Node Deployment and Mobile Sinks for Wireless Sensor Networks Lifetime Improvement

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1. Introduction

In the last two decades, and owing to advances in MEMS technologies, wireless communications and low-power electronics, the development of low-cost micro sensor nodes was possible. This enabled the deployment of Wireless Sensor Networks (WSN) comprising large numbers of nodes to monitor various physical phenomena in real-time. This can be of prime importance in several industrial, environmental, health, and military applications (Akyildiz et al., 2002; Tavares et al., 2008).

A WSN may have up to hundreds or even thousands of sensor nodes densely deployed either inside or close to a monitored area. Nodes process data prior to transmission, to ensure acquisition of accurate and detailed information. Processed information is then passed on to a sink node, which transmits necessary data to some base station. Nodes may also be divided into clusters, with nodes in each cluster sending data to a particular sink node. Sensor nodes typically operate in an unattended environment, and are equipped with small, often irreplaceable batteries with limited power capacity. Thus a major consideration in WSN research is to ensure reliable transmission of data while prolonging network lifetime by making maximum use of the available energy in the nodes (Heinzelman et al., 2002).

In this chapter, recent work by the authors in the area of WSN is presented with particular emphasis on maximizing the lifetime of the network. In Section 2, algorithms are described that build upon two well known WSN routing techniques, namely LEACH (Heinzelman et al., 2000) and LEACH-C (Heinzelman et al., 2002) to further optimize network lifetime through carefully planned selection of the sink nodes. Simulation results that illustrate the resulting improvement in network lifetime are presented. The position of sensor nodes need not be predetermined, which allows random deployment in inaccessible terrains. However, in some applications, the deployment of nodes at pre-specified positions is feasible. Taking advantage of this feature is thus considered to achieve further enhancement in network lifetime by considering the effect of various geometrical distributions of nodes and relative sink locations.

Further reductions of the transmission energy requirements can be attained by making use of uncontrolled mobile sinks in addition to the distant fixed sinks. It is not possible to depend solely on mobile sinks as their presence is not guaranteed in any time interval, so a hybrid approach is necessary. A hybrid method for message relaying is presentd in section 3, satisfying efficiency and load balancing requirements. A node either uses a single hop transmission if a nearby mobile sink is present, or a multi-hop transmission to a far fixed node depending on the predicted sink mobility pattern. Analysis is used to adjust system parameters such that all sensor nodes dissipate the same amount of energy. This prevents the problem of losing connectivity as a result of rapid power drainage of the nearest node to the fixed sink. Numerical results indicate the improvements in lifetime compared to other traditional methods.

2. Lifetime optimization

This section focuses on routing protocols that prolong Wireless Sensor Network (WSN) lifetime (Akkaya & Younis, 2005; Mahfoudh & Minet, 2008; Narasimha & Gopinath, 2006). Two of the most famous hierarchical protocols are LEACH and LEACH-C (Heinzelman et al., 2000; Heinzelman et al., 2002). In both protocols, sensor nodes are clustered. A cluster head receives data from all other nodes in the cluster, aggregates it and sends it to a fixed sink. The work presented next describes two algorithms that produce longer system lifetimes when compared to LEACH or LEACH-C. Both algorithms assume that sensors are randomly-distributed in the area under study. Geometric distributions of sensors are studied next as well as different fixed sink locations. More details about these issues can be found in (Botros et al., 2009; Nouh et al., 2010).

2.1 System description

The WSN under study is composed of homogeneous sensor nodes that are deployed in the area of interest. Sensors are randomly distributed in the deployment area. This is the most common case. It may be required that hundreds or thousands of sensors be deployed in a remote, unreachable or dangerous environment. In such cases, sensors may be thrown from an aircraft flying over that dangerous area to extract information in ways that would not have been possible otherwise. The sink node is fixed and located far away from the sensors field.

System lifetime is usually defined as one of the following (Mahfoudh & Minet, 2008): 1) The time to the first node failure due to battery outage. 2) The time to the first network partitioning. 3) The time to the unavailability of application functionality. 4) The time to the failure of certain percentage of the nodes. In this work, the first definition is considered since it does not depend on the type of application and it is suitable for any network architecture, either divided into groups, clusters or not. This definition is also preferred since it guarantees that during the whole lifetime of the network, it is fully covered with active nodes which collect data from all positions in the network. This may be a primary requirement in some application classes, such as security monitoring and node tracking scenarios. The proposed algorithms deal with all sensors as one network. The cluster head approach is used to manage the communications within the network. One of the sensors in the whole area is selected as a master. It is called a Network Master node to differentiate it from the cluster head used in LEACH or other algorithms. The Network Master (NM) for the network receives data from the other sensors in the network. The NM then performs data aggregation and compression to remove redundancy and send the useful information to the sink or base station. This is similar to the idea of LEACH and LEACH-C (Heinzelman et al., 2000; Heinzelman et al., 2002) and some others, but here it is applied to the whole network.

2.2 System assumptions and network parameters

In the model under study, several basic assumptions are considered. These are:

- All sensors in the network are homogeneous and energy constrained.
- All sensors are sensing the environment at a fixed rate, and thus always have data to send.
- All sensors can transmit with enough power to reach the fixed sink if needed.
- Sensors can use power control to vary the amount of transmit power.
- Each sensor has the computational power to perform signal processing functions.
- Sensors have a method to be aware of their position after deployment.

The parameters used are as shown in Table 1. Some values given in the table are based on the electronics of most commonly used sensor nodes while the others are used for the sake of comparison with other algorithms.

Parameter	**Symbol**	**Value**
Network Size	M X M	100 × 100 m
Number of Sensors	N	100 Sensors
Transmitter / Receiver Electronics	E_{elec}	50 nJ/bit
Transmitter Amplifier for short distance Transmitter Amplifier for long distance	$E_{amp\text{-}short}$ $E_{amp\text{-}long}$	10 pJ/bit/m^2 0.0013 pJ/bit/ m^4
Pass Loss Factor for short distance Pass Loss Factor for long distance		2 4
Aggregation Energy	E_{agg}	5 nJ/bit/Signal
Data Packet Size		500 B
Overhead Packet Size		125 B

Table 1. Network parameters

Two algorithms are proposed next and it is shown that they produce longer lifetimes than the algorithms presented in (Heinzelman et al., 2000; Heinzelman et al., 2002).

2.3 Algorithm I

Assume that all the sensors are aware of their positions, as assumed in (Heinzelman et al., 2002), and that the sink knows these positions. The algorithm consists of rounds. Each starts with the NM selection by the sink. This node remains as NM for a fixed number of cycles "C", after which a new round starts. Before the selection of the NM, the energies of sensors are compared with two thresholds "En_{Th}" and "En_{ThNM}". The first threshold, "En_{Th}", is the energy required by each sensor to transmit its data to the farthest possible NM node for one complete round. This is calculated for each sensor assuming the worst case that the NM is the farthest node from this sensor. A sensor that has energy below this threshold is not active anymore and cannot perform any useful function. The second threshold, "En_{ThNM}", is the energy required by the sensor to act as an NM, gathering data from sensors, aggregating it and sending the resulting packet to the far away sink. Again, this is energy needed for one complete round. It is calculated for each sensor according to its distance from the sink. A sensor that has energy below this threshold, cannot act as an NM for the network. Sensors are classified according to these thresholds before NM selection into one of three categories: 1) Active nodes that can act as NMs. 2) Active nodes but cannot act as NMs and 3) Inactive nodes or dead nodes.

Once a node is classified as a dead node, the network is considered dead, according to the definition of lifetime used in this study. The sink has knowledge about the whole network and is responsible for selecting the NM and informs all other sensors about the current NM. It selects a sensor as an NM for the current round according to the following criteria. 1) The node belongs to the first category. 2) The node has energy greater than the average energy of all active nodes and 3) The sum of its distances to the active nodes is least. In this algorithm, it is assumed that a node can be selected as an NM for many rounds throughout network lifetime. A simulation model is built using MATLAB (MatLab) with the same network parameters used in (Heinzelman et al., 2002) and described above. The system is run for different values of the number of cycles "C" per round, and the corresponding network lifetime is as shown in Fig. 1. The figure shows that there is an optimum number of cycles for which each sensor remains acting as NM, before another round starts over and a new NM is selected. For the parameters considered, the longest lifetime is achieved for "C=3", resulting in a lifetime equivalent to "3702" cycles.

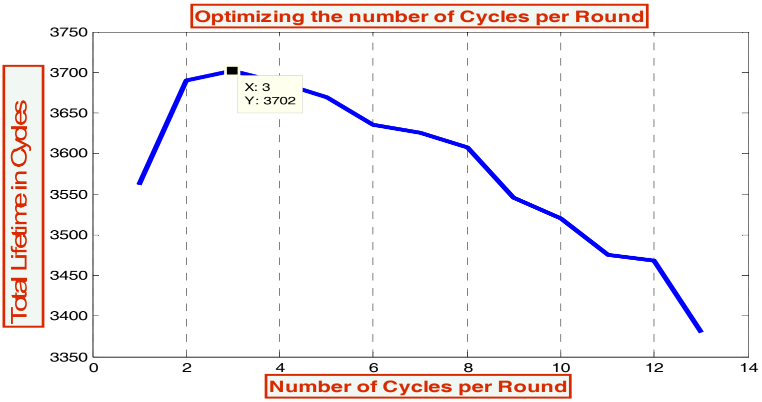

Fig. 1. Network lifetime vs number of cycles per round

2.4 Algorithm II

The previous algorithm selected a fixed optimum number of cycles "C" per round in order to achieve a longer lifetime. It is observed that with this relatively small number of cycles, a sensor is chosen as an NM for many rounds. It is observed also that not all sensors act as NMs for the same number of rounds. So, if these could be gathered together such that each sensor is selected as an NM only once, but without exhausting sensors which require more energy to act as an NM, a longer lifetime for the network will be achieved. Another observation in previous techniques is that after the death of the first node, there is still some residual energy for some sensors. This residual energy is not used efficiently. One reason is that it is distributed to all the sensors, and hence, the share of each sensor is not large enough to work as NM. Another reason is that the full coverage of the network, which may be a primary concern in many applications, is lost. Both observations lead to an algorithm which requires that each sensor be selected as an NM only once, and acts as an NM for a certain number of cycles "C_i", which need not be the same for all sensors. The algorithm also requires the most usage of the available energies for each sensor.

The algorithm is simply run once at the sink based on its knowledge of the locations of the different sensors. The sink can calculate the energy "$E_{txi\text{ to }NMj}$" required by each sensor "i" to transmit its data to any of the other nodes "j" acting as an NM, as well as the energy "E_{NMi}" needed by the node "i" to act as an NM itself. Assuming that each sensor acts as an NM for a certain number of cycles "C_i", before and after which it acts as an ordinary node, the energy consumed by any sensor "i" through the network lifetime can be calculated as:

$$E_{sensor\ i} = C_i \times E_{NMi} + \sum_{\substack{j=1 \\ j \neq i}}^{j=N} C_j \times E_{txi\text{ to }NMj} \tag{1}$$

for $i = 1, 2, \cdots, N$

Since each sensor will act as a NM only once for "C_i" cycles, then the total lifetime, in number of cycles, is the summation of the different "C_i"s.

$$T = \sum_i C_i \tag{2}$$

If each sensor node "i" has an initial energy "$E_{o\,i}$", it must be that the energy consumed by any sensor is less than or equal its initial energy. That is:

$$E_{sensor\ i} \leq E_{0i} \tag{3}$$

In order to make the best use of the available energies for the sensor, the following set of "N" equations in "N" unknowns, { C_1 , C_2 , C_3 , ….., C_N }, is solved.

$$E_{sensor\ i} = E_{0i} \tag{4}$$

for $i = 1, 2, \cdots, N$

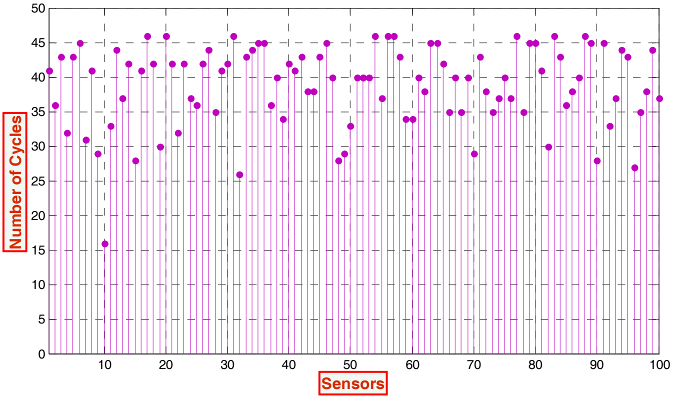

Fig. 2. Number of cycles "C_i" assigned to each sensor to act as a Network Master

The solution set S = {C_i} indicates that the network will have maximum lifetime. Any other set, S′ = {C_i′}, will not be a solution for the set of equations. It should be noted that the solution of such equations does not guarantee integer values for the "C_i"s; therefore, the fractional part of the solution set must be truncated. The simulation environment used before is used for the new scheme. The solution of the set of equations in (4) resulted in the set of "C_i"s shown in Fig. 2 after truncation. It can be observed that the different values of "C_i" range between 16 and 46 cycles per round. The summation of these "C_i"s causes the expected lifetime of the network to be almost 3900 cycles which is higher than the lifetime obtained from the first algorithm.

2.5 Geometric distributions

Random distributions, which were used in (Botros et al., 2009), are more suitable for certain applications where the network locations are inaccessible (Tavares et al., 2008), such as military applications. However, as mentioned before, in some applications (such as urban applications), the deployment of nodes at pre-specified positions is feasible (Onur et al., 2007). Hence, this subsection focuses on geometric distributions instead of random distribution and their effect on maximizing the network's lifetime.

2.5.1 Star topology

The Star topology is one of the most common geometric distributions used in networks (Cheng & Liu, 2004; Bose & Helal, 2008). Therefore star topologies are chosen for testing as geometric distributions. By using the same previous parameters (Botros et al., 2009), it is found that the star with 3 branches and 33 sensors per branch (3×33 star) produces 5% increase in network lifetime. Furthermore, several stars with different numbers of branches are generated for simulation. The main characteristics for the used star distributions in this study are as follows:

- Sensors are distributed in circles from the centre to the borders of the area and each circle has an equal number of sensors.
- Equal angles between branches and equal distances between sensors in the same branch.

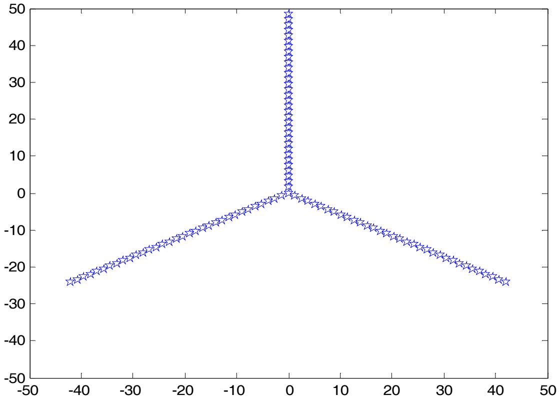

Fig. 3. 3x33 Star

The number of branches that were tested ranges between 3 and 20 with a suitable number of sensors in each circle to constitute the used number of sensors which is N=100 sensors used by (Botros et al., 2009; Minet & Mahfoudh, 2009). The 3×33 star (shown in Fig. 3) has 3 branches, 33 sensors per branch and the 100th sensor is located in the center of the star. The network parameters used in this study are as follows:

- Number of Sensors (N): 100 Sensors
- Initial Energy: 2 J
- Transmitter/ Receiver Electronics: 50 nJ/bit
- Transmitter Amplifier : 100 pJ/bit/m^2
- Path Loss factor: 2
- Aggregation Energy: 5 nJ/bit/Signal
- Data packet size (K): 2000 bits
- Sink location: (0; –125)

2.5.2 Proposed algorithm

A simulation model is built using MATLAB considering the above network parameters. The lifetime in case of geometric distributions is computed by using the algorithm described in section 2.4.

2.5.3 Simulations and results

By simulating the proposed algorithm with different star distributions, it was found that the 3×33 star achieves the maximum lifetime compared to the other star distributions as shown in Table 2. It was found that the 3×33 star extends the lifetime of the network by 35.6% compared to the random distribution used in (Botros et al., 2009). The numbers of sensors that can act as NMs in 3×33 star were 70 out of 100 sensors and the number of cycles allocated for each NM are as shown in Fig. 4. All the simulations results are specific to the orientation of the used topology.

Star Distribution	Lifetime (Cycles)
3x33	4612
4x25	4510
5x20	4278
6x16	4346
7x14	4437
8x12	4399
9x11	4510
10x10	4466
12x8	4314
14x7	4388
20x5	4412

Table 2. Lifetimes of different star distributions

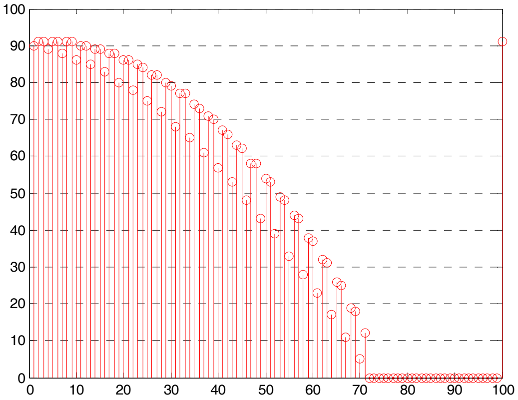

Fig. 4. Number of cycles for each NM in a 3x33star

2.6 Sink locations

The different star distributions used in the previous section were tested to achieve the best distribution with respect to the lifetime using the sink location at (0; –125) which was used by (Botros et al., 2009). The results showed that 3×33 star produces the highest lifetime. This result was taken a step further by applying other sink locations in order to explore the effect of the other sink locations on network lifetime. The sink locations used in this study are (0; 125), (125; 0), (–125; 0), (–125; –125), (125; –125), (125; 125), (–125; 125) and (0; 0).

Simulating the different sink locations on the best star (3×33 star) results in better and worse lifetime with respect to the (0; –125) sink location. But the objective is to increase network lifetime, so sink locations that achieve higher lifetime are of great concern. The (0; 0) sink location increased the network's lifetime of the 3×33 star from 4612 cycles, in the case of the (0; –125), to 5205 cycles, which is an improvement of approximately 13%.

In order to find the reason why changing the sink location to (0; 0) increases the lifetime, some calculations were computed to measure the total distance traveled by data. As mentioned before, each sensor acted as a NM for a certain number of cycles for only one round. This NM collects data from all other sensors, aggregates it then sends the aggregated data to the sink. Therefore, two communication distances must be measured for each sensor as follows:

- $d_{sensor-NM}$;

which is the communication distance between every sensor and the selected NM.

- $d_{NM-Sink}$

which is the communication distance between the selected NM and the sink. By adding all the distances between the sensors and every NM and the distance between every NM and the sink, a new metric is derived as follows:

$$d_{data} = \sum_{j=1}^{M} \sum_{\substack{i=1 \\ i \neq j}}^{N} d_{sensor_i - NM_j} + \sum_{j=1}^{M} d_{NM_j - Sink} \tag{5}$$

where N is the number of sensors and M is the number of NMs. Comparing the distance travelled by data for each sink location, it was found that at sink (0;0), d_{data} was the lowest.

2.7 Uniform distributions

Using the star topologies was successful in prolonging the lifetime of the network. But the star distributions are not suitable for all WSN applications. Some WSN applications such as chemical, environmental and nuclear sensing systems require uniformly distributed sensors (Bestavros et al., 2004). Therefore, some distributions with uniform densities were investigated in this study. The distributions were tested at the different sink locations and it was found that the maximum lifetime was obtained at the (0; 0) sink location. First, the hexagonal distribution was tested due to its wide and comprehensive coverage (Prabh et al., 2009; Gui & He, 2009). The second distribution is the Homogeneous Density Distribution in which a sensor was placed every meter square over the entire area (see Fig. 5). Finally, a circular distribution is tested with uniform density in which the number of sensors per circle increased as they move towards the border of the area. The homogeneous density distribution resulted the highest lifetime compared to the other uniform distributions. It produced 3301 cycle, while the hexagonal and the circular distributions produced only 3293 and 2876 cycles respectively.

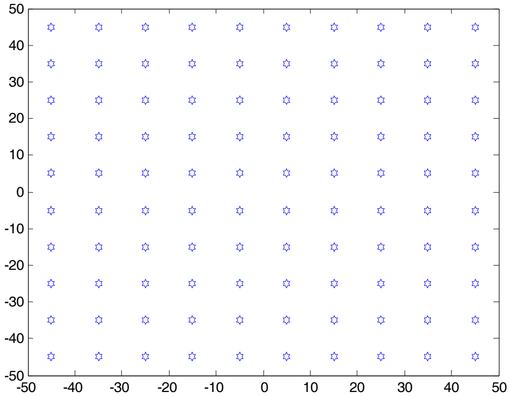

Fig. 5. Homogeneous Density Distribution

3. Relaying data collection

The fact that a sensor drains much of its power in trying to send its data to a fixed sink makes it necessary to use a mobile sink in addition to the fixed one. This is called a hybrid system. This section considers the problem of maximizing system life time (i.e., reducing the energy consumption) by properly choosing the destination; either the fixed sink or the mobile one (which is not controlled). More details about this work can be found in

(Zaki et al., 2008; Zaki et al. 2009). Using a hybrid model for message relaying, an energy balancing scheme is proposed in a linear low mobility wireless sensor network. The system uses either a single hop transmission to a nearby mobile sink or a multi-hop transmission to a far-away fixed sink depending on the predicted sink mobility pattern. Taking a mathematical approach, the system parameters are adjusted so that all the sensor nodes dissipate the same amount of energy. Simulation results showed that the proposed system outperforms classical methods of message gathering in terms of system lifetime. On the single node level, the average total energy consumed by the hybrid system is equalized over all sensors and the problem of losing connectivity due to the fast power drainage of the closest node to the fixed sink, is resolved.

3.1 System description

Fixed wireless sensor networks are described in the form of two tiers: the sensor and the fixed sink (observer). Another approach is the introduction of a third tier which is the mobile sink. Sensors send their data to the mobile sink as the second relay point instead of sending to the fixed sink. There are many benefits of using this approach where the most important is the reduction of power consumption during the transmission phase. The sensor is not required anymore to send its messages to faraway points as the mobile sink approaches the sensor to get the data. This system has many other advantages including robustness against the failure of nodes, higher network connectivity and reduction of the control messages overhead required to set up paths to the observer (Al-Karaki & Kamal, 2004).

The Data Mules (Shah et al., 2003), approach aims at addressing the operation of using existing mobile sinks, termed MULEs (Mobile Ubiquitous LAN Extensions) to collect sensed data in the environment. In a vehicular traffic monitoring application, the vehicles can serve as mobile agents, whereas in a wildlife tracking application, the animals can be used as mobile agents. The MULEs are fitted with transceivers that are capable of short-range wireless communication. They can exchange data with sensors and access points when they move into their vicinity. The main disadvantage of the basic implementation of the Data Mules scheme is its high latency. Each sensor node needs to wait for a MULE to come within its transmission radius before it can transfer its readings. Another disadvantage is that the system assumes the existence of mobile agents in the target environment, which may not always be true. The sensor nodes need to keep their radio receivers on continuously to be able to communicate with MULEs. In this section, a hybrid message transmission system that takes advantages of the data MULEs concept as well as the basic protocols of data routing, is developed. The system solves the inherit disadvantages of the basic MULEs architecture and increases network lifetime by reducing the single node power consumption and by balancing the overall system energy.

A typical three layers architecture for environmental monitoring system in urban areas consists of (Jain et al., 2006):

- The lowest layer consists of different types of sensor nodes.
- The second layer consists of the mobile agent that can be a moving car, a personal digital assistant or any moving device.
- The higher layer consists of the fixed sink. It represents the collection point of the sensed data before its transmission through a WAN to a monitoring point.

Considering this architecture for a city, a large number of fixed sensor nodes are deployed on both sides of the street to monitor different phenomena. Sensors work on their limited energy reservoir. Fixed sinks are the collection points that receive the sensed data directly from the sensor modules or from mobile sinks. They have higher capability than the sensor modules in terms of computational power and connectivity. The number of fixed sinks is usually smaller than the number of sensors; that is why it is not a costly operation to connect them to permanent power supplies or large energy scavenger and different communications facilities. When the sensed data is received by the fixed sinks, it can be forwarded to central databases through the wired or wireless infrastructure network for further processing. The mobile sinks periodically broadcast a beacon to notify nearby sensors of their existence. Upon reception of the beacon message, the sensor module can transmit its data to the nearby mobile node as the next overlay, thus saving its energy. The mobile agent can then send the sensed data to the fixed sink or to the remote database using other communication means.

3.2 Underlying system models

The models used in the system under study are explained next.

3.2.1 Routing, MAC and mobility models

The fixed part of the network operates the routing protocol suggested in (Younis et al., 2002). The basic assumptions are:

1. Appling a MAC protocol that allows the sensor to listen to the channel in a specified time slot as TDMA based protocol that minimizes the idle listening power when routing to fixed points.
2. The gateway which can be seen as the fixed sink has high computational power. All system algorithms are run on the gateway and the system parameter values are then broadcasted to the sensor nodes.
3. The sensor can determine transmission distance to its next hop and adjust its power amplifier correspondingly.
4. The radio transceiver can be turned on and off.

In mobile sink WSN, various basic approaches for mobility are involved: random, controlled and predictable. Random objects such as humans and animals can be used to relay the sensed data when they are in the coverage range. As the main issue in the described system is the moving cars in a street, therefore only one-dimensional uncontrolled mobility is considered. Different techniques are used to model vehicular traffic flows (Hoogendorn & Bovy, 2001). One well known example of mesoscopic model is the headway distribution model where it expresses the vehicular time headway as a probability distribution (Al-Ghamdi, 2001). Typical distributions are negative exponential and gamma distributions. The inter-arrival time T between two successive cars is modeled as a negative exponential distribution with an average β.

$$F(T,\beta) = \frac{1}{\beta} e^{-\frac{T}{\beta}} \tag{6}$$

During a 24-hour period, the traffic flow rate varies between heavy traffic during rush hours and low traffic at the end of day. Therefore, the one day cycle can be divided into several time intervals in which the value of β is considered constant.

3.2.2 Energy model

There are three basic operations in which sensors consume their energy (Shebli et al., 2007). First the sensor node has to convert the sensed phenomena to a digital signal. This is called aquisition. Second, the digital signal may be processed before transmission. Finally the sensor has to wirelessly communicate the data it aquire or receives. In this work, the focus is on the communication operation which is the basic source of power consumption.
The wireless node transceiver may be in one of four states:

1. sending a message,
2. receiving a message,
3. idle listening for a message,
4. in the low power sleep mode.

The linear transceiver model is used where:

1. The energy consumed to send a frame of size m over a distance of d meters consists of two main parts: the first one represents the energy dissipated in the transmitter and the second represents the energy dissipated in the power amplifier.

   $$E_{TX}(m,d)=m\left(e_{elec}+e_{amp}d^{k}\right) \tag{7}$$

   where m is the message length in bits, e_{elec} is the amount of energy consumed by the transmitter circuits to modulate one bit and $e_{anp}d^K$ is the amount of energy dissipated in the power amplifier in order to reach acceptable signal to noise ratio at the receiver that is located d meters away. k is an integer constant that varies between two to four depending on the surrounding medium. e_{anp} takes into account the antenna gain at the transmitter and the receiver:
2. To receive an m bits long message, the receiver then consumes:

   $$E_{RX}(m)=m\cdot e_{rx} \tag{8}$$

   where e_{rx} represents the reception energy per bit and m the message length. In order to send a message to a nearby mobile sink, the sensor node has to ensure the presence of the sink. The mobile node continuously sends out a detection message (beacon) to detect a nearby sensor. This requires a sensor to listen for discovery messages.
3. The idle listening energy is dissipated in two cases: when the sensor node communicates to fixed nodes, the suggested MAC protocols require that the nodes wake up in the same time to exchange messages. The second source of idle listening energy consumption is when communicating with a mobile sink. The sensor node stays in the idle listening state until it detects a mobile agent beacon. The low power idle listening protocol proposed in (Polastre et al., 2004) is used where the receiver samples the channel with a duty cycle. Each time the node wakes up, it turns on the radio and checks for activity. If activity is detected, the node powers up and stays awake for the

time required to receive the incoming packet. If no packet is received (a false positive), the node is forced back to sleep. In this model, the sensor has to be in the low power idle listening state for a given amount of time denoted by T. The power dissipated during this period is denoted by P_{idle}. Thus the idle listening energy is given by:

$$E_{idle} = P_{idle} \cdot T \tag{9}$$

4. Finally the low power sleeping state is when the sensor shuts down all its circuitry and becomes unable to neither send nor receive any message. The microcontroller is responsible for waking up the transceiver when the sensor node wants to communicate. This energy is neglected when comparing between any two systems as it does not differ for both systems.
   In this hybrid model, the mobile sink only notifies its presence to one hop away nodes only (Zaki et al., 2008). The sensor node decides either to route its message to the next fixed node or to the mobile sink depending on the parameter T_o. After the sensor collects the required data, it goes to the idle listening state for a maximum waiting period of T_o. During T_o, if the sensor receives a beacon, the next relay point will be the mobile sink; otherwise the sensor transmits to the fixed sink after spending T_o seconds in the idle listening state. After sending its message, the sensor node goes to the low power sleeping state. A cycle is defined as the state of the sensor from when it is required to send a message to the next relay point until it sends the message. The sensor energy states versus time graphs are shown in Figs. 6 and 7.

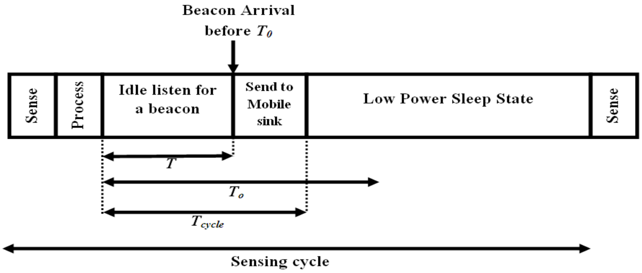

Fig. 6. Sensor states vs time in case of a mobile sink

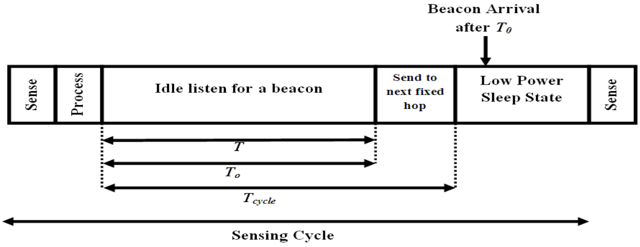

Fig. 7. Sensor states vs time in case of a fixed sink (hop)

Assuming that the beacon message arrives to the sensor after T seconds from the beginning of the listening state, then the energy consumed by the sensor during a cycle W_{cylce} equals:

$$W_{cycle} = \begin{cases} P_{idle} \cdot T + E_s & \text{if } T < T_o \\ P_{idle} \cdot T_o + E_l & \text{if } T > T_o \end{cases} \tag{10}$$

where:

$$E_s = m\left(e_{elec} + e_{amp} D_s^K\right) \tag{11}$$

$$\text{and } E_l = m\left(e_{elec} + e_{amp} D_l^K\right) \tag{12}$$

D_s and D_l are the distances between the sensor and the mobile sink and the fixed relay point respectively. Note that $D_l > D_s$ as D_l is proportional to the street length. D_s is the required distance to communicate with the mobile sink which is proportional to the street width. By investigating the effect of T_o on the system when transmitting a message during W cycles, the energy dissipated in the circuits $m.e_{elec}$ is constant for both interval definition of W_{cycle} and can be neglected. Also the energy required to receive the beacon is neglected as the discovery message is small compared to the sensor message.

There are many advantages of using such methodoly. Some of them are spacial reuse of the bandwith by allowing short range communication, simple scalability of the system, extendability of the system and guaranteed delivery of the sensed message as the there is always an alternative fixed path to route the data.

3.3 Single node simulation

From the sensor point of view, the system can be modeled as shown in Fig. 8.

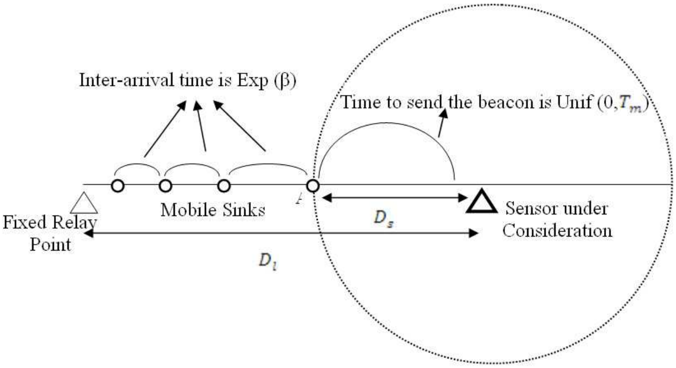

Fig. 8. Beacons transmission time

Point A is taken as the observation point. Given the mobility model described above, the inter-arrival time between the mobile sinks to point A is exponentially distributed with a mean β. In this section, the system is studied for a time interval when β can be considered constant. The mobile sinks periodically send a beacon to the nearby sensor every T_m. It is important to note that very low values of T_m is not a practical solution as the mobile sink will use the channel all the time preventing other communications to take place. The time taken by a mobile sink to send its first beacon after arriving to the sensor coverage area varies uniformly between Zero and T_m. The uniform distribution is assumed as the cars have started their message broadcasting at some points in time that are completely independent. The sensor can receive the beacon if it has been sent from a distance D_s or fewer meters away from it. The cars are assumed to be moving with a velocity V during their journey in the sensor range. MATLAB (MatLab) simulations of the described system is used to model the system kinematics and obtain guidelines on system behavior.

3.3.1 Simulation setup

The energy required to send a message is calculated using the transceiver properties of the Mica2 Motes produced by Chipcon CC1000 data sheet (Chipcon, 2008) and the values mentioned in (Polastre et al., 2004). The transmitter power needed to achieve a dedicated signal to noise ratio at the receiver is highly dependent on the system deployment. $e_{elec} + e_{amp}D_l^K$ and $e_{elec} + e_{amp}D_s^K$ are taken as the maximum and minimum powers that can be generated from the transceiver respectively. The simulation parameters are as shown in Table 3.

Parameter	Description	Default value
B	Cars inter-arrival mean time	8 to 30 seconds
P_{idle}	Idle listening power	173 µJoules
$R_{bit}\ (e_{elec} + e_{amp}D_l^K)$	Maximum output power per bit	26.7 mA * 3 V
$R_{bit}\ (e_{elec} + e_{amp}D_s^K)$	Minimum output power per bit	6.9 mA * 3 V
M	Number of bits per message	120*8
D_s	Lower sensor transmission radius	22.5 m
T_m	Beacon sending period	3 seconds
V	Moving sink velocity	15 m/s
$Sensing_{cycle}$	Sensor sensing cycle	60 seconds
R_{bit}	Transmission bit rate	19.2 kbps

Table 3. Default simulation parameters

The average energy consumed per cycle during 6500 cycles with respect to the value of T_o is simulated and given in Fig. 9 for exponential distributions with different values of β.

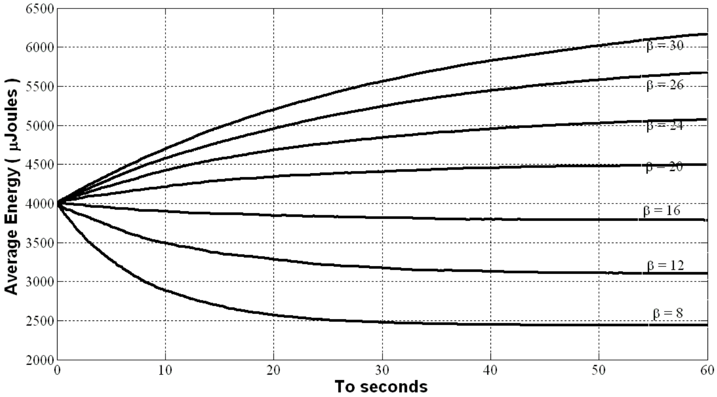

Fig. 9. Average energy for different traffic flow

3.3.2 Single node analysis

It can be seen from Fig. 9 that the optimum values for T_o are infinity for β equals 8, 12, 16; and zero for β equals 20, 24, 26, 30. The Low Traffic state will be applied when the optimum value of T_o equals zero. In this case, the sensor is synchronized by the cluster head (the fixed sink) to previously determined time instants in which it can send its message to the next faraway fixed relay point in the route path. In other words, the sensor will not wait for the mobile sink beacon. In this case the amount of energy dissipated by the sensor equals E_l, where D_l is the inter sensor node distance.

The second case, the High Traffic state, is when the optimum value of T_o equals infinity, i.e., the sensor goes to the idle listening state until it detects a beacon from a nearby mobile sink. Upon reception of the beacon, the sensor sends its message to the mobile sink and goes to the low power sleeping state. It is important to note that T_o equals infinity does not mean that the sensor will wait for an infinite time to receive a beacon, but the sensor is allowed to wait an unconstrained time until it receives the beacon. In Fig. 9, the three curves are for β equals 8, 12 and 16 seconds; the average energy consumed can be considered constant when T_o > 40 seconds. The value of T_o can be constrained by another system performance metric such as latency. When the optimum value is infinity, the average amount of energy dissipated equals:

$$E_{\text{inf}} = E_{idle} \cdot \tau_b + E_s \tag{13}$$

where E_s is the energy required to send its message to the mobile sink. τ_b is the average time during which the sensor will be in the idle state during the W cycles.

From Fig. 9, the threshold value of τ_b that determines the system state can be calculated by getting the minimum of E_l and E_{inf} where:

$$\tau_{b\,\text{threshold}} = \frac{m \times e_{amp}\left(d_l^K - d_s^K\right)}{P_{idle}} \tag{14}$$

The sensor will be in the Low Traffic state (LTS) when $\tau b > \tau b$ threshold and it will be in the High Traffic state (HTS) when $\tau_b < \tau_{b\ \mathrm{threshold}}$.

3.4 Energy balanced linear network with mobile sinks

In the previous section, the energy improvement of a single sensor node using the suggested hybrid system was proven. In this section, the work is extended to investigate the impact on overall network performance. The main goal of environmental monitoring WSN is maximizing the network lifetime while keeping its connectivity. This can be done by several ways on different network layers starting from the physical to the application layer.

3.4.1 Basic problem

In all the possible wireless sensor network topologies, two basic approaches can be used to deliver messages to the sink node: direct transmission and hop-by-hop transmission (Mhatre & Rosenberg, 2004). As shown in Fig. 10, in direct transmission where packets are directly transmitted to the fixed sink without any relay, the nodes located farther away from the sink have higher energy consumption due to long range communication, and these nodes die out first. On the other hand, in multi-hop linear networks, the total energy consumed in the nodes participating in the message relaying is less than the energy consumed in direct transmission; however, it suffers from the fast energy drainage in the nearest node to sink. Both cases inherit the energy unbalance problem of wireless sensor networks due to the many to one communication paradigm. Although all the previously mentioned protocols consider energy efficiency but they do not explicitly take care of the phenomena of unbalanced energy consumption. In such networks, some nodes die out early, thus resulting in the network collapse although there is still significant amount of energy in other sensors.

Next, a new solution using the hybrid message transmission method mentioned previously, is presented.

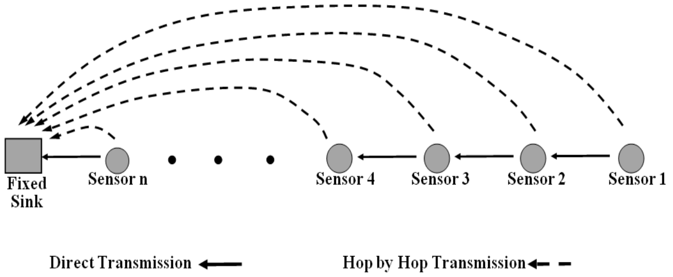

Fig. 10. Direct and Hop by Hop transmission for linear network

3.4.2 Using hybrid message transmission schemes

The problem of unbalanced load distribution in case of multi-hop networks can be manipulated by using a hybrid message transmission system. The basic idea lies in mixing single-hop with multi-hop message transmission. A simple way to implement the hybrid scheme would be to make the sensor node spend a period of its lifetime using one of the modes while spending the other period using the second mode.

In (Efthymiou et al., 2004; Mhatre & Rosenberg, 2004; Zhang et al., 2007), the authors calculate the optimized ratio of the time by which the sensor decides either to send directly to the fixed sink or to overload its neighbors using hop-by-hop transmission as in Fig. 10. The basic idea is simple: find an alternative –and usually higher energy- way for faraway nodes to send their message to the sink in order to reduce the load on closer nodes. The proposed solutions are efficient for small networks; but for large networks practical limitations can prevent a far-away node from sending a message using high transmission power.

Another approach for message transmission energy reduction is the usage of mobile sinks. As stated previously uncontrolled mobile-sink WSN suffer from energy overhead required to detect the presence of mobile agents. In the previous subsection, the sink detection *controlled* overhead was modeled as the maximum period that the sensor nodes stay in the idle listening state.

In this subsection and based on the results obtained previously, energy balanced linear sensor network with one fixed sink and multiple uncontrolled mobile sinks, is achieved. Based on the system current status and using a hybrid message transmission algorithm, the sensor nodes can decide either to send to the next fixed relay node or to wait for the mobile sink a maximum period of time T_o. Energy balancing is performed for different mobile sinks behaviors. In the low mobility state, every node is assigned a maximum waiting time for the mobile sink before it sends to the fixed relay node. A mathematical formulation is shown to obtain the best waiting time values that balance the energy among all nodes. The system is solved for different parameters' values using a generic numerical algorithm.

3.4.3 Model under study

The environmental monitoring system studied here consists of a linear sensor network with one fixed sink and multiple uncontrolled mobile sinks. The sensor nodes are equidistantly distributed with a distance D_l. The fixed and mobile sinks are assumed to have a continuous power supply while the sensors are energy constrained. Sensors are assumed to be able to adjust their transmit power amplifiers to exactly meet the required signal strength at receivers with different distances. The sensor nodes can receive or send a message to the mobile sink if it is located at a distance that is less than D_s meter away from it. The network model is shown in Fig. 11.

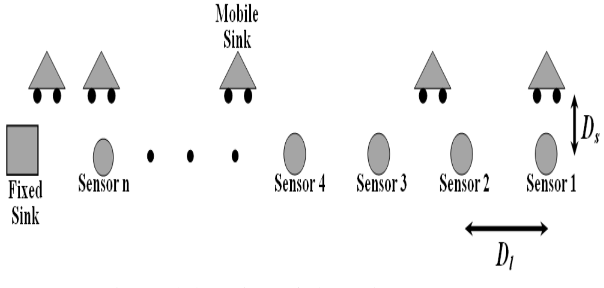

Fig 11. Linear sensor network model with mobile sinks.

3.4.4 Basic notations

Let ε_X denote the expected value of energy consumed for $T_o = X$. For every sensor that has a maximum waiting time of $T_o(i)$; $\varepsilon_{T_o(i)}$ can be obtained by multiplying equation 10 with the PDF of the waiting time *T* and integrating on the range of *T*. The resultant points for different valued of T_o are given in Fig. 9 using the equation:

$$\varepsilon_{To} = P_{idle}\beta + E_s + \left(E_l - P_{idle}\beta - E_s\right)e^{\frac{-T_o}{\beta}} \tag{15}$$

When T_o equals infinity, the average energy consumed per cycle can be calculated as:

$$\varepsilon_{\inf} = P_{idle} \times \beta + E_s \tag{16}$$

Finally for T_o = zero,

$$\varepsilon_o = E_s \tag{17}$$

Let $\varsigma(i)$ denote the total energy dissipated by the sensor node *i* during a sensing cycle. $\varsigma(i)$ takes into consideration two loads: The energy required to send the message generated by the node itself and the energy required to relay possible messages from nearby nodes during a sensing cycle.

Let $E[*]$ represents the expected value of any quantity *. For the mentioned network to be energy balanced, the total expected energy consumed by any sensor node i, $E[\varsigma(i)]$, during the system lifetime must be the same for all the nodes.

From the result shown in Fig. 9, in the HTS the optimum average energy consumed by any sensor node to send its self generated message $E[\omega_{cycle}(i)]$ equals $\varepsilon_{\inf}$. In this case all the sensor nodes always send their message to one of the mobile sinks. Consequently, sensor nodes do not relay messages generated by other sensor nodes. Every sensor dissipates the same average amount of energy: $E[\varsigma(i)] = \varepsilon_{\inf}$;therefore, energy balancing is achieved.

In the LTS the best solution from the sensor point of view is that it directly forwards all incoming packets to the next fixed node. In this case, the total energy consumed by a node *i* during a sensing cycle equals:

$$\zeta(i) = E_l + (i-1) \times (E_l + E_{rx}) \tag{18}$$

since the node has to send the data message generated by itself and relay $(i-1)$ messages from the other nodes in the queue. In the LTS, $\varepsilon(i) = E_l$ $\varepsilon(i)$ obtained by substituting T_o with zero in equation 15. It is assumed that the sensor will wake up in pre-determined time instants to send its message to the next relay point in the routing path. It can be shown that every node dissipates different amount of energy depending on its position where sensor *n* is the highest loaded node. Energy balancing is required in the LTS.

3.4.5 Balancing the low traffic state

Energy balancing can be done by increasing the energy required by the relatively far-away nodes from the fixed sink for sending a data message, to reduce the number of messages that a relatively nearby node has to relay. This can be done by finding an alternative path to send the message. In the system under study, the alternative is a longer waiting time in the idle listening state for an approaching mobile sink.

For the LTS in the hybrid message transmission system described above, waiting any amount of time for hearing a beacon from a mobile sink increases the average energy required to send the message. It also decreases the probability that a node sends its messages to the next fixed node to relay it (Zaki et al., 2009).

3.4.6 Problem statement

Given a linear wireless sensor network that consists of *n* sensor nodes, a sensor node *i* may transmit a data message to the next fixed point or to one of the mobile sinks depending on the maximum waiting time $T_o(i)$. The mobile sinks have an exponentially distributed waiting time with mean $\beta > \beta_{threshold}$. What are the values of $T_o(i)$ for $i = 1,2,\ldots\ldots,n$ that equalize and minimize the total average energy consumed by every sensor causing the maximization of the network life time?

$$E[\zeta(i)] = E[\zeta(j)] \text{ for } i, j = 1,2,\ldots,n \tag{19}$$

3.4.7 Mathematical formulation

Let P_i denote the probability that a node *i* sends to the mobile sink. Using the exponential distribution as the Probability Density Function (PDF) of the waiting time and the definition of $T_o(i)$, then:

$$P_i = \int_0^{T_o(i)} \exp(t,\beta)dt = 1 - e^{-T_o(i)/\beta} \tag{20}$$

Let $N_r(i)$ denote the number of relayed messages by sensor *i*. The total energy consumed by sensor *i* during a sensing cycle is given by:

$$\varsigma(i) = \omega_{cycle}(i) + N_r(i) \times \left(E_{rx} + \omega_{cycle}(i)\right) \tag{21}$$

as $N_r(i)$ depends on the amount of messages relayed from successor nodes for nodes 1 to node $i-1$, and $\omega_{cycle}(i)$ depends on $T_o(i)$. Therefore, $N_r(i)$ and $\omega_{cycle}(i)$ are both independent variables. The expected total energy consumed by node *i* equals:

$$E[(\varsigma(i))] = E[\omega_{cycle}(i)] + E[N_r(i)] \times \left(E_{rx} + E[\omega_{cycle}(i)]\right) \tag{22}$$

For every sensor that has a maximum waiting time of $T_o(i)$, $E[\omega_{cycle}(i)] = \varepsilon_{T_o(i)}$ can be obtained from equation 15.

The average number of the total messages that node *i* receives from all previous nodes $E[N_r(i)]$ is given by:

$$E[N_r(i)] = \sum_{k=1}^{i-1} \prod_{j=k}^{i-1} \left(1 - P_j\right) \tag{23}$$

From equations 22 and 23, the total average energy consumed by the sensor node i equals:

$$E[\varsigma(i)] = \varepsilon_{T_o(i)} + \left[\sum_{k=1}^{i-1} \prod_{j=k}^{i-1} \left(1 - P_j\right)\right] \times \left(E_{rx} + \varepsilon_{T_o(i)}\right) \tag{24}$$

where *i* varies from 1 to *n*

The energy balancing problem can be solved by equating the above equations 24. Thus, there are *(n-1)* equations. The last equation can be deduced from node *n* average transmission energy. Knowing that the last sensor will not overload any other subsequent node, the optimum average energy consumption for node *n* is when $T_o(n) = zero$ or:

$$\omega_{cycle}(n) = \varepsilon_{zero} = E_l \tag{25}$$

3.4.8 Solving the system states

The algorithm shown in Fig. 12 solves *N* simultaneous equations resulting from equating the equations in 24 and using 25. It can be implemented on a processing unit for any PDF of the arriving beacon time *T* other than the exponential distribution. It is important to note that using the LTS graph and knowing the value of ε_{To} is sufficient to calculate T_o. Rewriting the general equation of $E[\varsigma(i)]$ in order to get $\varepsilon_{T_o(i)}$:

$$\varepsilon_{T_o(i)} == \frac{E[\varsigma(i)] - \left[\sum_{k=1}^{i-1} \prod_{j=k}^{i-1} \left(1 - P_j\right)\right] \times E_{rx}}{1 + \sum_{k=1}^{i-1} \prod_{j=k}^{i-1} \left(1 - P_j\right)} \tag{26}$$

The numerical algorithm works a follows:

```
1. Calculate the LTS graph for $T_o$ varying form zero to Max_$T_o$ with an
   appropriate resolution.
2. $N$ = Number of sensor nodes.
3. Calculate $\varepsilon_{zero} = E_l$ and $\varepsilon_{inf}$ using equations 16 and 17.
4. Assume $\varepsilon_{To(1)} = \frac{\varepsilon_{zero} + \varepsilon_{\inf}}{2} = E[\zeta(i)], \forall i = 1 to N \cdot$
5. $\Delta\varepsilon = \frac{\varepsilon_{\inf} - \varepsilon_{zero}}{1000} \cdot$
6. For $I$=1 to 1000.
          node = 1.
          While ( $\varepsilon_{To(node)} > \varepsilon_{zero}$) and ( node < N )
                    Get $T_o(node)$ and $P_{node}$.
                    Use (26) to calculate $\varepsilon_{To(node+1)}$
                    node = node + 1.
              If ( $\varepsilon_{To(node)} > \varepsilon_{zero}$ )
                    $\varepsilon_{To(1)} = \varepsilon_{To(1)} - \Delta\varepsilon$
              Else
                    $\varepsilon_{To(1)} = \varepsilon_{To(1)} + \Delta\varepsilon$
7. $Error = \left| \frac{\varepsilon_{To(node)} - \varepsilon_{zero}}{\varepsilon_{zero}} \right| \times 100.$
8. If (Error > 5)
      Repeat from step 6 for $N = N-1$
9. If node < $N$
      Assume that all the nodes from 1 to (N-node) work at $T_o$ = infinity and they
      dissipate $\varepsilon_{inf}$
```

Fig. 12. Solving the system equations.

From equations 24, it is clear that $\varepsilon_{To(i)} > \varepsilon_{To(i+1)}$ for all values of i. The algorithm starts by assigning node *1* an average energy $\varepsilon_{To(1)}$ in the middle of the LTS curve. All next nodes are solved correspondently. The algorithm iteratively tries to assign the last node (e.g. the closest to the fixed sink) an average energy consumption of E_l.

3.4.9 Simulation results

Using MATLAB, the algorithm was run using the values presented in Table 3 and for a network of 10 sensor nodes. The system is simulated for two cases. Case 1 is when $\beta = 100$ seconds. In this case, the algorithm succeeded to get the values of $T_o(i)$ for all 10 nodes. The percentage of error between $\varepsilon_{To(10)}$ and E_l equals –0.238%. The results are shown in Fig. 13.

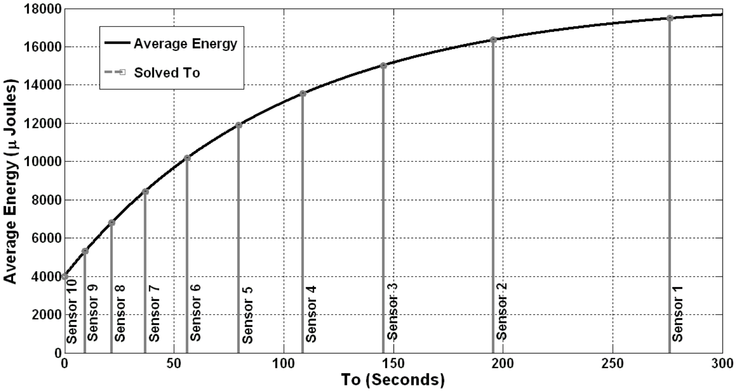

Fig. 13. Waiting time $T_o(i)$ for all the 10 sensor nodes versus $\varepsilon[T_o(i)]$ for $\beta = 100$ seconds.

Case 2 is simulated for $\beta = 40$ seconds (see Fig. 14). The values of $T_o(i)$ for 8 nodes starting from node 3 to node 10 is obtained and the solutions for nodes 1 and 2 are approximated to T_o = infinity (or a relatively high value as mentioned in the graph). In this case, all the sensor nodes dissipate $E[\zeta(i)] \approx \varepsilon_{inf}$, i = 1, 2,….,N and the hybrid message relaying method has the same performance as always relaying to the mobile sink. However, using the hybrid system the upper bound on the delay can be calculated and message delivery is guaranteed.

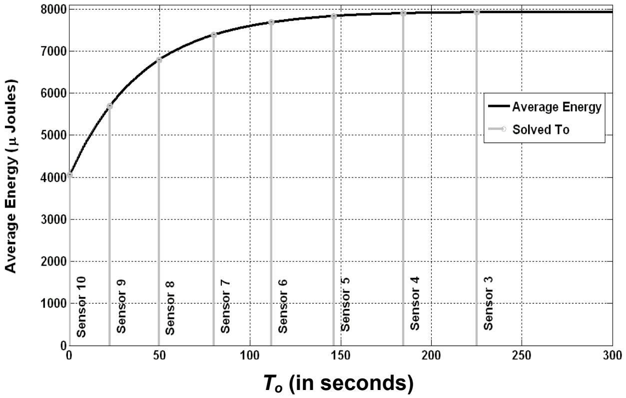

Fig. 14. Waiting time $T_o(i)$ for all the 8 solved nodes versus $\varepsilon[T_o(i)]$ for $\beta = 40$ seconds.

The system life time is calculated as follows: assume that all the nodes are given initially the same amount of energy X. The total number of sensing cycles ψ can be calculated by dividing the total amount of energy by the average total energy consumed in a cycle. Taking the conservative approach mentioned in (Mhatre & Rosenberg, 2004), the system is said to be dead when the first sensor node dies, i.e., the node that consumes the most energy.

The system lifetime is compared to the two classical cases: All-Mobile system when all the nodes always send to the mobile sink, i.e., T_o = infinity, and All-Fixed system when all the nodes always send to the fixed relay node, i.e., T_o = zero. In the All-Fixed system, node n

will die first. In this case, ψ_{fixed} is calculated for the average energy consumed per node n $E[\zeta(n)]_{fixed}$ which is obtained by substituting i with n in equation 18. In the All-Mobile system, all the nodes always send to the mobile sinks; they dissipate the same amount of energy. ψ_{mobile} is calculated by substituting $E[\zeta(i)]_{mobile}$ by $\varepsilon_{\text{inf.}}$. Similarly, in the hybrid model described here, all the nodes dissipated the same amount of energy. Ψ_{hybrid} is calculated by substituting $E[\zeta(i)]_{hybrid}$ by $E[\zeta(1)]$.

$$\Psi = \frac{X}{E\left[\varsigma\left(\text{most energy dissipating node}\right)\right]} \tag{27}$$

Fig. 15 shows the average total average energy consumed in the three mentioned systems for different ascending values of β starting from $\beta_{threshold}$. It is clear that the hybrid system moves from the All-Mobile performance to the All-Fixed performance for low and high values of β respectively.

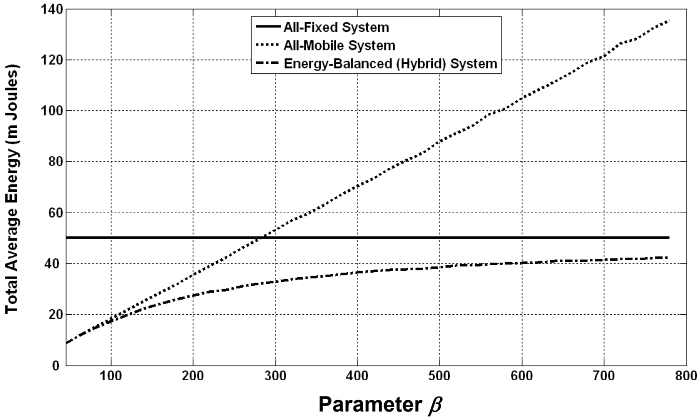

Fig. 15. Comparison between the total average energy consumed in the All-Fixed, All-Mobile and Energy-Balanced systems.

4. Conclusion

The advantages of WSNs using low-cost and low-power sensors in several application areas justify the research interest in network lifetime optimization techniques. In this chapter, results pertaining to this research problem were presented. First, a modification of LEACH-C method was described that obtains the optimum number of cycles for each sensor to act as a network master such that the network lifetime is maximized. Then, it was shown that use can be made of geometric node distributions and sink locations to prolong the network lifetime compared to the case of random node distributions. Then, an energy efficient relaying data collection system is considered. It can be used for different applications such as environmental monitoring in urban areas. Using moving cars as uncontrolled mobile sinks, a hybrid model that proposes a maximum sensor waiting time for the mobile agent before sending to the fixed node was investigated both in high and low traffic states. Also suggested was a hybrid message transmission scheme that decreases the load on nodes nearby to the fixed sink while maximizing the network lifetime. Simulation results that indicate the benefits of each of the proposed techniques were given throughout the chapter.

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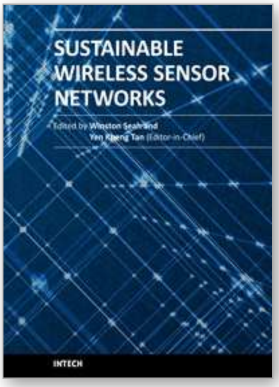

Sustainable Wireless Sensor Networks
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Wireless Sensor Networks came into prominence around the start of this millennium motivated by the omnipresent scenario of small-sized sensors with limited power deployed in large numbers over an area to monitor different phenomenon. The sole motivation of a large portion of research efforts has been to maximize the lifetime of the network, where network lifetime is typically measured from the instant of deployment to the point when one of the nodes has expended its limited power source and becomes in-operational â€“ commonly referred as first node failure. Over the years, research has increasingly adopted ideas from wireless communications as well as embedded systems development in order to move this technology closer to realistic deployment scenarios. In such a rich research area as wireless sensor networks, it is difficult if not impossible to provide a comprehensive coverage of all relevant aspects. In this book, we hope to give the reader with a snapshot of some aspects of wireless sensor networks research that provides both a high level overview as well as detailed discussion on specific areas.

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