Energy-aware Node Placement in Wireless Sensor Networks

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***Abstract* – One of the main design issues for wireless sensor networks is the sensor placement problem. In this paper, we formulate a constrained multivariable nonlinear programming problem to determine both the locations of the sensor nodes and data transmission pattern. The two objectives studied in the paper are to maximize the network lifetime and to minimize the application-specific total cost, given a finite number of sensor/aggregation nodes in a region with certain coverage requirement. We first study a linear network, and find optimal placement strategies numerically. Through numerical results, we show that the optimal node placement strategies provide significant benefit over a commonly used uniform placement scheme. Furthermore, we also present a performance bound as a benchmark. Lastly we extend the results to a more sophisticated planar network, and use numerical results to evaluate the performance of the proposed strategies.**

I. INTRODUCTION

The rapid progress of wireless communications and micro-sensing MEMS technologies has enabled the development of low-cost, low-power sensor nodes, each capable of sensing, processing, and communicating with neighboring nodes via wireless links. Wireless sensor networks [1] are composed of a great number of sensor nodes densely deployed in a fashion that may revolutionize information collecting, which makes it a very promising technique for surveillance in military, environmental monitoring, target tracking in hostile circumstances, and traffic monitoring.

Extensive research has focused on almost every layer of the network protocol, including network performance study [5], energy-efficient media access control (MAC) [6], topology control [7] and min-energy routing [8], enhanced TCP [9], and domain-specific application design [10]. Sensor networks are different from other networks due to the limitations on battery power, node densities, and the significant amount of desired data information. Sensor nodes tend to use energy-constrained small batteries for energy supply. Therefore, power consumption is a vital concern in prolonging the lifetime of a network operation. Many applications, such as seismic activity tracking and traffic monitoring, expect the network to operate for a long period of time, e.g., on the order of a few years. The lifetime of a wireless sensor network could be affected by many factors, such as topology management, energy efficient MAC design, power-aware routing, and energy-favored flow control and error control schemes.

Different methods for reducing power consumption in wireless sensor networks have been explored in the literature. Some approaches [3] were suggested, such as increasing the density of sensor nodes to reduce transmission range, reducing standby power consumption via suitable protocol design, and advanced hardware implementation methodology. Algorithms for finding minimum energy disjoint paths in an all-wireless network were developed [8]. SEAD [4] was proposed to minimize energy consumption in both building the dissemination tree and disseminating data to sink nodes. Few researches have, however, studied how the placement of sensor/aggregation nodes can affect the performance of wireless sensor networks.

In this paper, we will examine many-to-one wireless sensor networks, where information collected from all nodes is aggregated to a sink node or fusion center. Typical applications of a many-to-one sensor network include collecting traffic information along the road and feeding the data to the traffic control center, and gathering data from individual sensor nodes and aggregating towards a central controller where snapshot images of sensed region are constructed. Traffic load is generally *asymmetric* in many-to-one wireless sensor networks. Nodes closer to the sink node have heavier traffic load, since they not only collect data within their sensing range but relay data for nodes further away as well. Such an unbalanced traffic load introduces an uneven power consumption distribution among different sensor nodes. Since traffic load and power consumption of each node are location-dependent, the lifetime of a sensor network can be limited by those nodes with heavier traffic load and thus greater power consumption. Hence, node placement schemes will have considerable impact on the lifetime of the whole sensor network.

Our contributions are threefold. First, we formulate a constrained multivariable nonlinear programming problem to determine both the locations of the nodes and the data transmission pattern considering two objectives: maximize the network lifetime and minimize the application-specific total cost, given a finite number of sensor/aggregation nodes in a geographical coverage. Second, we present two optimal placement strategies, together with performance bounds, for linear networks, i.e., sensors deployed along a straight line. Traffic monitoring and border line control are some possible applications of linear networks. Numerical results are also evaluated. Third, after exploring and understanding the fundamentals of a linear network, we extend the results to a more sophisticated planar network.

The rest of this paper is structured as follows. In Section II, we formulate the problem and describe the system model. In Section III, we present in detail our optimal strategies for linear networks. Heuristic bounds are computed, and numerical results are evaluated in Section IV. We propose our methodology for planar networks and compare it with the approximation method in Section V. Finally, conclusions are given in Section VI.

II. SYSTEM MODEL

A. Communication Model

It has been observed that communication-related power is usually a significant component of the total power consumed in a sensor network [1, 3, 11]. We will mainly focus on the distance-dependent and communication-related power in this paper. We assume perfect media access control and thus the background noise is the only interference. It is reasonable to assume that the energy consumed to transmit a data unit is directly proportional to the total energy consumption by a constant number. Hence, we only consider transmission power in this paper. For a sender to transmit a stream of data at rate R to a receiver, the corresponding transmission power P can be modeled as:

$$P = R * d^r, \tag{1}$$

where $2 \le r \le 4$ is the path loss exponent, depending on different channel models. Obviously, communication over a long link is severely penalized, because power consumption over a long link is much higher than the total power consumption over several short links, i.e.,

$$(d_1 + d_2 + \cdots + d_n)^r >> d_1^r + d_2^r + \cdots d_n^r. \tag{2}$$

We also notice from the numerical results that transmission over long links does not occur.

B. System Model

We first consider a linear sensor network, which consists of a set of sensor nodes or aggregation nodes placed along a long and narrow area with sink node at the end. Each node collects the sampled data within its sensing range, relaying information towards the sink node for further processing or control, as shown in Fig. 1. Node n is the sink node. Note that each node also relays data for nodes further away, i.e., node i also relays the data collected by nodes 1 to $i-1$. This can model different tiers of a hierarchical sensor network where each sensor node within a cluster only sends data to its aggregation node and the aggregation node relays information to the sink node. For a higher tier, we need to consider how aggregation nodes build a network and relay data to a sink node. For a lower tier, we could regard each cluster as a sensor network where the aggregation node is the sink node. Hence, we will investigate the approaches that apply to both tiers unless it is assumed that aggregation nodes have infinite amount of energy and each sensor node is only one hop away from its aggregation node.

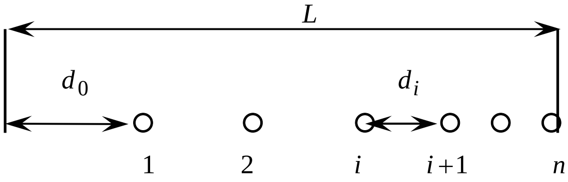


Fig. 1. A linear network

Each sensor has a certain amount of initial energy E_0 and a sensing range D. Let d_i be the distance between node i and $(i+1)$, $i = 1, \cdots, n-1$, and d_0 be the area covered by node 1. Here we consider a general scenario where each sensor node continuously or periodically collects constant bit rate data, e.g., continuous temperature monitoring, traffic monitoring system. Thus, it is reasonable to assume that the amount of data generated in a unit area per unit time is a constant, namely the data density denoted by c. We assume that node i collects all the data between nodes $(i-1)$ and i, i.e., $d_{i-1}c$ per unit time. Note we have $d_i \le D$ for all i, which guarantees the coverage. The linear network covers the area of length L.

A commonly used approach for deploying sensor networks is the uniform placement in which sensor nodes are placed with equal distance in between. Such a deployment is usually the easiest. Its performance could be modeled as follows:

$$P_i = i\frac{L}{n}\left(\frac{L}{n}\right)^r c \tag{3}$$

$$T = \min_i \left(\frac{E_0}{P_i}\right) \qquad i = 1, 2, \cdots, n-1 \tag{4}$$

where P_i denotes the power consumption of the ith node to relay all the collected data, L the length of the total area, n the number of nodes, E_0 the initial energy allocated to each node, T the lifetime of the network, c the data density. L/n is the sensing area of each node, thus, the total traffic load node i carries is $i(L/n)$.

Since we place the sensor/aggregation nodes in such a way that the total volume of the data from the whole area will be aggregated to the sink node, the lifetime of a linear network defined in this paper is the period of time from the network initialization to a point when one of the nodes runs out of energy without any other node covering the same sensing area. For the uniform placement, nodes closer to the sink carry more relay loads, consume more power, die more quickly, and thus limit the network lifetime. We will show in later sections that placing nodes optimally provides significant benefit over a commonly used uniform placement.

There are several possible approaches to extend the network lifetime. One possible method is to allocate more initial energy to nodes closer to the sink node, considering the impact of unbalanced traffic loads on the network lifetime. However, such a heterogeneous energy allocation scheme may be inconvenient in sensor production and deployment. Alternatively, data aggregation or compression is another possible solution. Reduced amount of relaying load by means of efficient aggregation techniques can certainly be energy-saving, prolonging the lifetime of a sensor network. However, the trade-off between information accuracy and power consumption should be taken into account when designing an efficient data aggregation model.

In this paper, our objective is to find an optimal node placement and data transmission scheme such that the lifetime of a sensor network can be maximized with a given total number of nodes in a certain area, assuming homogeneous initial energy. The alternative objective is to minimize the application-specific total cost, i.e., total power consumption.

III. SENSOR NODE PLACEMENT

As discussed earlier, it may be infeasible in practice to allocate energy arbitrarily among different nodes. We consider homogeneous sensor nodes with the same initial energy E_0. Let f_{ij} be the amount of traffic load sent directly from node i to node j per unit time, where $i < j$. Thus, the corresponding energy consumption per unit time is $f_{ij}\left(\sum_{k=i}^{j-1} d_k\right)^r$. Note that f_{ij} infers the routing decision from node i to node j. Possible relaying patterns are shown in Fig.2.

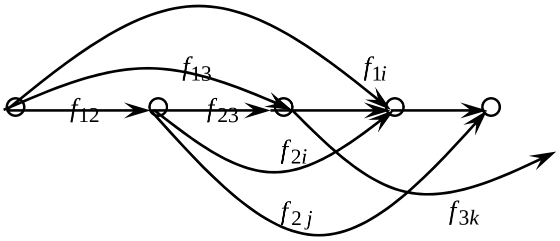


Fig. 2. Possible relaying patterns

The problem is generally formulated as follows:

$$MAX\left(Network\ Lifetime\ T\right) \quad or \quad MIN\left(Total\ Cost\right)$$

$$Subject\ to: \quad \sum_{j=i+1}^{n} f_{ij} = \sum_{k=1}^{i-1} f_{ki} + d_{i-1}c, \quad i = 2,\cdots,n-1 \qquad (5)$$

$$\sum_{j=2}^{n} f_{1j} = d_0 c, \qquad (6)$$

$$\sum_{j=i+1}^{n} f_{ij}\left(\sum_{k=i}^{j-1} d_k\right)^r \le \frac{E_0}{T}, \quad i = 1,\cdots,n-1 \qquad (7)$$

$$\sum_{i=0}^{n-1} d_i = L \qquad (8)$$

$$0 \le d_i \le D, \quad i = 0,1,\cdots,n-1 \qquad (9)$$

Eq. (5) is the flow constraint: $\sum_{k=1}^{i-1} f_{ki}$ is the amount of data relayed to node i by other nodes, $d_{i-1}c$ is the amount of data collected by node i itself, and $\sum_{j=i+1}^{n} f_{ij}$ is the total amount of data that node i sends to all other nodes. Eq. (6) is the flow constraint at node 1. Eq. (7) is the energy constraint at each node. Note that the lifetime of the network is defined as the time until one node runs out of energy. The last two equations are the distance constraints. In this section, we study two objectives: to maximize network lifetime and to minimize application-specific total cost. The definition of application-specific total cost will be explained in detail in part *B*.

A. Network Lifetime

The goal here is to place sensor nodes in an optimal way to maximize the lifetime of a sensor network consisting of n sensor nodes with the same initial energy deployed in a certain area. We propose a greedy placement scheme as a heuristic algorithm to maximize the network lifetime. In this proposed algorithm, all nodes run out of energy at the same time. The algorithm is greedy in the sense that each node tries to take best advantage of its energy resource, prolonging the network lifetime. The reasoning of this approach is that node i should not directly send data to node j where $j \ge i+2$, because communication over long links is not desirable. This could be identified as a heuristic solution for our objective. According to the problem setup, maximizing the lifetime is equal to minimizing the power consumption per unit time for each node. We impose an additional constraint that all nodes die at the same time. The problem is reformulated as in Eq. (10) – Eq. (13), where P_i denotes the power consumed for node i to relay all the collected data, d_i the distance between nodes i and $(i+1)$, $i = 1,\cdots,n-1$, and d_0 the area covered by node 1, D the sensing range. Note that d_i is monotonically decreasing, i.e., $d_i \le d_j$ if $i \ge j$. The reason is that nodes closer to the sink node carry heavier traffic loads, while nodes farther away relay less data. To compensate, the closer the node is to the sink node, the shorter its relay distance. The greedy algorithm is the solution to the problem defined in Eq. (10). We name it optimal strategy 1.

$$\mathit{Minimize} \quad P_i = c\left(\sum_{k=0}^{i-1} d_k\right) d_i^r \quad i = 1, 2, \cdots n-1 \tag{10}$$

$$\mathit{subject\ to}: P_1 = P_2 = \cdots = P_{n-1} \tag{11}$$

$$\sum_{i=0}^{n-1} d_i = L \tag{12}$$

$$0 < d_i \le D, \quad i = 0, 1, \cdots n-1 \tag{13}$$

In our algorithm, all nodes run out of power at the same time. In other words, at any given time, the residual energy of all nodes is kept the same given the same initial energy. Performance evaluations will be presented in section IV.

B. *Application-specific Cost Minimization*

One alternative problem is to minimize the application-specific total cost. Considering some scenarios where replacing individual sensor/aggregation node is possible, we could replace a sensor/aggregation node whenever it runs out of energy. Let C_o be the cost of replacing either a sensor node or an aggregation node, T_o the operating period of time required by a specific application, t_i the lifetime of node *i*. The total cost of replacing out-of-energy nodes to operate the network in the period of time T_o is proportional to the total times the nodes are replaced. Such a problem could be identified as:

$$\mathit{Cost} = \sum_{i=1}^{n} \frac{C_o T_o}{t_i} = \sum_{i=1}^{n} \frac{C_o T_o}{E_0 / P_i} = \sum_{i=1}^{n} P_i \frac{C_o T_o}{E_0}. \tag{14}$$

where P_i is the energy consumed per unit time for node i, E_0 is the initial energy of each node, thus $\mathrm{C}_0 T_o / E_0$ is considered as a constant. Accordingly, the problem could be reformulated to minimize the total power consumption:

$$\mathit{Minimize}: \sum_{i=1}^{n-1} P_i = \sum_{i=1}^{n-1} d_i^r \sum_{k=0}^{i-1} d_k c \tag{15}$$

$$\mathit{Subject\ to}: \sum_{i=0}^{n-1} d_i = L \tag{16}$$

$$0 < d_i \le D \quad i = 0, 1, \cdots, n-1 \tag{17}$$

where $\sum_{k=0}^{i-1} d_k c$ is the total traffic load of node i. In this case, node i should not directly send data to node j where $j \ge i+2$, because communication over long links is not desirable, i.e., $(d_1 + \cdots + d_i)^r >> d_1^r + \cdots + d_i^r$. Thus, a node should only relay data to its nearest neighbor to the right. By solving this nonlinear programming problem to find a minimum of a constrained multivariable nonlinear function, we could get optimal solution for this problem. We name it optimal strategy 2 in the paper.

IV. PERFORMANCE BOUND AND NUMERICAL RESULTS

A. *Performance Bound*

We first introduce a performance bound for the optimization problems. We divide the whole area into blocks of length D, i.e., total number of blocks is L/D. We calculate the minimum energy needed to transfer the data in each block to the sink node. To be more specific, in order to collect the data from the first block (the block farthest away from the sink node), we need to place the first node at a point to collect data from the first block of length D. The maximum distance of the node to the leftmost boundary is D for the coverage requirement. Then we place the other $n-1$ nodes uniformly in the rest of the area to minimize the power consumed to transmit the first block of data to the sink node. Similarly, to collect the data from the second block, we put the second node at a point with the distance D away from the first node, relaying the data generated between these two nodes towards the sink node. In this case, due to the sensing range constraint, at most $n-2$ nodes can help relay the data of the second block. The $n-2$ nodes should be uniformly placed within the rest of the area. The same procedure continues until all the data volume in the whole area has been calculated. We present the bound achieved in this calculation as a heuristic bound to compare with our solutions although it might be infeasible in practice to implement in the sensor network. Note we have n sensor nodes to be deployed in a given area with length of L. The performance bound is formulated as follows:

$$P_i = cD\left(\frac{L - iD}{n - i}\right)^r \tag{18}$$

$$P_{total} = \sum_{i=1}^{\lfloor L/D \rfloor} P_i (n-i) \quad i = 1, 2, \cdots, \lfloor L/D \rfloor \tag{19}$$

$$T_{average} = \frac{nE_0}{P_{total}} \tag{20}$$

where $P_i(n-i)$ denotes the power consumed to relay the ith block of data, P_{total} the total power consumption of the whole sensor network, which is a heuristic lower bound for the total power consumption. Meanwhile, the average network lifetime $T_{average}$ is an upper bound for the life time of the sensor network.

B. *Numerical Results and Evaluations*

We illustrate the numerical results and compare the performances of the proposed optimal strategies, performance bounds, and the uniform placement scheme in terms of network lifetime and total power consumption respectively with the same total number of nodes.

Fig. 3 and Fig. 4 show the numerical results of the optimal strategy 1, 2, the uniform placement and the performance bounds in terms of total power consumption and network lifetime respectively. Note that we optimize the node placement for a given total number of nodes. We set $L = 10, D = 2, c = 1, r = 2, E_0 = 1$ in the simulations.

The network lifetime increases while the total power consumption decreases with more nodes relaying the data in the region, because the burden is evened out when the total number of nodes increases. The numerical results show that the optimal strategies outperform the uniform placement in terms of both network lifetime and total power consumption. We notice that when $n = 15$, the network lives 130% longer using the optimal strategy 1 than the commonly used uniform placement scheme. Furthermore, it consumes almost 10% less total power using optimal strategy 2 than strategy 1, and 20% less total power than the uniform placement scheme. From the numerical results, it justifies that the optimal strategy 2 can achieve lower power consumption than the optimal strategy 1, while the optimal strategy 1 can have longer network lifetime.

Fig. 5 illustrates the distance between adjacent nodes for both optimal strategy 1 and 2 when 11 nodes in total are available. Optimal locations of sensor nodes can be obtained by the formulated algorithm. As we expect, the closer the sensor nodes to the sink node, the smaller the distance between two adjacent nodes, because the relay load is heavier. We notice that the difference between the node locations of the two strategies is not significant, which indicates that allocating nodes properly can benefit both the network lifetime and the total power consumption at the same time.

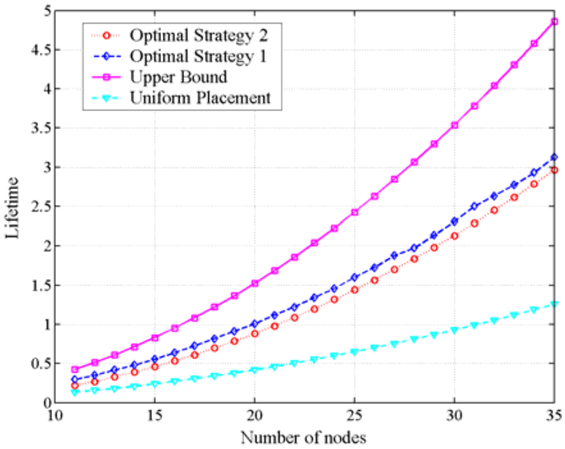


Fig. 3. Compare the network lifetime for optimal strategy 1, 2, uniform placement, and upper bound

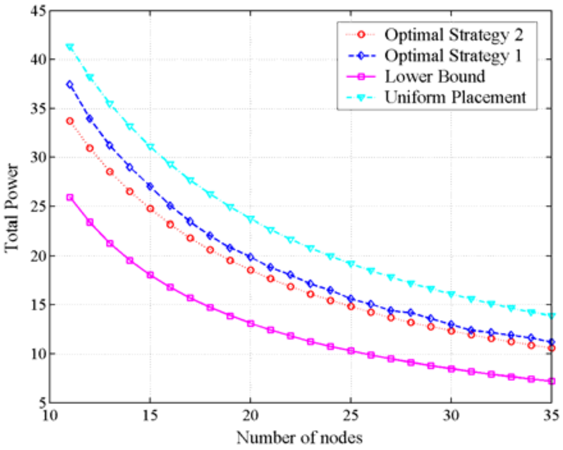


Fig. 4. Compare the total power of optimal strategy 1, 2, uniform placement, and lower bound

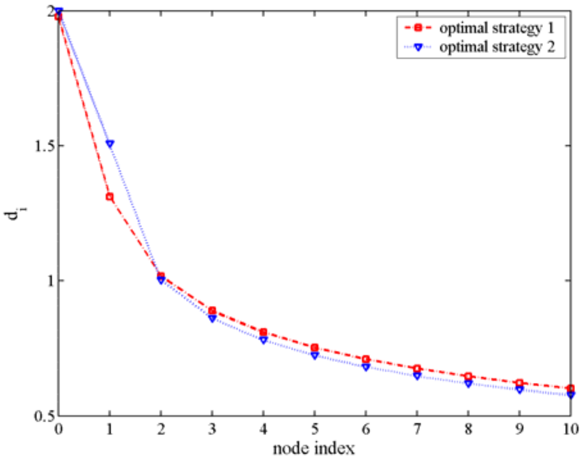
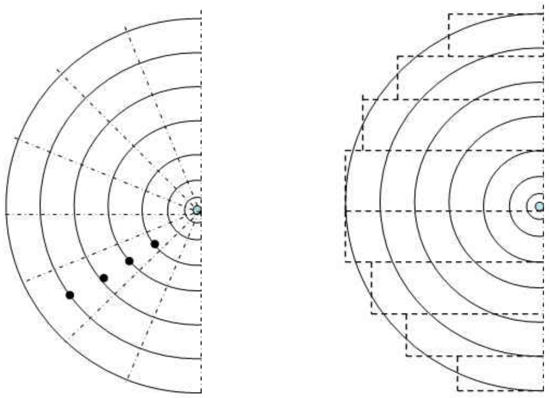


Fig. 5. The distance between adjacent nodes for optimal strategy 1, 2

V. PLANAR NETWORKS

In the previous sections, we investigate the fundamentals of the linear sensor networks and explore two optimal strategies in terms of network lifetime and application-specific total cost (total power consumption) respectively. Our strategies could be applied to some application of planar sensor networks where we can divide the area into multiple narrow strips with sink nodes at the end of each strip. However, the coverage problem is much more complicated. It is also possible to take triangular routes as a relaying pattern in a planar network. In addition, the search space for the location of each node is the entire region. Hence, it becomes extremely hard to find an optimal deployment strategy in a planar network. Our approach is, therefore, to provide heuristic algorithms based on the insights from the linear network.

Here we consider a more general scenario where all the data within a circle area is aggregated to the center. Due to the symmetry characteristics, we only consider the half circle area as shown in Fig. 6(a). Our heuristic node placement strategy is to place nodes along the radius in a star mode and collect all the data from its local segment aggregating towards the center. We assume that nodes only relay data in the direction of the radius. Even if we have decided that node placement and data relaying is along the radius, it is still desirable to allocate nodes in an optimal way such that the total power consumed to relay data is minimized given a certain total number of nodes.



(a) Star mode (b) Linear approximation

Fig. 6. Two different node placement strategies in 2-D network

In addition, we use multiple linear networks as an approximation to the region of interest without changing the total area, thus keeping the same data volume, as shown in Fig. 6(b). Besides allocating nodes along multiple linear networks optimally, we also need to place nodes at the end side of each linear network in an optimal way to minimize the total power of relaying data vertically towards the sink node. We name this method as linear approximation.

In Fig. 7, we compare the star mode heuristic strategy and the linear approximation method. In both cases, we optimize the node placement for each given total number of nodes. We use a similar parameter setup as in section IV: $R = 10$, $D = 2$, $c = 1$, $r = 2$, $E_0 = 1$. Where R is the radius, D is the sensing range, c denotes the data density, i.e., data generated per area per unit time, r is the path loss exponent in power consumption model, and E_0 is the initial energy. Although the linear approximation method covers the same amount of area as the heuristic strategy, it consumes more total power in that a portion of the power is consumed to detour the data instead of sending them directly towards the center. Furthermore, in the linear approximation method, we need to deploy more nodes to relay data at the end side of those multiple networks where the data load is much heavier. The total energy saving of the star mode strategy over the linear approximation method is about 15% with 30 nodes in total and about 25% with 60 nodes in total.

Fig. 8 illustrates the optimal distance between adjacent nodes along the radius for our star mode heuristic strategy when the number of nodes along the radius $n = 10$. By comparing with Fig. 5, the distance differences between adjacent nodes in planar networks are a little smaller than those in linear networks. The reason is that more area is covered by nodes father away from the center in the case of star mode strategy, which reduces the distance difference.

We observe that nodes in adjacent “pies” get much closer when they approach the center. Hence, one possible improvement of the node placement is to combine those very close nodes and merge the data traffic at certain point to construct a tree-like structure.

VI. CONCLUSIONS

In this paper, we investigated the important problem of sensor node placement in wireless sensor networks. We formulated a constrained multivariable nonlinear programming problem to determine both the locations of the nodes and data transmission pattern in terms of network lifetime and total power consumption. We first studied linear networks and proposed the strategies to optimize the network lifetime or the total power consumption. Simulation results show that using the optimal node placement and data transmission pattern leads to a significant benefit over the uniform placement. Lastly, we proposed the star mode heuristic strategy in planar networks and compared it with the linear approximation scheme. Our approach can be applied to different tiers in hierarchical sensor networks. A challenging direction for future work is to explore and analyze the impact of data sampling and aggregation techniques, together with node placement, on network lifetime and power consumption in a more general sensor network with non-uniform data density.

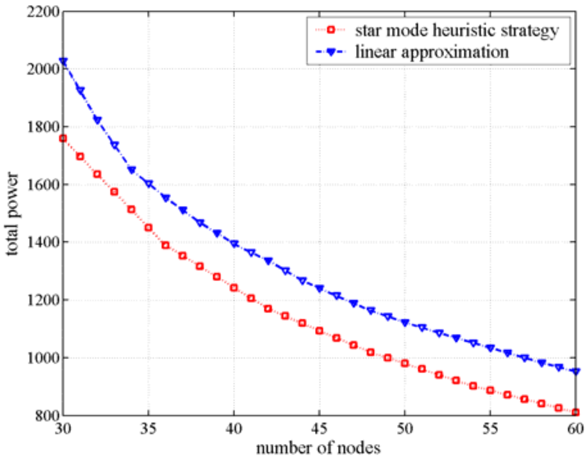


Fig. 7. Comparison between star mode heuristic strategy and linear approximation scheme

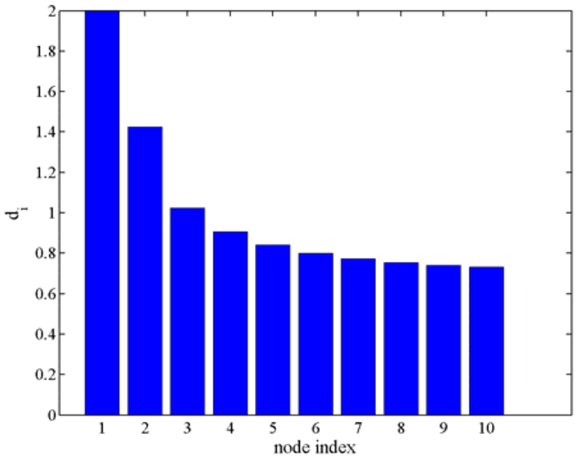


Fig. 8. The distance between adjacent nodes along the radius for star mode heuristic strategy

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