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TECHNIQUES AND SYSTEMS FOR INDOOR LOCALIZATION IN WIRELESS SENSOR NETWORKS

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ABSTRACT

Day-to-day life is increasingly being enhanced by a growing number of applications of wireless sensor networks (WSNs). Environmental monitoring has as many industrial as personal applications. The self-organization aspect of WSNs enables diverse applications, such as location-based services (LBS), tracking people, monitoring patients, applications in security, emergency services, and many others. In these scenarios, it is usually crucial to determine the location of a particular node. However, software and hardware restrictions typical for WSNs pose major challenges for localization techniques. Providing localization services in a WSN implies additional hardware, complex calculations, and an increased energy consumption. In addition to these issues, there also is an ever-increasing demand for greater accuracy. This paper reviews a selection of major systems for indoor localization based on various techniques. The theoretical review is complemented by a discussion of our own experiences with and test results of a subset of these systems.

Index Terms— Sensor Networks, Tracking, Localization, Algorithms

1. INTRODUCTION

Many WSN applications depend on the ability to locate a node for one purpose or another. This information may be used to associate a measured value with a location or as a metric in the optimization of a routing protocol. Tracking a mobile object represents one of the most demonstrative applications, yet simultaneously also one of the most demanding.

The distribution of individual modules is often random and their position not known in advance. Additionally, a sensor network is expected to be capable of quickly adapting to changes in connectivity and location. Nevertheless localization solutions should still obey typical WSN requirements such as energy efficiency and scalability.

To date, a broad variety of positioning techniques has been proposed, differentiated by the underlying hardware, the measurement procedure, and their consideration of application-specific requirements.

2. LOCALIZATION IN WSNS

2.1. Application Requirements

There are a large number of indoor localization systems and techniques — however, there is no ultimate solution. The diversity of application scenarios requires a solution tailored to the case at hand. From these, requirements of localization systems can be inferred.

In the following, characteristics of localization systems will be discussed, and a selection of promising approaches will be reviewed in more detail.

2.1.1. Coordinate System

A node's position can be specified in both a physical and a symbolic notation [1]. In the case of a symbolic location, the node's position is identified by a metadata description. In contrast to this, a physical location requires an adequate ***coordinate system***. The basis of the coordinate system may be global (e.g., GPS-determined) or relative coordinates.

2.1.2. Beacons

A relative coordinate system is based on so-called ***beacons***. These are static reference nodes with known positions within the network. Based on the known positions of beacons, the positions of unknown nodes can be determined. Some localization techniques discussed below in turn use the nodes for which positions have been computed as secondary beacons in order to incrementally, much like of a chain reaction, determine the locations of all of the network's nodes.

2.1.3. Decentralized or Centralized Computation

Depending on the localization technique, specific measurements, such as signal strength or transmission times, are performed in order to localize a node. Based on these measurements, the computation of the position can be done either locally on the involved nodes or at a central place. Consequently, such localization systems are classified as either centralized or decentralized, respectively [2]. It is normally possible to transform a decentralized system into a centralized one (and vice versa, if required) by forwarding the data required to perform the computations to some central instance.

2.1.4. *Accuracy*

The requirements on accuracy are often determined by the specific application scenario and may vary significantly. The spectrum includes tracking systems which are both temporally and spatially highly accurate and operate with high update rates, and also ones with rather inaccurate positioning performed on request only. A positioning system's accuracy in most cases depends on the precision of the measurements performed and the robustness of the computational algorithm (position estimation). Typically, accuracy is directly proportional to both the set-up effort and the solution's costs. A sophisticated post-calculation, particularly a filtering of the measurement data, can significantly increase the accuracy of a localization system.

2.1.5. *Dynamics and Time Constraints*

Indoor systems often employ fixed beacons. The frequency of changes in position and speed of the nodes to be localized (sometimes referred to as tags) directly correlate with the temporal requirements on the system. The faster and more frequently a node changes its position, the faster and more frequently the system has to react, performing measurements and computations. The measurement data are furthermore subject to various QoS parameters, such as the latency from the moment of the measurement to the one the data are available to the processing units, or the possibility of a loss of individual measurements' data.

2.1.6. *Energy Constraints*

Wireless sensor nodes are often operated using batteries or even energy-autonomously. The amount of energy available and the way it is used determines the life span of the overall system. Localization systems with short measurement intervals, many peripheral components which additionally consume power, or complex post-calculations negatively influence the energy budget of a sensor node. Managing the available resources in an optimal way and ensuring a reliable operation represent challenges for the implementation of a localization algorithm as well.

2.1.7. *Form Factor*

Some application scenarios impose specific requirements on the shape and appearance of the sensor nodes and a system's components in general. For example, a localization system in an office building should be unobtrusive for its occupants, and a sensor node carried by a user should be sufficiently small to not be an encumbrance (keyring pendant or name tag).

2.1.8. *Costs*

Depending on the specific localization system, a varying number and type of hardware components may be required; some even require dedicated hardware. A pure software implementation utilizing commonly- measurable values, such as the RSSI value measured by the transceiver circuit, avoids additional hardware components and thus costs.

Another matter of expense which must not be neglected is the set-up effort which may be brought about by additional components.

2.1.9. *Set-up Effort*

Setting up a localization system may consist in the simple placement of beacon nodes but may as well imply complex pilot surveys such as on-site operational-test measurements, the determination of an environmental profile in order to increase the precision of measurements, or general efforts concerning both time and additional equipment. In total, this may lead to a significant increase in costs.

2.1.10. *Integration*

The positioning data obtained have to be forwarded and processed during a subsequent procedure. This may be a visualization of the localized node or the provisioning of an interface towards other systems.

2.1.11. *Environment*

The application environment directly influences a large number of system parameters. For example, subaqueous applications and outdoor systems impose specific requirements on the isolation and robustness of housings, whereas indoor systems often set a higher value on appearance and shape. On the other hand, indoor systems often have to take into account more demanding propagation characteristics as well as multi-path effects. Consequently, a localization system well-suited for one particular environment may perform worse or even cease to function in another. One example of this is GPS [3], which is usually an option for outdoor systems but offers only a limited performance in indoor scenarios.

2.2. Localization Techniques

Figure 1 shows the traditional classification of different localization techniques.

2.2.1. *Neighborhood Relations*

The class of coarse localization systems includes all of those implementations whose computations consider neighborhood relations and the network's topology. Assuming the communication range of a node as D, the

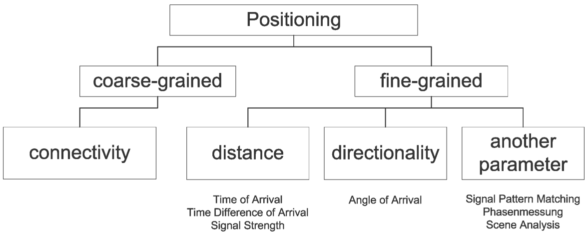


Fig. 1. Classification of localization techniques.

distance among two communicating nodes can be assumed to be smaller than D. The basis of computations in this case is the communication range assuming an ideal radio model.

2.2.2. Distance Calculation

Another group of techniques is based on the calculation of distances among nodes. This approach presumes that the distance among three or more beacons is known. In a first step, the distance of the (potentially mobile) node from the beacons is determined (al least from the 3 beacons for 2D). The result of this defines circles around the beacons whose intersection represents the area in which the node in question is located. The size of the area is an indication of the error. This technique is called trilateration (fig. 2).

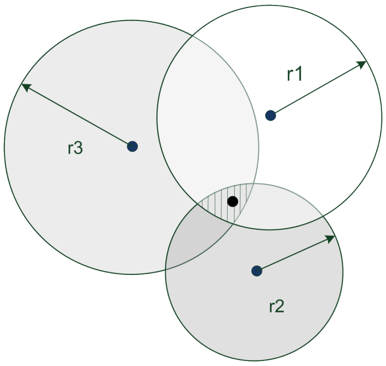


Fig. 2. Positioning using trilateration.

In order to reduce the error, commonly the distance to a greater than 3 of nodes is considered, which is called multilateration.

The distance from the beacons can be determined using various measuring methods. Typical methods for sensor networks include:

- signal strength measurements (RSSI, Received Signal Strength Indicator)
- temporal measurements (Time of Arrival or Time Difference of Arrival)

Signal strength measurements are the most commonly used means of distance determination. According to the ideal radio model, the field strength in between the nodes drops monotonously as the distance increases. In reality however, obstructions, multi-path effects, and other sources of error render correlating a measured value with a particular distance a difficult endeavor.

The time of transmission is directly proportional to the distance in between sender an receiver. Determining the distance to the sender requires the receiver to obtain precise information on the speed of propagation of the signal and the time of the transmission. This requirement necessitates a synchronization among the nodes. The speed of propagation depends on the type of signal (ultrasonic, radio) and the medium. The speed of propagation of radio signals is close to the speed of light, the distances among the nodes are small, and clocks and micro-controllers are slow by comparison. Consequently, precise time measurements on sensor nodes are hardly viable. Because of the requirements implied, this approach can only be realized using complex solutions in both hardware and software and is thus rarely implemented in practice.

2.2.3. Directional Reference

This technique determines the angle of arrival of the received signal. This requires two or more antennas or an array of antennas. Based on the measured angle and the known distance among two beacons, angulation allows for the two missing sides of the resulting triangle to be calculated and the position of the sender thus to be determined.

2.2.4. Fingerprinting

The signal pattern matching or fingerprinting method requires the area in which nodes are to be located to be subjected to reference measurements beforehand. During a subsequent localization process, the recorded signal properties in the area are compared to later measurements, and the closest-matching tuple is used to determine the position.

2.2.5. Further Techniques

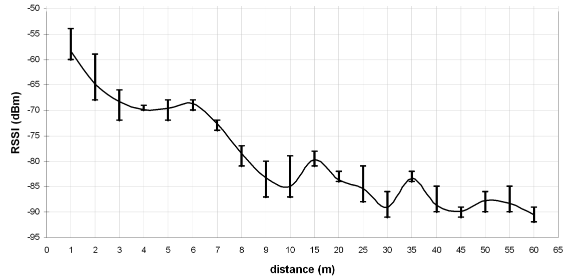
There are a number techniques which cannot readily or at all be assigned one of the classes discussed above. One example of a common such technique is based on the measurement of the phase of the received signal. Another example is known as scene analysis. This technique is based on a visual analysis of the environment. The position is then determined by evaluating images. At first glance, this technique seems the least adequate for sensor networks. Nevertheless a simplification of this technique by substituting a recording of environmental characteristics for taking an image is plausible [1].

3. LOCALIZATION SYSTEMS

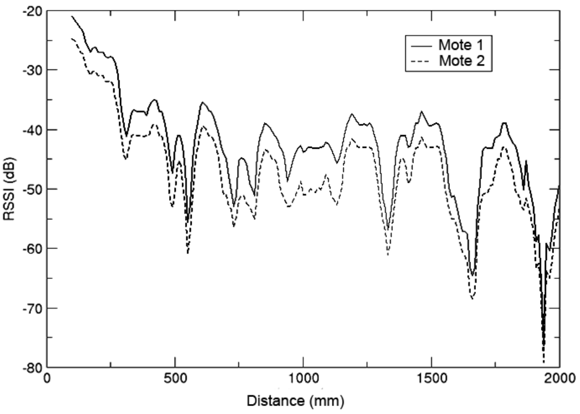
This section introduces and compares a selection of five localization systems, focusing on indoor positioning.

3.1. RSSI-based Localization

RSSI-based localization represents the most simple approach to localizing sensor nodes. This type of measurement does not require additional hardware as the transceiver circuit is able to supply the signal strength value of received messages (or the received signal). A major disadvantage of this technique consists in its strong dependence on environmental conditions affecting radio transmission properties (fig. 3). Thus multi-path effects and reflections, particularly in indoor scenarios, lead to great variances in the measured values, which furthermore even tend to vary temporally. RSSI values moreover vary with the particular transceiver circuit used with respect to resolution, depend on the output power of the transmitter, and are subject to per-component variances. Because of this, RSSI measurements of different modules are often not comparable.



(a) Results of outdoor measurement.



(b) Bidirectional communication of two motes.

Fig. 3. Received signal strength measurements.

3.2. MoteTrack

MoteTrack [4] is a freely-available software system based on TinyOS [5]. This RF-based system has been implemented for Tmote-, Tmote-Sky-, Sky-, MicaZ-, Mica2- and Mica2Dot-type sensor modules. Its localization technique depends on a rather large number of beacon nodes, requiring tags to be able to receive the signals of at least six beacons from everywhere in the positioning area. The localization process consists of two steps:

1. *Data Collection* — Aggregation of signal strength measurements of N frequencies at M output power levels in a database. Each measurement is associated with coordinates.

2. *Location Tracking* - Comparation of measured data with the database and determination of the current position.

This system aims to improve accuracy using multiple RSSI measurements at different frequencies and varying output power levels. During the set-up of the system, calibration measurements of the environment have to be performed. Based on these, a signal propagation profile is inferred — an approach which is commonly referred to as fingerprinting. This increases both the accuracy of the positioning and the set-up effort.

Measurements in a room sized X m by Y m yielded the following results:

Error (m)	6 beacons	10 beacons	16 beacons
max.	2,20	1,80	1,70
min.	0,10	0,10	0,10
avg.	0,79	0,69	0,68

Table 1. Localization using MoteTrack and Tmote-Sky-type modules [6], 2.4 GHz, channels 12 and 14, RF power level 0 dBm

3.3. nanoLoc

NanoLOC is an example of a robust chirp technology [7] operating in the 2.4 GHz ISM band. Besides offering functionality for data transmissions, it also performs highly precise transmission-time-based distance measurements among radio systems. The technological basis of nanoLoc is Symmetrical Double-Sided Two-Way Ranging (SDS-TWR) [8]. The set-up involves the placement and recording of the position of beacon nodes.

Table 2 summarizes the results of a test of the nanoLoc system. For reasons of comparability, the measurements have been performed in the same indoor environment.

3.4. RIPS

The Radio Interferometric Positioning System (RIPS) represents a promising localization technique based on the phase of the composite signal of two senders. A

System	**Accuracy**	**Measurement technique**	**Set-up Effort**	**Access methods**	**Environment**	**Hardware costs**
RSSI-Localization	> 1 m	signal strength	simple	mote layer	indoor/outdoor	cheap
MoteTrack	~ 1 m	signal strength	complex	host layer	indoor	cheap
nanoLoc	~ 1 m	SDS-TWR	simple	host layer	good adapted for indoor	middle
RIPS	~ 3 cm	interferometry	simple	host layer	outdoor, indor(?)	cheap
Ubisense	~ 15 cm	AoA and TDoA	complex	Localization Server API	good adapted for indoor	very expensive

Table 3. Classification of some localization schemes.

Error (m)	**distance**	**location**
max.	3,00	1,07
min.	0,01	0,10
avg.	0,69	0,54

Table 2. nanoLoc: Distance measurement and localization error.

small difference among the frequencies of the two transmitters results in a composite signal with a low- frequency envelope at the receiver. This can rather easily be measured using an A/D channel of a microcontroller. The relative phase shift among the received envelopes of two receivers allows for their positions to be computed. This technique has also been implemented for [5] and is freely available. The currently-available implementation is intended for the Mica2 [9] platform. According to [10], the localization error at a distance of 160 m amounts to approximately 3 cm. However, multi-path effects inside buildings have such a detrimental effect on the measurements that the system becomes highly inaccurate and thus potentially unfit for serious applications.

3.5. Ubisense

The Ubisense system incorporates three components: active, battery-powered tags generating UWB impulses (as location signals), fixed sensors for receiving and evaluating signals, and the Ubisense software platform recording, processing, and visualizing location information for users and other IT systems. By using a combination of Angle of Arrival (AoA) and Time Difference of Arrival (TDoA) techniques, Ubisense achieves an accuracy of up to 15 cm [11]. The implementation employs AoA antenna arrays, and the utilization of TDoA requires a wired backbone for synchronization, which implies additional set-up efforts.

4. CONCLUSION

Table 3 summarizes advantages and disadvantages of the evaluated localization systems.

This contribution has given an overview of localization techniques, their areas of application, and their suitability for wireless sensor networks. A number of systems differing with respect to their areas of application, accuracy, as well as hardware and software requirements have been introduced.

Given specific requirements, each system is invariably characterized by individual strengths and weaknesses. Therefore, a combination of different techniques often represents the most sensible approach to the practical realization of a localization solution.

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