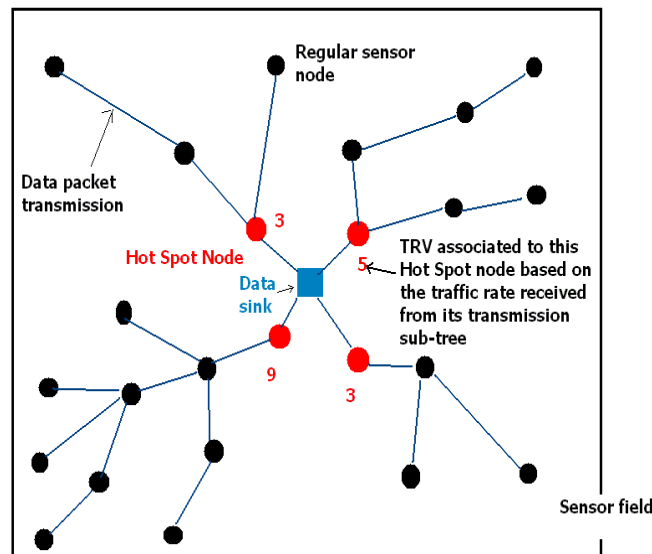


Figure 3: TRV assignment for Hot Spot nodes after time T_{obs}

Step 2: After the Observation Period, the data sink must assess the succession of positions that it will evolve to, based on the TRV of each Hot Spot node. Three concerns are raised:

- What is the first position it should move to?
- What order/direction should it take?
- How does it determine the exact spatial position it should move to at each displacement on the path?

First position: the sink, could pick the Hot Spot node with the highest TRV and move to a certain extent within that node's transmission sub-tree. Instead, the sink rather moves in a location between the two sub-trees of the two nodes with the highest sum of TRV. This motion forces a more efficient system tree restructuring relieving two Hot Spot nodes instead of one in one motion. More displacement patterns are applicable (see Chapter VI). If there is more than one maximal sum of TRV, the sink selects one randomly.

Position ordering: once the first position is determined (exact spatial location will be detailed in the next paragraph), the sink must evolve around the network in an organized fashion, feasible in a real-world application. The sink must not be expected to jump from one extremity of the network to the other. That is why ordering the successive positions of the path can not be achieved by a descending ordering of TRV.

We opted for a circular motion around the network's center since it is the position where the sink is placed generally when initially disposing the nodes in the field [7].

The second position on the path is determined by the highest sum of TRV of the Hot Spot nodes that are already involved in the first position determination. Following the same pattern, the sink places the rest of the nodes in a geographical, circular order and moves periodically between two consecutive sub-trees, producing a smooth circular motion around the center.

The only knowledge the sink has of the geographical topology of the sub-trees can be induced from the spatial location of their respective roots: the Hot Spot nodes. Using the directional reception antenna, the sink has the ability to list the Hot Spot nodes in a circular order after determining the first position as the starting point and the second position assessing the rotation direction.

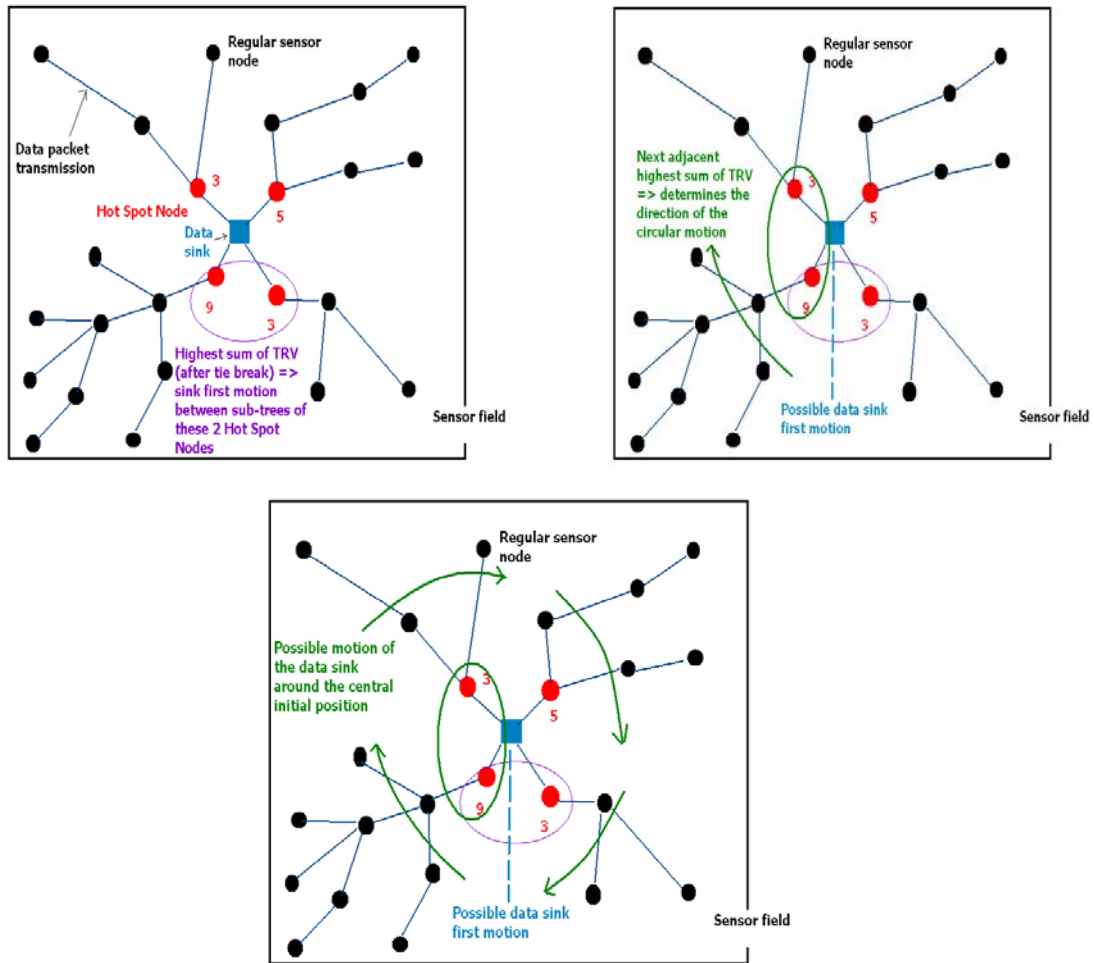


Figure 4: Determination of the sink's circular motion around the initial center position.

Note: In most wireless sensor networks the sink is initially placed in an approximate central position within the sensor field. The initial position of the sink in our mobile scheme will be set to the center of the network for the duration of the Observation period. That allows the sink to have a better assessment of the network traffic pattern [9] before doing its first motion. The central position is also the sink's optimal position when it is fixed over a large dense sensor network. The analytical formula that determines the optimal sink position (OSP) in the network given its nodes' position and data rates is the following:

$$\mathbf{OSP} = (\sum(\mathbf{P(x)} * \mathbf{T(x)}) / \sum(\mathbf{T}))$$

Where the summation is for all nodes in the network, P(x) represents the location of node x, and T(x) represents the traffic generation of node x.

Exact spatial sink positioning: The exact positioning of the sink between two regions is important: the length of the sink's displacement in that area will determine the extent of the transmission tree reconstruction. If the distance is insignificant, the Hot Spot node problem is only pushed to the next sub-node(s) in the tree. If great enough, the transmission topology changes (see Figure 2).

The exact position between two regions is determined as follows:

a/ We find the center position C(xc,yc) between the two Hot Spot nodes n1(x1,y1), n2(x2,y2) that are roots of the two concerned sub-trees.

b/ We draw a line from the initial data sink position to that center position C. The distance between the initial sink position Co(xo,yo) and C is D.

c/ On the same direction of the line drawn we shall place the sink's new position on a distance (2*D) from the center of the two Hot Spot nodes in position New(X,Y).

$$\mathbf{xc} = (\mathbf{x1} + \mathbf{x2}) / 2 , \mathbf{yc} = (\mathbf{y1} + \mathbf{y2}) / 2$$

$$\mathbf{X} = (\mathbf{3} * \mathbf{xc}) - (\mathbf{2} * \mathbf{xo})$$

$$\mathbf{Y} = (\mathbf{3} * \mathbf{yc}) - (\mathbf{2} * \mathbf{yo})$$

'New' will be one of the positions of the sink in its motion path when relieving these two sub-trees.

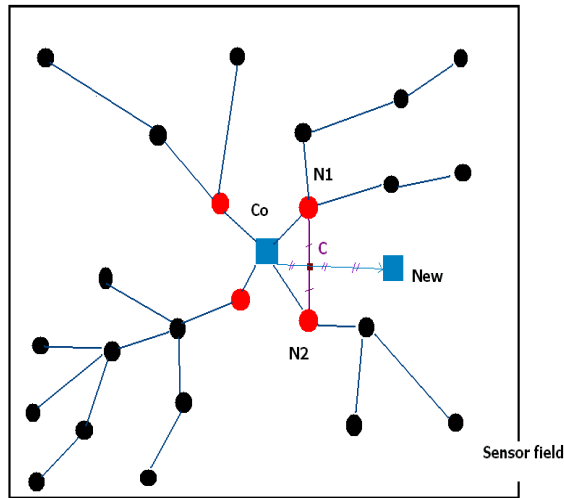


Figure 5: determination of the exact position of the mobile sink between two sub-trees

The sink has no means in figuring out the exact layout of the sub-trees within the sensor field. Nevertheless, for a high density network (over 5 sensors/meter square) this algorithm seems to determine an acceptable positioning of the sink at an approximate equal distance from the two sub-trees involved and provides efficient restructuring of the traffic pattern in that area as it will be illustrated in our performance evaluation (Chapter IV).

Step 3: The displacement of the data sink between system transmission sub-trees must provide fairness in balancing the energy consumption among them. When assessing a position between two sub-trees it also needs to assess a time span for that position. It assesses the time that needs to be spent in each position based on the traffic rate that it receives from each Hot Spot node. Therefore, the time span is relative to the TRV associated to those two sub-trees root.

The sink moves in-between the two sub-trees (R1, R2) and stay in that position for a time span $T(R1, R2)$ calculated as follows:

$$T(R1,R2) = k * (TRV(R1) + TRV(R2))$$

Where $T(R1,R2)$ is the time spent between region1 (R1) and region2 (R2), $TRV(R1)$ is the TRV associated with the Hot Spot node that is the root of the sub-tree R1 and k is the loitering constant set to 0.01 in this work.

For each in-between region the sink estimates the time to spend still in that area based on this formula.

In these three steps, (1) the sink has established a traffic pattern for the network and assigned a value for each Hot Spot node representing the traffic volume that it receives from its sub-tree; (2) the sink has assessed ordered positions between each pair of those sub-trees; (3) the sink has assessed the time spans for each position based on the sub-trees traffic rate.

Figure 6 illustrates the determination of the sink's motion path in the mobile data sink scheme based on the Hot Spot nodes' TRV and their geographical locations in the sensor field:

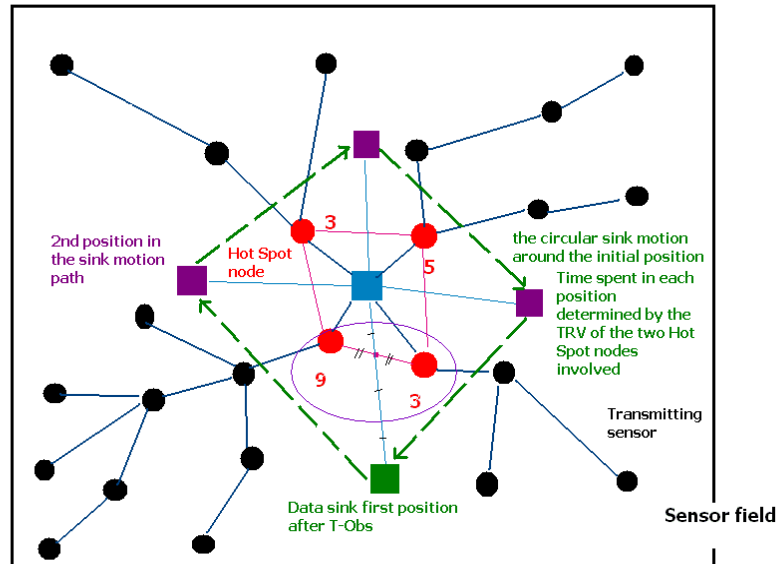


Figure 6: Path determination for data sink motion based on TRV of Hot Spot sensors and their geographical positions.

III.3 Cost & Overhead:

Our main concern with this new technique is the computation cost for restructuring the transmission tree and adapting the forwarding of the information according to the spatial evolution of the sink.

Many schemes that consider sink mobility, including SEAD [6], force the mobile data sink to always communicate with an “access sensor” or “gate”: the sink knows the its gate’s spatial position, transmits its changing position and gets all data packets from the sensor field through that gate. This gives us a better understanding of why sink mobility in those schemes is not meant to decrease the Hot Spot effect, since the gates are Hot Spot nodes.

Our approach is based on an important fact: the data sink is equipped with much greater energy resources and transmission capacity than the rest of the network sensors. Therefore, our scheme takes full advantage of that inequality: it relies heavily on the sink ability to inform the sensors about every displacement and help them assess the most appropriate neighbor to transmit to.

Second important fact: packet reception cost is several orders less energy-costly than a packet transmission. In our scheme, the sink broadcasts its new position and by doing so the node can always determine to which neighbor node it shall transmit just as if the data sink was in fixed position. The sensor having spatial information about all its 1-hop away neighbors, the directional transmission is computable by a majority of sensor models.

We argue that such a technique does not increase the transmission overhead. This is mainly because such broadcast takes place in a fixed sink network as well: the sensors being by design low-power devices, their average lifetime is relatively short. In a network lifetime, nodes are constantly dying in the transmission tree and an efficient restructuring scheme is crucial whether

the data sink is mobile or not. Transmitting nodes need to adapt constantly to the collapse of their neighbors when forwarding their information towards the sink.

For example, our scheme may then be combined to the one proposed by Li and Halpern [5] so that each node always determines the minimum energy path towards the sink once it acknowledges its position. This approach is based on “echo packets” that the data sink sends towards the data sink through all possible paths and the cost of each path is recorded as the packet is forwarded from lower to upper node in the tree. The sink eventually receives the packet and sends a packet back informing the transmitting node of the optimal path. The process needs to be redone periodically because of all the sensors that collapsed between two “echoes”. In our case, the time span could be set to the time-spans spent in each new sink position within its motion path .We leave this as our future work.

Note that our scheme does not require the knowledge of an energy map for all nodes as it has been proposed in the past [11]: a transmitting node always transmit to the same 1-hop away neighbor towards the sink until that nodes die. Then, it finds the next best placed neighbor to transmit to. The transmitting nodes within the network are not responsible for balancing the energy consumption among neighbors. The sink in motion is the only factor in balancing the energy usage.

Maintaining an energy map is very costly because it requires many transmissions/receptions between neighbor nodes to keep the maps accurate. It can become a significant negative factor whenever the network density is increased.

In our technique, nodes in their transmitted packets won't have to forward information about energy status of lower nodes, which is not much of an energy saving on a single packet

transmission but becomes significant when considering the totality of transmissions over a network lifetime.

The extra computation cost at the data sink is limited. Note that this is also related to the Loitering Constant.

The only energy that needs to be considered as additional for a mobile scheme is the one that the data sink itself uses to move around the network but as assumed above it can be considered as a larger device with “unlimited energy resources”; the nodes will also use extra energy receiving “location packets” from the sink (for every new position it takes) and will use energy computing those information, but both of those costs can be neglected compared to the one of packet transmissions [8].

IV Performance Evaluation:

IV.1 Methodology:

Before we can implement our mobile data sink scheme, we need to create an accurate wireless sensor network model to be able to compare throughputs. The model needs to be as close to real life applications as possible. We must be able to determine the optimal sink position for any network topology and also determine a thorough multi-hop packet transmission among nodes.

An energy consumption model is needed to determine the energy ratio deducted from the node's reserves after each transmission (E_{trans}).

The energy consumption model for a packet transmission is the following:

$$E_{\text{trans}} = D^w + k$$

where D is the distance between the source and the immediate receiver, k is the constant energy consumption (set to 10 in this work), unrelated to distance, and w is the path loss exponent (assumed to be 2 in this work)

If node P transmits N number of data packets to node Q , the energy consumption for packet transmissions from the power resources of node P are $N * E_{\text{trans}}$.

Energy consumption for packet reception being several orders of magnitude smaller than the one for a packet transmission [8], it will not be taken into consideration in this work.

The same energy deduction per transmission is used for both our 1D and 2D network models.

IV.2 1D network:

We investigate a 1-dimensional network of 1000 meters containing $N=100$ nodes, which are distributed on a line. All nodes have the same initial battery level, 10^5 , except the data sink that has unlimited resources. The transmission range of each sensor is set to 20 meters. In the transmissions, we choose a multi-hop transmission where each node transmits to the closest node “alive” towards the sink.

The data sink is moved along that network. For each position, we estimate the network lifetime considering heterogeneous traffic pattern in the network: *high node density regions* and *high traffic rate regions*.

Figure 7 provides an illustration of the optimal sink position determination considering those features in a 1-D network. The network lifetime as a function of the data sink's location is shown. Graph I represents the network lifetimes according to the sink position when 30% of the nodes are located within the area [200,300] of the network (the rest of the nodes are placed in the other regions randomly). Graph II represents the network lifetimes according to the sink position when all nodes within the area [200,300] have twice the transmission rate of the rest of the nodes of the network (all nodes in that case are evenly spread along the linear network). Graph III is similar to Graph I but 50% of the nodes are within [200,300]. Graph IV is similar to Graph II but the nodes in [200,300] transmit 4 times the number of packets the nodes in other regions of the network do. Graph V finally represents the base case: nodes evenly distributed along the network with equal traffic rate transmissions.

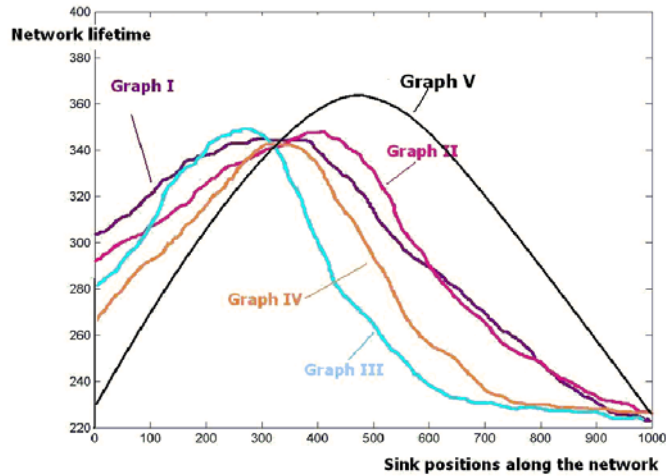


Figure 7: Impact of high traffic rate and high node density regions on the optimal data sink position within 1D network

Obviously, the optimal data sink in both cases shifted from its central position (Graph V) towards the high traffic rate region (338 for Graph I, 442 for Graph II, 282 for Graph III, 347 for Graph IV).

Interestingly, the optimal sink location “reacts” similarly to high traffic rate regions and high node density regions since a node transmitting twice more packets than another node could be thought of as two nodes in the same location transmitting the same number of packets as all other nodes.

After comparing the values of the network lifetime for a large set of traffic patterns, alternating equivalent increment in traffic rates and node density within the same regions (as illustrated in Figure 7), the following induction could be stated: we consider heterogeneity of node density as a combined effect of different node density and different traffic load.

IV.3 2D network - Assumptions: Our 2-D network model is designed as follows:

- Network is a 100x100 array containing 100 nodes: 1 node per meter square (our network node density is conform to usual wireless sensor network high node densities as seen in [7,8]).

- The network is considered “dead” when 40% of the nodes have exhausted their batteries. This percentage is acceptable [7] since most researches consider that a network is in the “high collapse risk level” when more than a third of its sensors have exhausted their power resources.

- All nodes have similar transmission rates and a 10^5 energy unit initial battery level, the energy consumption for each packet transmission being the one proposed above (E_{trans}).

- All nodes use a *hybrid energy map*: instead of keeping track of the energy level of each 1-hop way sensor and dispensing energy resources maintaining that energy map, the transmitter only keeps track of the ability of its neighbors to retransmit a single packet. This relies on the action on the receiver side: when a sensor transmits packets from a lower to an upper node in the tree structure, it informs the lower node when reaching a “danger state”. When that state is reached, the “router node” will not have the necessary energy resources to retransmit packets in the future and will probably send an extra information packet of its own before collapsing. The lower node being informed of that will not lose energy transmitting towards that node and transmits instead to the next available 1-hop away neighbor that is able to forward the information up the tree.

Thus, multiple unnecessary transmissions to a “dead node” are avoided and a level of energy awareness among 1-hop away nodes is instated without excessive energy-informative data sent back and forth.

- Multi-hop packet transmission*: each node has a 20 length unit transmission range and transmits its packets to the closest node within that range that is closer to the sink, if that node is still “alive”. The neighbor node must be 1-hop away from the transmitter on an established path towards the sink. Initial path establishment from node to sink will not be detailed in this work since it is based on the same approach as any basic wireless sensor network.

If no such neighbor node exists, the transmitter keeps increasing its range until it can reach, but will exhaust more energy doing that [7] since its energy consumption per transmission is proportional to the distance to the receiving node/sink.

Notes:

- The Hot Spot node never being farther than 20 length units from the sink’s initial position (because of restraints on their transmission range) mathematically the data sink in determining its motion path will never surpass the network limits. In fact, it hardly ever exceeds the 60 length unit displacement. In WSN, the transmission range hardly exceeds a tenth of the network’s radius. Our scheme implies then that the sink displacement never exceeds a third of the network’s radius, which reflects the “real life” realism of the scheme that we are proposing: not expecting from the data sink to reach the limits of the network in order for it to collect all its information.

•In this work, we neglect the time for the mobile data sink moves from one location to another location. While such movement isn't instantaneous, we argue that the data transmission periods are usually higher than the time needed to complete the movement.

IV.4 Results:

All our simulations have been run on Matlab 6.5, and our data set consists of 100 different network topologies generated by our program.

IV.4.1 Mobile vs. Fixed Data Sink:

The energy transmission analytical formula helped determine the optimal sink position in a 2-D network relying on the knowledge of the geographical location of the nodes and their traffic rates. We estimated the average lifetime of the network over the data set using each network's **optimal, fixed sink position**. The average lifetime was equal to **140.65 time units**.

Afterwards, we ran the same number of tests over the same set applying the **mobile sink algorithm** and the average network lifetime was equal to **187.75 time units**. The lifetime extension is equal to **33.48%**.

Figure 8 presents the comparative throughputs for fixed and mobile data sink schemes. Plot I represents the network lifetime considering our 2D network model; plot II represents the network lifetime when the number of nodes is multiplied by 1.5 (150 nodes); plot III represents the network lifetime when the node traffic rate is doubled.

The results clearly show that the mobile data sink approach outperforms a network with a fixed sink respectively increasing the network lifetime by 33%, 19% and 15%. The reduced performance gain of the mobile data sink scheme as node density or traffic increases can be

explained as follows: when the node density is too large, there are many nodes suffering the hot spot effect and it is difficult for the mobile data sink to cover all such nodes.

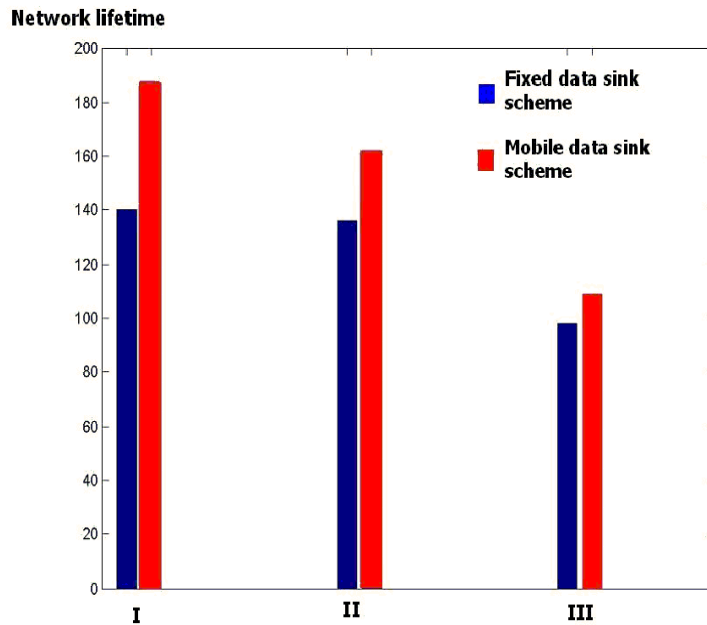


Figure 8: Comparative network lifetimes for fixed sink network and network implementing the Mobile Data Sink scheme with variable node density and data traffic rate

Our second goal was to have a better distribution of the energy consumption among the network nodes.

Figure 9 displays the standard variance of the traffic rates of all nodes within distance d of the network center. The variance is estimated over the average transmission rate per node over each node's lifetime. The results were measured prior to any node dies.

Curve I represents the standard variance of the transmission traffic rates among nodes when the data sink is fixed. Curve II represents the same variance when using our mobile sink scheme.

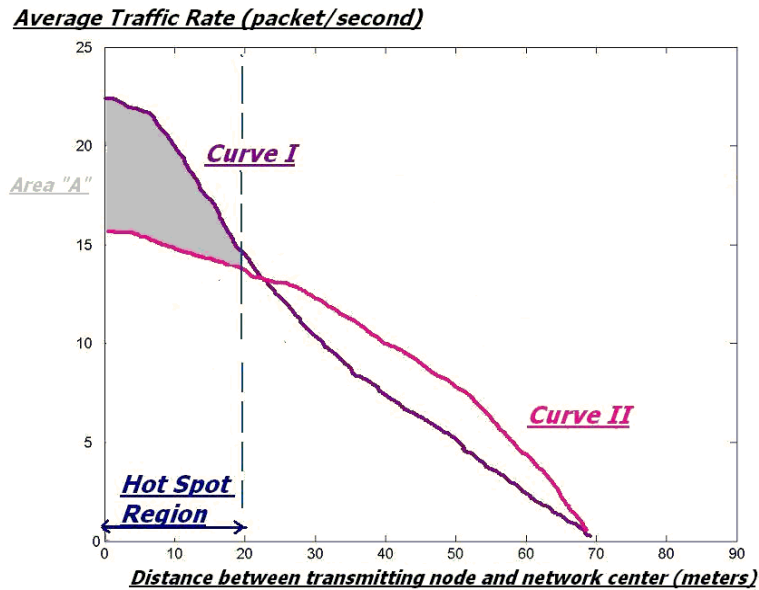


Figure 9: Comparative standard variance of traffic rate among nodes for both fixed and mobile data sink schemes.

Over a hundred different network topologies, the average global traffic rate within the Hot Spot region nodes for a fixed sink scheme was 171 packet/second, while the average for a mobile data sink scheme was 121 packets/second. The traffic rate decrease within the Hot Spot area is equal to 41.32%. That difference is represented by area A in Figure 9.

Meanwhile, the traffic rate among the rest of the nodes, excluding the leaves of the transmission tree, is greater by 41.32% when using the mobile sink scheme, but that traffic increase is distributed among a larger number of nodes. In fact, the average traffic rate for regular nodes is 8.3 packet/second for a mobile sink scheme while it equals 5.2 packet/second for a fixed scheme. This explicitly demonstrates the better distribution of energy consumption among the network nodes and the reduction of the Hot Spot effect on the network.

We propose another illustration of that distribution normalization within the network nodes. In the following figure, we are displaying the node lifetime values considering their distance to

the data sink position at the moment of their “death”. Note that these curves only represent the 40% of nodes that died causing the network collapse.

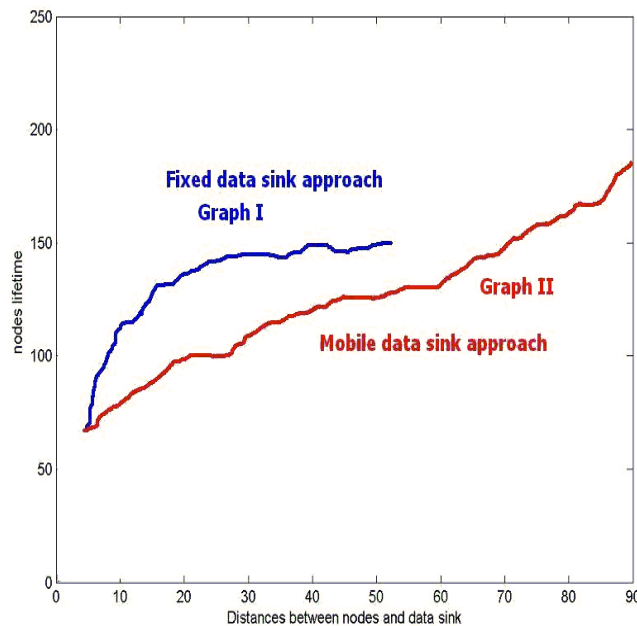


Figure 10: Comparative average distribution of energy consumption among network nodes for fixed and mobile data sink schemes.

By comparing the two curves, we see clearly that graph II representing the mobile data sink approach extends further and has a smoother slope than graph I, representing the fixed data sink approach. Three points can be made in that matter:

First, the maximum value of graph II (approx. 180 time units) is greater than the one for graph I (approx. 142 time units), and that tells us explicitly that **the network has a longer lifetime using a mobile data sink**: the last node to die (after what the network collapses) has a greater lifetime value for Graph II, and that node’s lifetime is equal to the network lifetime since after its “death” the network is considered non-operational.

Second, the slope of graph I (fixed sink) is greater than graph II, which can be explained by the fact that the closest nodes to the sink in a fixed sink approach die very quickly while the ones just a little further die considerably slower (which reflects a bad distribution of the energy consumption in that area); while the slope for a mobile data sink is smaller which tells us that the nodes that are very close to the sink die almost at the same time as the ones much farther from it, and that is what we wanted in a matter of **normalized distribution of the energy consumption over the network nodes**.

Third, graph II spreads larger than graph I, which finally tells us that some of the nodes that are much farther from the data sink have also exhausted their energy resources while the shortness of graph I tells us that most of the nodes involved in the “heavy” packet transmissions (fastest to die) are the ones closest to the data sink (direct illustration of the Hot Spot effect). We can get from that a second proof of the normalization of the energy consumption among nodes and the fact that **more nodes within the network are involved in the retransmissions when applying a mobile data sink approach**.

IV.4.2 Mobile Data Sink scheme vs. Energy Balanced Propagation scheme [4]:

We propose to compare throughputs between our Mobile scheme and the Energy Balanced Propagation scheme [4]. The test will be run on a set of 100 different network topologies.

The Energy Balanced Propagation scheme serves the same purpose as our work: normalize the power consumption among all nodes to extend the network lifetime. It is based on a probabilistic approach determining if a sensor node should transmit to a neighbor sensor towards the sink or increase its transmission range instead and transmit directly to the sink. The transmitter bases its decision on the energy level of the neighbor responsible for the packet

forwarding. The transmission decisions over a node lifetime help reduce the packet forwarding among neighbor sensors and decrease consequently the Hot Spot effect, based on the heavy forwarding towards the sink.

We compared our scheme to [4] and Figure 11 displays the comparative results:

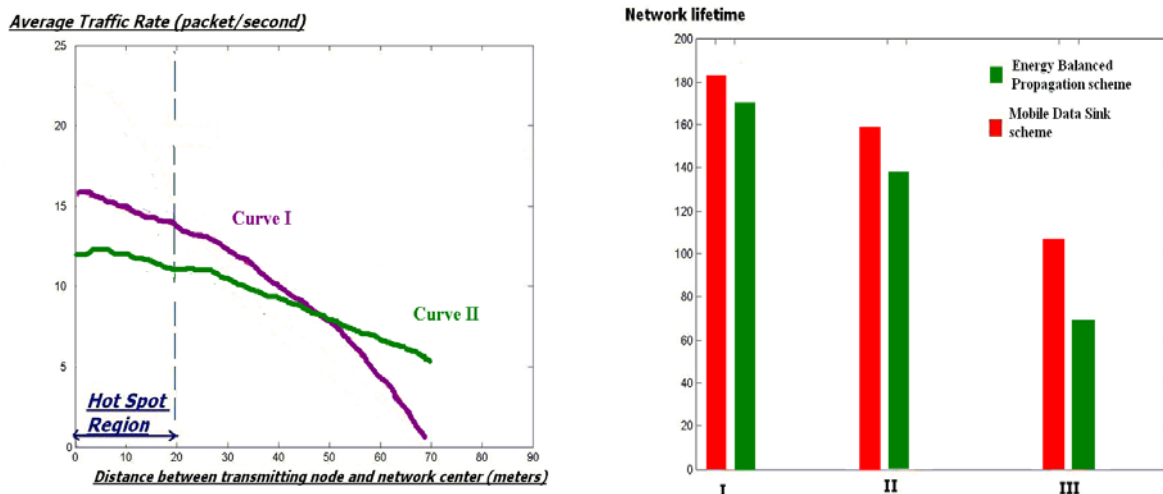


Figure 11: Comparative throughputs in standard variance of node traffic rate and network lifetime for Mobile sink and Energy Balanced Propagation schemes.

The first figure (left) compares standard variance of node traffic rate against distance between transmitting node and sink for the two schemes. Curve I stands for the Mobile Data sink scheme while Curve II represents the standard variance for the Energy Balanced Propagation scheme.

When comparing the slope of the curves we can induce that the Energy Balanced Propagation algorithm leads to a more efficient normalization of the traffic rate, and therefore a more efficient normalization of the energy consumption among the network sensors than the Mobile Data Sink scheme.

It also reduces more efficiently the Hot Spot effect within the network since the average traffic rate among nodes within a range of 20 meters for the balanced scheme outperforms our

scheme by -2.3 packets/second (11.3 packets/second for balanced scheme vs. 13.6 packets/second for mobile sink scheme).

On the other hand, when comparing average network lifetimes for the two approaches we can notice on the second figure (right) that the Mobile Data Sink is more efficient than the balanced scheme.

Result (I) is obtained from simulations on our 2D model. Result (II) is obtained when increasing the number of sensors by 1.5. Result (III) is obtained when doubling the node traffic rate.

In all scenarios our scheme leads to a longer network lifetime and outperforms the balanced approach respectively by 5%, 13% and 36%.

The important gap in lifetime extension when increasing the traffic rate for the sensors can be explained by the fact that nodes in the balanced scheme exhaust an important amount of energy when they decide to transmit directly to the data sink instead of a neighbor sensor. The energy transmission cost being related to the distance between transmitter and receiver (see IV.1), the high number of packets to transmit at a high cost reduces severely the average node lifetime and therefore the network lifetime as well.

We can now make the following observation: normalizing the traffic rate among nodes implies extending the network lifetime *only if the average energy consumption per transmission is kept equal or smaller than its initial value.*

In this comparative case, the balanced scheme leads to a more balanced traffic pattern among sensors and a more efficient reduction of Hot Spot effect, but their average energy consumption per transmission becomes greater than the one for our Mobile Data scheme, which leads to a shorter network lifetime.

Note: The probability pattern used when making the transmission decision for the Energy Balanced Propagation scheme has been simplified from its original version but does not affect the scheme throughput in any ways. Comparative results to our basic fixed sink network's throughput confirm it.

IV.4.3 Mobile Sink scheme using Hybrid Energy Map vs. Fixed Sink scheme using Node Energy Map [11]:

In research [11] is detailed the use of an energy map scheme. According to the scheme, all nodes use a list of energy level of their 1-hop away neighbor sensors and maintain that energy map through several energy-related communications. Whenever a node needs to transmit a data packet it consults its energy map to decide which the appropriate neighbor to transmit to is. It balances the number of packets it sends to all neighbors so that the forwarding load is shared when packets are going from the bottom to top of the transmission tree.

Our scheme uses a variant of the Energy Map scheme that we call *Hybrid Energy Map*: the transmitter only keeps track of the ability of its neighbors to retransmit a single packet (see IV.3 for details).

The variation proposed in our scheme aims to reduce the unnecessary energy consumption when sending a high number of informative packets about power levels among neighbor nodes.

Our scheme affords not using a regular energy map because the normalization of energy consumption among network sensors is based on the sink motion and not on the Energy Map scheme. The Hybrid model allows the transmitting node the minimum necessary information about the possible receivers to complete a successful transmission.

To prove the sufficiency of our Hybrid energy map for the Mobile Sink algorithm and its superiority to a regular wireless sensor network using an Energy Map algorithm we compare throughputs of both implementations over a set of 100 different network topologies.

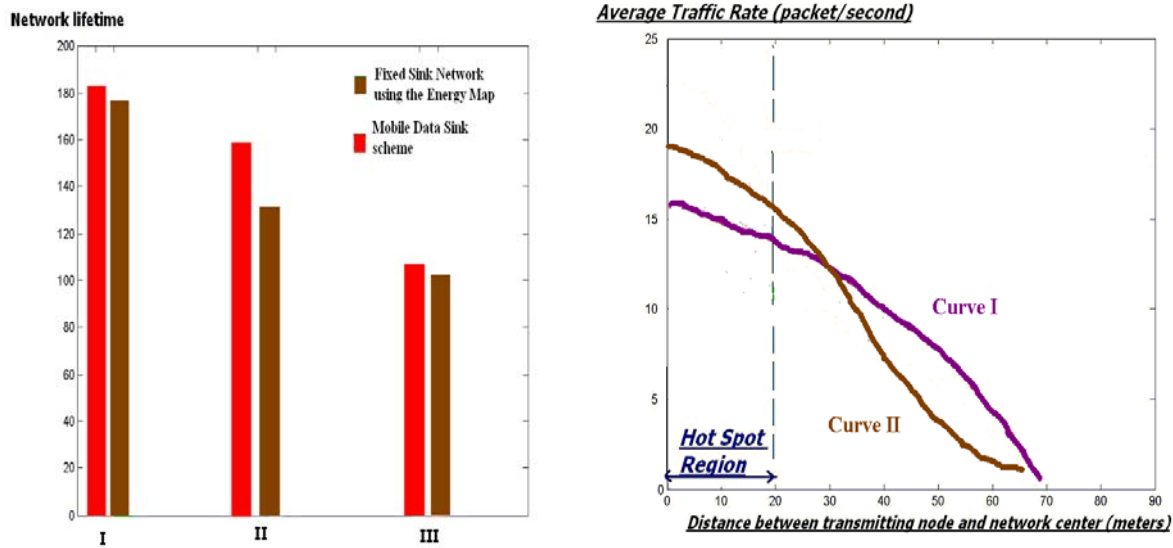


Figure 12: Comparative throughputs in network lifetime and standard variance of node traffic rate for Mobile sink scheme and fixed data sink using the Energy Map scheme.

From the figure on the left we notice that the Mobile scheme offers longer lifetime to the network than a network with a fixed sink using the map. For our 2D model (I) it outperforms the map scheme by 4%; for the 2D network with 150 sensors (II) it outperforms significantly the map scheme by 17%; for the 2D model with a doubled initial node traffic rate (III) it outperforms the map scheme by 4% as well.

The difference of efficiency between the two schemes is high for high node density networks because it implies more proximity among sensors, which leads to a high ratio of neighborhood among nodes. Therefore it requires a high traffic rate among those neighbors just to maintain the energy maps and the power consumption for those transmissions reduces consequently the sensors lifetime.

On the other hand, the Hybrid approach does not imply an important increase in the “energy map maintenance traffic” since the ratio of transmission per new node in the region is equal to an extra informative transmission to the lower nodes in the tree when that node can not forward their packets anymore.

The energy saving using the Hybrid scheme becomes crucial whenever the network node density is increased and the network is already using a scheme to balance the energy consumption among the sensors.

From the second figure (right) we can finally conclude that using the energy map does not efficiently reduce the Hot Spot effect in the network in comparison to our Mobile data sink scheme. The average traffic rate in the Hot Spot region is 156 packets/second for the Energy Map scheme while equal to 121 packets/second for our Mobile Sink scheme.

The Map usage helps balance the packet distribution among neighbors, but in a tree structure the number of neighbors decreases gradually when narrowing towards the root and ultimately all packets will still be transmitted through the Hot Spot nodes. The slight decrease in the Hot Spot effect is then due to the possibility of sensors having more than one Hot spot node within their transmission range and balancing their packet distribution among them.

V Conclusion:

We have proposed a mobile data sink technique to extend the network lifetime.

The mobile data sink is designed to move towards the high node density and traffic regions and to relieve the nodes that are responsible for forwarding the information from those regions to the sink. The determination of the sink's timed motion path has been detailed thoroughly and the purpose of each displacement feature has been given. The round-robin motion among the overloaded traffic regions of the network balances the power consumption among the network sensors and ultimately extends the network lifetime.

Throughout extensive simulations, we have shown that our scheme extends the network lifetime by more than a third, compared to a fixed data sink approach. We have also proposed comparative throughputs with networks using an Energy Balanced Propagation scheme and networks using an Energy Map.

The performance gain has been shown to be achieved through balancing the traffic rates of all nodes in the hot spot region without increasing the average energy consumption per transmission. Also, using a Hybrid Energy Map that allows a transmitting node partial knowledge of the energy pattern surrounding it proved to be sufficient to outperform a basic network with a fixed data sink using an energy map.

Finally, the efficiency of our scheme in comparison to the two mentioned above has been proven when altering the network node density and the sensors' initial traffic rate and produced competitive results.

VI Future Work

Through our model we tried to come as close as possible to a real-world situation. Nevertheless, the breadth in wireless sensor network topologies and traffic patterns leaves room for many possible improvements to our scheme.

The multitude of parameters that need to be considered when implementing the Mobile Data Sink scheme allow further research to optimize the path determination during the motion.

For instance, when the data sink is in the idle time determining the positions it must take and the time period it must spend in each of these positions, it will not adapt to the network evolving topology once it leaves that initial central position. Although the constant transmission tree restructuring might change the traffic pattern after the first motions of the sink.

One could explore how much the network lifetime can be extended if the data sink could adapt at each step: decide to reduce the time spent within a high density region or even skip that position because a farther region might have a higher priority within the updated pattern.

More parameter values can be shifted in order to reach a longer network lifetime:

- the exact spatial positioning of the sink during the motion can be modified to allow the sink to go farther (or not) inside the Hot Spot regions;
- The time span in each region can be proportional to the residual energy resources of the neighbor nodes. If our scheme is combined to an Energy Map (non Hybrid) scheme, the time slot determination might be more efficient.

It would be also interesting to evaluate the trade-off of the scheme for an entire mobile network where mobility is considered for regular nodes as well, as it might be the case in wireless sensor networks. May be in that case our technique could be introduced in a multi-sink mobile network implementation as proposed in the SEAD algorithm [6].

Other combined schemes can be considered: using an Energy Map in our Mobile Data Sink so that the energy consumption normalization is factor of the sink mobility and the sensors' local power knowledge.

Finally, the throughput of the scheme could be tested on a network with multiple data sinks and used to challenge the SEAD algorithm's performance.

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Vita

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