E-STROBE: An Adaptive Beacon Activation Algorithm for Sensor Localization

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Abstract— **Spatial localization is an important building block for wireless sensor networks. Beacons that know their position and serve as reference are a vital aspect of nearly every localization system. In this paper, we look at dense beacon placement, which has a significant impact on the overall quality of localization. Based on the premise that uniformly dense beacon placement is not practical, we motivate the need for adaptive beacon activation in dense sensor networks. In this paper, we consider STROBE, a previously proposed beacon activation algorithm, and modify it to be energy aware. Our simulation results show that the addition of residual energy as a parameter in the STROBE algorithm results in a longer network lifetime and better coverage on the periphery of the network.**

Keywords - localization; sensor networks; low-power wireless; self-configuration; localized algorithms

I. Introduction & Motivation

Wireless sensor networks have been attracting increasing research interest given the recent advances in miniaturization and low-cost, low-power design. Consisting of a large collection of small wireless, low-power, unattended sensors and/or actuators, wireless sensor network technology poses unique system design challenges. Wireless sensor networks will enable fine-grained observation and control of the ambient conditions such as temperature, movement, light, acoustic events or the presence of certain objects. The low per-node cost will allow these wireless networks of sensors and actuators to be densely distributed.

Localization, or the ability of a node to determine its location, is an important building block for such systems. Localization is indispensable for context aware applications that select services based on location. In dense networks, localization can assist sensors in determining if they are redundant, and can thus be idle to save energy and extend the lifetime of the network. Finally, localization information on a scale with transmission range can enable geographic routing algorithms that can propagate information efficiently through a multi-hop network.

In this paper, we consider STROBE [4] (Selectively TuRning Off Beacons), a beacon placement and activation algorithm for dense sensor networks proposed by Nirupama et al. We augment the STROBE algorithms with energy metrics so that its decisions consider the residual energy of the beacons in the network. Our simulation results show that our new algorithm, E-STROBE, results in a 30-50% system lifetime increase, a higher percentage of coverage over a longer period of time, and a longer maintenance of the network diameter.

The remainder of this paper is organized as follows: in Section II we present previous work including background on the original STROBE algorithm; in Section III we describe the extensions to the algorithms that result in E-STROBE; in Section IV we present the evaluation methodology and in Section V we discuss our results; we conclude in Section VI.

II. Previous Work

Researchers [1, 2] have thus far focused on building and demonstrating proof of concepts of spatial localization systems. Researchers have also built upon the idea of empirical adaptation, self-configuration and localized algorithms for different densities of sensor network localization systems [3, 4, and 5]. They have considered sensing coverage under stringent energy constraints to increase system lifetime. There has also been a good amount of research on loosely [1] and tightly [2] coupled localization systems. Optimal placement problems have been studied in various contexts by researchers including facility location [7] and pursuit evasion problems in robotics [8]. Position estimation and navigation in robotics is a fundamental issue, which has been dealt in detail by the Monte Carlo Localization (MCL) [9]. They have used a common Bayesian formulation of the localization problem. Other position estimation work includes convex optimization techniques [10] in sensor networks in an off-line, centralized manner. Iterative techniques for robust position estimation in sensor networks have also been explored [11].

Researchers have recognized that these systems will be deployed at large in an ad-hoc fashion, without controlling the placement of each and every node. Instead, they have focused on developing techniques to identify problems in a deployed sensor field. Researchers have also proposed algorithms for coverage in wireless ad hoc sensor networks given global knowledge of node positions using Voronoi diagrams [12] to compute maximal breach paths and find gaps [13].

These state of the art developments in systems and algorithms, the fundamental challenges of localization in a very dense sensor network in terms of scalability, environment condition variation and computational resources used, have been well explored by Nirupama et al [6]. They have focused on the fundamental characteristics of sensor networks such as extremely high ratio of devices per human and the consequent need for robust, unattended operation. These conditions, in turn, build up the need for a self-configuring system in response to the varying environment conditions. They have proposed algorithms like HEAP and STROBE for medium and dense beacon deployment densities. In unattended sensor networks, an approach of a very dense initial deployment of location aware nodes (beacons) is very practical. Redundant beacons can be placed in an idle mode to increase their lifetime, and hence the lifetime of the network. In this paper we have focused on STROBE as a solution for dense beacon deployment densities for a longer, unattended, efficient and scalable provisioning of localization [4]. The goal of the basic STROBE algorithm is to achieve an adaptive operational density of beacons. We augment STROBE to render it energy aware resulting in a new algorithm called E-STROBE.

In STROBE, each beacon has three states as shown in Figure 1: *voting*, *designated*, and *sleep*. In *voting* state, each beacon transmits and listens for neighboring beacon transmissions for T_v seconds. At the end of the voting period, a node decides if it should be an active beacon and transition to the *designated* state, or idle and transition into the *sleep* state. It makes this decision based on the number of other beacons it observes during the voting period compared with a safe threshold, ρ_a. This decision is made on a probabilistic basis. If the node transitions to *sleep* state, it will remain sleeping for T_s seconds. Likewise, if it transitions to *designated* state it will remain active for T_d seconds. While in the *designated* and *voting* states, a beacon advertisement is transmitted with a period of T_b. Also, the beacon transitions back to *voting* state after T_d and T_s seconds from the *designated* and *sleep* state respectively.

The probabilistic decision can be explained with an example. Consider six active beacons aware of each other in a neighborhood with a beacon threshold, ρ_a, of three. With probability ρ_a/L_a = ½, each beacon moves to the *designated* state. The probabilistic nature of the decision allows the network designer to pick ρ_a so that an acceptable probability of no beacons being active can be achieved. In this case, the expected number of beacons being active is three, and the probability that no beacons are active is 1/64. As the number of active beacons in a neighborhood increases, the probability of an individual beacon going to the *designated* state is reduced.

STROBE has quite a few inherent performance advantages over other localization algorithms proposed to deal with power saving sensor localization. STROBE, being a dynamic and adaptive algorithm, gives more control of the actual coverage in different terrains. The ratio of parameters like T_v, T_d, T_s and T_b in the beacon state transition can be specifically altered to increase system lifetime. The value of the threshold parameter ρ_a can also be altered depending on the sensor network deployment terrain and communication channel characteristics. There is an interesting tradeoff between the quality of localization and lifetime of the system as a whole.

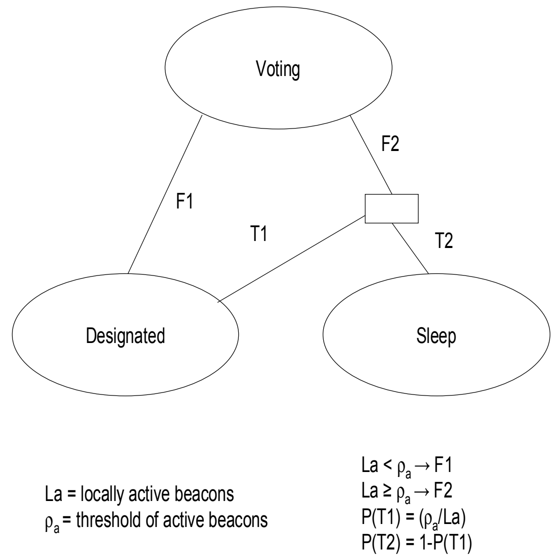

Figure 1. STROBE State Transitions

III. E-STROBE

In spite of being a dynamic and self-configuring algorithm with good scalability, STROBE has certain limitations. First, the use of the parameter ρ_a and probabilistic decision process make the STROBE algorithm very robust, stable and distributed, but results in more beacons than required being active. These excessive beacons lead to self-interference and a general noisier sensing environment, which can result in excessive energy used in transmission and a lower system lifetime. Second, beacons at the edge of the network have fewer neighbors so they tend to stay active for a longer period of time and hence die out early. The result is that the beacon network diameter decreases over a period of time irrespective of the initial beacon density of the beacon network.

We believe that the above limitations motivate the introduction of an energy parameter. An energy aware algorithm could ensure a proper load-balanced system and reduce the number of excessively redundant beacons. We augmented the STROBE probabilistic transition decision process to incorporate residual beacon energy, as shown in Figure 2. In essence, beacons with more remaining energy have a higher probability of becoming active, while those with lower energy will have a higher chance of conserving their energy for later use. The trade-off considered is how to weigh the residual energy metric compared to ρ_a, to achieve the proper balance between coverage, accuracy, and network lifetime. Because the new beacon decision process now has a "selfish" quality, beacons on the edge of the network are more aggressive in conserving their energy and hence help maintain the network diameter for a longer period of time.

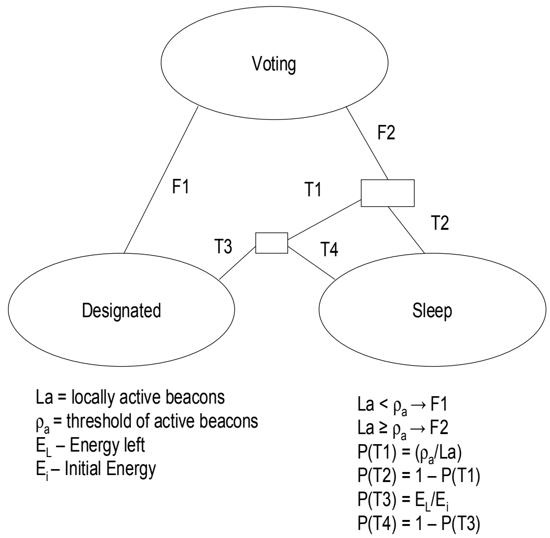

Figure 2. E-STROBE State Transitions

Consider for example, six active beacons in a network with ρ_a set to three as the beacon threshold. In STROBE, on average, three out of the six will go to the *designated* state where as one might have been sufficient for the neighborhood. With E-STROBE the beacons in the process of transitioning to the *designated* state will further consider their residual energy before completing the transition (transitions T3 and T4 in Figure 2). The impact is that a beacon with low energy reserves has a lower probability of going to the *designated* state. This results in fewer active beacons, proper load balance and a longer system lifetime.

IV. Performance Evaluation

To evaluate the performance of E-STROBE, we emulated a sensor network with both the STROBE and E-STROBE algorithms. Each node emulated was run on an independent thread, which had its own global data structure. All the node threads ran simultaneously to a 'monitor' thread, which periodically measured various performance metrics shown in Table I.

A node thread reduces its energy reserves every time it transmits messages to or receives messages from its neighbors based on the energy consumption model to mimic realistic sensor radios [4]. A node thread joins the main emulator thread when its energy reserve has been exhausted and the emulator comes to a halt when all the node threads and the 'monitor' thread have joined the main thread.

The global data associated with every node has node information such as its position, state (*voting*, *designated*, *sleep*), energy left in the node, and a message queue, which every node maintains to receive messages from its neighboring nodes during the *voting* state. The message queue includes sender node ID, sender's state (*voting* or *designated*) and a sequence number of messages, which is incremented every time a sender broadcasts a new advertisement.

TABLE I. Performance Metrics

Performance Metric	Description
Coverage %	Percentage network area covered by beacon advertisements
Peripheral Coverage %	Percentage network area covered by beacon advertisements in the peripheral network area (20 % of total area)
System Lifetime	Time elapsed between the start of the network and the coverage dropping below 70%.
Active Beacons	Total number of beacons at a given time in voting and designated state
Alive Beacons	Total number of beacons at a given time with energy reserves greater than zero
Mean Localization Error	Mean distance from the centroid of the active neighbors when a beacons state changes to Designated.

We emulated a terrain with 100 beacons distributed uniformly at random in a 100m*100m area each having an initial energy of 10,000J. The nominal radio range for these beacons is 25 meters, which defines their neighborhood. The corresponding beacons per neighborhood are 19 which is around 3 times the threshold number of beacons, ρ_a. Several combinations of parameters were tested with STROBE, and those that resulted in the best performance were chosen as a common ground for comparing STROBE and E-STROBE performance [6].

The parameters and values used in the simulations are shown in Table II. The parameters T_v, T_d, and T_b were set to provide good performance in terms of system lifetime. The parameters E_t, E_s, and E_r were set to be comparable to the values used in [6].

V. Results

Figures 3-7 compare the performance of STROBE and E-STROBE for a T_d/T_v ratio of 100 with respect to performance metrics coverage %, peripheral coverage %, system lifetime, number of active beacons, number of alive beacons, and mean localization error, respectively.

TABLE II. Simulation Parameters

Parameter	Description	Value
Ei	Initial energy	10,000J
E_t	Energy to transmit	.65J
E_s	Energy to sleep	0J
E_r	Energy to receive	.4J
T_v	Time in voting state	$2T_b$
T_d	Time in designated state	$100T_v$
T_s	Time in sleep state	$50T_v$
T_b	Beacon period when in voting or designated state	1 second
ρ_a	Threshold beacons	6

Figure 3 shows a clear increase in beacon coverage of the network for a longer period of time when using E-STROBE. Also, a 30% increase in the system lifetime was observed, which can be attributed to 'selfish' energy conserving beacon decisions. The 100% and 70% coverage periods of E-STROBE were approximately 50% and 30% longer than STROBE, respectively.

As shown in Figure 4, the peripheral coverage of E-STROBE is very similar to the overall coverage of the beacon network, as opposed to the results with STROBE, which indicate a trend of network contraction. This confirms our belief that the beacon network coverage diameter is not reduced and the network contraction issue with STROBE is handled well by E-STROBE.

Another interesting observation is that the coverage provided by E-STROBE is more stable than that of STROBE. That is, E-STROBE tends to have constant coverage for a longer period of time than STROBE, and then has a rapid decline. This makes it easy for the E-STROBE system provider to guarantee system lifetime. From Figure 5 we observe a reduction of approximately 20% in the number of Active beacons (beacons in *designated* or *voting* state) in E-STROBE when compared to STROBE. This reduction greatly assists the beacons in conserving their energy, which in turn causes a later first beacon death. There are also a greater number of beacons alive (those in *designated*, *voting*, or *sleep* state) at any given time of observation in E-STROBE, as shown in Figure 6.

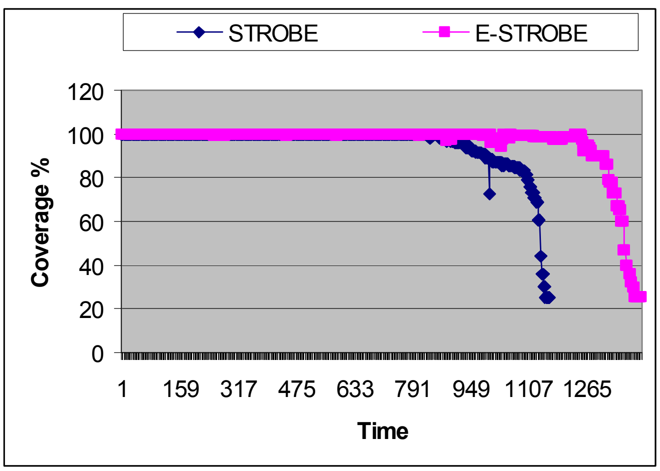

Figure 3. Coverage % vs. Time

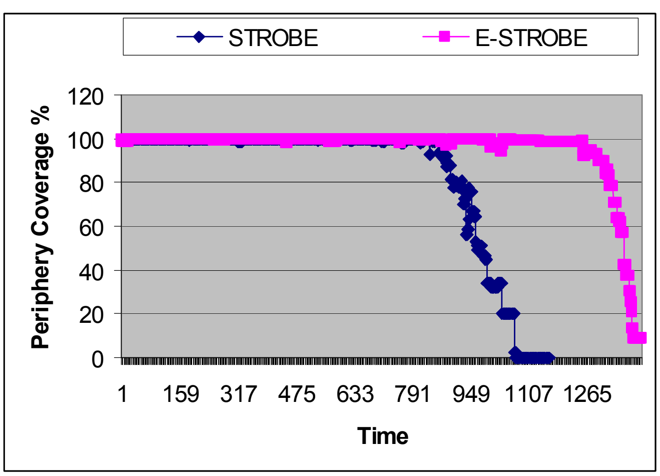

Figure 4. Periphery Coverage % vs. Time

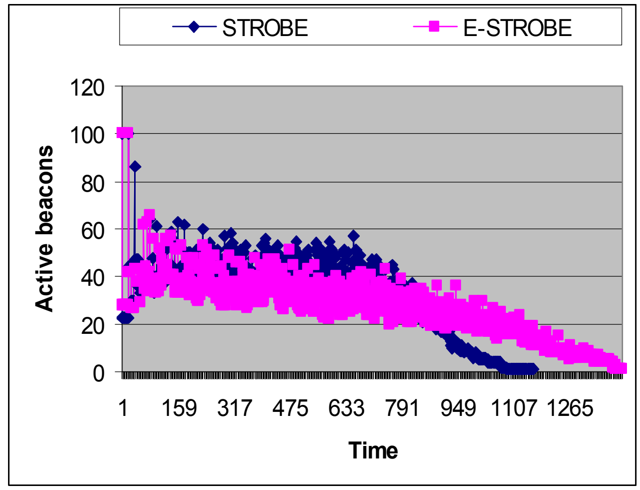

Figure 5. Active Beacons vs. Time

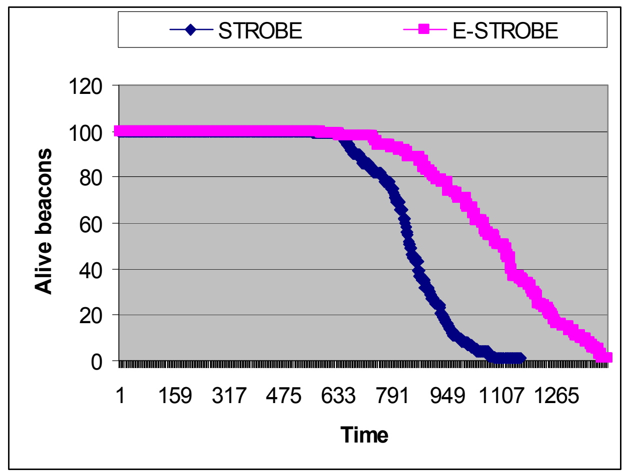

Figure 6. Alive Beacons vs. Time

Finally, in Figure 7 we see that E-STROBE has similar mean localization error as STROBE. During the initial 40% of the system lifetime E-STROBE had about 3% higher mean localization error. This is because fewer beacons are active during this period when using E-STROBE. The small magnitude of the difference indicates some of the beacons activated by the STROBE algorithms were redundant. For the remaining 60% of the system lifetime E-STROBE shows similar localization error pattern. This is because during this period beacons are dying when using STROBE, thus bringing the number of active beacons in the two systems closer in value.

VI. Conclusions

In this paper, we introduced an energy-based metric to enhance the performance of STROBE, an algorithm for dynamically activating beacons in a sensor network with the goal of increasing network lifetime. We quantitatively compared the two algorithms in terms of quality of localization, system lifetime and optimum threshold of active beacons in a given neighborhood.

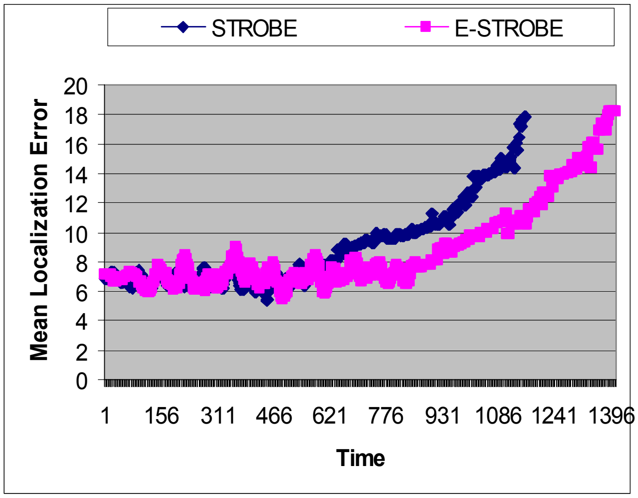

Figure 7. Mean Localization Error vs. Time

The following observations can be drawn:

- Network lifetime was increased by 20-50%;
- The number of redundant beacons active was reduced;
- Network diameter was maintained indicating that periphery nodes were operating more efficiently;
- The beacons in the network remained alive roughly for the same duration, indicating proper load balancing in the distributed system;
- The quality of localization achieved by STROBE is degraded by 3% during the initial 40% of the system lifetime but the mean localization error by STROBE is quite similar to STROBE during the last 60% of the system life.

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