Investigating Wireless Sensor Network Lifetime under Static Routing with Unequal Energy Distribution

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***Abstract*— In a Wireless Sensor Network (WSN) the sensed data must be gathered and transmitted to a base station where it is further processed by end users. Since that kind of network consists of low-power nodes with limited battery power, power efficient methods must be applied for node communication and data gathering in order to achieve long network lifetimes. In such networks where in a round of communication many sensor nodes have data to send to a base station, it is very important to minimize the total energy consumed by the system so that the total network lifetime is maximized. The lifetime of such sensor network is the time until base station can receive data from all sensors in the network. In this work[1], besides the conventional protocol of direct transmission or the use of dynamic routing protocols proposed in literature that potentially aggregates data, we propose an algorithm based on static routing among sensor nodes with unequal energy distribution in order to extend network lifetime and find a near-optimal node energy charge scheme that leads to both node and network lifetime prolongation. Our simulation results show that our algorithm achieves longer network lifetimes mainly because the final energy charge of each node is not uniform, while each node is free from maintaining complex route information and thus less infrastructure communication is needed.**

I. INTRODUCTION

Advances in electronics and wireless communications have enabled the development of low-cost, low-power multifunctional nodes that are small in size and communicate possibly unattended in short distances using Radio Frequency (RF), Infrared (IR) or Optical transmission medium [1]. These tiny nodes which consist of sensing, data processing, energy and communication components leverage the idea to build inexpensive wireless sensor networks (WSN). These networks can be used to collect information from an area of interest, especially where the physical environment is harsh. The applications of WSN range from military to civilian, weather monitoring to petroleum, industry automation to smart houses and may be realized by using different type of sensors with different capabilities [9].

These inexpensive sensors are equipped with limited battery power and therefore their main constraint is their energy levels, which limits the lifetime and possibly the quality of the network. Due to this constraint, one of the fundamental problems in WSN is how to maximize network lifetime. Network lifetime is defined in this work as the time when any node doesn't have enough energy to send its data to the base station. The aim in a WSN is the efficient transmission of all data to the base station so that the network lifetime is maximized in terms of rounds, therefore a round is defined as the process of gathering all the data from sensor nodes and sending them to the base station. In this work we measure the performance of our algorithm in terms of network lifetime which is defined as the number of rounds before the first node in the network has expended all its energy [7][8].

Significant research has been carried out to extend the lifetime of the network. Because of the energy constraints of sensor nodes, the protocols running on sensor networks must use the resources of each node efficiently in order to achieve longer network lifetime[5][6]. Additionally, protocols should minimize the total communication messages that are exchanged among nodes used for synchronization and broadcasting information about energy levels. Some of the existing routing protocols take a cluster-based approach while others use linear programming methods to solve the problem [3]. In the cluster based approach [4][5][6] the whole network is divided in groups where each group has a leader, also known as cluster head, which is responsible to collect information from its member nodes, possibly aggregate or fuse data and send them to the base station or any nearest group leader. In linear programming approach the lifetime of a typical WSN is formulated as a maximum flow problem and solved using linear programing [4][10].

Direct transmission is a simple approach for the problem of extending network lifetime in which each node transmits its own data directly to the base station [7]. However, if the base station is far away, the cost of sending data to it becomes large and it is not an energy efficient way of communication for sensors. In order to solve this problem, data transmission should be based on multi-hop routing and each node should choose its neighbor node according to some criteria, such as minimum distance or maximum residual energy levels or an energy-based definition of a link cost function for packet propagation [10]

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Despite the various protocols for energy efficient routing proposed for WSN [10][13], no consideration is given to the large overhead created by the node's communication and synchronization messages. These messages could be a serious factor responsible for depleting the node battery fast [14]. Taking this into consideration, we propose a new method to extend the network lifetime which is based on an initial unequal node energy distribution charge scheme and static routing. So, instead of initially charging all nodes in the network topology with the same amount of energy, our heuristic finds a non-uniform energy allocation scheme that is used instead. Moreover, static routing means that each node individually chooses its neighbor node to transmit its data which doesn't change with time, so messages for node communication are not needed to be exchanged. Our algorithm is based on static routing decisions to minimize the infrastructure messages among nodes, so it behaves well for static network deployments.

This idea leads to a non-uniform battery charge for nodes in the network. So, nodes that do not take a great part in routing process, should be loaded with less initial energy levels compared to those that are focal points of data dissemination. The main idea of our algorithm is to share an initial energy load among all nodes in the network non-uniformly in a manner that will extend the total network and node lifetime. To do so, the network goes through a phase of "training" throughout our simulation scenario and converges to near - optimal values of network lifetime.

The rest of this work is organized as follows. In Section 2, we formulate our system model and give the problem statement. Our proposed algorithm is described in detail in Section 3. Next, in Section 4, we present our simulation results and show the network energy gains that lead to higher network lifetime. Finally we conclude the paper and present future research directions in Section 5.

II. SYSTEM MODEL AND PROBLEM

A. Radio Model

We use the first order radio model described in [4] [6]. In this model, energy required to run the transmitter or receiver circuitry in a WSN node, is $e_{elect} = 50\ nJ/bit$, for the electronic subsystem and $e_{amp} = \frac{100pJ}{bit}/m^2$ is the energy to run the transmitter amplifier. It is also assumed $\approx \frac{1}{r^2}$ loss due to channel transmission. Therefore the energy required to transmit a data packet of size *k bits* from a node *i* to node *j* to a distance d_{ij} is given by the following equation:

$$E_{Tx}(k, d_{ij}) = e_{elect} \times k + e_{amp} \times k \times {d_{ij}}^2 \quad (1)$$

where d_{ij} is the distance between node *i* and node *j*. The energy required to receive a packet of size *k* bits from any node *j* is given by the following equation:

$$E_{RX}(k) = e_{elect} \times k \quad (2)$$

It is also assumed that the radio channel is symmetric, which means that the energy cost of transmitting a message from node *i* and node *j* is the same as the cost of transmitting a message from node *j* and node *i*. As it is also mentioned in [6], the energy required for receiving a message is not negligible. Therefore, the routing protocols should minimize the number of receive and transmit operations.

B. Problem Statement

Consider a wireless sensor network of *n* nodes, with $n \in Z^+$, that are randomly distributed over an area of interest. A WSN can be considered as a graph $G(V, E)$ where *V* expresses the number of nodes *n* and *E* the total edges that connect the nodes. The position of every sensor node could accrue from a well-known random statistical distribution in the 2D plane, such as uniform, Gaussian, Poisson, etc. However the topology could be pre-engineered for a specific kind of application. In every situation of node position generation, we consider only one gateway node, which is responsible to collect all the network measurements. The gateway or base station node has theoretically infinite energy levels. Usually the gateway node (or base station), which is responsible to collect all network data, is placed in a position according to the application scenario, either at the center of the network topology, or outside of it. In our situation we arbitrarily choose to place it at the south-east corner of the 2D plane, as it is shown in Fig. 1.

Throughout our simulations we are focused on a specific network model. However, there are various models for sensor networks proposed in literature [2]. The characteristics of our network model are:

- Each node periodically senses its environment and sends its measured data to a base station, located at a fixed and possibly distant point.
- A sensor node sends its data in every round with a probability *p*.
- Sensor nodes are homogenous, in terms of hardware characteristics, such as memory, CPU and radio, and highly energy constrained, but with the ability to show variable energy reserves such as power packets.
- Sensed data are highly correlated.
- Every node could be used as a relay for other nodes' data in case of a multi-hop routing decision.
- Every node has at least one neighbor. The distance d between two neighbors is $1 \leq d \leq \sqrt{2}$.
- The entire deployed sensor network is stationary and the topology of the network does not change.
- The channel assumed for radio communication is characterized as Additive White Gaussian Noise Channel (AWGN).
- Each data packet has length of 1000 bits.
- Data is sent as a unicast packet, but due to the wireless shared medium, other nodes in range can hear it, thus overhearing phenomena are present[14]. This means that every node that belongs to the wireless channel neighbor of the sender node will hear all packets and will consume energy to read the header of each frame. If it is not the intended receiver, then it will drop the packet. Otherwise it

will accept the packet. In either case the node will consume energy.

Each node generates a fixed length data packet of k bits and wishes to transmit it to base station. If a node cannot reach the base station directly, mostly due to the fading phenomena, that causes the signal reaching the receiver to be below its reception sensitivity threshold, it routes its packet to a neighbor nearby. A node chooses each neighbor node according to the following two criteria: a) *Minimum distance* and b) *Minimum residual energy*. In *(a)*, a node searches its neighbor list and always chooses the one node with the minimum distance d. This means that each node has a static way of relaying, which excludes the need to receive information each time about its neighbors positions. Alternatively, in *(b)*, a node searches its neighbor list and chooses the one node with the minimum residual energy reserve. This means that each node switches among many neighbor choices each time, depending on criterion *(b)*. So this decision depicts a dynamic way of locally choosing a neighbor.

The locations of the sensors, either random or pre-engineered, remain fixed for every simulation scenario and the base station knows them all. In a real sensor network deployment the gateway node may know the position of every single node if sensor nodes are equipped with GPS or by other means such as triangulation [12].

Many researchers in the WSN field that have proposed various network models and routing protocols to prolong node or/and overall network lifetime [5][6] have considered an initial uniform energy charge among sensor nodes, given that the network under consideration is considered homogenous. So for the total network lifetime to be prolonged and possibly maximized under certain network load, bandwidth, delay criteria and network topology, a routing protocol should propose energy optimal paths for the data, taking into account an initial but same energy charge for every node. However in our work we show that a uniform energy distribution scheme is not always the best choice in terms of network lifetime. Our work does not focus on a new routing algorithm. Conversely each node could choose its neighbor node for relay according to criteria (*a)* and (*b)* as previously stated, but this decision is local and does not lead to a complete path selection.

The problem under the system model given above is to propose an energy distribution / allocation of the initial total energy reserve of the network to each node such that the network lifetime is maximized in terms of static routing among sensor nodes. The total network lifetime is estimated under the following different strategies:

Strategy 1: In this strategy, all nodes start with an equal energy reserve of e.g. 1 Joule and they choose their neighbor node in case of relaying according to (*b)* criterion, i.e. dynamic routing, as mentioned previously. In this situation a uniform energy distribution is applied to every node and after the first node death the total network lifetime is calculated. We may also refer to strategy 1 as: *Uniform Charge – Dynamic Neighbors*

Strategy 2: In this strategy, nodes start again with the same energy reserve but they choose their neighbor according to (*a)* criterion. In this situation a non-uniform energy distribution is achieved and according to that, the network lifetime is calculated. We may also refer to strategy 2 as: *Non – Uniform Charge – Static Neighbors*

We should note that the definition of lifetime differs according to the application of each applied WSN. In applications where the quality of the system is dramatically decreased after the first node death, the time that all the nodes are active is important and thus lifetime is defined as the number of rounds until the first sensor is drained of its energy. This definition is applied to our work. Alternatively, in case where a WSN is densely deployed, the quality of the system is not affected until a significant amount of nodes die, since near neighbor nodes will record identical and highly correlated data. In that case, the lifetime of the network is the time elapsed until, e.g., half of the nodes or some other specific portion of the nodes die.

For our work, the time in rounds where the first node depletes all of its energy defines the overall network lifetime. Taking this consideration into account, our work gives the timings of the first node death under different energy distributions.

III. PROPOSED ALGORITHM DETAILS

In this section, we describe an iterative algorithm to generate a non-uniform energy distribution for nodes in a WSN. Given the locations of nodes in the network, and according to our proposed network model, we are interested to propose an energy distribution according to strategy 2 that will lead to longer network lifetime values as compared to strategy 1.

As previously mentioned, each node sends its data to the gateway either directly or through multi-hop communication. We furthermore assume that data is sent and received according to a probability p. This assumption is made because we want to depict situations in the wireless medium, where possibly due to harsh environmental conditions or due to high number of collisions some nodes are unable to route their data. This probabilistic assumption is introduced in order to depict the stochastic behavior of the wireless environment.

In this work, we do not deal with error correction techniques for WSN such as ARQ or HARQ [11] that are based to retransmission policies, or with MAC layer techniques to deal with collisions. However because we want to depict a more realistic communication scenario among nodes, we choose the probabilistic method above for expressing the success data delivery. Specifically, in each round each node that has data to send calculates a number from the set (0...1) according to a uniform probability distribution function and to a certain seed number. This seed number is necessary by the uniform probability distribution function (PDF) in order to produce each time different pseudo-numbers. So, by changing the seed value in every iteration, we know that the decision to send a packet will not be deterministic. For convenience, the seed value can be also considered as a variable that get incremented in every iteration of the simulation scenario. If this probability is above a threshold then nodes' data is transferred successfully. Alternatively, the packet that carries data is discarded.

Our proposed algorithm attempts to achieve a non – uniform energy level distribution among nodes, thus implements strategy 2. The steps of the algorithm are the following:

1. Choose an initial total energy load of *M* Joules, which characterize the network energy capacity.
2. Charge all nodes with a same initial energy value, such as $^{M}/_{\sum nodes}$, defining a uniform energy distribution.
3. For each *seed* (iteration) do

   While (*Avg(nodes_energy) >En_ thres)* do

   Begin

   a. Every node $n \in G(V,E)$ transmits packets with a certain probability *p*.
   b. $\forall\, node$ Calculate charge energies and save them to a table named as *charges.*
   c. $\forall\, node$ Calculate residual energies and save them to a table named as *residuals.*
   d. Find the *MAX* and *MIN* value in *residuals* and the position *k, l* of *MAX* and *MIN* respectively in the *residuals.* The MIN value is always 0, but possibly in different position in every iteration.
   e. Calculate the recharge factor, named *rf,* as: $rf = MAX/2$ (3)
   f. $\forall$ Value in *residuals* that belong to a position i where $(i \neq k)$ *or* $(i \neq l\,)$ calculate a recharge portion, named *rp_new* = *charges(i),* for the next iteration . Alternatively,
      i. if $(i = k)$ then the recharge portion for the next iteration is *rp_new* = *charges(i)* – *rf* (4)
      ii. if $(i = l)$ then the recharge portion for the next iteration is *rp_new* = *charges(i)* + *rf* (5)
   g. Calculate the value *res* that depicts the accumulation of all the energy values of *residuals* such as:

$$res = \sqrt{\frac{1}{N}\sum_{i=1}^{N} residuals(i)} \qquad (6)$$

   End. {While}

End.{For}

where *N* is the total number of nodes at the topology and *En_thres = 0,001.*

From the above algorithm steps and from (6) above, it is obvious that the *res* value defines its convergence. The rate of convergence depends on how *rf* is defined and *rp_new* is calculated. If *res value* is small enough, it means that we have a situation of almost uniform node deaths. So our *rp_new* values, from which the energy distribution arises, for each node recharge is near optimal and leads to longer network lifetime rounds.

IV. SIMULATIONS AND RESULTS

In order to evaluate the performance of our proposed algorithm, we used a custom simulator in C++ where many networks with various sizes were tested. The physical dimensions of each network that were tested are 100m and 100m correspondingly in a 2D plane. However the simulator is not strict in that aspect, leaving the user the choice to create non-symmetrical networks, as far as the choice of the dimension size is concerned

In every simulation scenario, the topology creation took place first according to the following steps:

1. Choose the size of the network. This means that the user chooses the size of each of the 2-dimentions in the 2D plane.
2. Choose the total number of nodes to place in the network.
3. Place the nodes according to one of the following, i.e. density rules:
   a. Choose the node's coordinates randomly using a well-known probability distribution. Check if a node position is proposed more than once. If this is true, then run again the distribution to propose another position.
   b. Statically selecting each node's coordinates and places it.
   c. Upload a ready network topology from a file, where each node's coordinates are recorded.
4. Filter the random topology proposed by step 3 and create a connected graph G where each node has at least one neighbor. Networks produced by step 3a. which are non-connected, i.e. with nodes that do not have neighbor within distance *d* in the range $1 \leq d \leq \sqrt{2}$, are not taken into consideration.

Let's take an example of a random network with 30 nodes, distributed over a 2D plane of 100x100 meters. Initially, all nodes are charged with 1 Joule. The network topology is depicted in Fig. 1 where 1 indicates an active node and 0, no node. In particular, a node can be in three distinct states: 1) Active state 2) Idle state 3) Sleep state. Active state means that the node's radio is ON and is capable of listening to packets, receiving packets from other nodes and sending packets to other nodes. Idle state means that the node can measure its physical environment, but the radio is OFF, so no packet transmission/reception activity is considered. Lastly, sleep state means that all node hardware components are OFF. In this state, the node's energy consumption is zero.

Figure 1 depicts the random network topology used for our simulation. The representation of a 2D network is a 10x10 matrix with 100 cells. Each cell of the matrix holds either 0 or 1. If an active node is present, then the cell has 1. The lack of a node or if the node is in sleep state means that the cell has 0. Moreover, next to each 1 there is another number, that accounts for each node ID. The base station or gateway node has no ID and is placed at the south-east corner of the matrix. Finally, we assume that each cell is a rectangle, with size of which represents a distance of $30m \times 30m$. So for example the distance between nodes with ID=1 and ID=3 is $\sqrt{2} * 30 \approx 43m$.

0	0	0	0	**1(1)**	0	0	0	0	0
0	0	**1(2)**	**1(3)**	0	**1(4)**	**1(5)**	0	0	0
1(6)	**1(7)**	0	0	0	**1(8)**	0	0	0	**1(9)**
0	**1(10)**	**1(11)**	0	0	**1(12)**	0	**1(13)**	**1(14)**	0
0	0	**1(15)**	0	**1(16)**	0	**1(17)**	0	**1(18)**	0
0	0	**1(19)**	0	**1(20)**	0	**1(21)**	**1(22)**	0	0
0	**1(23)**	0	**1(24)**	0	0	0	**1(25)**	0	0
0	0	**1(26)**	**1(27)**	0	0	0	0	**1(28)**	**1(29)**
0	0	0	0	0	0	0	0	**1(30)**	0
0	0	0	0	0	0	0	0	0	***1(GW)***

Fig. 1 Random Network Topology with 30 nodes and their ID's

Fig. 2 depicts the *res* value from (6), i.e. the residual energy value accumulation of nodes, as a function of iterations. As previously mentioned, the *res* value defines the algorithm's convergence. As simulation proceeds and iterations increases, there will be a situation of near-uniform node deaths.

Specifically, from Fig. 2 it is obvious that, residual energy accumulation expressed by (6) gets lower in every iteration. After 40 iterations, the residual value starts to oscillate, and no further reduction is noticed. At iteration #69, the *res* value takes its minimum value, which is 0.0077. This means that every node has almost the same residual energy level and this practically means that nodes die almost simultaneously.

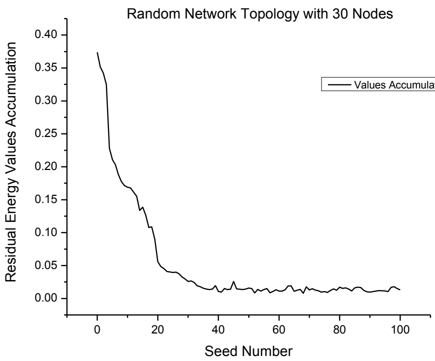

Fig. 2 Node Residual Energies Values Accumulation

So, from the point of minimal residual energy (res = 0.0077) we can get the near optimal energy charge distribution which is depicted in table II. These are the final and intended energy charges for every node. We can clearly observe from table II and Fig. 6 that 14 out of 30 nodes should be charged with initial energy < 1 Joule, while the rest 16 out of 30 node with energy > 1 Joule. This means that almost 50% of nodes will get a larger that 1 Joule charge and the other 50% of node will get less that 1 Joule. In Fig. 5, we have a graphical representation of the final energy allocation for all nodes. The flat line corresponds to energy value of 1 Joule and is the energy charge for every node according to strategy 1. Furthermore, the biggest energy charge is given by the algorithm to node with ID=22. This is reasonable, because this node has 5 neighbors to serve.

In Fig. 3, we simulate our wireless sensor network, depicted in Fig. 1, and plot the lifetime for the 2 strategies. It is clear that by using strategy 1, the network lifetime is constant. On the contrary, with strategy 2, and for the first 40 iterations, the lifetime value is increasing. This is due to the training phase of our algorithm. This is naturally expected, because we the *res* value has not reached its minimum value yet. When *res* reach its minimum, then the lifetime shows a more stable behavior.

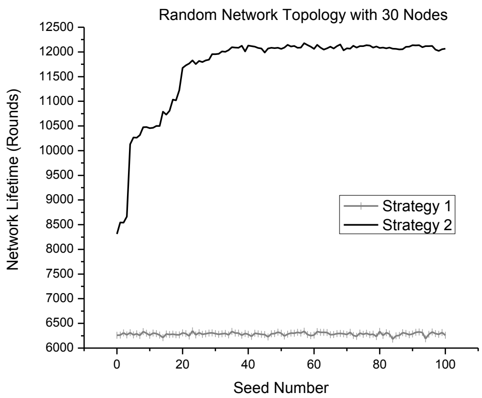

Fig. 3 Network Lifetimes per seed number (iteration) according to Strategy 1 and Strategy 2

Moreover, from Fig. 3 and Table I, we clearly see that adopting strategy 1 with flat energy charge of 1 Joule for every node, the average network lifetime after 100 iterations is 6286. While iterations ≤40 the lifetime increases, because there is a training in the network in order the near optimal energy distribution to arise. After that iteration, the lifetime stays in a steady level and oscillates around 12000, an improvement of almost a factor of 2.

However we should note that this difference in lifetime values between the strategies is a function of the node's energy cost for communicating their energy values in order the neighbor selection criterion based on the maximum residual energy is met. For our simulations we consider that each time a node has to make a decision about selecting a neighbor according to criterion (b) it has to receive packets from its neighbors that inform it about their residual energy levels. So for this communication to take place we consider 10% energy expenditure for both sender and receiver in order for such infrastructure communication to take place, compared to the total energy expenditure for sending/receiving a complete data packet of 1000 bits.

In order to propose a final node energy distribution that will form a charge scheme for a specific network, one could follow the steps:

1) Find minimum *res* value from (6) and record the corresponding seed value which tells us the number of iterations that are needed for this minimum to be found.

2) a) Simulate the network up to that *res* value, and reach the near optimal final energy charge scheme to use.

OR

b) Set a certain threshold (used as a stop criterion) in *res* value according to a criterion, record the seed (iteration) number and go to step 2 (a)

Either way we could estimate when there is a convergence.

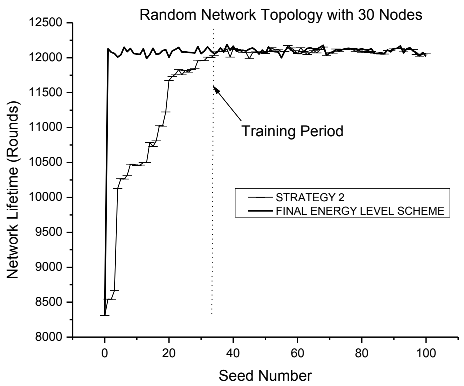

Fig. 4 Network Lifetimes per seed number (iteration) according to Strategy 2 and Final Scheme

In order to depict the training period from which the network goes through so as to find the optimum energy charge scheme, we do the following simulation scenario: We plot the network lifetime values from strategy 2, and the network lifetime arise, from the optimal energy values according to table II. We observe from Fig. 4, that from seed = 1 we get to almost 12000. Using strategy 2, we get to that value after several iterations. So, strategy 2 has an average lifetime of 11679 at the end of the simulation and if we use from the beginning the values from table II, the average lifetime is 12060, which is a 3.15% improvement. From Fig. 4 we clearly understand that in a real sensor network deployment, we can use from the beginning the optimal energy charge scheme and get the maximum average network lifetime.

Finally, we should state that for all our results about 100 runs were conducted and the values depicted in all the figures are averages. In order to test our algorithm for a bigger network, we constructed a second random network with 60 nodes, the deployment of which is based on that in Fig. 1 and 30 more nodes were added using a uniform distribution. From table I we observer, that for a bigger network strategy 2 is still better in terms of extending average network lifetime.

TABLE I

NETWORK LIFETIMES FOR VARIOUS NETWORK SIZES

Initial Energy (Joules)	Number of Nodes	Strategy	Average Network Lifetime	% Lifetime Improvement
1	30	1	6286	46
		2	11679	
1	60	1	4251	49
		2	8312	

V. CONCLUSIONS AND FUTURE WORK

In this paper, we propose an algorithm based on static routing among sensor nodes with unequal energy distribution in order to extend network lifetime. Our algorithm is based on the concept that nodes do not need to exchange messages to inform one another about their residual energy levels in order to select their neighbors for relaying data. This type of message exchange takes place frequently and leads to a non-negligible energy cost for nodes which leads to shorter network lifetime. We propose an iterative method which leads to different node energy distributions that the uniform one. So, nodes that have many neighbors should be charged initially with a greater amount of energy that others with less neighbors.

In all our simulations, strategy 1 -based on dynamic routing -with equal energy charges among nodes leads to a lesser network lifetime compared to strategy 2 -based on static routing- with non-uniform energy distribution. As a continuation of this work, we will simulate much more random networks, varying the number of nodes per network to compare the lifetimes of both strategies. Furthermore, we will explore other recharge policies different from this one presented at (4) and (5) to calculate the recharge portion for each node and observe if network lifetime will be prolonged or not. In conjunction with our algorithm and for several networks, we will also consider the effects of well-known channel error correction codes, such as Automatic Repeat Request (ARQ), Forward Error Correction (FEC) in the total energy consumption for sensor node communications.

TABLE II

FINAL ENERGY CHARGE VALUES PER NODE

Node ID	Energy Charge	Node ID	Energy Charge	Node ID	Energy Charge
1	0.58725	11	1.16402	21	1.16511
2	0.58728	12	1.16211	22	1.4739
3	0.6151	13	1.13329	23	0.85667
4	1.12989	14	1.18865	24	0.88725
5	0.85847	15	1.15545	25	1.18116
6	0.86185	16	0.61815	26	0.85987
7	1.44075	17	1.40844	27	0.61785
8	1.19243	18	1.15722	28	1.16609
9	0.58845	19	1.18316	29	0.86531
10	1.43596	20	0.58293	30	0.87594

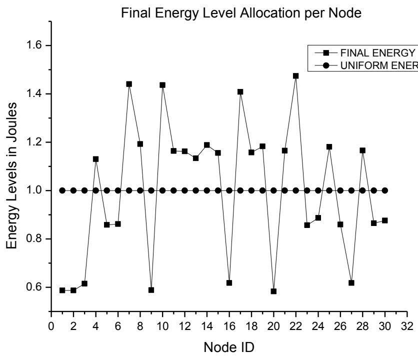

Fig. 5 Final Energy Level Allocation per Node

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