A Practical Approach to Deploy Large Scale Wireless Sensor Networks

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Abstract

In a wireless sensor network, a sensor measures environmental data. It also relays data for other sensors. While sensing workload is the same among sensors, relaying workload differs. Sensors closer to the data sink carry more data traffic. This becomes more prominent as the network scales up. The drawback of this is that nodes in the network degrade unevenly and the network ages in a non-uniform way. This paper seeks the ways to deploy the network so that the workload is evenly distributed, thus the network overall behavior degrades in a smooth fashion. Assuming that the sensors should be evenly deployed within the monitored area, we look at the approach where a set of more powerful nodes (routers) are designated for data relaying. We look at the approach to deploy these relaying nodes that are easy to implement in practice. In particular, we select sub-regions to deploy them at calculated density. We propose a simple method where the density is simply based on the size of the area whose data will be relayed by these nodes. Our experimental results verify the theoretical estimation of the routers' density. We demonstrate through the experiments that our deployment approach can dramatically extend the lifetime of the network while maintain a low router-sensor ratio and an even power consumption rate of both the sensors and routers.

I. INTRODUCTION

In this paper we look for economic ways to deploy a large scale wireless sensor network. The deployed network must deteriorate evenly and be easy to maintain and replenish.

Wireless sensor network is deployed to collect environmental data for a certain region. The basic functionalities of a node in the sensor network include sensing and transmission. For a node, in addition to transmitting its own data, relaying data for other nodes is also a significant task. In fact, one major advocated advantage of sensor network is its ability to route data safely to the collecting host.

The drawback that comes with above advantage is the resulting unevenness of sensor usage. Let's look at how data is routed. The data collecting host is normally connected by wire to a set of points, which we shall call data sinks. A sink functions as if it is a node in the sensor network, but only receives data wirelessly. Any data generated within the sensor network is considered collected if it reaches one of the sinks. We do not worry about the communications between the host and the sinks. Obviously sensors closer to a sink carry more workload of relaying data. With a fixed amount of energy source, usually in the form of batteries, their lifetime would be shorter than the rest of the sensors. We calculated the limitations of a large scale wireless sensor network in [5], which we shall briefly discuss in the next section.

With uneven sensor lifetimes, the sensor network becomes problematic. First of all, less data will be collected in areas whose sensors die early. This results in a biased picture of the monitored region. Even worse, once all sensors close to the sinks die, data sampled from sensors that are still good could not reach the host anymore. Replenishing these sensors could remedy the problem, but then we have to spend effort to locate the sensors to replenish.

Deploying more sensors near the sinks could relieve some relaying workload, but then extra sensing capabilities are wasted. Besides the network becomes non-uniform and more difficult to deploy than if the sensors are evenly distributed.

If we want evenly distributed sensors and also evenly distributed life time, a set of dedicated relaying nodes is required in the network architecture. In this design, all sensors perform the same job, sampling data and transmit the data to the relaying nodes. This is similar to the ZigBee [28] architecture. And we shall use its terminology to call the relaying nodes "router" nodes. Our paper will concentrate on this approach, which will be detailed in Section IV.

It should be pointed out that if we have mobile sinks, we could achieve the same goal in which a sensor does not relay data. All it does is to sample data and send it to the mobile sink once the sink comes by. This, however, will not be addressed in this paper.

The sensor deployment now becomes straight forward. We calculate the sensor density based on the sensor capacity and required data density. Then we simply disperse the sensors in the monitored region according to the sensor density.

Consequently, what we shall address is how to deploy the routers. Routers differ from sensors in that they do not contain sensing device and have usually more powerful battery and longer transmission range. For the same reason, however, we still want them to be easily deployed and maintained, and carry even workloads. In many cases the routers may be mainline powered, such as is suggested in ZigBee. But still we think it better they carry even workload.

The rest of the paper is organized as follows: Section II briefly describes the related work. The lifetime model of the sensor is presented in Section III. Section IV describes the underlying intuition of the proposed deployment approach. Section V discusses in detail how to deploy routers in different shapes of regions. Section VI proposes a simple method to calculate router sub-regions and densities. This method is based on Section V and tries to achieve equal workloads. The performance studies are demonstrated in Section VII and we finish this paper in Section VIII.

II. RELATED WORK

There has been a lot of work on the capacity limit of wireless sensor network lately [1], [2], [3], [4], [5], [6]. Most of these work accordantly draw the conclusion that the network capacity decreases as it scales up and the decrease rate varies for different topologies and measurements.

Considering the difficulty to replace or recharge the sensor's battery, the capacity limit problem encumbers the deployment of large scale sensor networks. To prolong the network lifetime, many aspects of the problem have been extensively studied.

[7], [8], [9], [10], [11], [12] aim to minimize the transmit power expenditure by reducing the power level of the transmitter while maintaining the network connectivity. [7] formulates the adjustment of the nodes' transmit powers as a constrained optimization problem and presents two centralized algorithms and also the proof of their optimality. In [10], two distributed algorithms which dynamically adjust transmit power level on a per-node basis are proposed. [11] presents a novel pairwise transmit power control algorithm in which every node builds a model for each of its neighbors, describing the correlation between transmit power and link quality.

In the Medium Access Control (MAC) layer, multiple power saving approaches [13], [14], [15], [16], [17] are proposed focusing on conserving battery power by switching off their radio when they do not have to send or receive packets. [16] presents a new power saving MAC protocol, NPSM, which removes the ATIM window overhead from PSM in IEEE 802.11 in order to increase channel capacity for data transmission and reduce the energy consumption. In [13], sensor-MAC (S-MAC) protocol is explicitly designed for wireless sensor networks. It reduces the waste of energy from collision, overhearing, control packet overhead and idle listening by accepting some reduction in both pre-hop fairness and latency.

Power-aware routing is also a hot research topic and has been explored in several previous work [18], [19]. These protocols are proposed in different scenarios to maximize sensor network lifetime. [18] studies three power-aware routing algorithms: centralized version of *max-min* zP_{min}, distributed version of *max-min* zP_{min} and zone-based routing and demonstrates their good empirical competitive ratios with the off-line optimal algorithm. To support real-time communication, [19] proposes the real-time power-aware protocol (RPAR) which achieves application-specified communication delays at low energy cost by dynamically adapting transmission power and routing decisions.

Current research work on sensor network deployment mainly focus on maximizing network coverage and maintaining the connectivity of the network [20], [21], [22], [23], [24], [25]. In [20], the idea of random sampling in geometric sets is applied. It proposes a sampling based approach to decide how many samples (sensor units) must be drawn to make every point in a possibly unknown scene covered by at least one sensor. [23] studies the problem in the mobile sensor network scenario and deploys nodes one-at-a-time into an unknown environment with each node making use of information gathered by previously deployed nodes to determine its target location and ensuring that nodes retain line-of-sight with one another. With the constraint that the sensor mobility is restricted to a distance-bounded flip, [22] proposes a minimum-cost maximum-flow based solution to determine a movement plan for the sensors in order to maximize the sensor network coverage and minimize the number of flips. In a cluster-based distributed sensor network scenario, [25] presents a virtual force algorithm (VFA) to use a judicious combination of attractive and repulsive forces to determine virtual motion paths and the rate of movement for the randomly-placed sensors. All these approaches target at achieving the network connectivity with a small number of sensors but they ignore the capacity limit problem and are not scalable. our proposed sensor network deployment approach differs from these methods in three ways. First, we deploy the sensors in a random manner. Secondly, we maintain the network connectivity with the introduce of routers which are also used to relay the packets from sensors to the sink. Last and most importantly, we achieve the even energy consumption rates for both the sensors and the routers to prolong the lifetime of the network and make the recharge or re-deployment process easy.

III. SENSOR LIFE TIME IN A LARGE SCALE NETWORK

In [5] we studied the effect of data collection on the battery and buffer of a sensor node, and on the overall sensor network. We determined the relationship among battery life, sampling frequency, buffer size, etc. We claimed that using identical sensors throughout a large scale sensor network may not achieve the best result.

Let's look at sensors in a circular band within the network as is shown in Fig.1. Sensors are deployed with equal density throughout the region. The radius of the inner circle is R. The width of the band is D, which is the maximum sensor

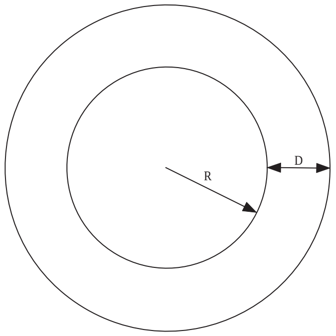

Fig. 1. Sensor lifetime calculation

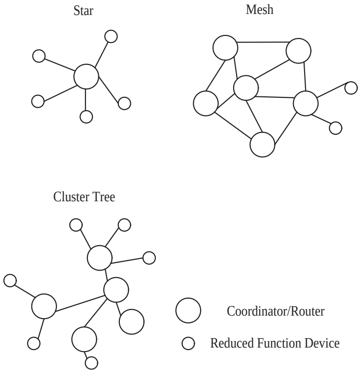

Fig. 2. ZigBee topology models

transmission range. Any data generated within the circle has to be relayed by sensors within the band to reach the sinks in the outside. We calculated that the average life time L of a sensor within the band is

$$L = \frac{E}{W_0 + r_1(W_1 + \frac{W_2}{(1+D/R)^2} - 1)} \tag{1}$$

In (1), E is the total battery energy of a sensor. W_0, W_1, and W_2 are energy use rate for sensor maintenance, per-data sensing and per-data relaying. r_1 is the sensor average data generation rate.

With everything identical among the sensors, we see that the life time of a sensor decreases as R increases. Sensors with larger R must be replenished more often, but not because that their sensing ability is exhausted. The replenishment must also be scheduled in proportion to R. Also there is an upper bound on R beyond which data will be lost due to limited buffer size and data rate of sensors in the band.

In above analysis the sinks are outside. We may think this case is not too hard to manage, but for many other scenarios the network will become very difficult. For example, if we assume the single sink is at the center in Fig. 1, all data will be routed inward. We will have far less sensors near the center to relay data from the peripheral. They will be overwhelmed with the relaying task.

For replenishment purpose there is a need to deploy sensors equally within the region and keep them the same lifetime, especially for large scale networks. It may be too costly or impossible to diagnose individual sensors. Instead of finding out which sensor dies, we hope to simple redeploy new sensors evenly within some sub-regions where all old sensors are expected to die. If we want to deploy sensors evenly throughout the region, relaying data by the sensors may not be a good idea.

IV. DESIGNATED WIRELESS RELAYING NODES

A router node does not measure data. It receives data collected by sensor nodes and routes the data to the sinks via other router nodes. A sensor belongs to a router, to who all its measured data is sent. This requires that for every sensor there must be at least one router within its transmission range.

This is not new. In fact it is one of the many possible topologies defined in ZigBee standard [28], shown in Fig. 2. ZigBee defines "Reduced Function Device" that does not relay data. There is a "Full Function Device" connecting to each reduced function device to relay its data. Routers and Coordinator are full function devices. Coordinator coordinates routers and devices. In small scale, routers are mainline powered and wired to the host. Fig.2 shows three basic topologies in ZigBee. In a star topology, sensors are connected to a central router/coordinator. In a cluster tree topology, routers form a tree. Sensors connect directly with tree nodes. In a mesh topology, stars and cluster trees are connected via their routers. A large scale ZigBee network is a mesh. The Reduced Function Device in Fig. 2 is what we call sensor in this paper.

The deployment of the network now becomes the deployment of the routers. Just like with sensors, we want routers to be easily deployed and maintained. If routers are mainline powered, we could afford uneven energy usage among routers. And the simple approach would be to deploy routers evenly within the region. However, we shall look at how to deploy the routers that they consume power at close rate; Hence they deteriorate at close rate and could be replenished at the same time. This is especially important if routers are also battery powered. In the following we shall assume battery powered routers when we talk about their lifetime.

Since routers do not measure data, they do not need to be deployed throughout the region. We could afford uneven router deployment because the number of routers is far less than the number of sensors. Routers are more powerful, transmit more data, and have longer transmission range than the sensors. They also last longer. We could, on the other hand, think of a router as a sensor in which the data it senses is the data it collects from its sensors. In this thought the router as a sensor can measure different size of area. They do not need to be evenly deployed.

The energy consumption rate of the sensors is the same except the energy to send data. The further a sensor is from a router, the more energy it consumes. Now let's consider the energy consumption by the router. For each bit of data received and forwarded to the next router at distance d, the energy used E is

$$E = a_1 + a_2 \times d^n \tag{2}$$

In (2) a_1, a_2, and n are constants [4], [6]. If the data rate passing a router is r, then its energy consumption rate is

$$P = (a_1 + a_2 \times d^n) \times r \tag{3}$$

The time to replenish the routers could be calculated by dividing the total battery power by P. Or given required router life time, we could calculate P, which in turn dictates how many routers should be deployed.

Our task is now to design a deployment method so that P is the same among routers. To achieve this, we propose to locate a set of sub-regions and define the density within each region, then deploy routers uniformly within each sub-region of the calculated density.

There are several ways to find the region and density:

1) Pre-select the sub-region, then calculate densities.

TABLE I

SYMBOLS AND DEFINITIONS

Symbol	Definition
R	the radius of a circular area or the length around an area
D_s	the sensor deployment density
D_r	the router deployment density
r_s	the sensor data generation rate
d	the distance between two sub-regions
w	the width of the router deployment line
N	the total number of routers deployed
A,B,C	the names of areas in consideration

2) Pre-define the same density among all sub-regions, then locate regions accordingly.
3) Pre-select sub-region and same density, then calculate the size of each sub-region.

We shall give some examples in the next section and once we have the sub-regions and densities, the deployment and replenishment become easy.

V. EXAMPLE OF ROUTER DEPLOYMENT

In this section we examine a representative shape of region, round region with sink at the center, to deploy the sensor network. We provide three methods. They are equal distance between sub-regions, equal density among sub-regions, and equal distance and density. Table I summaries the symbols which will be used.

A. Round Region with the Sink at the Center

In Fig. 3(a) is a round region. The sensors will be evenly deployed within the region. Data will be routed to the center of the region, where a sink is deployed. The routers will be deployed in circles. For ease of discussion, we assume all sensors send data to the routers in the immediate circles towards the center. For example, in Fig. 3(b), all sensors in area A send data to the routers in the circle of radius R. Now let's decide the location of the circles and the router density within each circle.

1) Equal distance: First we choose to allocate circles with equal distance from each other as shown in Fig. 3(b). Let's assume that the width of the circle w is one unit. We now calculate the router density D_r in the circle of radius R. The routers must relay all data generated in area A to the routers in the circle of radius $(R-d)$. The total number of sensors in A is $\pi(R_0^2 - R^2) \times D_s$, the total data rate in A is $\pi(R_0^2 - R^2) \times D_s \times r_s$. The total number of routers is $2\pi R \times D_r$. On average each router handles data rate of $\pi(R_0^2 - R^2) \times D_s \times r_s/(2\pi R \times D_r)$. So the energy consumption of a router is $P = (R_0^2 - R^2) \times D_s \times r_s \times (a_1 + a_2 \times d^n)/(2R \times D_r)$. Hence we have the router density

$$D_r = \frac{(R_0^2 - R^2) \times D_s \times r_s \times (a_1 + a_2 \times d^n)}{2P \times R} \tag{4}$$

As we go from outer circles to inner circles, the router density has to increase dramatically.

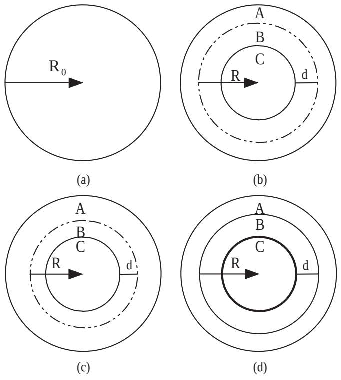

Fig. 3. Round region with center sink

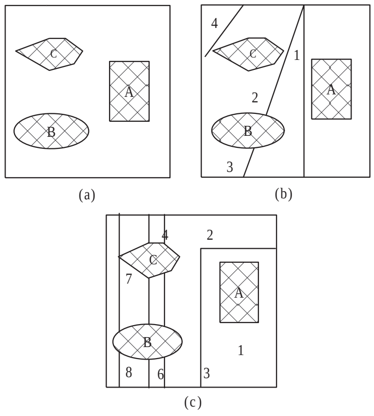

Fig. 4. Irregular region

We are more interested in equal router life time than how long the life time is. But it is difficult to compare the ratio of router densities between circles with (4).

Here is the strategy of router deployment. After deciding on d and the lifetime, we calculate the density of each circle. Then we simply deploy the routers in each circle according to the densities. After they reach the life time, we could repeat the same deployment.

2) Equal density: We could not achieve equal density if the circle width is kept at one unit, no matter where we allocate the circles. The routers in the inner circle have to relay more data than those in the outer circles, but the size of the inner circle is smaller than the outer circles.

We could break outer circles into sections and do not deploy routers in the whole circle as shown in Fig. 3(c). We shall not address this case here.

3) Equal distance and density: This is similar to equal distance. Instead of increasing density of the inner circles, we increase circle width so that the same amount of routers could be deployed with the basic density.

Let the basic density to be D_0. Applying similar calculation, we get:

$$w = \frac{(R_0^2 - R^2) \times D_s \times r_s \times (a_1 + a_2 \times d^n)}{2P \times R \times D_0} \tag{5}$$

The deployment is similar to that in Section V-A.1.

Note there is a limit on how big w could be. The innermost circle has to relay data from all sensors. The biggest w will fill up the whole circle. Suppose in Fig. 3(d) the whole area C is deployed with routers and the sensors within C send data to the sink directly. All data outside C must be relayed by the routers in C, which put a limit on how big R_0 could be.

B. Comparisons

By design, our methods result in equal workload among routers hence equal lifetime. In comparison, we look at the lifetime distribution of the deployment method where routers are evenly deployed thorough out the region. Fig. 7 shows the distribution of power consumption rate, hence the estimated lifetime distribution. The horizontal axis is the distance from the routers to the sinks and the vertical axis is the power rate usage. The power consumption increases with the distance to sinks for both region shapes while the distributions produced by our methods in this section are flat lines.

We could have analyzed with more shapes of deployment regions such as round region with the sink at the border and rectangular regions [26], but what we have done could lead us to the proposed generic method in the next section.

VI. A SIMPLE DEPLOYMENT METHOD

We have illustrated the ways to locate router deployment sub-regions and calculate the densities within each sub-region. In practice, however, the monitored region does not have perfect geometric shape. For example, in the region in Fig. 4(a), we need to deploy a sensor network in the rectangular area. It contains a building A, a lake B, and a tree C. The host resides in the building A. The sinks are installed around A's walls. Sensors are deployed in the rest of the areas. Applying methods in above section is not straight forward.

Based on our analysis in above section, we propose a simple method that does not produce exact workload among routers, but is simple and produces even enough workloads. It contains the following steps:

1) Draw lines in the area for router deployment. The lines are selected so that sensor data could be relayed from routers in one line to the routers in the next line, until it reaches the sinks. The distance between two adjacent lines d should be the same and less than the transmission range.
2) For each line, calculate the router density factor f. f is the value of the length of the line dividing the size of the sensor area it covers. If a sensor's data passes through this line, the area monitored by the sensor is covered by the line. For the region in Fig. 4(a), we draw lines as in Fig. 4(b). In it, the covered area of line 1 is all sensor areas to the left of it; the covered area of line 4 is the left upper corner.
3) Deploy routers on the lines with the density $D_r = f \times D_0$, proportional to its density factor f. D_0 is the basic density value. The average power rate of the routers could be estimated as $P = D_s \times r_s \times (a_1 + a_2 \times d^n)/D_0$. From P we can estimate the average lifetime.

This method is the same as the method in Section V-A.1 for region in Fig. 3(a).

The actual application of the method is depicted in Fig. 4(c). Seven lines are drawn with equal distances, which is close to the maximum transmission range. Line 1 covers all the area to the left of and above it; line 2 covers the area to the left of it and above the second dotted line; line 3 covers the area to the left of it and below the second dotted line; etc.

We should point out that although we may not derived exact energy usage rate because of the complexity of the energy rate equation, we could at least achieve close usage rate among routers.

Some explanations are necessary to defend our approach.

The method we proposed assumes uniform sensor distribution and is hence based only on geometric analysis. In a large scale sensor network, uniform sensor distribution makes practical sense. It makes deployment simple. In cases where sensors could not be deployed individually, even sensor density is most likely we can hope for.

TABLE II

EXPERIMENT PARAMETERS

Parameters	**Meaning**	**Value**
(S_x, S_y)	Position of the sink	$(30, 30)$
R	Radius of the simulation region	$[12, 30]$
d	Distance between two sub-regions	$[3, 7.5]$
D_s	The sensor deployment density	$[0.3, 1.0]$
r_s	Sensor data generation rate	1
w	Width of the router deployment line	1

As we have argued in [5], data generated turns to be evenly distributed as well in a large scale area. At some point in time some small area may have more dynamics and generate more data, but over the long run the total amount of data generated from a unit-sized area equals. This also justifies equal sensor distribution. After all, we have equal interest in every place of the whole area covered by the large scale network.

If the covered area is small and we could set up sensors individually, the approach proposed in this paper does not apply. There are many active researches on this case.

Combining large scale and practical, we need a deployment method that is quick and easy, which is exactly what we set off to achieve. The method is not perfect. For example, we do not consider the energy cost difference between sensors of different distances to the routers; we assumed that all sensors could reach a router in one hop. In reality, sensors may not die out as evenly as we hope, but the proposed approach could be a starting point to practically deploy large scale sensor networks.

We finish this section with a few words on data routing. In general the sensors send data to routers in the immediate sub-region towards the sink. It is desirable that all routers in the sub-region share sensors equally. Likewise, a router in one sub-region receives data from equal number of routers in another sub-region. This is straightforward for cases in Section V. However, we have not discussed routing establishment in this paper. Methods studied in other research could be applied.

VII. PERFORMANCE EVALUATION

This section presents important results from our simulation studies of the proposed sensor network deployment approach. Section VII-A presents our simulation model and parameters. Section VII-B demonstrates important properties of the proposed approach. The goal of the experimental studies is to demonstrate that our approach can dramatically extend the lifetime of the sensor network while maintain a low router-sensor ratio and an even router power consumption rate.

A. Simulation Model and Parameters

We focus our performance study on the scenario discussed in Section V-A.1. The sink is deployed in the center of the round simulation region where sensors are evenly distributed. The routers are deployed in circles with equal distance from each others. The energy dissipation model follows the setting in [6] and for each experiment, 100 trials with different sensor distributions are conducted to get the average simulation results. A summary of the parameters and default settings used in the experiments are presented in Table II.

B. *Experimental Results*

In this subsection, we first evaluate the accuracy of our calculations for the required router number in the deployment, the router-sensor ratio and the router power consumption rate respectively comparing with the theoretical analysis in Section V-A. Then, we demonstrate that compared with centralized collection approach and CREM [27], our approach can dramatically extend the lifetime of the wireless sensor networks.

1) Approach Properties: In this subsection, we evaluate three important properties of the proposed deployment approach: the required router number, the router-sensor ratio and the power consumption rate of the router. For each property, we compared the practical requirement with the theoretical analysis and the comparisons demonstrate the accuracy of our calculations.

Fig.5 presents the comparison between the practical required router number and the theoretical estimation. In Fig. 5, we have the observation that the practical routers required are consistently larger than the theoretical estimation. This is because some remedy routers are need to maintain the network coverage. But this difference is shrinking along with the increase of the network density and their curves converge when the density is equal or larger than 0.95 in our experiments.

Fig. 6 compares the practical router-sensor ratio with the theoretical results. According to the analysis in Section V-A, the router-sensor ratio should be not sensitive to the network density which is clearly shown in Fig. 6. Considering the effect from remedy routers in practice, the practical router-sensor ratio is larger than the theoretical one but they will quickly converge when the density is increased to 0.95. Another important observation is even when the network density is as low as 0.3, the router-sensor ratio is just around 0.04 and only 39 routers are needed to help relay the packets from more than 850 sensors.

In Fig. 7, our proposed approach is demonstrated to achieve an even power consumption rate theoretically regardless of the distance from the router to the sink. This property make it easy to estimate the lifetime of the routers and recharge them periodically. The practical simulation results are presented in Fig. 8 and Fig.9 in which we increase the network density to 1 to get rid of the infection from remedy routers. In Fig. 8, we sort the routers according to their distance to the sink and have the observation that the routers in the distant circle away from the sink will relay more sensors' packets in their sub-region. The reason for this phenomenon is the routers in the inner circle also need to help relay the packets transmitted from outer routers. Fig. 9 presents the total number of packets needed to be relayed by each router from the total simulation region. We observe from Fig. 9 that statistically the routers will relay similar number of packets to the sink regardless of their distance to the sink but there exists a fluctuation especially when the router is close to the sink. This is because in our deployment approach, the outer circle will have less routers compared with the inner circle and the routers in the outer circle will only relay their packets to the nearest router in the inner circle which causes this fluctuation. An simple improvement is to let the router in the outer circle relay their packets to several near routers but not only the nearest one.

2) Lifetime Comparison: In this subsection, we demonstrate the lifetime comparison among our deployment approach, the centralized collection approach and a cluster-based monitoring approach with data aggregation, named CREM [27]. The centralized collection approach flushes the sensor network and constructs a topology tree before the monitoring stage. It collects the packets along the topology tree from leaves to the root. CREM partitions the sensor network into clusters and organize

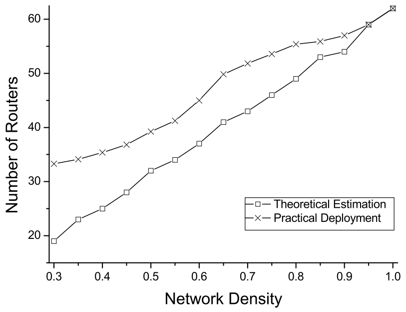

Fig. 5. Router number: theoretical vs. practical

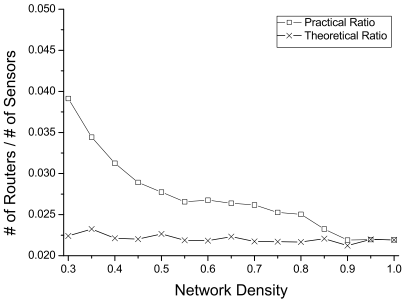

Fig. 6. Sensor numbers vs. router numbers

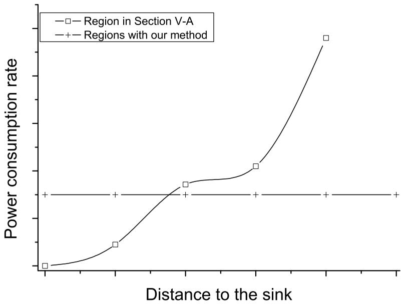

Fig. 7. Router lifetime distribution

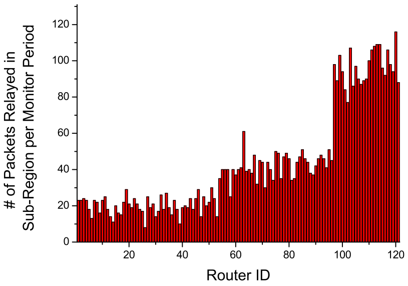

Fig. 8. Packets relayed from Sub Region

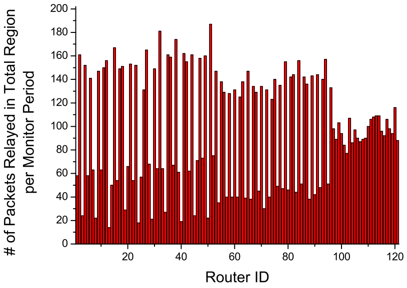

Fig. 9. Packets relayed from Total Region

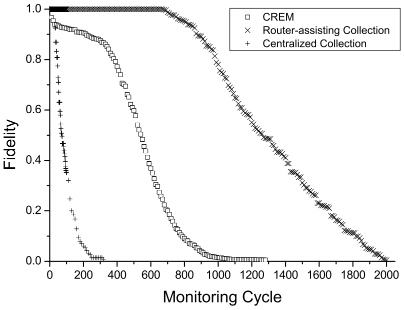

Fig. 10. Fidelity vs monitoring cycles

the sensor information in an aggregated way to reduce the transmission cost. If we define the fidelity as the percentage of the sensors whose packets can be received by the sink, and assume a fidelity of about 90% is acceptable, then from Fig. 10, we have the observation that our approach can dramatically extend the lifetime of the sensor network. It results in a 25 fold increase compared to centralized collection approach and a 4 fold increase compared to CREM. At the same time, the fidelity of our approach is much higher than that of CREM as the fidelity will be reduced as a result of the data aggregation. The underlying principle of this improvement is: in our approach, the sensors only need to relay their data to the associated router in one-hop which eliminate the data redundancy in centralized collection approach and the inaccuracy raised from the data aggregation in CREM.

In summary, in this section, extensive experiments are conducted to present that the proposed sensor network deployment approach achieves a set of important features including the low router-sensor ratio and even router power energy consumption ratio. Based on these properties, our proposed approach can easily deploy and recharge a small set of routers and greatly extend the lifetime of the sensor network compared with other approaches.

VIII. CONCLUSION

In this paper we study ways to easily deploy, maintain, and replenish large scale wireless sensor networks.

The deployment of large scale wireless sensor network has practical concerns. Many times we could not configure and deploy sensors individually because of either cost or time. Another concern is that we expect even workload so that the network could be easily maintained and replenished. We concluded in [5] that evenly distributed sensors contradict evenly distributed workload if the sensors have to relay data. In order to resolve this problem, we look at two layered approach. While sensors measured data, routers relay data. The deployment of sensors is simplified, as well as maintenance and replenishment. Routers do not need to be deployed evenly throughout the region because they are bigger, more powerful, have longer transmission range and bandwidth, and are less in quantity. Still, by pre-selecting sub-regions for routers, we simplify the deployment, maintenance, and replenishment of routers. Our approach is aimed at keeping workload equal among routers. The method could be applied to different energy usage equations, although we used the one in Equation (2) for our calculations. It is demonstrated through extensive experiments that the proposed deployment approach can extremely extend the lifetime of the sensor network and maintain even power consumption rates for both the sensors and routers.

REFERENCES

[1] T. F. Abdelzaher, S. Prabh, and R. Kiran, ”On Real-time Capacity Limits of Multihop Wireless Sensor Networks,” *Real-Time Systems Symposium*, December 2004.

[2] G. Barrenechea, B. Beferull-Lozano, and M. Vetterli, ”Lattice Sensor Networks: Capacity Limits, Optimal Routing and Robustness to Failures,” *the third international symposium on Information processing in sensor networks*, April 2004.

[3] P. Gupta and P. R. Kumar, ”The Capacity of Wireless Networks,” *IEEE Transactions on Information Theory, 46(2)*, March 2000.

[4] M. Bhardwaj, T. Garnett, and A. P. Chandrakasan, ”Upper Bounds on the Lifetime of Sensor Networks,” *IEEE International Conference on Communications*, Pages 785 - 790, 2001.

[5] D. Chen, A. K. Mok, J. Yi, M. Nixon, T. Aneweer, and R. Shepard, ”Data Collection with Battery and Buffer Consideration in a Large Scale Sensor Network,” *The 11th IEEE International Conference on Embedded and Real-Time Computing Systems and Applications*, August 2005.

[6] Z. Hu and B. Li, ”On the Fundamental Capacity and Lifetime Limits of Energy-Constrained Wireless Sensor Networks,” *Real-Time Technology and Applications Symposium*, May 2004.

[7] R. Ramanathan and R. Rosales-Hain, ”Topology Control of Multihop Wireless Networks using Transmit Power Adjustment,” *in Proceedings of the IEEE Conference on Computer Communications (INFOCOM), pages 404-413*, March, 2000.

[8] R. Wattenhofer, L. Li, P. Bahl, and Y. M. Wang, ”Distributed topology control for power efficient operation in multihop wireless ad hoc networks,” *in Proceedings of the IEEE Conference on Computer Communications (INFOCOM)*, 2001.

[9] S. Narayanaswamy, V. Kawadia, R. S. Sreenivas, and P. R. Kumar, ”Power control in ad-hoc networks: Theory, architecture, algorithm and implementation of the COMPOW protocol,” *in European Wireless Conference*, 2002.

[10] M. Kubisch, H. Karl, A. Wolisz, L. Zhong, J. Rabaey, ”Distributed algorithms for transmission power control in wireless sensor networks,” *Wireless Communications and Networking (WCNC)*, March, 2003.

[11] S. Lin, J. Zhang, G. Zhou, L. Gu, J. A. Stankovic, T. He, ”ATPC: adaptive transmission power control for wireless sensor networks,” *in Proceedings of the 4th international conference on Embedded networked sensor systems*, 2006.

[12] G. Ferrari, O. K. Tonguz, S. Panichpapiboon, ”Optimal Transmit Power in Wireless Sensor Networks,” *IEEE Transactions on Mobile Computing, 5(10)*, 2006.

[13] W. Ye, J. Heidemann, and D. Estrin, ”An energy-efficient MAC protocol for wireless sensor networks,” *in Proceedings of the IEEE Conference on Computer Communications (INFOCOM)*, 2002.

[14] S. Singh, C. S. Raghavendra, ”Power efficient MAC protocol for multihop radio networks,” *The Ninth IEEE International Symposium onPersonal, Indoor and Mobile Radio Communications*, 1998.

[15] Y. Tseng, C. Hsu and T. Hsieh, ”Power-Saving Protocols for IEEE 802.11-Based Multi-Hop Ad Hoc Networks,” *in Proceedings of the IEEE Conference on Computer Communications (INFOCOM)*, 2002.

[16] E.-S. Jung and N. Vaidya, ”A power saving mac protocol for wireless networks,” *Technical Report, UIUC*, July 2002.

[17] S. TAKEUCHI, K. SEZAKI and Y. YASUDA, ”An Improved Power Saving Mechanism for MAC Protocol in Ad Hoc Networks,” *IEICE Transactions on Communications, E88-B(7):2985-2993*, 2005.

[18] J. Aslam, Q. Li, and D. Rus, ”Three power-aware routing algorithms for sensor networks,” *Wireless Communications and Mobile Computing, vol. 2, no. 3, pp. 187–208*, Mar. 2003.

[19] O. Chipara, Z. He, G. Xing, Q. Chen, X. Wang, C. Lu, J.A. Stankovic and T.F. Abdelzaher, ”Real-time Power-Aware Routing in Sensor Networks,” *IEEE International Workshop on Quality of Service (IWQoS’06)*, June 2006.

[20] V. Isler, S. Kannan, K. Daniilidis, ”Sampling based sensor-network deployment,” *IEEE/RSJ International Conference on Intelligent Robots and Systems*, 2004.

[21] S. Kuo, Y. Tseng, F. Wu, C. Lin, ”A Probabilistic Signal-Strength-Based Evaluation Methodology for Sensor Network Deployment,” *Proceedings of the 19th International Conference on Advanced Information Networking and Applications*, 2005.

[22] S. Chellappan, X. Bai, B. Ma, D. Xuan, ”Sensor networks deployment using flip-based sensors,” *IEEE International Conference on Mobile Adhoc and Sensor Systems Conference*, 2005.

[23] A. Howard, M. J. Matadd, and G. S. Sukhatme, ”An incremental self-deployment algorithm for mobile sensor networks,” *Autonomous Robots, Special Issue on Intelligent Embedded Systems*, 2002.

[24] S. Poduri and G. S. Sukhatme, ”Constrained Coverage for Mobile Sensor Networks,” *In IEEE International Conference on Robotics and Automation*, April, 2004.

[25] Y. Zou and K. Chakrabarty, ”Sensor deployment and target localization based on virtual forces,” *in INFOCOM*, 2003.

[26] M. Sheldon, D. Chen, M. Nixon, and A. K. Mok, ”A Practical Approach to Deploy Large Scale Wireless Sensor Networks,” *Workshop on Resource Provisioning and Management in Sensor Networks*, 2005.

[27] S. Han and E. Chan, ”Continuous residual energy monitoring in wireless sensor networks,” *The 2nd International Symposium on Parallel and Distributed Processing and Applications*, December 2004.

[28] ZigBee Alliance, http://www.zigbee.org.