Localization in Wireless Sensor Networks

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Abstract—Localization of nodes in wireless sensor networks (WSNs) is important to many applications. Data are generally meaningless without location information; knowing the location of a node is a common goal in WSN applications. In this paper we study the possibilities of localization in WSNs, based on RSS measurements. We first studied the properties and methods of localization in general, followed by properties and algorithms specific to WSNs. We restricted our research to algorithms which use radio frequency received signal strength as a ranging method. Our study finds that no single best algorithm for localization exists to date. Each algorithm has a different purpose and properties. Learning from these algorithms and techniques, a more advanced localization system is feasible.

Index Terms—Wireless Sensor Network, WSN, RSSI, localization, TelosB, TinyOS.

1 INTRODUCTION

Wireless sensor networks (WSNs) are a set of small autonomous systems, called sensor nodes, which cooperate to solve at least one common application [1]. Their tasks include some kind of sensing of physical phenomena. These nodes are cheap, smart and communicate in short distances through wireless links. They are deployed in great numbers for monitoring and controlling the environment.

Localization is very important to mobile computing applications because we want to know where things are. Location information is or will be indispensable for many applications as time information is now. For example, biologists studied endangered redwood trees for two months using 50 motes measuring: light, temperature and humidity [2]. Citation The obtained data is meaningless without knowing where the data were collected. There are many other situations where localization can be used such as logistics, health monitoring, military surveillance, habitat monitoring and security.

We also want to localize items in real time. Real Time Locating Systems (RTLS) are electronic systems that are intended to locate small electronic devices on people or things at any time [3]. The popularity of RTLS is increasing because it has become affordable, and mobile devices are small and convenient.

Many algorithms exist to find the location of an item or person in WSNs. We narrow these algorithms down to the ones that are based on Reduced Signal Strength Indication (RSSI). RSSI is a standard feature in most radios, which means that there is no need for additional hardware.

The rest of the paper will be organized as follows: section 1 describes the general properties of localization systems; while section 2 explains different positioning techniques in general. These two sections provide the necessary background and introduce the reader to localization. Section 3 describes concepts and properties which are unique to localization for WSNs. Section 4 gives information about RSSI and explains why it is a difficult but useful ranging method. Finally, section 5 summarizes algorithms relevant to WSN localization using RSSI as a ranging technique.

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2 PROPERTIES

Location systems generally have properties which are independent of the technologies or techniques that they use [4].

2.1 Absolute versus relative reference of location information

Location can have an absolute reference or a relative reference:

- An absolute reference system has a shared reference grid for all objects that need to be located. For example, the Global Positioning System (GPS) uses an absolute reference, so all GPS receivers will show the same place for a given coordinate [5].
- A relative reference system can have its own reference grid for all objects. Thus, in this system each object can use different coordinate systems or refer to the coordinates of another object.

2.2 Localized versus centralized computing

Systems like GPS can calculate the position on the device itself. The advantage of localized position computing is that the user is able to maintain his privacy and there is no need to make a connection with a centralized computing power. You do, however, need sufficient resources to calculate the position. Centralized computing is mostly used by systems which require an object to update his coordinates so that an external source can calculate the position. For example, Ekahau [6] uses centralized computing for locating objects in the Wi-Fi network.

2.3 Accuracy and precision

Accuracy is the distance of the calculated position to its actual position. Precision denotes how often that accuracy occurs. For example, a basic GPS receiver can locate an object with an accuracy of 10 meters for 95

2.4 Scale

With regard to the scale of a location system, we need to consider its coverage area per unit of infrastructure, as well as the number of objects that the system can locate per unit of infrastructure per time interval. The time interval needs to be adapted to the available bandwidth; for example, in WSNs the bandwidth is limited and can end up congested if chosen too highly.

2.5 Recognition

The location system needs to recognize the objects that it is tracking. This is useful when you want to classify objects to make location based actions. This is usually done with a globally unique ID (GUID). The object usually sends his ID simultaneously with his location information.

2.6 cost

The cost of a location system is based on:

- Time cost: time it takes to install and manage the system
- Space cost: amount of infrastructure that needs to be installed, hardware etc.
- Other costs: licence, the prices per mobile unit, infrastructure etc.

3 POSITIONING TECHNIQUES

There are many techniques for finding the location of an object; we can divide these into 4 major groups: triangulation, proximity, scene analysis and sensor localization [7].

3.1 Triangulation

This is the process by which the location of a mobile radio transmitter is calculated, using the measurements of radial distance, or the direction, of the received signal of multiple known reference points. The intersection shows the location of the mobile radio.

3.1.1 Lateration

We use the distance between the mobile radio and the reference points to calculate the position of the mobile object. Working in two dimensions, we need the distance measurements from three non-collinear reference points (i.e. points that do not all lie on a single line). In 3D we need measurements from 4 non-coplanar points (i.e. points that are not all in present in one plane). Distance measurements can be obtained with time-of-flight or attenuation:

3.1.1.1 Time of flight: We measure the time that it takes for a signal to propagate from its radio to one of the reference points at a known velocity. We translate this time in distance. The disadvantage of this technique is obtaining accurate time information: multipath signals create false data. There are different ways to obtain the time:

- Time of Arrival (ToA): we transmit a packet with a timestamp to one of the reference points and check when it arrives. The problem with this technique is that the clocks need to be synchronized with each other [8].
- Time Difference of Arrival (TDoA): this is a solution for ToA, because it is difficult to sychronize all the clocks. We only need to synchronize the clocks of the reference points. The mobile radio transmits a signal to the different reference points and records the timestamps when they have received it. The differences between these timestamps are combined to produce intersecting hyperbolic lines to find an estimation of the location.
- Round Trip Time (RTT): the mobile radio transmits a packet to a reference point and directly sends it back. The mobile radio records the time it takes to get the packet back. The problem with this technique is that you do not know how it takes for the reference point to process and transmit the packet.

3.1.1.2 Attenuation: Received Signal Strength Indicator (RSSI) gets weaker if it is moved further from the emitting source. The decrease relative to the original signal strength is the attenuation. When there are several obstructions in the area that is being monitored, then the attenuation is usually less accurate than time-of-flight.

3.1.2 Angle of Arrival (AOA)

AOA uses angle measurements instead of distance measurements to locate a mobile radio. It is defined as the angle between the direction of the propagation of an incident wave and some reference direction [9]. We obtain AOA measurements by using an antenna array on each sensor node. Phase antenna arrays can be used for this technique. Multiple antennas, which are separated with a known distance, measure the time of arrival of a signal. Next, we calculate the difference between these arrival times and use the geometry of the receiving array to find the angle where the signal originates from. In 2D we need two angle measurements and one length measurement; this is the distance between the reference points. In 3D we need two angle measurements, one length measurement and one azimuth measurement (this is the angle between the reference plane and a point). The accuracy is limited by the direction of the antenna, by shadowing and by multipath reflections.

3.2 Proximity

The location of a mobile radio is determined by checking if it is close to a known reference point. This can easily be done by means of physical contact (pushbuttons, sensors) and access points: check if it is in range of a certain access point.

3.3 Scene analysis

The environment is analyzed to determine the location of an object. Certain features which are present in the scene are used to find the location of the observer or of the objects that need to be located in the scene. This can be further classified into two techniques;

3.3.1 Image analysis

A camera observes a certain scene. With the help of known objects in the scene, we can compute the position relative to the objects.

3.3.2 Fingerprinting

Basically, we create a map based on radio signals. In the first phase (offline-phase) we measure RSSI on different points on our map and store them in a database. The second phase (real-time phase) measures the RSSI of a mobile node and compares it to reference points on the map constructed during the first phase to determine the location of the mobile node. The problem with this technique is that the RF pattern can change in the environment, which means that the r̈adio mapïs not up to date anymore and your accuracy will thus drop dramatically.

3.4 Sensor localization

This technique uses the sensor data to localize an object. This technique contrasts sharply with other techniques which use pair-wise measurements between nodes, for example, an RSSI reading. [10] demonstrate the use of sensor localization by pointing a laser at nodes equipped with a photo detector. When the laser points at a node, the node signals the central processor, which in turn can determine the node's location based on the rotation of the laser.

4 LOCALIZATION IN WIRELESS SENSOR NETWORKS

A plethora of literature exists on location estimators in WSNs. Whilst, there are many similarities with more general localization platforms, WSNs have some unique properties which must be considered in the design of a location estimator. One of the major properties of WSNs is their energy constraint. A WSN node typically operates on batteries; its lifespan is thus determined by its remaining battery power. Recent advances in IC technology have made the microcontrollers much smaller and requiring less power. If Moore's law holds true, the power consumption of the logic will continue to decline when the performance requirements stay the same. The radio, however, will continue consume about the same level of power. New modulation schemes and better antennas may be devised; however, they will not keep up with advances in IC technology. We can thus conclude that the radio will consume most of the node's battery power. Any networked application must thus seek to minimize all radio communication. A good example of this observation is the rising interest in data aggregation techniques [11][12]. Second, considering the low cost of a WSN node, there should be as little specialized hardware as possible. For this reason, RSSI-based localization is very interesting. It may not be the most accurate, but does not require any specialized hardware that TOA, ultrasound and many other techniques do. Another thing that evolves from this observation is that the amount of reference nodes should be limited. A reference requires either additional hardware such as a GPS receiver or for the network administrator to map the position of the node. This increases the costly deployment of the network. Given the sparse amount of reference nodes, blind nodes should be able to locate themselves solely with the help of other blind nodes. An implementation of such a system is given in [13]. This may, however, propagate localization errors. Third, the density of WSNs is another factor that should be accounted. A WSN can consist of several thousand nodes, all placed in a relatively small area. [14] and others argue that the localization error declines when the number of nodes in a network increase. Many existing localization algorithms iterate over many ranging measurements from different nodes, thereby improving the localization. It is also widely noted that RSSI errors scale linearly with distance. Thereby we can profit from the density of WSNs. Finally, in WSNs, there is a bigger emphasis on distributed localization algorithms. This is due to the fact that individual nodes and links between nodes are more prone to failure than in a traditional computing environment. Batteries may be depleted and radio links can be obscured. For example, consider the case where a WSN is to assist firefighters in finding an asset in a burning home. If the node where centralized processing occurs fails, due to the fire, the whole localization system fails. It is clear that a distributed algorithm has its benefits. [rabbat2004dos] compares the energy-efficiency of centralized and distributed systems. Generally, when the average number of hops to the central processor needed by a centralized algorithm exceeds the number of iterations in a distributed algorithm, then the latter will save energy.

5 RSSI RANGING

5.1 What is RSSI?

Radio signals attenuate with distance. We make use of this property to estimate the position of wireless sensor nodes with low-power IEEE 802.14.5 radios. These radios have Radio Signal Strength Indicator (RSSI) as a standard feature, so we can use the same radio hardware for communication and localization. This makes RSSI very interesting because there is no need for additional hardware.

5.2 Major Problems

RSSI suffers from many destructive effects which make it less accurate:

- Multipath: this is a propagation phenomenon where the radio frequency (RF) signals reach the receiving antenna by two or more paths. On their way, the RF signal encounter objects that reflect, refract, diffract or interfere with the signal. With RSSI the effects of multipath act as destructive interference: the signal experiences differences in attenuation, delay and phase shift.
- Shadowing of the RF signal: the signal fails to propagate, due to obstructions or disruption of the waves.
- Transmitter variability: when different transmitters are configured in exactly the same way, they can still behave differently. So, if a transmitter is configured to transmit data at a power level of ? dBm, it will transmit it at a power level close to ? dBm. This leads to inaccurate location estimation.
- Receiver variability: the sensitivity of different radios is different.
- Antenna orientation: RSSI varies as the antenna orientation of the transmitter or receiver is changed. Each antenna has a non-uniform radiation pattern.
- Atmospheric condition: Transmitted samples of the same transmit power have a small standard deviation, due to atmospheric conditions.

These errors can be divided into two categories, environmental errors and device errors. Environmental errors are due to the wireless channel; these include multipath, shadowing effects and interference from other radio sources. Device errors are generally calibration errors. The most important consideration here is to keep the transmitted power constant, despite inter-device differences and depleting batteries. Environmental errors can also be divided into two parts: Rapid time vary errors and static environment dependant errors. The first are due to movement of people, additive noise and interference. This can mostly be modeled as Gaussian noise. As a result, this can be reduced considerably by averaging multiple RSSI measurements [15]. The second type of error is due to the varying properties of the environment, such as multipath and shadowing. Since the layout of the environment, and the placement of doors and furniture cannot be known without prior knowledge, this error should be modeled as random. The previous paragraph considered environmental errors, but many other factors need to be accounted for as well. These are mostly calibration errors of the radios themselves. The orientation of the antenna should be considered, as well as differences between nodes of the same kind. A solution proposed in [14] is to use only the differences in received power between two nodes, thereby ruling out the differences in transmission power. The relation between battery voltage and transmitted radio power needs to be looked into as well. To make an accurate localization system based on RSSI, the wireless channel properties and these other degrading effects must be modeled as accurately as possible. All these factors seem to give RSSI measurements a large random factor, thus making it very unpredictable.

6 Localization algoritms

As stated above, a great deal of literature exists about this topic. If we rule out fingerprinting and proximity algorithms, the topic becomes much more manageable. Since fingerprinting and proximity algorithms differ quite a bit from trilateration algorithms, this is not an issue. Still, explaining every algorithm is a huge task and falls out of the scope. Instead, an overview of the algorithms will be given. All algorithms are either distributed or centralized, whereby centralized algorithms are usually computationally more complex. The algorithms can also be classified as one-hop or multihop. In one-hop algorithms, each blind node needs to be in direct range of a reference node. The blind node can then perform classic trilateration. However, when a blind node is not in range of three reference nodes, another method is required to determine its position. The conventional approach is to use multihop ranging, where blind nodes of which the position is determined are also used. A problem with this approach is that positioning errors may propagate.

6.1 Centralized

Centralized algorithms are focused on achieving the highest accuracy possible. A mathematical tool for calculating the lowest variance and thus the highest accuracy possible given a ranging technique is the Cramr Rao Bound [16]. When an algorithm is close to this lower bound, there is no point in improving the algorithm further. The MLE [17] and dwMDS [18] proposed by Patwari et al. achieve a very high accuracy of one to two meters. Given a high SNR, these algorithms can approach the CRB. However, they lack the advantages of distributed algorithms. [19] confirms that the ML algorithm has better performance than other centralized algorithms.

6.2 Distributed

A large amount of distributed algorithms exist at this date [20], [21], [22], [23], [24], [25]; however, they are all optimized for different purposes [26]. The algorithms can be divided into three basic steps:

1) Determine the distances between individual nodes
2) Derive a position using the reference nodes
3) Refine these positions through iteration.

Nodes that are not in the neighborhood use the newly located blind node's positions to determine their own position. [26], [?], [27], [28], [25], [29] compare different algorithms.

7 Future work

Most of these algorithms based on RSSI are built for specific needs; for example, the MLE algorithm is very accurate, but very computationally intensive and is not optimized to be a distributed algorithm. Each algorithm makes trade-offs to suit its desired application. It should be interesting to combine the advantages of several algorithms. The behavior of each node platform needs to be examined as well, so that they can be calibrated optimally.

8 Conclusion

Localization in WSNs is an essential service and is important to many applications. Given the large scale, low cost and varying conditions, using a GPS for every node is not feasible. Since each node has a radio, RSSI is a very practical method compared to ultrasound, TOA techniques which require extra hardware. The summarized algorithms provide an accuracy that should be enough for a variety of applications. Other algorithms are very robust and scalable, and are meaningful in a variety of scenarios where accuracy is not the sole important metric.

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