On the Lifetime Analysis of Always-On Wireless Sensor Network Applications

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***Abstract*— Majority of papers in the area of wireless sensor networks (WSNs) have an element of energy-efficiency and associated with it an analysis of network lifetime. Yet, there is no agreement on how to analyze the lifetime of a WSN. As a result, errors are frequently made on both sides. Some underestimate the network lifetime by an order of magnitude, while others end up overestimating the lifetime by a significant factor. This paper presents a first step towards standardizing the lifetime analysis of WSNs. We focus on WSNs deployed for *always-on* applications, where the problem of power management is most severe because the environment needs to be monitored continuously. Underestimation of network lifetime is common when proposing sleep-wakeup schemes, where it is frequently assumed that in the absence of a sleep-wakeup scheme, a sensor node from the Mica family lasts 3-5 days on a pair of AA batteries. We show that the same sensor node can be made to last more than 36 days, even if it is continuously monitoring the environment. Overestimation typically occurs when proposing non-sleep-wakeup power management schemes such as in-network data aggregation. Overestimation occurs because several network activities (e.g periodic routing messages) are assumed to have negligible effect on the network lifetime and therefore are ignored in the lifetime analysis. We use our recent experience in deploying ExScal (a large-scale WSN for intrusion detection) to identify major components in the network lifetime analysis. We then present a careful lifetime analysis of ExScal and show how to analyze the effects of using various non-sleep-wakeup power management schemes such as hierarchical sensing, low-power listening, and in-network data aggregation on the network lifetime. Our lifetime analysis will be useful as a template in analyzing the lifetime of other WSNs deployed for always-on applications.**

I. Introduction

The problem of power management is a major impediment in achieving long-term unattended operation from large-scale wireless sensor networks (WSNs). Therefore, most new protocols and algorithms proposed for WSNs are energy-aware. To analyze the energy-efficiency of a new proposal, an analysis of network lifetime is frequently performed. Since there is no agreement on how to analyze the lifetime of a WSN, some underestimate the network lifetime by an order of magnitude, while others end up overestimating the network lifetime by a significant factor.

Underestimation is common when proposing sleep-wakeup schemes for WSNs. It is frequently assumed that a sensor node from the Mica family [6] lasts 3-5 days on a pair of AA batteries, if it needs to monitor the environment continuously [5], [9]. This is an underestimation by a factor of more than 12.

Overestimation typically occurs when proposing non-sleep-wakeup schemes to save energy. An example is [4]. Because this work focused on presenting the power-saving features of XSM (a Mica family sensor node designed for ExScal), it ignored the effect of several energy-consuming network activities such as periodic control messages on the network lifetime. Taking these factors into consideration will reduce the network lifetime estimate by a factor of more than 2. The story is similar with papers proposing energy-efficient MAC schemes and in-network data aggregation. Our analysis reveals that the maximum lifetime extension achievable in ExScal by data aggregation is less than 9%, which may come as a surprise to several readers. Although these numbers will change as the application parameters change and as the hardware properties will change, the methods to analyze the lifetime will likely remain the same (with minor changes needed to adapt to different platforms). Therefore, it is important to arrive at an agreement on how to analyze the lifetime of a WSN.

Although simulation tools (e.g. PowerTOSSIM [14]) exist today to obtain an accurate lifetime estimate of an application before it is deployed, they are not a substitute for analysis. Ideally, we should have a standard method for analyzing the network lifetime, whose results should match the lifetime estimate obtained from PowerTOSSIM, which, in turn, should match the actual lifetime observed in the field. To the best of our knowledge, however, there does not exist any work that focuses on presenting a method for the lifetime analysis of a WSN.

In this paper, we take a first step in this direction by identifying major factors in the lifetime analysis of a WSN. We focus on WSNs deployed for *always-on* applications (e.g. intrusion detection [1], [2], shooter localization [15]), where the problem of power management is most severe because the environment needs to be monitored continuously[1]. Further, we only focus on non-sleep-wakeup schemes to save energy because these schemes, in contrast to sleep-wakeup schemes, do not require deploying additional sensor nodes to increase the network lifetime.

We perform a careful analysis of ExScal [1], [2], a recently fielded large-scale WSN ($\sim$ 1000 sensor nodes) to detect and classify intruders of different kinds. Our analysis shows that if no power saving techniques are used, each sensor node in ExScal will last 3 days. We further show that each node can be made to last more than 36 days, even if each node is continuously monitoring the environment, by making use of two non-sleep-wakeup power-saving techniques that are already feasible today — Low Power Listening [12] and Hierarchical Sensing. We then show how to analyze the effects of other non-sleep-wakeup power saving techniques such as reducing the frequency of periodic messages and in-network data aggregation, on the network lifetime. Our lifetime analysis of ExScal will be useful as a template in analyzing the network lifetime of other always-on applications of WSNs.

[1]This is in contrast to *almost always-off* applications (habitat monitoring [13], subgalacial bed formation [11]), where it is not necessary to monitor the environment continuously because the environment does not change very abruptly.

We would like to note that the difficulty of underlying mathematics is not the challenge in network lifetime analysis. Rather, it is the incorporation of major factors, which comes from experience with real projects. We are able to identify several major factors in the lifetime analysis missed previously because of our experience with ExScal, the largest WSN deployed on ground till 2004. As the experience of research community with real WSN projects grows, the lifetime analysis will likely become more and more accurate.

Organization of the Paper. In Section II, we provide an overview of the ExScal application, the sensor platform used in ExScal, and major requirements and features of the ExScal application that affect the network lifetime. In Section III, we present the results of our lifetime analysis of ExScal, illustrating the lifetime extensions achievable by using various non-sleep-wakeup power management schemes. Section IV concludes the paper.

II. The ExScal Application and the XSM Platform

In this section, we provide an overview of the ExScal application, an overview of the sensor platform used in ExScal (called XSM) and the major factors that have a significant impact on ExScal's lifetime.

The goal in the ExScal application is to deploy a wireless sensor network over a large region to monitor intrusion activities. The network is required to detect different types of intruders breaching the perimeter of the protected region (i.e. provide barrier coverage [10]), classify them into some predetermined category (e.g. person, soldier, car, tank), and track their trajectory of intrusion. The network is also required to notify the nearest base station of an intrusion event in less than 2 seconds.

The key issues in ExScal are to minimize the cost of coverage, minimize the power consumption to maximize the network lifetime, provide accurate (i.e. low false alarm rate) and timely detection of intrusion events (i.e. less than 2 seconds from the occurrence of the event) in the face of unavoidable hardware and software failures, and do all of this with low human involvement.

To demonstrate the concept, approximately 1000 XSMs were deployed in a 1,200m×288m rectangular region [7] and intruders such as persons and Sport Utility Vehicles (SUVs) were shown to be detected and classified by the sensor network. At the end of year 2004, this was the largest wireless sensor network in the world deployed on the ground. For more details on the ExScal project we refer the reader to [1], [2].

A. The XSM Platform

The XSM (Extreme Scale Mote) is a sensor platform developed for the ExScal project. It is a refinement of the Mica 2 platform [3]. Its design was optimized for use in intrusion detection applications. It had three sensors — a 2-axis Magnetometer to detect ferrous materials, a Passive Infrared (PIR) sensor to detect motion, and an Acoustic sensor to detect objects making sounds (e.g. vehicles). For more details on the XSM platform, we refer the reader to [4].

B. Factors Affecting ExScal's Lifetime

The major factors affecting the network lifetime of the ExScal are as follows:

1) **Continuous Monitoring:** The region should be continuously monitored so that intruders can be detected instantly. This may require keeping at least one sensor continuously active, consuming significant energy.
2) **Event Notification Requirement:** Intrusion detection events should be communicated to a base station quickly. In the ExScal application, the requirement is to receive event detection notification at the nearest base station within 2 seconds. In order to communicate event-notification messages quickly over a multi-hop wireless sensor network, several, if not all, sensors need to keep their radio in the receive mode either continuously or frequently enough so that they can route an urgent event-detection message towards the base station. This again consumes significant energy.
3) **Periodic Control Messages:** Two middleware services namely, *routing* and *time synchronization* require every XSM to transmit periodic messages. As we will see in Section III, sending periodic control messages consumes significant energy.
4) **One Time Control Operations:** There are several one time activities performed in the ExScal application. The major ones among them are wireless reprogramming and localization. These operations require the sensor nodes to be active for a long duration (on the order of tens of minutes), send a large number of messages (in reprogramming), and perform actuation activities (e.g. sounding buzzers). All of these consume significant energy.
5) **Frequency of Events:** Every event requires the sensors near the event to not only stay awake for few seconds to detect the event but also to transmit messages in a multi-hop sensor network, and potentially route other XSM's messages. Staying awake with the processor and all the sensors active, consumes significant energy.

III. Results of ExScal Lifetime Analysis

In this section, we present the results our lifetime analysis of the ExScal application. For lack of space, we only present the results here and refer the reader to [8] for details of the analysis.

We define the lifetime of a WSN to be the time period during which the network continuously satisfies the application requirement. The application requirement can be stated in various forms. One simple way to express the requirement of an always-on application is in terms of the degree of coverage and the notification latency. For example, in ExScal, all intruders were required to be detected by the network at least 5 times in their trajectory through the network (i.e. provide 5-barrier coverage) and the event notification was required to reach the closest base station in at most 2 seconds.

In this paper, we derive a lower bound on the lifetime of a WSN. The purpose of doing so is to allow some buffer so that even if some factors are missed in the analysis (which almost always are), the network has a high likelihood of lasting at least as long as predicted by the analysis.

Now, we state the results of our analysis. We state the achievable lifetime when different power saving techniques are used.

No Power Management: If no power saving techniques are used, an XSM will last 72.2 hours (or 3 days).

Low Power Listening (LPL): If low power listening mode is used to duty cycle the radio and processor, then an XSM will last 187.99 hours (or 7.83 days), which represents a lifetime increase of 2.6 times. Low power listening [12] is a power saving technique that saves energy by putting the radio and the processor to sleep periodically. The radio and the processor wake up periodically to sample the channel. This goal of this technique is to reduce the energy consumed in idle listening.

Hierarchical Sensing: If hierarchical sensing is used together with LPL, then an XSM will last 878.55 hours (or 36.63 days), which represents a lifetime increase of 12.16 times. In the hierarchical sensing technique, only one sensor out of several installed on an XSM is continuously active. Rest are put to sleep to be woken up upon detection of an event. The choice of a wakeup sensor is critical in this technique. For details on how to choose a wakeup sensor we refer the reader to [8].

Reducing Periodic Control Messages: Periodic control messages can take a toll on the lifetime of an alway-on WSN. In ExScal, an XSM can be made to last for 1157.1 hours (or 48.2 days), if there were no need for any periodic control messages, assuming LPL and hierarchical sensing continue to be used. Examples of periodic control messages are maintenance messages sent by the routing and time synchronization subsystems.

In-Network Data Aggregation: In-network data aggregation is often thought of as a major technique for energy saving. In ExScal, however, the maximum lifetime extension achievable from in-network data aggregation is only 8.91%. If LPL and hierarchical sensing continue to be used, the lifetime of an XSM can be increased from 878.85 hours to 954.6 hours using the most optimistic data aggregation.

Finally, we discuss some more results pertaining to the effect of actuation on the network lifetime. Today's sensors have limited actuation abilities (e.g. blinking LEDs or sounding a buzzer). In future, sensor nodes are expected to have more actuation abilities. Actuations are often a major source of energy drain. Below, we mention the effect of two actuation activities on ExScal's lifetime:

Lighting Up LEDs: If even one LED is kept continuously on, the lifetime of an XSM will decrease from 878.85 hours to 412.4 hours (i.e. reduce it by more than half).

Sounding Buzzer: If buzzer is sounded for 1 minute every hour, the lifetime of XSM will reduce from 878.55 hours to 780.38 hours (a decrease of more than 90 hours of life).

See [8] for the details of our lifetime analysis.

IV. Conclusion

Majority of papers in the area of wireless sensor networks (WSNs) have an element of energy-efficiency and associated with it an analysis of network lifetime. But, there is no agreement on how to analyze the lifetime of a WSN. This paper presents a first step in this direction. Although we have accounted for several major factors in the lifetime analysis by leveraging our experience in deploying a large-scale WSN, we may not have accounted for all the major factors. It is a continuous process to keep identifying major factors in network lifetime analysis as the research community experiences with more and more WSN projects. Ideally, we should have a standard energy profile for a given platform and a standard method for network lifetime analysis that researchers can use to obtain an accurate estimate of network lifetime.

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