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On demand-driven movement strategy for moving beacons in sensor localization

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ABSTRACT

In wireless sensor networks, estimating sensor location demands a large number of neighbor location references due to the unavoidable wireless signal attenuation problem. However, the cost of deployment increases with the increase in beacon location references. This limitation can be overcome using moving beacons exploiting the control over the number, position, and strength of beacon transmissions. In this scenario, the trade-off between localization cost and accuracy, which are directly linked up with anchor movement and transmission pattern, introduces many challenges that have recently attracted research interest. This paper aims to propose a noise-tolerant and cost-effective range-free localization technique using moving beacons that localize randomly deployed sensor nodes within a maximum localization error bound while minimizing the cost of beacon traversal and transmissions. We found that the mean localization error can be kept within 20–35% of the maximum transmission radius by selecting the movement and beacon transmission parameters according to user demand. The proposed schemes are compared with other works and also shown to be robust against positional errors of the moving beacon.

1. Introduction

Wireless sensor networks (WSNs) are usually deployed in a random fashion throughout a large unattended area to sense data of interest. The sensed data are transmitted, periodically or on-demand basis, to the nearest base station for further processing. Unless the coverage of a WSN is confined to a small area, collecting sensed data without any information on locality makes little sense. Moreover, the location of sensor nodes are required in many network operations, such as geographic routing, topology control that uses location information as a priori knowledge to adjust network connectivity for energy saving, and security service where positional information can be used to prevent malicious attacks. Since it is not economically feasible to equip every sensor with location computing devices such as GPS, the widely used alternative is to use localization process periodically. Some of the nodes called anchor or beacon nodes are equipped with GPS. They transmit their own location information to other nodes in the vicinity. The non-anchor nodes compute their locations based on these received beacon signals using a localization technique.

Localization techniques fundamentally vary in two ways based on whether ranging information is used or not. Range-based techniques try to estimate absolute point to point distance between sender and receiver by using one or more features of the transmitted signal e.g., radio signal strength (RSS), time of arrival (TOA), angle of arrival (AOA), etc. (Mao et al., 2007). The estimated distance is then used to estimate sensor's location by employing geometrical techniques such as triangulation, trilateration, or multilateration or the convex optimization methods. However, some of those suffer from the requirement of high-precision expensive hardware at every node for precise time synchronization. They are also more susceptible to environmental interference (Xiao et al., 2008). Although range-based techniques using RSS is of low additional hardware cost, the reflection and attenuation caused by naturally existing objects may degrade the quality of inferred distance from RSS to unacceptable extent (Zhong and He, 2009). A widely used alternative is range-free technique that avoids estimation of range and instead localize nodes within a bounded area from constraints like anchor proximity or wireless connectivity. Range-free localization schemes require less expensive hardware due to much relaxed precision and synchronization requirements and also are less vulnerable to environmental interference and signal fading (Zhong and He, 2009). The major limitation of range-free approaches is coarse precision of location estimation as they only confine the possible location to the area of intersection of the fixed range of received beacon signals and then approximate all sensor locations within this area by a representative point.

To improve localization quality the number of anchor references needs to be increased, which eventually increases the

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overall hardware cost. Localization quality of both range-based and range-free approaches is also affected by malicious anchor nodes broadcasting false location (Iqbal and Murshed, 2010). These limitations are addressed by using moving beacons (e.g., mobile robots or unmanned vehicles) in Xiao et al. (2008), Caballero et al. (2008), Li et al. (2011), Wu and Chen (2009), Iqbal and Murshed (2011), Galstyan et al. (2004), Huang and Zaruba (2009, 2007), Pathirana et al. (2005), Teng et al. (2009), Kushwaha et al. (2005), Yang et al. (2011), Cui et al. (2011), Boukerche et al. (2008), Chen et al. (2010), Zhang et al. (2009a, b), Priyantha et al. (2005), Kanchi and Wu (2008), Koutsonikolas et al. (2007), Iqbal et al. (2010), Kim and Lee (2007), Xiao et al. (2007), Sichitiu and Ramadurai (2004), and Chen et al. (2010). In these approaches, a beacon periodically broadcasts its position in the vicinity while traversing the area of interest at one or multiple transmission power levels. If a node receives multiple beacons from different positions, it is more or less similar to receiving beacons from multiple anchors only at different times. Since a moving beacon with auto-guided mobility can cover a vast area within a reasonable time, a single beacon in a reasonably small area, or a few beacons in case of very large area are sufficient to deploy. So, the use of moving beacons can ensure a similar localization accuracy to what a large number of static anchors may produce alternatively. Since a small number of moving beacons is sufficient to cover a large area, they can be easily monitored and thus the threat of malicious attacks on localization is assumed to be mitigated.

While using moving beacon, range-based techniques suffer from additional co-linearity problem of beacon transmissions if the trajectory is straight-line based (Wu and Chen, 2009). Considering this problem along with the drawbacks of range-based technique regarding hardware cost and environmental noise, we have used range-free localization scheme in this work.

1.1. Motivation

In many deployment scenarios, localization has to be done at regular time intervals as sensors may be drifted by natural phenomena such as wind, erosion of soil, snow, rainfall or moving human/animal traffic. Being a regular process, localization needs to be cost-effective. In case of moving beacons, the cost is compounded with traverse path length and the number of beacon transmissions. Although the recent trend of research expects faster mobile sensors, the delay of localization and energy consumed by movement of the beacon still remain highly relevant and hence, optimizing the traversed path length is a significant research issue (Xiao et al., 2008). Like any other mechanical device, mobile sensors' expected life time and the wear and tear they suffer are also directly proportional to their traversed path length. Even if a human carries a GPS and acts as beacon, traversed path length remains an important criterion to optimize. The other cost component, i.e., the energy consumed by beacon transmissions, is related to the number and radius of beacon transmission. Specifically, when the path lengths are the same, the transmission energy becomes the major cost component which distinguishes the quality of different localization algorithms.

Another important issue to consider in this context is that the cost of localization should be optimized according to the user demand, which is likely to vary with respect to the application scenarios, e.g., military applications to monitor hidden explosives and environment monitoring schemes have quite different tolerance levels of location estimation error. Whereas high precision demands a high number of beacon transmissions, low precision tolerant applications prefer conservation of energy by reduced movement and transmissions from beacons. The importance of considering an application's accuracy requirement while designing a localization scheme is emphasized in Wang et al. (2010). On-demand localization accuracy can be conveniently ensured while using moving anchors since the beacon transmission number, position and radius can easily be controlled.

The existing works that design path strategy for the moving beacon have one or more of the following limitations:

- Designed movement strategies to optimize the path length only; without considering a composite cost including the number of beacon transmissions.
- The movement parameters such as successive horizontal and vertical transmission intervals and the pattern of transmission positions are not jointly optimized according to the user demand of localization quality.
- In the case of multiple beacon transmissions from each position along the traversed path, the beacon transmission radius, which is proportional to transmission energy consumption, is not optimally determined with respect to the localization quality target.

Considering these limitations, we aim to design a movement strategy in this paper where the user can flexibly configure a beacon's movement parameters and the number or radius of transmissions to achieve a desired localization quality at optimal cost. In a planner region, finding these optimal beacon transmission positions and trajectory is computationally intractable. Therefore, we have designed a heuristic that searches at finite-precision to find the optimal vertical displacement of successive straight-line beacon paths and at the same time the horizontal distance of beacon transmission positions that achieve a desired localization quality. The alternative paths, such as random or circular ones, are found inferior in the literature (Xiao et al., 2008; Wu and Chen, 2009) due to their leaving a wide area uncovered and so these are excluded from our consideration.

1.2. Contribution

While designing a range-free localization scheme that supports a demand-driven movement strategy of the beacon, we have to first formulate a theoretical localization quality estimator considering the random deployment of sensor nodes throughout the region of interest with equal likelihood. Without making any assumption regarding the distribution of distance estimates of the sensors from their beacon position, it is impossible to model the mean localization error in any analytical framework. So, we have derived an estimator of worst-case or maximum localization error to optimize the beacon movement strategy. Worst-case localization error can guarantee the user demanded localization quality. We also show by simulation that this analytical optimization can successfully govern the beacon movement parameters to satisfy mean localization error as well.

To compute the worst-case error incurred by a range-free technique, we need to consider the maximum possible localization error of all the intersecting regions induced by transmitted beacon signals. Estimating maximum possible errors of all intersecting regions of beacon transmissions and also the area of those regions eventually require accurate computation of all intersecting regions defined by arc boundaries. This is also required by multiple coverage or event detection problems in WSN. This challenge is successfully overcome by developing a novel arc-coding technique that constructs polygon of arcs from the intersection of circular beacon signals in $O(n^2 \log n)$ computational complexity. Next, the center of each intersection region that would represent the location of every sensor within that polygon is estimated in such a way that the maximum distance of this center from any sensor within that polygon is the minimum. This scheme is termed as