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Location error estimation in wireless ad hoc networks

Jeremy Gribben *, Azzedine Boukerche

School of Information Technology and Engineering, University of Ottawa, Ottawa, Ontario K1N 6N5, Canada

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ABSTRACT

Many ad hoc network applications rely on nodes having accurate knowledge of their geographic locations. However, inherent in all localization systems is a degree of error in computed positions, which can compromise the accuracy and efficiency of location dependent applications and protocols. We propose a scheme in which nodes estimate the amount of error present in their derived positions with a certain probability. Localization error variance is modeled with a function based on the calculated theoretical lower bound on estimator variance, given by the Cramér–Rao Lower Bound (CRLB). Probabilistic methods then use this variance model to estimate upper bounds on localization error, which are computed locally by wireless devices. Best fits between the model and the actual location error variance using both time of arrival (TOA) and received signal strength (RSS) distance measurements were determined by a least squares estimator over repeated localization simulations. The proposed method was used to accurately estimate location error at given probabilities in a multitude of randomly generated network topologies within ±10% of the actual localization error. Once known, estimates can be integrated into location dependent schemes to improve on their robustness to localization error.

1. Introduction

Wireless ad hoc networks have become increasingly important with the prevalence of wireless sensor networks (WSN) [1] and vehicular ad hoc networks (VANets) [2]. Many applications and protocols associated with these networks require precise location information as a precursor to their functioning, such as data mining in WSN, coverage, and routing. However, there is often a significant amount of positioning error associated with even the best localization systems [3], which can have a significant impact on the accuracy and efficacy of location-dependent applications. In this paper, we provide a means for wireless devices to probabilistically determine the amount of error present in their estimated positions for a given localization system, which can be incorporated into location sensitive applications to improve on their robustness and overall effectiveness.

A typical scenario for WSN consists of randomly deployed sensors collecting data and transmitting it to a base station for analysis [4]. If accurate location information is necessary for the proper interpretation of measured data, then inaccuracies of node positions can lead to false observations. By predicting the degree of localization error, one can assign a lower confidence or even reject sensed events associated with low position accuracy. Another fundamental problem in WSN is coverage, where we want to know if all points in a region are monitored by one or more sensors [5], so that additional sensors can be deployed to inadequately covered areas, or sensors can enter sleep mode to conserve energy in overly covered areas [6]. Most of these schemes assume that precise location information is available for calculation of coverage. However, in the presence of location errors, additional coverage holes or overly redundant sensor deployment can occur. With estimates on the amount of localization error, overly covered or under covered regions can be avoided. Location information

* Corresponding author. Tel.: +1 6139838360.
E-mail addresses: jgrib080@uottawa.ca (J. Gribben), boukerch@site.uottawa.ca (A. Boukerche).

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is also useful for geographic routing [7], where data is routed based on geographic locations instead of network addresses. With location error estimation, nodes with larger position errors can be less used to avoid potentially inefficient paths. Location verification in secure localization schemes is another area of open research which aims to differentiate between errors due to malicious nodes, and error inherent to the localization system itself [8–10], the latter of which can be characterized by a suitable error estimation method. Finally, target tracking of mobile devices through an area using range and position information from other deployed nodes can involve very different levels of localization error depending on the available information in a given region [11]. Determining the amount of error in location estimates could thus help to guide decisions of mobile devices. For example, vehicles in a VANET would only have semi-automated driving and collision avoidance functionality available when highly accurate location information is available.

Localization systems aim to determine the physical locations (coordinates) of all nodes in a network [3]. Most systems require a fraction of the nodes, called beacons or anchors, to know their positions *a priori* [12–15]. Other systems do not have such a requirement, but instead employ a relative coordinate system [16]. In the Global Position System (GPS) and Cricket location-support system [17] unlocalized nodes are a single communication hop away from beacons nodes, while in the Ad Hoc Positioning System (APS) and its variants [13–15,18] beacons can be multiple hops away. Computation of positions can either be distributed throughout the network, or computed centrally [19–23]. This paper focuses on multihop distributed localization systems such APS; however, regardless of the system used localization errors can be 10–20 m or more [3,13,24], necessitating the ability to detect poorly localized nodes.

There are two key contributions which this paper makes to the localization problem in wireless ad hoc networks. First, we propose a model for location error variance in localization systems which wireless devices can use to estimate their true location error. The model is based on the fact that localization error variance behaves similarly to the theoretical lower bound on the variance of location estimators, given by the CRLB. The CRLB is easily computed locally, and is used in the location error variance model along with the number of available beacon nodes. The second contribution of this paper is a scheme for nodes to determine the amount of error in their position estimates with a given probability, p, where p is an input thresholding parameter to the system. The scheme uses the proposed model of error variance and the cumulative distribution function (cdf) of localization error to probabilistically determine the amount of error in nodes' location estimates. Once known, nodes can compensate for this error in future applications which rely on location information.

The remainder of this paper is organized as follows. Section 2 briefly describes the related work. Section 3 formally describes the problem under investigation. Section 4 discusses the proposed algorithm for error estimation. Section 5 presents simulation results for our scheme. Finally, the paper is concluded in Section 6.

2. Related work

Localization in wireless ad hoc networks is a problem which has received a great deal of attention due to the importance of obtaining reliable position information. Open access services such as the Global Positioning System (GPS) are often unfeasible in these networks due to cost, energy usage, imprecision, and unavailability [25]. A number of shorter-range single-hop localization systems have been proposed to deal with some of these issues [12,17,26]. When reference nodes are not within radio range of unknown nodes, multi-hop localization techniques must be used. The Ad Hoc Positioning System (APS) [13] extends the concept of GPS in WSN by broadcasting beacon positions over multiple hops, where the number of hops and average hop size are calculated to allow estimation of the distances to beacon nodes without requiring direct communication. APS has been extended by numerous schemes to include an iterative refinement phase [14,15,18], where after obtaining initial position estimates from APS, nodes exchange position estimates with their one-hop neighbors, and treat these neighbors as intermediary reference devices. Nodes continually update their positions using the new positions of one's neighbors, until each device eventually converges on a solution. For a complete review of wireless localization schemes we refer the reader to the many recent surveys available [3,27–29].

Much effort has been devoted to the theoretical analysis of localization error and its potential applications. First and foremost, analysis techniques are required to evaluate the performance of localization systems as compared to theoretical limits. The Geometric Dilution of Precision (GDOP) [30] is a widely used metric by the GPS community to quantify the difficulty of specific geometries for localization, by essentially relating position accuracy to measurement accuracy. The CRLB provides a lower bound on the variance of unbiased estimators [31], and was derived for single-hop RSS and TOA location estimators [32]. The CRLB was derived for DV-Hop based localization systems [33], and for general multi-hop localization systems using noisy range or angle measurements [34]. The position error bound (PEB) was derived by Jourdan et al. [35], which is based on the CRLB for ultra-wideband (UWB) systems and takes into account biases on range measurements found in cluttered environments. Furthermore, the concept of ϵ-localization accuracy outage was proposed which gives an indication of the PEB that can be expected with probability ϵ as we move through an area [35]. A performance measure called the squared position error bound (SPEB) was derived by Shen and Win [36] which quantifies the limits of wideband localization in the presence of non-line-of-sight (NLOS) and multipath propagation, by analyzing the received waveforms themselves rather than the signal metrics such as TOA or RSS.

A number of localization analysis techniques not based on information theory have been researched. Localizability testing aims to determine how many and which nodes in an arbitrary network can be successfully localized, and can be tested with triangulation [37], or more recently by nodes evaluating membership with ones neighbors in