Energy-Efficient Surveillance System Using Wireless Sensor Networks*

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ABSTRACT

The focus of surveillance missions is to acquire and verify information about enemy capabilities and positions of hostile targets. Such missions often involve a high element of risk for human personnel and require a high degree of stealthiness. Hence, the ability to deploy unmanned surveillance missions, by using wireless sensor networks, is of great practical importance for the military. Because of the energy constraints of sensor devices, such systems necessitate an energy-aware design to ensure the longevity of surveillance missions. Solutions proposed recently for this type of system show promising results through simulations. However, the simplified assumptions they make about the system in the simulator often do not hold well in practice and energy consumption is narrowly accounted for within a single protocol. In this paper, we describe the design and implementation of a running system for energy-efficient surveillance. The system allows a group of cooperating sensor devices to detect and track the positions of moving vehicles in an energy-efficient and stealthy manner. We can trade off energy-awareness and surveillance performance by adaptively adjusting the sensitivity of the system. We evaluate the performance on a network of 70 MICA2 motes equipped with dual-axis magnetometers. Our results show that our surveillance strategy is adaptable and achieves a significant extension of network lifetime. Finally, we share lessons learned in building such a complete running system.

Categories and Subject Descriptors

C.2.1 [**Computer Communication Networks**]: Network Architecture and Design

General Terms

Design, Performance, Experimentation, Measurement

Keywords

Sensor networks, Energy conservation, Tracking, Wireless

1. MOTIVATION

One of the key advantages of wireless sensor networks (WSN) is their ability to bridge the gap between the physical and logical worlds, by gathering certain useful information from the physical world and communicating that information to more powerful logical devices that can process it. If the ability of the WSN is suitably harnessed, it is envisioned that WSNs can reduce or eliminate the need for human involvement in information gathering in certain civilian and military applications. In the near future, sensor devices will be produced in large quantities at a very low cost and densely deployed to improve robustness and reliability. They can be miniaturized into a cubic millimeter package (e.g., smart dust [16]) in order to be stealthy in a hostile environment. Cost and size considerations imply that the resources available to individual nodes are severely limited. We believe, however ,that limited processor bandwidth and memory are temporary constraints in sensor networks. They will disappear with fast developing fabrication techniques. The energy constraints on the other hand are more fundamental. According to R.A. Powers [20], battery capacity only doubles in 35 years. Energy constraints are unlikely to be solved in the near future with the slow progress in battery capacity and energy scavenging. Moreover, the untended nature of sensor nodes and the hazardous sensing environment preclude manual battery replacement. For these reasons, energy awareness becomes the key research challenge for sensor network protocol design. Several researchers have addressed energy conservation recently. Most of them

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*This work was supported by the DAPRPA IXO offices under the NEST project (grant number F336615-01-C-1905).

MobiSYS'04, June 6–9, 2004, Boston, Massachusetts, USA.

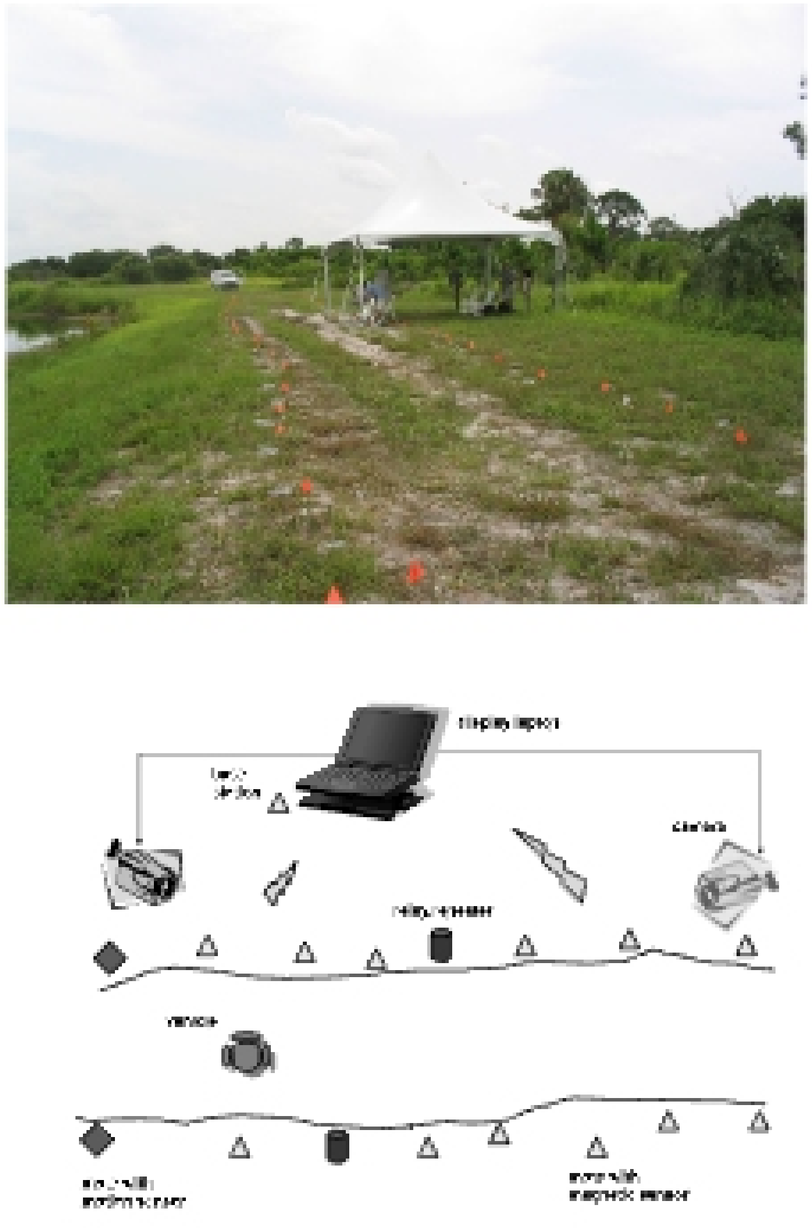

Figure 1: Sensor Network Deployment

focus on particular protocols and investigate whether their energy conservation goal can be achieved. To the best of our knowledge, none of them investigate energy-conservation for a running system as whole. Normally they evaluate their approach through simulations. Simulation approaches tend to make simplified assumptions that often do not hold well in practice and they are subject to incompleteness. For example, in [22][23][21], several sensing coverage schemes are proposed for energy conservation. None of them consider energy consumption in activities other than sensing.

In this paper, we describe our effort that involves system design and implementation on a MICA2 platform with 70 MICA2 motes. The primary goal of the system is to support the ability to track the position of moving targets in an energy-efficient and stealthy manner. Our experimental results show that the probability of false alarms observed reaches zero when aggregation is achieved among more than 3 member motes. The experimental results we obtained also show that with 5% of deployed motes serving as sentries and the non-sentries operating at a 4% duty cycle, our algorithm extends the lifetime of a sensor network by up to 900%.

The main contributions of this paper are: 1) the design and implementation of a running system with energy-awareness as the main design principle across multiple components, 2) Mechanisms for dynamic control, which allow tradeoffs between energy-efficiency and system performance by adjusting the sensitivity of the system, and 3) a physical implementation and field evaluation that reveal the practical issues that are hard to capture in simulation.

The remainder of this paper is organized as follows. Section 2 describes the requirements of a typical ground surveillance application. In Section 3, we describe the system setup and hardware components. In Section 4, we provide an overview of our system design. In Section 5, we elaborate on how the individual components of the system contribute to energy-efficient tracking. In Section 6, we discuss implementation issues concerning our system. We present experimental results in Section 7, and summarize the lessons learned from our experience in Section 8. Finally we conclude in Section 9 and discuss some future work in Section 10.

2. APPLICATION REQUIREMENTS

Our system design is motivated by the requirements of a typical ground surveillance application. The general objective of such an application is to alert the military command and control unit in advance to the occurrence of events of interest in hostile regions. The event of interest for our work is the presence of moving vehicles in the deployed region. The deployed sensor devices must have the ability to detect and track vehicles in the region of interest. Successful detection and tracking requires that the application obtain the current position of a vehicle with acceptable precision and confidence. When the information is obtained, it has to be reported to a remote base station within an acceptable latency. Several application requirements must be satisfied to make this system useful in practice:

- **Longevity:** The mission of a surveillance application typically lasts from a few days to several months. Due to the confidential nature of the mission and the inaccessibility of the hostile territory, it may not be possible to manually replenish the energy of the power-constrained sensor devices during the course of the mission. Hence, the application requires energy-aware schemes that can extend the lifetime of the sensor devices, so that they remain available for the duration of the mission.

- **Adjustable Sensitivity:** The system should have an adjustable sensitivity to accommodate different kinds of environments and security requirements. In critical missions, a high degree of sensitivity is desired to capture all potential targets even at expense of possible false alarms. In other case, we want to decrease the sensitivity of the system, maintaining a low probability of false alarms in order to avoid inappropriate actions and unnecessary power dissipation.

- **Stealthiness:** It is crucial for military surveillance systems to have a very low possibility of being detected and intercepted. Miniaturization makes sensor devices hard to detect physically; however, RF signals can be easily intercepted if sensor devices actively communicate during the surveillance stage. A zero communication exposure is desired in the absence of significant events.

- **Effectiveness:** The precision in the location estimate, and the latency in reporting an event are the metrics that determine the effectiveness of a surveillance system. Accuracy and latency are normally considered important metrics of tracking performance. However, the requirement of these two metrics can actually be slightly relaxed in many tracking applications. For example, it may be acceptable to obtain location estimation within a couple of feet and receive a detection report within a couple of seconds. We, therefore, focus primarily on the first three metrics mentioned above.

3. SYSTEM DESCRIPTION AND REQUIREMENTS

Figure 1 shows the deployment of our ground surveillance system. We deployed 70 tiny sensor devices, called MICA2 motes [14], along a 280 feet long perimeter in a grassy field that would typically represent a critical choke point or passageway to be monitored. Each of the motes is equipped with a 433 MHz Chipcon radio with 255 selectable transmission power settings. While this radio is sufficient to allow the motes deployed in the field to communicate with each other, it is not capable of long-range (> 1000 ft) communication when put on the ground. Therefore, we assume that in a real system where the command and control units may be deployed several thousands of feet away from the sensor field, devices capable of long-range communication, such as repeaters, will be deployed as gateways to assist the sensors to relay back information from the motes in the field to the base station. In our prototypical deployment, we use a mote as the base station that is attached to a portable device, such as a laptop. The portable device is the destination of the surveillance information and is mainly used for visualization in our prototype system. The camera devices shown in Figure 1 are controlled by the laptop to provide the next level of surveillance information, when triggered by the sensor field.

Each mote is equipped with a sensor board that has magnetic, acoustic, and photo sensors on it. While the different sensors make it possible for a mote to detect different kinds of targets, only the magnetic sensors are relevant to the application described in this paper. We use the HMC1002 dual-axis magnetometers from Honeywell [13]. These magnetic sensors detect the magnetic field generated by the movement of vehicles and magnetic objects. They have an omni-directional field of view and are therefore less sensitive to orientation. They have a resolution of 27 μGauss and their sensing range varies with the size of the magnetic object they are sensing. From our experiments, we found that these sensors can sense a small magnet at a distance of approximately 1 ft and slowly moving passenger vehicles at a distance of approximately 8-10 ft.

4. SYSTEM OVERVIEW

The key contribution of this work is the design and implementation of a wireless sensor network prototype that enables energy-efficient tracking and detection of events. Such a system is useful for surveillance applications, such as the one outlined in Section 2. The system we have designed is organized into a layered architecture comprised of higher-level services and lower-level components, as shown in Figure 2. It is implemented on top of TinyOS [12]. We first provide an overview of the different software components we have designed and then follow that with a detailed discussion of the role played by those components in the context of our tracking and surveillance application.

Time synchronization, localization, and routing comprise the lower-level components and form the basis for implementing the higher-level services, such as aggregation and power management. Time synchronization and localization are important for a surveillance application because the collaborative detection and tracking process relies on the spatio-temporal correlation between the tracking reports sent by multiple motes. The time synchronization module is responsible for synchronizing the local clocks of the motes with the clock of the base station. The localization module is responsible for ensuring that each mote is aware of its location. In our prototype system, we use a simple localization configuration, which statically assigns motes their location at the time they are programmed, assuming we know about where they will be placed. In actual deployment, such as a battlefield in which it is important to track the absolute geographical coordinates of the hostile tanks, the static configuration can be replaced with dynamic localization schemes such as in [10].

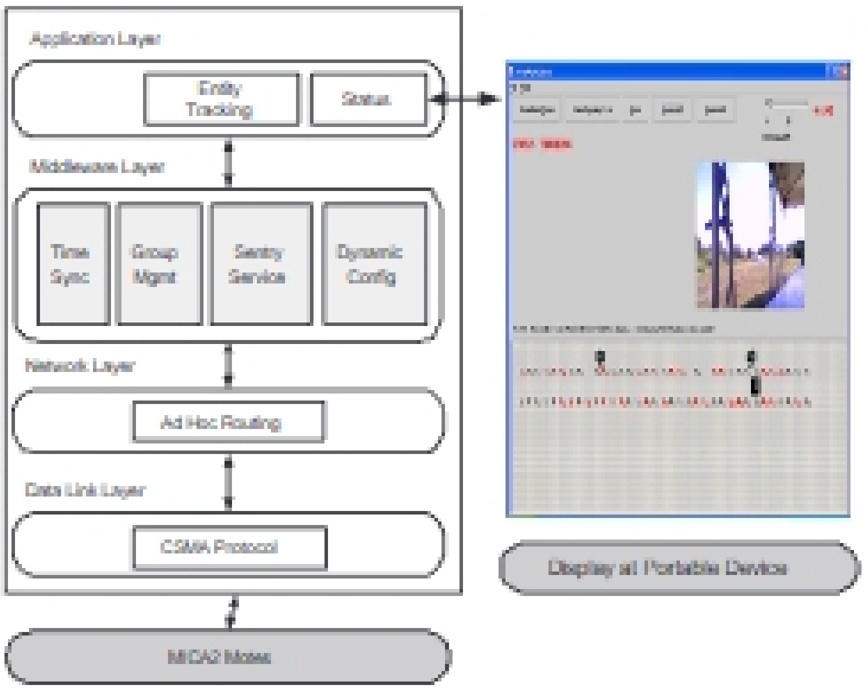

Figure 2: Energy-Efficient Tracking System

The routing component establishes routes through which the motes exchange information with each other and the base station.

Power management and collaborative detection are the two key higher-level services provided by our system. The sentry service component is responsible for power management, while the group management component is responsible for collaborative detection and tracking of events. The sentry service conserves energy of the sensor network by selecting a subset of motes, which we define as *sentries*, to monitor events. The remaining motes are allowed to remain in a low-power state until an event occurs. When an event occurs, the sentries awaken the other motes in the region and the group management component dynamically organizes the motes into groups in order to enable collaborative tracking. Together, these two components are responsible for energy-efficient event tracking.

All the deployed motes are programmed to run the distributed application. Our system supports the ability to reprogram the motes dynamically with new configuration parameters such as sensitivity . This eliminates the need to download the application code on all the motes each time the configuration is modified. We have a display module for portable devices (Figure 2)which is not part of the soft-