

Localization for Wireless Sensor Networks: Protocols and Perspectives

Michele Battelli and Stefano Basagni
Department of Electrical and Computer Engineering
Northeastern University
Boston, MA
Email: {battelli,basagni}@ece.neu.edu

Abstract—This paper briefly reviews the wide variety of methods proposed for localizing wireless sensor nodes. We describe the major recent solutions where sensor nodes may use *beacons* (devices that know their location and can broadcast it) or not, and ranging measurements or not. Our discussion presents pros and cons of using different information or devices, and ends up with describing where research in this field is going.

I. INTRODUCTION

Making network nodes aware of their physical location has been a problem widely investigated in recent years, especially in wireless networks where nodes are deployed “ad hoc.” Wireless sensor networks (WSNs) [1] are an example of such networks, where energy-constrained nodes are deployed in large scale for monitoring functions, surveillance, remote health-care, and other emerging applications. Nodes communicate wirelessly, and have to deliver their sensed data to some data collection points often in a multi-hop fashion.

Localizing a node with respect to a suitable reference system is of the essence for all those emerging applications that are location aware. This includes protocols for “geo-routing,” which have been recently demonstrated effective for energy-efficient and scalable data dissemination in WSNs. Whenever well-established systems such as the Global Positioning Systems (GPS) are not viable, localizing network nodes becomes quite a challenge.

This paper briefly reviews the wide variety of methods proposed for localizing sensor nodes. We present a taxonomy of localization protocols based on the availability of information (e.g., measurements of the distance between two nodes, and/or of the angle of arrival, AoA, of the wireless signal), and on the presence of a network infrastructure (whether “beacons” or “anchor” nodes are available or not). In particular, Section II lists the methods for localization that distinguish between having some infrastructure to aid the process or not. The following Section III explore instead the larger collection of protocols that are based on the availability of ranging information (or lack thereof).

We conclude the paper with some considerations on where research on localization is going based on what found on a collection of papers published very recently on this topic.

II. BEACON-FREE AND BEACON-BASED SOLUTIONS

A possible classification of localization algorithms is based on the type of *beacons* that are in the system [2], [3]. A beacon is a “more powerful” network node that is part of an infrastructure available to assist the nodes in the localization process. Algorithms within this classification can be partitioned in beacon-free, with static beacons or with mobile beacons.

Beacon-free solutions include the following. Doherty et al. [4] propose an algorithm in which the network is modeled as a system of equations representing proximity constraints between nodes and a central location (the beacon). The system is then solved by mean of optimization techniques. In [5] the authors suggest a GPS-free and infrastructure-free solution that simply exploits range measurements between nodes in order to determine the final coordinate system representing the network deployment. A beacon-less localization scheme is described in [6]. Instead of beacon information, the proposed scheme exploits knowledge of the network deployment in order to derive nodes location.

Beacon-based solutions are commonly organized as follows. Beacon nodes are aware of their position through GPS or via manual set up. *Unknown* nodes, i.e., the sensor nodes that needs localization, use ranging or proximity information from the beacons in order to estimate their location by mean of a localization scheme. In general, a node needs to receive information from at least three beacons to be able to infer its position in a bidimensional plane. Certain localization schemes increase the number of beacon nodes simply by promoting unknown nodes that estimated their location to beacon nodes. This technique allows nodes to localize even in regions with low beacon density. However, it introduces the problem of error propagation through the localization process. The advantage of static beacon schemes is to keep the hardware at sensor nodes relatively simple and therefore reduce energy consumption at the nodes. (Since static beacon-based schemes are part of the classification based on the use of range or not references to this type of solutions are given in the following section.)

Most of the localization algorithms proposed in literature make use of static beacon nodes to assist the node localization process. Different approaches have been proposed in which

mobile beacons improve location information available at the sensor nodes. The use of mobile beacons can significantly reduce the deployment cost because the number of beacon nodes necessary to assist the localization process can be dramatically reduced—eventually to a single mobile beacon that visits all the sensor nodes. A mobile beacon based Bayesian approach to localizing network nodes has been proposed in [7]. In this scheme a single mobile beacon traverses the network while broadcasting information containing its current location. Sensor nodes collect the beacon packets and measure distance information by mean of Received Signal Strength Indicator (RSSI). When the number of received beacon packets is considered satisfactory, a Bayesian inference is used to estimate the node position. Sinath [8] also investigated the possibility of a single beacon (equipped with GPS) traveling the network and broadcasting its current coordinates. The mobile beacon acts like several virtual beacons assisting sensor nodes in the localization process. Nodes that estimated their coordinates help neighboring nodes using an n-ranging technique adopted from [9]. A similar solution has been suggested by Taylor et al. in [10]. The authors proposed *LaSLAT*, a Simultaneous Localization And Tracking algorithm in which target and beacons move across the network while sensors estimate their own location and track the target by mean of Bayesian filtering. Their system is based on acoustic measurements of the range between nodes and beacons. Previously, the integration of sensor nodes localization with an application task such as target tracking has been investigated in [11]. The authors suggest to exploit connectivity constraints derived by the localization process jointly with sensing constraints from target tracking in order to improve localization accuracy. The AllteRrain Advanced NeTwork of Ubiquitous mobiLe Asynchronous Systems (*TARANTULAS*) [12] is a further example of mobility-assisted localization. In *TARANTULAS* sensor nodes and mobile robots carrying sensor and actuators cooperate in order to improve each others tasks. Robots enhance connectivity and localization by moving into low density areas and building communications links while sensors nodes provide assistance to robot for target tracking. A solution for wireless image sensor networks has been investigated in [13]. The proposed technique is based on visual observations of a mobile target and subsequent in-node image processing that produces a system of equations containing sensor nodes position and angle of orientation as unknown parameters. The authors suggest three techniques to solve the system of equations based on the space of data matrix or least squares. Mobile beacons has also been employed jointly to Ultra-Wide Band (UWB) in [14] where a mobility-assisted secure localization scheme (*SLS*) is proposed. In *SLS* a set of mobile beacons move across the sensor field on predefined routes and help sensor nodes in the positioning process. Most of the techniques with mobile beacons need to define a priori the beacons path. Koutsonikolas et al. highlighted the need for path planning of robots and mobile beacons in [15]. Literature shows that mobility of beacon or targets can be exploited to improve the localization of sensor nodes and mutually aid in the target

tracking process.

III. RANGE-FREE AND RANGE-BASED SOLUTIONS

Algorithms belonging to the category of range-free protocols do not rely on range or angle information to calculate nodes position. These solutions aim at keeping the hardware at the sensor nodes as simple as possible. In order to gather information about their position, nodes are assisted by special network devices called beacons (or anchors or landmarks) capable of providing accurate information about their own positions (either via GPS or manual setting). Several solutions have been proposed in literature and can be classified as centroid-like [16]–[19], hop-count (like DV-hop [20] or the work in [21], [22]), and area-based algorithms [23], [24]. In proximity based solutions beacons transmit their position periodically. Nodes with unknown position collect beacons information and estimate their coordinates by calculating the centroid of beacons locations [16]. Other solutions attempt to estimate the average hop-length and calculate nodes position by counting the number of hops from the beacons [20], [25] or intersecting areas of possible presence of the node [26]. In general, range-free solutions result in a coarse positioning of the nodes and require a high exchange of messages between nodes which increase the cost of the solution in terms of power. The accuracy of range-free localization is quite poor, and the localization error often exceeds the nodal transmission range.

Range-based localization schemes rely on the availability of ranging and/or angle information at the nodes. Sensor nodes are equipped with extra hardware capable of measuring distance or angle by mean of techniques such as Time of Arrival (ToA), Time Difference of Arrival (TDoA), Angle of Arrival (AoA) or the Received Signal Strength Indicator (RSSI).

Schemes using RSSI to estimate distance between nodes have to deal with problems caused by large variances in reading, multi-path fading, irregular signal propagation patterns and background interference. Early solutions based on RSSI measurements are proposed in [27], where the authors present *RADAR* an RF-based technique for indoor localization. Other solutions can be found in [28] (*SpotON*) and [29]. *DV-Distance* [20] is a solution similar to *DV-Hop* that uses RSSI to measure distances between sensor nodes. This algorithm reaches better accuracy with respect to *DV-Hop* but it is more sensitive to measurement errors since RSSI techniques are error prone to multi-path, interferences and other environmental characteristics of the transmission channel. A second alternative to *DV-Hop* is presented by the authors in the same work: *DV-Euclidean* utilizes distance calculated by node that have at least two distance measurements from a node that has estimates of the distance from a landmark. Simulations performed by the authors show that the two range-based solutions perform worst because of the error due to distance measurements and error propagation through the localization process. Attempts to improve RSSI-based techniques have proposed in [30] and in [25]. *Hop-TERRAIN* [25] is a distributed localization algorithms consisting of two phases. In a

first phase the hop-count technique produces an approximate estimate of nodes coordinates. Subsequently, a second phase of refinement applies an iterative multilateration in order to produce a more accurate positioning. Since not all the nodes have access to beacon information nodes that have established their coordinates are promoted to beacon nodes and contribute to the localization process of neighbor nodes with unknown position. This process leads to accumulation of localization errors because the inaccurate position estimates of the nodes promoted to beacons will contribute to the localization of downstream nodes increasing their localization error. Finally, Fretzagias and Papadopoulou [31] presented a voting algorithm in which nodes try to determine their position on a grid-based representation of the terrain.

The typical solution that uses TDoA is the MIT Cricket system [32], [33], which requires the use of RF and ultrasounds for TDoA estimation. Similar solutions have been proposed in [34]–[36]. *AHLoS* (Ad-Hoc Localization System) [34] is a TDoA based solution that allows to estimate distances by measuring the Time Difference of Arrival between RF and ultrasound signals leading to a better estimation of the distance between source and destination compared with RSSI method.

Another promising range-based technique for localization is based in measuring the angle of arrival (AoA) of an RF signal rather than the distance between two nodes. Although the AoA can be effectively measured via arrays of antennas, steerable antennas or acoustically (arrays of microphones), there are no solutions that easily apply to resource constrained sensor nodes. An example of localization algorithm using AoA is APS [37], which is similar to *DV-Hop*. The angle measurements are here used to improve the accuracy of the nodes position estimation.

Recently, we have proposed an algorithm that couples range measurements and angle of arrival in order to obtain increased localization accuracy [38]. We start by describing a localization protocol, termed Range-Based Centroid (RBC), that starting from a single node (the beacon) with given coordinates localizes all the network nodes accuracy which is typical of methods based on the sole measurement of range. We then propose a new localization protocol that achieves greater accuracy by containing the propagation of the localization error as the process progresses away from the beacon. We quantify the improvements of the proposed protocol, termed MEC² (for *Minimum Enclosing Circle Containment*) by simulations. We observe that MEC² keeps the localization error within 21% of the nodes' transmission radius, with 20–30% improvements over RBC, and in general over common localization methods. We observe that combining range and angle of arrival produces better localization without requiring a higher number of beacons or extra hardware. The MEC² solution, for instance, achieved accuracy which is acceptable for most geo routing and location aware applications with just one beacon and using ranging as obtained from RSSI (which is available in all wireless sensor platform/OSs).

IV. PERSPECTIVES

Based on what has been published recently we are able to observe where most of the interests and the research have gone in the field of WSN localization.

Although initial solutions for localization were centralized (i.e., node coordinates were computed by a centralized entity after having collected pertinent information), given the needs and nature of WSNs, the vast majority of localization protocols were distributed: Basically 4 papers out of 5, recently, presented distributed algorithms.

There has been an increasing interest in using mobility to aid localization. However, mobility in WSNs is still largely uncharted territory, and this is reflected also in the field of WSN localization. Only 20% of the papers we found published in 2006 were proposing to exploit mobility to localize nodes.

Finally, a more composite picture emerges when we consider the different ranging techniques (or their absence) that are used for localization. The relative majority of papers still present algorithms for localization where it is assumed that the needed measurements are provided “in some way.” In other words, there is no specific indication on how to obtain AoA or the distance among network nodes. Still there are papers where range-free protocols are proposed. The use of ToA/TDoA account for a fifth of the methods we found: The use of these techniques is advocated because of their greater precision. More recently, for networks where nodal energy is not much of a restriction, vision-based technique are proposed in quite a number of papers (10%). RSSI and AoA (rarely their combination) finally account for the remaining 20% of the papers on this topic.

V. CONCLUSIONS

Localization for wireless networks, and especially for WSNs, has been and still is quite a vital area of research. The most recent trends show that combining simple techniques such as RSSI that are made available by most platforms for wireless sensor nodes as well as AoA measurements starts to produce results whose accuracy satisfies the requirements of most applications and geo-routing algorithms. This is also confirmed by experiments on testbeds that are more and more built to confirm what seen by simulations.

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