Study of RSS-Based Localisation Methods in Wireless Sensor Networks

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Abstract

Localisation of nodes in wireless sensor networks (WSNs) is important to context-aware and position-dependent applications. Many algorithms exist for localising nodes using received signal strength. In this paper, we present a quantitative comparison of algorithms which use RSS as a ranging method and present a localisation software framework called Senseless. We conducted a survey about the influence of the orientation of a node. Our study finds that the received power is not equal in all directions and that no single best algorithm for localisation exists to date. Each algorithm has a different purpose and diverse properties. The optimal algorithm can be chosen for each environment. In our environment, MinMax is the current algorithm of choice. Using this framework, we implemented several centralised algorithms: Trilateration, Min-Max, Centroid Localisation and Weighted Centroid Localisation.
Keywords: *Wireless Sensor Network, received signal strength, localisation*

1 Introduction

A formal definition of Wireless Sensor Networks (WSN) is given in [1]. The purpose of a WSN is to monitor some physical phenomenon such as the ambient temperature, air humidity, and the presence or absence of a certain chemical agents. Usually, these data are collected at a common point, the data sink, where the data can be further processed or analysed by the user. WSNs enable a great deal of new applications including environmental and habitat monitoring, smart homes and battlefield control. Accurate and low-cost sensor localisation is an essential service and is important to many of these applications. The measured data is generally meaningless without knowing where it originated from.

Localisation techniques which are specific for WSNs are based on pair-wise measurements between nodes to estimate the positions. A small number of WSN nodes will need a priori knowledge about their location. These nodes are called anchor nodes (AN). The other kind of nodes, without a known position, are called blind nodes (BN). Thus, the goal of a localisation system is to determine the position of the blind nodes by communicating with the anchor nodes. We can divide these techniques into two categories: range-based and connectivity-based. Range-based methods estimate the distance between nodes with ranging method such as Time of Arrival (ToA), Angle of Arrival (AoA) and Received Signal Strength (RSS). These techniques typically provide better accuracy but are more complex. Connectivity-based algorithms do not estimate the distance between nodes but determine the position of a blind node by their proximity to anchor nodes [2].

Although many ranging techniques exist, in this paper we have narrowed them down to RSS-based ranging. RSS-based ranging is founded on the principle that RSS attenuates with distance due to free-space losses and other factors. RSS is generally considered as a bad method because of its high variability due to interference, multipath and shading. Errors can be divided into two categories, environmental 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 caused by inter-device differences and depleting batteries. Environmental errors can also be divided into two parts: rapid time varying errors and static environment dependent errors. The first is due to movement of people and objects, additive noise and interference. This can mostly be modeled as Gaussian noise. As a result, this can be reduced considerably by averaging multiple RSS measurements. The second type of error is due to the properties of the environment, such as multipath and shadowing. Since the layout of the environment and the placement of doors and furniture is unknown because we assume no prior knowledge of the environment, this error should be modeled as random.

In order to create an accurate localisation system based on RSS, the wireless channel properties and these other degrading effects should be modeled as accurately as possible taking the limited processing power of the nodes into account. All these factors seem to give RSSI measurements a large random factor, thus making it very unpredictable. Even with good modeling, it is inevitable that errors remain present because of the random factor; thus any good localisation algorithm should also account for these factors. The upside of using RSS as a ranging method is that the radio can be used for communication and localisation. This makes RSS very interesting because there is no need for additional hardware. Other ranging methods such as TOA, especially combined with ultrasound, usually yield better results, but require additional specialised hardware which adds to the size and cost of a node.

As WSNs have some unique properties, the algorithms have been developed or selected with the following goals in mind:

RSS-based Using this technique no additional hardware is required, thus the cost of a node can be kept low. However, because TelosB nodes have an antenna embedded on the PCB [3], it might be better to use an external antenna as these have a more uniform radiation pattern.

Distributed and self-organising The algorithm should be able to run locally on the nodes to avoid a central processing dependency. This is especially important for WSNs 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.

Responsiveness The localisation latency needs to be kept as low as possible. Mobility is fairly limited in WSNs as most nodes have a static position; however, certain nodes can be mobile, so this factor needs to be accounted for as well.

Energy usage Given the sparse amount of available energy, processing and communication should be kept to a minimum. Unfortunately, this means that certain applications are not suitable for WSNs because of the high computational requirements and the lightweight microcontroller that drives the nodes. Communication between nodes needs to be limited as well because traditionally the radio requires much more power than the microcontroller.

Adaptive We want our algorithm to be adaptive to the number of anchor nodes (ANs) and the density of the network. If the density or the number of ANs rises, the accuracy should improve. The algorithm should thus benefit from the high node density of the WSN. The algorithm should still perform well with a low network density and AN ratio.

The main contributions of this paper are an overview of the existing algorithms and literature, research on the influence of the orientation of a node compared to a node with an external antenna and a comparison of three algorithms with quantitative measurements.

2 Related Work

The amount of literature on this topic is quite substantial. It becomes more manageable if we limit ourselves to three categories: ranging algorithms, location estimation and frameworks. Limited surveys on this topic do exist; however, they fail to point out a superior algorithm and provide few quantitative comparisons, so further investigation is required.

Sum Dist is a distributed multihop algorithm that makes use of the hop count as a primitive distance metric [4]. The distance to the anchor nodes is determined by simply adding the ranges (RSS) encountered at each hop during the network flood of beacon messages by the anchor nodes. The downside of this algorithm is that the range errors rise exponentially when the beacon message travels over multiple hops. Thus, in large networks with little anchor nodes, it will lead to poor ranging. The paper "RSS-based location estimation with unknow pathloss model" [5] dynamically estimates the distance-power gradient; parameter of the radio propagation pathloss model. It adapts automatically to the environment, thus eliminating the need for extensive channel measurements. This leads to a more accurate conversion of RSS to distance. Sorted RSSI Quantisation [6] is a connectivity based algorithm that uses hopcount and RSS as a ranging method. It multiplies a hop by the radio range or a chosen distance. It sorts the obtained RSSI and applies a quantiser that represents a level of range in the hop. This makes the algorithm insensitive to RSSI errors.

MoteTrack [7] is a decentralised location tracking system based on RF. The location of each blind node is computed using a RSS signature from the anchor nodes to a database of signatures. This database is stored at the anchor nodes themselves. Cricket [8] is decentralised and uses RF and ultrasound to determine the location of a blind node. Anchor nodes broadcast beacon messages, together with te RF message, it will transmit a ultrasonic pulse. Blind nodes listen to beacon messages and upon receipt, they will listen to the corresponding ultrasonic pulse. A distance to the transmitting anchor node can be estimated with that pulse. A noteworthy survey is [4] by K. Langendoen. This survey describes three algorithms: Ad-hoc positioning [9], N-hop multilateration[10] and Robust positioning [11]. These algorithms are fully distributed algorithms; they require no central processing node and are designed towards multihop localisation. The survey concludes that no single algorithm performs best under different circumstances. Robust positioning works best when no or very bad ranging information is available. Ad-Hoc positioning only works well when the ranging error is very low (<20%). The N-hop multilateration is to be preferred in other situations. This survey identifies a common three-phase structure in these localisation algorithms. The first phase determines the distances between blind and anchor nodes. Note, however, that this does not mean that a specific ranging method, such as RSS, should be used,. The second phase derives a position using the RSS from the anchor nodes. These two phases are roughly equal to what was described in the introduction. Finally, there is a third phase called the refinement phase, where the positions are refined through iterative measurements.

Another comparison is given in [12] by Zanca et.al. This paper compares four algorithms: Min-Max and Multilateration [4], Maximum Likelihood [13] and ROCRSSI [14]. The absolute ranging errors of the algorithms are presented with the number of anchor nodes as a parameter. The authors conclude that ML provides superior accuracy compared to the other algorithms when the number of anchor nodes is high enough. Interestingly, despite its simplicity, Min-Max achieves reasonable performance. This is probably due to the fact that it localises the node in the center of the estimated area. The authors also note that a good radio channel model is required to obtain a relatively high accuracy. The algorithms presented in this paper are one-hop algorithms; they can only localise nodes in reach of enough anchor nodes.

3 Framework

We have developed a software framework, Senseless, which provides a common data interface to the WSNs and GUIs. It also controls the data flows between the WSNs and GUIs, and stores this data in a database for later retrieval. The system is capable of working with different algorithms and new algorithms can be easily added. If there are three anchor nodes available, we can work with range-based algorithms, thus obtaining a better accuracy. If, on the other hand, only one anchor node is available, a connectivity-based algorithm can and must be used. We will use this system to test the different localisation algorithms and analyse the RSS data.

3.1 WSN

The WSN consists of Telos rev.B nodes, which use a IEEE 802.15.4 compliant CC2420 radio. Each node fulfills one of the three different roles: root, anchor or blind node.

A **root node** (RN) node receives data from the network, and acts as a bridge between the WSN and the rest of the framework. The root sends these messages to the controller via an XML parser. It also receives commands from the controller and disseminates these to the right node.

An **anchor node** (AN) has a known location, and broadcasts a message with its ID to the blind nodes and anchor nodes for calibration.

A **blind node** (BN) has an unknown location and receives broadcast messages from the anchor nodes. The node uses these messages to determine the RSS, and transmits the RSS together with the ID of the anchor node to the root with location messages.

3.2 GUI

The user interfaces provides us with the ability to easily control and monitor the WSN. Rapid deployment was the key motivator to build this component. Using this, the user can set several node parameters, with a focus on localisation: sampling period, coordinates (in meters), inactive/active, blind/anchor and the leds. This can be done in a few seconds. In contrast to manually hardcoding every single node of the network, which can be very time-consuming and sometimes impossible due to the fact that TinyOS-programmed nodes and other types of nodes usually provide very little to no user interaction.

3.3 Controller

The controller is the core of our system. The controller acts as a gatekeeper to the database, ensuring that all data is stored in the correct table and is of the correct type. This is especially important for WSNs as a plethora of hardware platforms exist. The controller is also a central gathering point for all the data. By using the controller in our framework, every other component can use a single data interface and should only be aware of the location of the controller. The controller implements the centralised versions of our localisation algorithms. The user can instruct the controller to use an algorithm via a simple Windows Forms GUI.

The communication between the WSN and the controller is done using an XML parser, which translates the messages of both sides into XML and back into an internal format. The root node of the WSN receives all the messages (sensor, location and status) from the nodes and forwards these to the controller, or if the controller needs to pass a command, it will be forwarded to the root and transmitted over the WSN using the dissemination protocol.

4 Localisation Platform

We use the **log-normal-shadowing propagation model** to translate the RSS measurements to distances. It is the most widely used signal propagation model and the determination of the parameters is simple and can be obtained dynamically with Least Squares.

$$RSS(d) = PT - PL(d0) - 10 \times n \times \log(\frac{d}{d0}) + Xo$$

Where, *PT* is the transmitted power, *PL(d0)* is the path loss for the reference distance *d0*, *n* is the path loss exponent (the rate at which the path loss increases with distance) and *Xo* is a gaussian random variable with zero mean and standard deviation *o* dB. The most common reference distance is one meter. In the calibration phase of the WSN, we determine the path loss exponent and the path loss for the reference distance, so that the propagation model is adapted to the environment and thus more accurate.

Centroid localisation is a simple approach for coarse grained localisation. All blind nodes calculate their position as the centroid of the anchor nodes within their communication range. This algorithm has a low accuracy because it does not use signal strength to denote the range. A solutions to make CL more accurate is the Weighted Centroid Localisation (WCL) [15]. A weight is coupled to each anchor by its RSS:

$$Weight = |\frac{1}{RSS^g}|$$

The degree g has to ensure that the remote anchor nodes still have impact on the position determination. In case of a very high g, the calculated position moves to the closest position of the anchor node and the positioning error increases.

Min-Max is a popular and a very easy algorithm to implement. Anchor nodes, that are in range of the blind nodes, will create a box around them. This box has the anchor node as the center and has a height and width of twice the estimated distance to the blind node. In an ideal situation this algorithm will work, but the estimated distance between the node is often underrated. So, one or more boxes will not collide and thus a location can not be determined. In this case, the estimated distance between the nodes is expanded with 10% until all boxes collide.

Multilateration is used in a variety of localisation systems including GPS. Multilateration calculates the intersection of three or more circles. If these circles intersect in exactly one point, the coordinates of this point can be determined by linear equations. This method has one major flaw; the circles almost never intersect in a single point. They do not intersect at all or overlap a part of each other. In more dramatic cases one circle can entirely overlap another circle. This is due to the erroneous ranging. The range is over- or underestimated. Two solutions to solve this problem exist [16]. The first solution is based on non-linear LS . Through an iterative process the range of the circles is changed until a single point of intersection is found. This method can yield fairly accurate results. The downside however is that it is computationally intensive. The second solution is much simpler and requires that the circles overlap. Given x circles, the algorithm determines the x-nearest points. The centroid of these points is taken as the result. The second solution is simpler to implement but has the requirement that the three circles should overlap a part of each other. We present a simple solution to this problem. There are three cases in which the range of the circle should be modified:

- The circles are too far from each other and do not intersect
- One circle completely overlaps another circle
- A circle is completely inside another circle

In each of these cases the range should be adapted accordingly until these conditions are no longer met. The algorithm iterates through all the circles so that all circles are slightly changed instead of drastically changing one circle. The algorithm finally converges to the situation where all circles overlap each other. We chose to implement the seconds solution and an easier from of the first solution namely the normal least square [17], this algorithm is much simpler to implement and has a better performance.

5 Test environment

Our experiments were performed in- and outdoors. The indoor tests were done in a lab environment which houses a considerable amount of electronics including Wi-fi equipment operating in the same frequency range. People were walking in the room as well to further interfere with the signal. The outdoor test were done on a local basketball court. Nodes were placed at about five to ten meters from the fencing and few people were walking by.

5.1 Antenna orientation

The relative antenna orientation between receiver-transmitter pairs is a major factor in signal strength variability, even in the absence of multipath and shading effects [18]. This is due to the fact that antennas are not omnidirectional. For good localisation, the radiation pattern of an antenna should be uniform and it should look like a circle (2-D space) or a sphere (3-D space). However, in practice, the orientation of the antenna can influence the signal strength by several decibels. Thus, different antenna orientations can produce different sets of RSS values for the same distances between receiver and transmitter, increasing the position error and making a quantitative comparison of different localisation algorithms cumbersome.

A straightforward solution would be to use a more omnidirectional antenna to minimise these effects. For example, Telos rev.B nodes use an onboard Inverted-F microstrip antenna. The power received from this antenna can differ by as much as 20dB depending on the orientation [3]. Fortunately, an external antenna can be mounted on the circuit board via an optional standard SMA connector. We tested the difference between a node equipped with and without an omnidirectional dipole rod antenna.

Two Telos rev. B nodes were set in the outdoor environment. The experiment consists of two parts: In the first part, the two nodes are equipped with an external antenna with a gain of 5dBi and placed at a distance of one meter and at a distance of five meters from each other at a height of one meter. This way the ground will attenuate the signal. One node is set as an anchor node and will broadcast beacon messages at an interval of 200 ms. The anchor node was rotated and samples were taken at every 20 degrees. The other node, the blind node sends the RSS readings to the database. Approximately 25 samples were collected at every orientation. In the second part, only one node is equipped with the external antenna and placed at a distance of one and five meter. This node is set as the blind node and receives ideally the same power in every direction. The other node with an integrated antenna is the anchor node that will broadcast the beacon messages.

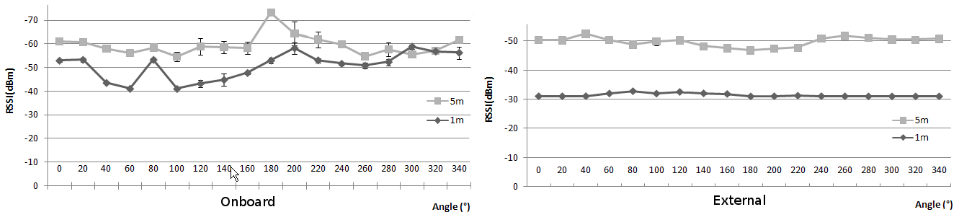

Figure 1: Average RSSI at a distance of 1m and 5m with one node equiped with an external antenna

Figure 1 displays the mean and standard deviation of the RSS when rotating the node for the two antennas. Note that the standard deviation is sometimes too small to be seen on the graph. These results show that RSS readings are more stable when the node is equipped with a more omnidirectional antenna. The results are consistent with the common belief that node orientation influences RSS readings. The results also clearly show that the external antenna is more invariant to orientation than the onboard antenna, hence all further tests were done using the external antennas.

5.2 In & outdoor positioning

This experiment was devised to test the accuracy of our developed localisation algorithms. We placed a total of 10 nodes in both the indoor and outdoor environments. Nine of them are configured as anchor nodes and the last one is configured as a blind node. Every node is placed at a height of one meter. The anchor nodes are placed randomly at fixed locations in a 4.69 m by 8.48 m rectangle.

Figure 2 shows the relative positioning error for indoor and outdoor positioning. The relative positioning error is measured as the absolute positioning error divided by the average distance to every connected anchor node. The relative positioning error of the algorithms in the outdoor environment is generally below 140%. The two trilateration algorithms perform really poor in the indoor environment. While Min-Max has a maximum relative positioning error of 68% and keeps dropping when more anchors are added.

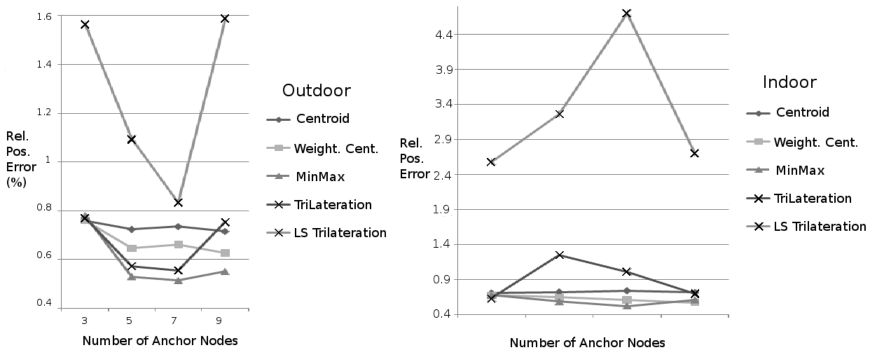

Figure 2: Average relative positioning error in the out- and indoor environment

The relative positioning error of the algorithms in the outdoor environment is generally below 80%. The trilateration with least squares has good computational performance but a very low accuracy in most cases. A better solution would be to use a more advanced form of least square like the weighted least square and the non-linear least square. Min-Max has the best accuracy, even under 50%. The results show that the accuracy improves when more anchor nodes are added to the system, but we do notice that the accuracy becomes stagnated when we reach the number of 7 anchor nodes. The trilateration algorithms lags behind in accuracy compared to the other algorithms. The Min-Max algorithm is computationally simple and delivers the best accuracy. Therefore it is our current algorithm of choice.

6 Conclusion

This paper investigates the core aspects of WSN localisation systems using RSS and makes an overview of the existing localisation algorithms. Different types of localisation systems were introduced and important properties were discussed as well. An overview of our localisation framework was given. Five centralised localisation algorithms were discussed. The results showed that the relative positioning error was lower than 100% in most cases and that accuracy improves when more anchor nodes are added, but stagnates around 7 anchor nodes. We can conclude that the Min-Max algorithm performs the best in both outdoor and indoor environments.

References

[1] I. Akyildiz, W. Su, Y. Sankarasubramaniam, and E. Cayirci, “Wireless sensor networks: a survey,” *Computer networks*, vol. 38, no. 4, pp. 393–422, 2002.

[2] J. Hightower and G. Borriello, “Location systems for ubiquitous computing,” *Computer*, vol. 34, no. 8, pp. 57–66, 2001.

[3] Moteiv, “Telos RevB datasheet,” December 2004. [Online]. Available: http://www.moteiv.com/products/docs/telos-revb-datasheet.pdf

[4] K. Langendoen and N. Reijers, “Distributed localization in wireless sensor networks: a quantitative comparison,” *Computer Networks*, vol. 43, no. 4, pp. 499–518, 2003.

[5] X. Li, “RSS-based location estimation with unknown pathloss model,” *IEEE Transactions on Wireless Communications*, vol. 5, no. 12, p. 3626, 2006.

[6] X. Li, H. Shi, and Y. Shang, “A sorted RSSI quantization based algorithm for sensor network localization,” in *Parallel and Distributed Systems, 2005. Proceedings. 11th International Conference on*, vol. 1, 2005.

[7] K. Lorincz and M. Welsh, “MoteTrack: a robust, decentralized approach to RF-based location tracking,” *Personal and Ubiquitous Computing*, vol. 11, no. 6, pp. 489–503, 2007.

[8] N. Priyantha, A. Chakraborty, and H. Balakrishnan, “The cricket location-support system,” in *Proceedings of the 6th annual international conference on Mobile computing and networking.* ACM New York, NY, USA, 2000, pp. 32–43.

[9] D. Niculescu and B. Nath, "DV based positioning in ad hoc networks," *Telecommunication Systems*, vol. 22, no. 1, pp. 267–280, 2003.

[10] A. Savvides, H. Park, and M. Srivastava, "The n-hop multilateration primitive for node localization problems," *Mobile Networks and Applications*, vol. 8, no. 4, pp. 443–451, 2003.

[11] C. Savarese, J. Rabaey, and K. Langendoen, "Robust positioning algorithms for distributed ad-hoc wireless sensor networks," in *USENIX technical annual conference*, vol. 2. Monterey, CA, 2002.

[12] G. Zanca, F. Zorzi, A. Zanella, and M. Zorzi, "Experimental comparison of RSSI-based localization algorithms for indoor wireless sensor networks."

[13] N. Patwari, R. O'Dea, and Y. Wang, "Relative location in wireless networks," in *IEEE VTS 53rd Vehicular Technology Conference, 2001. VTC 2001 Spring*, vol. 2, 2001.

[14] C. Liu, K. Wu, and T. He, "Sensor localization with ring overlapping based on comparison of received signal strength indicator," in *2004 IEEE International Conference on Mobile Ad-hoc and Sensor Systems*, 2004, pp. 516–518.

[15] S. Schuhmann, K. Herrmann, K. Rothermel, J. Blumenthal, and D. Timmermann, "Improved Weighted Centroid Localization in Smart Ubiquitous Environments," *Lecture Notes in Computer Science*, vol. 5061, pp. 20–34, 2008.

[16] A. Kaminsky, "Trilateration," 2007.

[17] A. Sayed, A. Tarighat, and N. Khajehnouri, "Network-based wireless location: challenges faced in developing techniques for accurate wireless location information," *IEEE Signal Processing Magazine*, vol. 22, no. 4, pp. 24–40, 2005.

[18] D. Lymberopoulos, Q. Lindsey, and A. Savvides, "An empirical characterization of radio signal strength variability in 3-d ieee 802.15. 4 networks using monopole antennas," *Lecture Notes in Computer Science*, vol. 3868, p. 326, 2006.