Lifetime Estimation of Large IEEE 802.15.4 Compliant Wireless Sensor Networks

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Abstract

Lifetime of a wireless sensor network is affected by key factors such as network architecture, network size, sensor node population model, data generation rate, initial battery budget, and communication protocols. We investigate accurate lifetime estimation of large sensor networks using discrete event simulation. Our experimental networks are large IEEE 802.15.4 compliant wireless sensor networks (WSNs). We take an iterative approach and obtain the ratio network lifetime over battery budget (LBR) by simulating only small budget networks. Using the converged LBR, we are able to accurately and efficiently estimate the lifetime of a network with full battery budget. Furthermore, this approach to lifetime estimation is both necessary and efficient when the network size is large.

1. Introduction

Wireless Sensor Networks (WSNs) have many important applications in monitoring and control of physical phenomena in environmental, health, home, industrial, and military areas [2]. Many sensor networks applications, for example, wildfire detection in environmental monitoring and seismic monitoring, require large scale deployment. Hence the design and performance evaluation of large sensor networks are called upon. Among many of the performance criteria of sensor networks, network lifetime is one of the most important.

The lifetime of a WSN is affected by many factors. These include network architecture, network size, sensor node population model, the generation rate of sensing data, initial battery budget available at each sensor, and data communication protocols. Key data communication protocols include those for medium access control, traffic routing, as well as sleep (or dutycycle) management. With such a large number of factors, accurate lifetime estimation of large sensor networks is a complex task. Analytical modeling may be used to predict lifetime of small sensor networks. However, analytical models for accurate lifetime estimation of large sensor networks are still beyond reach.

We investigate accurate lifetime estimation of large sensor networks using discrete event simulation. Our experimental networks are large IEEE 802.15.4 [1] compliant WSNs. We assume that network sensors are organized into clusters. A *data sink* is located at the border of the network. The cluster that contains the sink is called the *sink cluster*. Each cluster has one coordinator and some sensors (devices). The communication protocol used is beacon-enabled CSMA/CA [1]. The quality of service metric in such a network is called "event sensing reliability", which is the amount of sensing data collected and reported per cluster per unit time. Event sensing reliability is fixed in our investigation.

The network lifetime is defined as the time duration before a cluster in the network is first exhausted. Because the clusters that are closer to the sink assume more relay duty, they may be exhausted first. To equalize lifetime among clusters, a technique called *population adjustment* is used to adjust the number of nodes in each cluster [8]; clusters that are closer to the sink have more sensors thus higher budget. We are interested in answering the following question: how long can a sensor network survive when with specified topology while working to achieve satisfactory quality of service?

It is anticipated that the lifetime of a sensor network is approximately linear to the total battery budget within the network [11]. Our method is to obtain the constant *network lifetime* over *battery budget* (LBR) using simulation. Exhaustive simulation can be used. Because of excessive simulation time when using realistic battery budget, we only simulate battery budget levels until the system becomes stable and LBR converges. At that time, we are able to accurately and efficiently estimate the lifetime of a network that has full battery budget. This approach can be used to accurately and efficiently estimate the lifetime of large networks that have many clusters.

2. Related Work

There are many recent works on the performance evaluation of large-scale sensor networks and IEEE 802.15.4 compliant networks. Kiri, et. al. [7] simulated multi-hop sensor networks with different routing methods. The power consumption is used as the criterion to compare routing protocols. However, lifetime estimation is not considered. Chen, et. al. [5] studied a model in which sensors are uniformly distributed inside a circle. They found the relationship among battery life, buffer size, and sensor lifetime. However it was assumed that sensors work in peer-to-peer mode and dutycycle was not considered.

Lifetime estimation for sensor networks has been studied in literature. In [3] and [4], theoretical bounds on network lifetime were derived using a general energy consumption model for networks that have arbitrary topology, however, no specific MAC layer protocols were taken into account. In [10], a new MAC protocol for sensor networks was developed, power consumption and network lifetime were analyzed.

In [13], a Strawman iterative approach to simulating large-scale networks is presented. Using this approach, one can first simulate small-scale networks, then increase the scale of the networks, and observe the simulation results. The method presented in this paper is motivated by Strawman iterative approach. In searching for the invariant, we focus on finding the constant LBR. The iterative approach has been used previously in evaluating large-scale modular systems [12].

3. Performance Model

We assume a cluster-based network. Every cluster has one coordinator and some ordinary sensors (devices) that are organized using a star topology. In a star topology, devices only communicate with their coordinators and nothing else. A coordinator has much higher power supply than ordinary devices. A device is alkaline batteries-powered and is responsible for sensing data from environment and forwarding data to its coordinator. A coordinator collects all the data from the devices in the cluster and forwards the data to the data sink through other coordinators (called relaying nodes or bridges). In our model, all the data will be passed to the data sink, which then forwards the data to the monitor system through a wired link. For simplicity, we assume all data in the network are forwarded directly without aggregation, and all packets are of the same size.

Clusters are organized into layers that form a triangle. Layer 1 is the sink cluster; it contains the data sink. Figure 1 shows an example network that has 4 layers and 10 clusters.

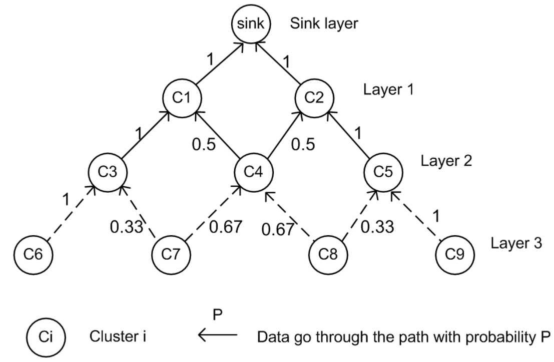

Figure 1. Routing in a 4-layer network

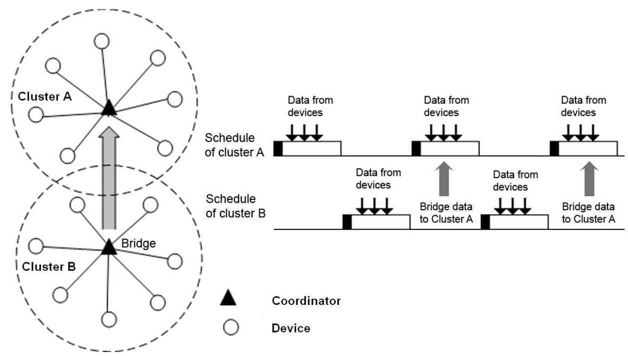

Figure 2. Operation of a M/S bridge

The communication protocol between devices and a coordinator is the beacon-enabled CSMA/CA, which is a collision-based protocol specified in IEEE 802.15.4 standard [1]. The inter-cluster communication is accomplished using a Master/Slave (M/S) bridge. In a M/S bridge, a coordinator acts as the intermediate node which collects data from its own cluster and passes data to the coordinator of the next cluster. This is illustrated in Figure 2, in which the coordinator in Cluster B is a bridge. It collects data from its own cluster for one superframe period within a beacon cycle, switches to Cluster A during the inactive period within the same beacon cycle, acts as an ordinary node within Cluster A, and forwards data to the coordinator in Cluster A.

In terms of routing, in our network model, data are always forwarded to clusters that are one layer closer to the sink, which automatically satisfies shortest path routing. We choose the routing scheme so that the workloads among the clusters within the same layer are balanced. This routing algorithm prolongs network lifetime. As an example, the routing within a 4-layer network is shown in Figure 1. In this figure, each circle denotes a cluster. An edge from Cluster S to Cluster D is labeled with the probability at which the data generated at Cluster S is sent to Cluster D.

Inside each cluster, a dutycycle technique [9] is applied on each device to put them to sleep. With this technique, we can control the event sensing reliability. We assume that sensing data arrives at the sensing data buffer at each sensor according to a Poisson process. The average data arrival rate at each sensor is 1 packet/sec. The buffer size of each sensor is 3 data packets. The size of each packet is 3 backoffs. It corresponds to 30 bytes (60 symbols) if all headers are included, or 15 bytes (30 symbols) if headers are excluded.

In our simulation model, we use a simple energy consumption model - sensors have constant energy consumption rate when they are active. One unit of battery budget is consumed at each sensor for every backoff during its active period. Thus the energy consumed each time a device wakes up is equal to the duration of its active period in number of backoffs. We ignore the energy consumption in sleep mode because it is vastly lower than the energy consumption in active mode. We implement the network model on Petrinet based Artifex [6]. Our program runs on a desktop computer under Windows XP operating system. The computer is equipped with a Pentium IV 1.9GHz CPU and 1GB of RAM.

4. Lifetime Estimation

We estimate sensor network lifetime using discrete event simulation. We carried out two investigations corresponding to two scaling factors that affect both the network lifetime and the simulation running time: node battery budget and network size. After population adjustment, the number of nodes in each cluster is 54-48 for two layers (i.e., 54 in the sink cluster, 48 per Layer 2 cluster), 62-50-46 for 3 layers and 77-55-47-43 for 4 layers. We assume that a sensor can keep working (i.e., remain in active mode) for 72 hours ($8.1 * 10^8$ backoffs) continuously without sleeping until the battery is exhausted. The event sensing reliability is assumed to be 300 bytes/sec with headers.

4.1. Scaling With Battery Budget

We select the node battery budget as the major factor and fix all other factors. We focus on finding the constant LBR. We first fix the network size to 3 layers (6 clusters). Our simulations start with a small node battery budget of 1000 units. We run the simulation until a cluster is first exhausted and obtain the lifetime of the network. We gradually increase the node battery budget to 2000, 4000, 8000, 16000, 32000, 48000, and 64000 and repeat the experiments. Figure 3 plots the network lifetime versus node battery budget. The results for a 4-layer (10-cluster) network are also included. We observe that the network lifetime increases almost linearly with the node battery budget. This applies to both network sizes. To find the contribution to lifetime

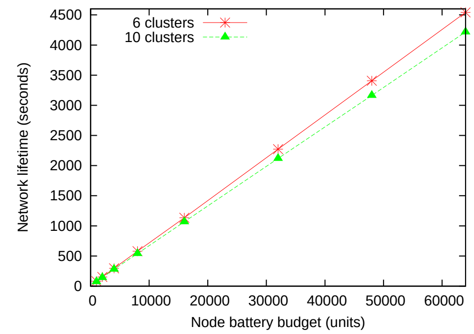

Figure 3. Lifetime vs. battery budget

per unit battery budget, we plot LBR versus node battery budget in Figure 4.

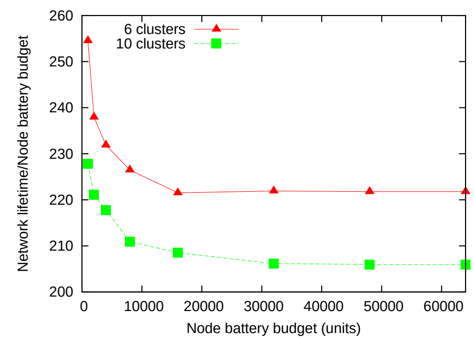

Figure 4. LBR vs. battery budget

We can observe that the ratio starts from a relatively high value and decreases as the node battery budget is increased; it converges to a stable value as the node battery budget is further increased. This holds for both network sizes. The higher values at low battery budget are the outcomes of the transient period. The energy consumption per unit time becomes stable after transient period and LBR converges. Using the converged results, we can estimate the network lifetime when with full budget. For a 3-layer (6-cluster) network, the lifetime will be 663 days (1.8 years); for a 4-layer (10-cluster) network, the lifetime will be 618 days (1.7 years).

The major advantage of our approach to estimating network lifetime is its capability to counter long simulation running times when with realistic battery budget. To illustrate this, we tracked the simulation running times for the 6-cluster case. We found that the simulation running time increases roughly linearly with the battery budget. Following the same ratio of simulation time and battery budget, exhaustive simulation may take 5.3 years to obtain the final results when with full battery budget, while with our approach, it takes 1.8 hours. We conclude that our approach to estimating the network lifetime is both necessary and efficient.

4.2. Scaling With Network Size

Our next investigation focuses on the reliability of our approach when network size is increased. We fix the battery budget and all other factors except the network size in our experiments. We start to simulate a network with one layer and increase the number of layers from 1 to 4 while keeping the average number of nodes per cluster to be 50; Population adjustment is again performed to equalize and extend the network lifetime.

Figure 5 shows the lifetime results when the network size is increased. Two levels of node battery budget, 35000 and 64000 units, are experimented. We can observe that the network lifetime slowly decreases as the network becomes larger. This is because as network becomes larger and more data is transmitted, the average load at each relaying cluster is higher. This is especially true for the sink cluster. Hence the network has shorter lifetime. However, the decrease is small, this means that both population adjustment and dutycycle management are still effective in preserving energy and extending network lifetime.

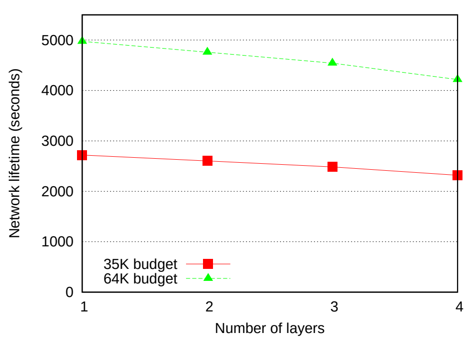

Figure 5. Lifetime vs. network size

Nevertheless, network size cannot be increased indefinitely. As load increases, the CSMA/CA protocol may approach its limit operating point. At saturation, every transmission encounters collision and no data can be sent successfully. We conclude that as long as the network is not overloaded, our approach to lifetime estimation can be applied to large networks with many clusters.

5. Conclusion

We developed a discrete event simulation model for large-scale IEEE 802.15.4 compliant sensor networks. Assuming fixed event sensing reliability, we are able to establish the constant *network lifetime* over *battery budget* via simulations. This constant is obtained when network operations become stable. Equipped with this constant, we are able to estimate network lifetime when with full battery budget. We also evaluate our approach for the cases of large networks in terms of the number of nodes. We found that as long as the network is not overloaded with respect to the underlying communication protocols, our approach to lifetime estimation is efficient when the network size is large. As future research, the simulation model built will be used to study lifetime estimation when network is overloaded.

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