A High-Efficient and Low-Cost Localization System for Wireless Sensor Networks

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ABSTRACT

The problem of localization of wireless sensor nodes has long been regarded as very difficult to solve, when considering the realities of real world environments. In this paper, we formally describe, design, implement and evaluate a novel localization system, called Spotlight. Our system uses the spatio-temporal properties of well controlled events in the network (e.g., light), to obtain the locations of sensor nodes. We demonstrate that a high accuracy in localization can be achieved without the aid of expensive hardware on the sensor nodes, as required by other localization systems. We evaluate the performance of our system in deployments of Mica2 and XSM motes. Through performance evaluations of a real system deployed outdoors, we obtain a 20cm localization error. A sensor network, with any number of nodes, deployed in a 2500m^2 area, can be localized in under 10 minutes, using a device that costs less than \$1000. To the best of our knowledge, this is the first report of a sub-meter localization error, obtained in an outdoor environment, without equipping the wireless sensor nodes with specialized ranging hardware.

General Terms

Algorithms, Measurement, Performance, Design, Experimentation

Keywords

Wireless Sensor Network, Localization, Event Distribution, Laser

1. INTRODUCTION

Recently, wireless sensor network systems have been used in many promising applications including military surveillance, habitat monitoring, wildlife tracking etc.While many middleware services, to support these applications, have been designed and implemented successfully, localization - finding the position of sensor nodes - remains one of the most difficult research challenges to be solved practically. Since most emerging applications based on networked sensor nodes require location awareness to assist their operations, such as annotating sensed data with location context, it is an indispensable requirement for a sensor node to be able to find its own location.

The constraints on power and cost for tiny sensor nodes preclude this as a viable solution. Other solutions require per node devices that can perform ranging among neighboring nodes. The difficulties of these approaches are twofold. First, under constraints of form factor and power supply, the effective ranges of such devices are very limited. For example the effective range of the ultrasonic transducers used in the Cricket system is less than 2 meters when the sender and receiver are not facing each other. Second, since most sensor nodes are static one-time localization. To overcome these limitations, many range-free localization schemes have been proposed.

2. RELATED WORK

The localization problem is a fundamental research problem in many domains. In the field of robotics, it has been studied extensively.The reported localization errors are on the order of tens of centimeters, when using specialized ranging hardware, i.e. laser range finder or ultrasound. Due to the high cost and non-negligible form factor of the ranging hardware, these solutions can not be simply applied to sensor networks.

The RSSI has been an attractive solution for estimating the distance between the sender and the receiver. The RADAR system uses the RSSI to build a centralized repository of signal strengths at In this section, we discuss prior work in localization in two major categories: the range-based localization schemes (which use either expensive, per node, ranging devices for high accuracy, or less accurate ranging solutions, as the Received Signal Strength Indicator (RSSI)), and the range connectivity information (hop-by-hop) as an indication of proximity among the nodes.
similar approach, MoteTrack distributes the reference RSSI valuesto the beacon nodes.
To the best of our knowledge, Spotlight is the first range-free localization scheme that works very well in an outdoor environment. Our system requires a line of sight between a single device and the sensor nodes, and the map of the terrain where the sensor field is located. The Spotlight system has a long effective range (1000’s meters) and does not require any infrastructure or additional hardware for sensor nodes. The Spotlight system combines the advantages and does not suffer from the disadvantages of the two localization classes.

3. SPOTLIGHT SYSTEM DESIGN

The main idea of the Spotlight localization system is to generate controlled events in the field where the sensor nodes were deployed. An event could be, for example, the presence of light in an area.

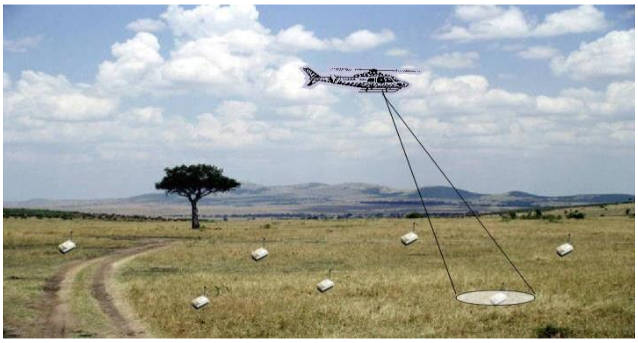


Figure 1. Localization of a sensor network using the Spotlight system

We envision, and depict in Figure 1, a sensor network deployment and localization scenario as follows: wireless sensor nodes are randomly deployed from an unmanned aerial vehicle. After deployment, the sensor nodes self-organize into a network and execute a time-synchronization protocol. An aerial vehicle (e.g. helicopter), equipped with a device, called Spotlight, flies over the network and generates light events. The sensor nodes detect the events and report back to the Spotlight device, through a base station, the timestamps when the events were detected. The Spotlight device computes the location of the sensor nodes.
During the design of our Spotlight system, we made the following assumptions:

- the sensor network to be localized is connected and a middleware, able to forward data from the sensor nodes to the Spotlight device, is present.
- the aerial vehicle has a very good knowledge about its position and orientation (6 parameters: 3 translation and 3 rigid-body rotation) and that is possesses the map of the field where the network was deployed.
- a powerful Spotlight device is available and it is able to generate spatially large events that can be detected by the sensor nodes, even in the presence of background noise (daylight).
- a line of sight between the Spotlight device and sensor nodes exists.

3.1 Definitions and Problem Formulation

Let’s assume that the space $A \subset R^3$ contains all sensor nodes N, and that each node N_i is positioned at $p_i(x, y, z)$. To obtain $p_i(x, y, z)$, a Spotlight localization system needs to support three main functions, namely an Event Distribution Function (EDF) $E(t)$, an Event Detection Function $D(e)$, and a Localization Function $L(T_i)$. They are formally defined as follows:

Definition 1: An event *e(t, p)* is a detectable phenomenon that occurs at time *t* and at point *p є A*. Examples of events are light, heat, smoke, sound, etc. Let $T_i=\{t_{i1}, t_{i2}, \ldots, t_{in}\}$ be a set of *n* timestamps of events detected by a node *i*. Let $T'=\{t_1', t_2', \ldots, t_m'\}$ be the set of *m* timestamps of events generated in the sensor field.

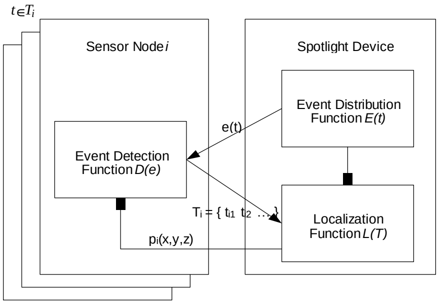


Figure 2. Spotlight system architecture

As shown in Figure 2, the Event Detection Function *D(e)* is supported by the sensor nodes. It is used to determine whether an external event happens or not. It can be implemented through either a simple threshold-based detection algorithm or other advanced digital signal processing techniques

With the support of these three functions, the localization process goes as follows:

1) A Spotlight device distributes events in the space *A* over a period of time.
2) During the event distribution, sensor nodes record the time sequence $T_i = \{t_{i1}, t_{i2}, \ldots, t_{in}\}$ at which they detect the events.
3) After the event distribution, each sensor node sends the detection time sequence back to the Spotlight device.
4) The Spotlight device estimates the location of a sensor node *i*, using the time sequence T_i and the known *E(t)* function.

3.2 Point Scan Event Distribution Function

To illustrate the basic functionality of a Spotlight system, we start with a simple sensor system where a set of nodes are placed along a straight line ($A = [0, l] \subset R$). The Spotlight device generates point events (e.g. light spots) along this line with constant speed *s*. The set of timestamps of events detected by a node *i* is $T_i=\{t_{i1}\}$. The Event Distribution Function *E(t)*.

3.3 Line Scan Event Distribution Function

Some devices, e.g. diode lasers, can generate an entire line of events simultaneously. With these devices, we can support the Line Scan Event Distributed Function easily. We assume that the sensor nodes are placed in a two dimensional plane ($A=[l \times l] \subset R^2$) and that the scanning speed is *s*. The set of timestamps of events detected by a node*i* is $T_i=\{t_{i1}, t_{i2}\}$.

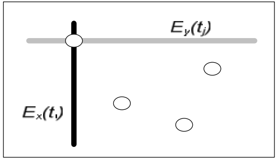


Figure 4. The implementation of the Line Scan EDF

The Line Scan EDF isdefined as follows:

We can localize a node by calculating the intersection of the two event lines, as shown in Figure 4. More formally:

3.4 Area Cover Event Distribution Function

Other devices, such as light projectors, can generate events that cover an area. This allows the implementation of the Area Cover EDF. The idea of Area Cover EDF is to partition the space *A* into multiple sections and assign a unique binary identifier, called code, to each section. Let's suppose that the localization is done within a plane ($A \subset R^2$). Each section S_k within *A* has a unique code *k*. The Area Cover EDF is then defined as follows:

$$BIT(k, j) = \begin{cases} \text{true}, & \text{if bit of k is 1} \end{cases} \qquad (8)$$

$\left. \text{false}, \quad \text{if bit of } k \text{ is } 0 \right.$

A more accurate localization requires a finer partitioning of the plane, hence the number of bits in the code will increase. Considering the noise that is present in a real, outdoor environment, it is easy to observe that a relatively small error in detecting the correct bit pattern could result in a large localization error. Returning to the example shown in Figure 5, if a sensor node is located in the section with code 0000, and due to the noise, at time *t* = 3, it thinks it detected an event, it will incorrectly conclude that its code is 1000, and it positions itself two squares below its correct position. The localization accuracy can deteriorate even further, if multiple errors are present in the transmission of the code.

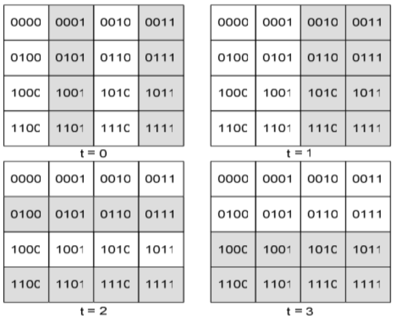
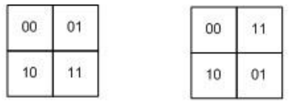


Figure 5. The steps of Area Cover EDF. The events cover the shaded areas.

Considering that a limited number of corrections is possible by any coding scheme, a natural question arises: can we minimize the localization error when there are errors that can not be corrected? This can be achieved by a clever placement of codes in the grid. As shown in Figure 7, the placement A, in the presence of a 1-bit error has a smaller average localization error when compared to the placement B. The objective of our code placement strategy is to reduce the total Euclidean distance between all pairs of codes with Hamming distances smaller than K, the largest number of expected 1-bit errors.



$A : \overline{Error} = 1$ $\quad B : \overline{Error} = (1+\sqrt{2})/2$

Figure 7. Different code placement strategies

method ends when no swap of codes can further minimize the objective function.

For evaluation, we compared the average localization error in the presence of K-bit error for two strategies: the proposed Greedy Placement and the Row-Major Placement (it places the codes consecutively in the array, in row-first order).

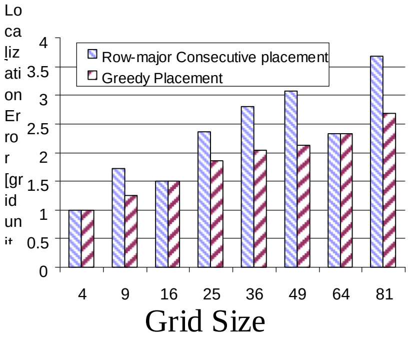


Figure 8. Localization error with code placement and no ECC

3.5 Event Distribution Function Analysis

Although all three aforementioned techniques are able to localize the sensor nodes, they differ in the localization time, communication overhead and energy consumed by the Event Distribution Function (let's call it Event Overhead). Let's assume that all sensor nodes are located in a square with edge size *D*, and that the Spotlight device can generate *N* events (e.g. Point, Line and Area Cover events) every second and that the maximum.

It is important to remark the ratio Event Overhead per unit time, which is indicative of the power requirement for the Spotlight device.For practical purposes, the Area Cover is a viable solution for small to medium size networks, while the Line Scan works well for large networks. We discuss the implications of the power requirement for the Spotlight device, and offer a hybrid solution in Section 6.

3.6 Localization Error Analysis

The accuracy of localization with the Spotlight technique depends on many aspects. The major factors that were considered during the implementation of the system are discussed below:

- Time Synchronization: the Spotlight system exchanges time stamps between sensor nodes and the Spotlight device. It is necessary for the system to reach consensus on global time through synchronization. Due to the uncertainty in hardware processing and wireless communication, we can only confine such errors within certain bounds (e.g. one jiffy). An imprecise input to the Localization Function *L(T)* leads to an error in node localization.
- Realization of Event Distribution Function: EDF defines locations of events at time t. Due to the limited accuracy (e.g. It is important to remark that the localization error is independent of the number of sensor nodes in the network. This independence, as well as the aforementioned independence of the execution cost, indicate the very good scalability properties (with the number of sensor nodes, but not with the area of deployment) that the Spotlight system possesses.
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4. SYSTEM IMPLEMENTATION

For our performance evaluation we implemented two Spotlight systems. Using these two implementations we were able to investigate the full spectrum of Event Distribution techniques, proposed in Section 3, at a reduced “one time” cost (less than $1,000).

The first implementation, called µSpotlight, had a short range (10-20 meters), however its capability of generating the entire spectrum of EDFs made it very useful. We used this implementation mainly to investigate the capabilities of the Spotlight system and tune its performance. It was not intended to represent the full solution, but only a scaled down version of the system.

The second implementation, the Spotlight system, had a much longer range (as far as 6500m), but it was limited in the types of EDFs that it can generate. The goal of this implementation was to show how the Spotlight system works in a real, outdoor environment, and show correlations with the experimental results obtained from the µSpotlight system implementation.

4.1 Spotlight System

The second Spotlight system we built used, as the Spotlight device, diode lasers, a computerized telescope mount (Celestron CG-5GT, shown in Figure 11), and an IBM Thinkpad laptop. The laptop was connected, through RS232 interfaces, to the telescope mount and to one XSM600CA [7] mote, acting as a base station.

The diode lasers we used ranged in power from 7mW to 35mW. They emitted at 650nm, close to the point of highest sensitivity for CdSe photosensor. The diode lasers were equipped with lenses that allowed us to control the divergence of the beam.

Figure 11. Spotlight system implementation

The telescope mount has worm gears for a smooth motion and high precision angular measurements.

The laptop computer, through a Java GUI, controls the motion of the telescope mount, orienting it such that a full Point Scan of an area is performed, similar to the one described in Figure 3(b). For each turning point *i*, the 3-tuple (Alt_i and Az_i angles and the timestamp t_i) is recorded. The Spotlight system uses the timestamp received from a sensor node *j*, to obtain the angular measures Alt_j and Az_j for its location.

4.2 Event Detection Function *D(t)*

The Event Detection Function aims to detect the beginning of an event and record the time when the event was observed. We implemented a very simple detection function based on the observed maximum value. An event *i* will be time stamped with time t_i, if the reading from the photo sensor d_{ti}, fulfills the condition:

$d\text{max} + \Delta < dti$

where d_{max} is the maximum value reported by the photo sensor before t_i and Δ is a constant which ensures that the first large detection gives the timestamp of the event (i.e. small variations around the first large signal are not considered). Hence Δ guarantees that only sharp changes in the detected value generate an observed event.

4.3 Localization Function *L(T)*

The Localization Function is implemented in the Java GUI. It matches the timestamps created by the Event Distribution Function with those reported by the sensor nodes.

The Localization Function for the Point Scan EDF has as input a time sequence $T_i = \{t_1\}$, as reported by node *i*. The function performs a simple search for the event with a timestamp closest to t_1. If t_1 is constrained by:

$x = {}^{x}{}_{e}n+1, y = {}^{y}{}_{e}n+ 1$

The case for the Line Scan is treated similarly. The input to the Localization Function is the time sequence $T_i = \{t_1, t_2\}$ as reported by node *i*. If the reported timestamps are constrained by:

4.4 Time Synchronization

The time synchronization in the Spotlight system consists of two parts:

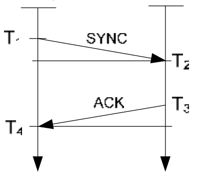

Figure 12. Two-way synchronization

We note that Equation 11 assumes that the one trip delays are the same in both directions. In practice this does not hold well enough. To improve the performance, we separate the handshaking process from the timestamp exchanges. The handshaking is done fast, through a 2 byte exchange between the Spotlight device and the sensor node (the timestamps are still recorded, but not sent). After this fast handshaking, the recorded time stamps are exchanged. The result indicates that this approach can significantly improve the accuracy of time synchronization.

5. PERFORMANCE EVALUATION

In this section we present the performance evaluation of the Spotlight systems when using the three event distribution functions, i.e. Point Scan, Line Scan and Area Cover, described in Section 3.

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For the Spotlight system evaluation, we deployed 10 XSM motes in a football field. The site is shown in Figure 13 (laser beams are depicted with red arrows and sensor nodes with white dots). Two sets of experiments were run, with the Spotlight device positioned at 46m and at 170m from the sensor field. The sensor nodes were aligned and the Spotlight device executed a Point Scan. The localization system computed the coordinates of the sensor nodes, and the Spotlight device was oriented, through a GoTo command sent to the telescope mount, towards the computed location. In the initial stages of the experiments, we manually measured the localization error.

- Localization Bias. This metric is used to investigate the effectiveness of the calibration procedure. If, for example, all computed locations have a bias in the west direction, a calibration factor can be used to compensate for the difference.

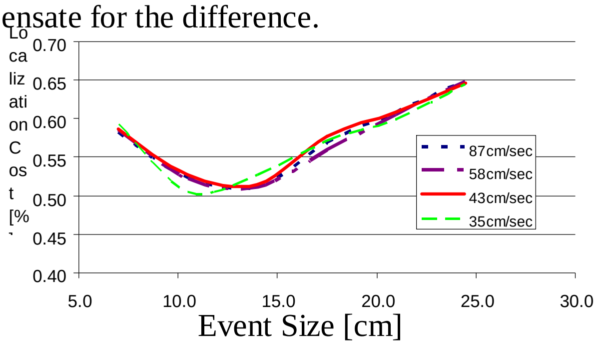


Figure 16. Localization Cost vs. Event Size for the Point Scan EDF

5.2 Line Scan - µSpotlight system

In a similar manner to the Point Scan EDF, for the Line Scan EDF we were interested in the dependency of the localization error and duration on the size of the event and scanning speed.

We represent in Figure 17 the localization error for different event sizes. It is interesting to observe the dependency (concave shape) of the localization error vs. the event size. Moreover, a question that should arise is why the same dependency was not observed in the case of Point Scan EDF.

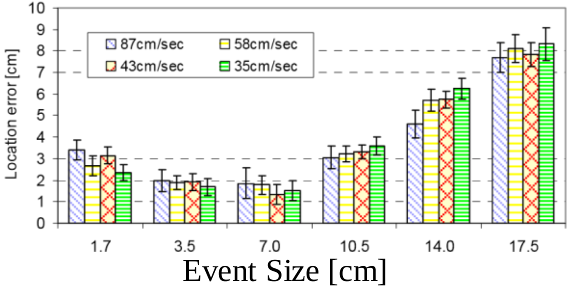
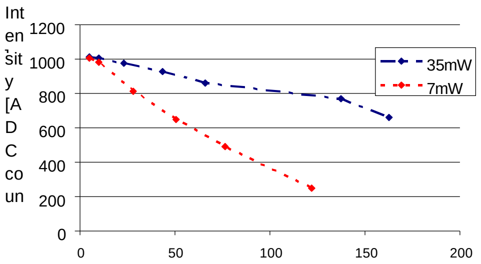


Figure 17. Localization Error vs. Event Size for the Line Scan EDF

The explanation for this concave dependency is the existence of a bias in location estimation. As a reminder, a bias factor was introduced in order to best estimate the central point of events that have a large size. The reason why we did not observe the same dependency in the case of the Point Scan EDF was that we did not experiment with event sizes below 7cm, due to the long time it would have taken to scan the entire field with events as small as 1.7cm.

Scan EDF, we observed evidence of a bias in location estimation. The estimated locations for all sensor nodes exhibited different biases, for different event sizes. For example, for an event size of 17.5cm, the estimated location for sensor nodes was to the upper-left size of the actual location. The scanning speed did not influence the bias.



6. OPTIMIZATIONS/LESSONS LEARNED

6.1 Distributed Spotlight System

The proposed design and the implementation of the Spotlight system can be considered centralized, due to the gathering of the sensor data and the execution of the Localization Function *L(t)* by the Spotlight device. We show that this design can easily be transformed into a distributed one, by offering two solutions.

One idea is to disseminate in the network, information about the path of events, generated by the EDF (similar to an equation, describing a path), and let the sensor nodes execute the Localization Function. For example, in the Line Scan scenario, if the starting and ending points for the horizontal and vertical scans.

6.2 Localization Overhead Reduction

Another requirement imposed by the Spotlight system design, is the use of a time synchronization protocol between the Spotlight device and the sensor network. Relaxing this requirement and imposing only a time synchronization protocol among sensor nodes is a very desirable objective.

6.3 Dynamic Event Distribution Function *E(t)*

An idea is to use two scans: one which uses a large event size (hence larger localization errors), followed by a second scan in which the event size changes dynamically. The first scan is used for identifying the areas with a higher density of sensor nodes. The second scan uses a larger event in areas where the sensor node density is low and a smaller event in areas with a higher sensor node density.

A dynamic EDF can also be used when it is very difficult to meet the power requirements for the Spotlight device (imposed by the use of the Area Cover scheme in a very large area). In this scenario, a hybrid scheme can be used: the first scan (Point Scan) is performed quickly, with a very large event size, and it is meant to identify, roughly, the location of the sensor network. Subsequent Area Cover scans will be executed on smaller portions of the network, until the entire deployment area is localized.

A solution to this problem, which we experimented with in the µSpotlight system, was to use an optical filter on top of the light sensor. The spectral response of a CdSe photo sensor spans almost the entire visible domain with a peak at about 700nm. As shown in Figure 31-top, the fluorescent light has no significant components above 700nm. Hence, a simple red filter (Schott RG-630), which transmits all light with wavelength approximately above 630nm, coupled with an Event Distribution Function that generates events with wavelengths above the same threshold, would allow the use of the system when a fluorescent light is present.

7. CONCLUSIONS AND FUTURE WORK

In this paper we presented the design, implementation and evaluation of a localization system for wireless sensor networks, called Spotlight. Our localization solution does not require any additional hardware for the sensor nodes, other than what already exists. All the complexity of the system is encapsulated into a single Spotlight device. Our localization system is reusable, i.e. the costs can be amortized through several deployments, and its performance is not affected by the number of sensor nodes in the network. Our experimental results, obtained from a real system deployed outdoors, show that the localization error is less than 20cm. This error is currently state of art, even for range-based localization systems and it is 75% smaller than the error obtained when using GPS devices or when the manual deployment of sensor nodes is a feasible option.

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