INDOOR LOCALIZATION SYSTEM USING RSSI MEASUREMENT OF WIRELESS SENSOR NETWORK BASED ON ZIGBEE STANDARD

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Abstract

To verify the validity of our previously reported autonomous indoor localization system in an actual environment, we implemented it in a wireless sensor network based on the ZigBee standard. The system automatically estimates the distance between sensor nodes by measuring the RSSI (received signal strength indicator) at an appropriate number of sensor nodes. Through experiments, we clarified the validity of our data collection and position estimation techniques. The results show that when the deployment density of sensor nodes was set to 0.27 nodes/m^2, the position estimation error was reduced to 1.5-2 m.

Keywords

performance evaluation, localization, RSSI, ZigBee

1 Introduction

Recent advances in wireless communications and electronics have enabled the development of microsensors that can manage wireless communication. If a large number of sensors are deployed, wireless sensor networks can monitor large areas and be applied in a variety of fields, such as for monitoring the environment, air, water, and soil. Sensor networks can also offer sensing data to context-aware applications that adapt to the user's circumstances in a ubiquitous computing environment. If they are appropriately designed, sensor nodes can work autonomously to measure temperature, humidity, luminosity, and so on. Sensor nodes send sensing data to a sink node deployed for data collection. In the future, sensors will be cheaper and deployed everywhere; thus, user-location-dependent services and sensor locations will become more important. Although GPS (global positioning system) is a popular location estimation system, it does not work indoors because it uses signals from GPS satellites [1]. Using sensor networks instead of GPS makes indoor localization possible. In the future, we expect an increase in applications that satisfy location-information requirements, such as navigation systems and target tracking systems in office buildings or in supermarkets. Sensor locations are important too, because sensing data are meaningless if the sensor location is unknown in environmental-sensing applications such as water-quality, seismic-intensity, and indoor-air-quality monitoring [2].

Methods using ultrasound or lasers achieve high accuracy, but each device adds to the size, cost, and energy requirements. For these reasons, such methods are not suitable for sensor networks. An inexpensive RF-based approach with low configuration requirements has been studied [3-6]. These studies showed that the received signal strength indicator (RSSI) has a larger variation because it is subject to the deleterious effects of fading or shadowing. An RSSI-based approach therefore needs more data than other methods to achieve higher accuracy [1, 7, 8]. However, collecting a large amount of data causes an increase in traffic and in the energy consumption of sensors and decreases the lifetime of sensor networks. Furthermore, increasing the data collection time has a negative influence on realtime operation of the location information collection method. Considering this background, we are studying a localization system that estimates the position of targets by using RSSI in sensor networks. To reduce the amount of data collected by the sink and extend the lifetime of the sensor networks, we have devised a data-collection technique in which sensors recognize the number of surrounding sensors [9]. These sensors autonomously decide whether to send sensing data and they operate when deployed randomly. Our system does not need centralized control or complicated calculations and does not send any more packets than necessary. We previously evaluated the effectiveness of our technique through simulation experiments [9].

In wireless sensor networks, it is important to keep energy consumption low, so IEEE 802.11 [10] for wireless LANs, which was designed for high-power devices such as PCs, is not suitable for wireless sensor networks. Many protocols that cut off wireless devices in order to reduce energy consumption have been proposed [11-13], but a standard has not been defined, so sensors are not subject to standardization, and a protocol has not been disseminated. IEEE 802.15.4 [14] for low-rate wireless personal area networks has appeared recently. This standard defines medium access control (MAC) and the physical layer (PHY) protocol for low-power devices. ZigBee [15], which includes IEEE 802.15.4 for MAC and PHY, is expected to be suitable for wireless sensor networks and is being offered in some products on the market. However, most past studies on localization systems carried out the performance

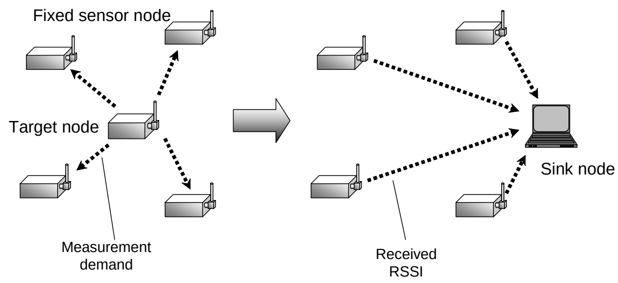


Figure 1. Localization system using RSSI measurement in sensor network.

evaluation on systems based on 802.11 for wireless LANs (e.g., [16, 17]), and there has been insufficient investigation of using ZigBee or IEEE 802.15.4. Accordingly, in this study, we implemented a positional estimation technique using RSSI in a sensor network in accordance with the ZigBee standard and evaluated its position-estimation ability. We implemented our technique in Ubiquitous Device, which is a sensor-network developed by Oki Electric Industry Co. Ltd., Japan, and investigated the distance measurement accuracy of our technique through actual experimental measurements.

The remainder of this paper is organized as follows. Section 2 explains our localization system. Section 3 describes its implementation on a ubiquitous device. Section 4 presents experimental results. Section 5 concludes with a brief summary and mentions future work.

2 Localization system model

2.1 Localization in sensor network

We consider a system in which sensors estimate the position of a target in an observation area. The target node is a wireless device that sends a packet to three or more sensor nodes, which measure the received power. If there are multiple targets, each packet includes the target's ID. After receiving a packet, sensors measure RSSI and send the results (sensing data) to the sink node, which calculates the target position from the sensing data. An outline of this localization system is shown in Fig. 1. The following points regarding the localization system must also be taken into account:

Sensor node placement
We assume that all sensor nodes have already been deployed and that they do not move. Sensor nodes are assumed to know their own position. There are two ways in which a sensor node can learn its position: 1) A manager registers the sensor node's position in the sink node's database. When the sensor node needs to know its position, the sink node sends the appropriate sensor node's position. It resolves a sensor's position when only a few sensor nodes are placed on a grid or if only a few sensors are placed randomly. But it cannot handle the registration of the positions of a large number of randomly placed sensor nodes. 2) A manager places a few beacon nodes that know their own positions, and a sensor node estimates its position by using information from some of the beacon nodes. A system based on such beacons can handle a lot of randomly placed sensors.

Data collection
Sensors receive packets from targets, measure the power of the packet, and transform the RSSI into distance for use in theoretical or empirical models. The packet includes a target ID and a packet number. By reading the packet, a sensor gets the target ID, packet number, and the distance between the sensor and the target. It then sends the following data to the sink: sensor ID, target ID, packet number, and sensor-to-target distance.

Position estimation calculation at the sink node
We use a maximum-likelihood (ML) estimation to estimate the position of a target by minimizing the differences between the measured and estimated distances. ML estimation of a target's position can be obtained using the minimum mean square error (MMSE) [18], which can resolve the position from data that includes errors. We explain the calculation for a two-dimensional case as follows. MMSE needs three or more sensor nodes to resolve a target's position. First, the sink node searches for the same data in terms of a target ID and a packet number by collecting data from sensor nodes. The difference between measured and estimated distances is defined by

$$f_i(x_0, y_0) = d_i - \sqrt{(x_i - x_0)^2 + (y_i - y_0)^2}, \quad (1)$$

where (x_0, y_0) is the unknown position of the target node, (x_i, y_i) for $i = 1, 2, ...N$ is the sensor node position, and $N(\geq 3)$ is the total number of data that the sink has collected, and d_i is the distance between sensor node i and the target. The target's position (x_0, y_0) can be obtained by MMSE. By setting $f_i = 0$, Eq. (1) is transformed into

$$-x_i^2 - y_i^2 + d_i^2 = (x_0^2 + y_0^2) + x_0(-2x_i) + y_0(-2y_i). \quad (2)$$

After getting Eq. (2), we can eliminate the $x_0^2 + y_0^2$ terms by subtracting kth equation from the rest, as follows.

$$-x_i^2 - y_i^2 + d_i^2 - (-x_k^2 - y_k^2 + d_k^2) = 2x_0(x_k - x_i) + 2y_0(y_k - y_i) \quad (3)$$

Then Eq. (3) is transformed into Eq. (4), which can be solved using the matrix solution given by Eq. (5). Position (x_0,y_0) can be obtained by calculating Eq.(5).

$$y = Xb \quad (4)$$

$$b = (X^T X)^{-1} X^T y, \quad (5)$$

where

$$X = \begin{bmatrix} 2(x_k - x_1) & 2(y_k - y_1) \\ \vdots & \vdots \\ 2(x_k - x_{k-1}) & 2(y_k - x_{y-1}) \end{bmatrix} \quad (6)$$

$$y = \begin{bmatrix} -x_1^2 - y_1^2 + d_1^2 - (-x_k^2 - y_k^2 + d_k^2) \\ \vdots \\ -x_{k-1}^2 - y_{k-1}^2 + d_{k-1}^2 - (-x_k^2 - y_k^2 + d_k^2) \end{bmatrix} \quad (7)$$

$$b = \begin{bmatrix} x_0 \\ y_0 \end{bmatrix}. \quad (8)$$

2.2 Effective data collection

Since the propagation characteristics change greatly with the environment, it is necessary to determine the number of data necessary to obtain a certain degree of accuracy in the environment where the sensor node is operating. A user can decide the number of data to collect based on prior knowledge and send it to all sensor nodes by flooding from the sink node. Targets can also inform sensors of the number of data by sending packets. If the resultant accuracy is less than that required for the application, the user can easily increase the number of data to be collected.

In our scheme, whether sensor nodes send data depends on the deployment density of sensor nodes around the sensor node itself and the distance between the sensor node and the target. Each sensor node sends data if it is closer to the target than a certain distance. Sensor nodes can measure the deployment density by receiving packets sent by other sensor nodes to announce their presence in each period of time. The deployment density around sensor i is approximately determined by Eq. (9), where R is the communication range and M_i is the number of sensor nodes within R from a sensor node.

$$D = \frac{M_i}{\pi R^2} \quad (9)$$

We define the number of data required by the system as Z. Sensor node i sends data if the measured distance is less than D_i to enable the sink node to collect Z data. The number of sensor nodes within D_i is proportional to the density, and D_i is defined in Eq. (10).

$$\frac{M_i}{\pi R^2} = \frac{Z}{\pi {D_i}^2} \quad (10)$$

By arranging Eq. (10), we get

$$D_i = R\sqrt{\frac{Z}{M_i}}. \quad (11)$$

Here, D_i depends on the density around sensor node i. The sink can collect the same number of data independently of the sensor-deployment density because if the density around sensor node i is high, D_i is small and if the density around sensor node i is low, D_i is high.

Figure 2. Ubiquitous Device equipped with the optional serial port.

Table 1. Specifications of Ubiquitous Device.

Radio frequency band	2.4 GHz
Transmission speed	250 kbps
Modulation	O-QPSK
Spread spectrum	DS-SS
Antenna	1/4λ monopole
Transmission power	1 mW

3 Implementation of localization system

To verify the validity of the system described in the previous section, we implemented it in Ubiquitous Device, which is a sensor network system that performs communication based on the ZigBee standard. Ubiquitous Device is equipped with four push switches, six LEDs, and a general-purpose analog I/O port. Various sensors, such as a temperature sensor, can be connected to this analog I/O port. Moreover, the collected data can be sent to a PC by serial communication if the optional RS-232C port is installed (Fig. 2). The CPU of this device is ML 67Q4003 (which is compatible with ARM7), which has 32 KB of RAM and 512 KB of programmable flash memory. To enable this device to be programmed, a POSIX compatible API is provided, which enables applications to be created in the C language. Moreover, this device is equipped with a CC2420 [19] radio controller from Chipcon Inc., which is used to perform communication based on the ZigBee standard. Other possible functions include control of the transmission power, acquisition of RSSI, and sleep control. Table 1 lists the other specifications of this device.

The system that we built consists of three kinds of nodes-targets, sensors, and a sink-. These all run on the ubiquitous device. Since the multi-hop communication function has not been developed yet, all communications are currently performed by a single hop. A packet transmitted from a certain node can be received by all the nodes within the communication range. Therefore, to ensure that the packet is received only by a specific destination node, each receiving node must compare the MAC address in the packet with its own. This ubiquitous device can transmit a maximum of 127 bytes of variable-length data as one packet. In this experiment, since our aim was target position estimation, we did not collect any sensor information other than RSSI from the target.

This system aims to perform position estimation using only information from a certain constant number of sensor nodes. We then set the threshold value of RSSI in each sensor node. And a sensor node decides to transmit a packet to a sink node only when the received signal from a target exceeds this value. We can change the number of data to collect by changing this threshold value.

We defined two kinds of messages exchanged in this system:

- Measurement demand message
  This message is used to request sensor nodes to measure the signal received from a target. Since this message is not intended for a specific sensor node, it is broadcast. In addition, to distinguish measurement demands, a sequence number is included in this message. Whenever a target transmits this message, it increments the sequence number.
- Received signal report message
  This message is used by a sensor node to report the measured RSSI value to the sink node. It contains the ID of the target and the sequence number.

These messages can be distinguished by the first byte of the packet. The packet formats are shown in Fig. 3. Position estimation is performed using these messages through the following procedure.

1. Sensor nodes are arranged in the sensing area, and their positions are stored in a database on a PC. The RSSI threshold is set in these sensor nodes.
2. A measurement demand message is broadcast to sensor nodes from a target.
3. Each sensor node measures RSSI at the time it receives the packet, if the received message is a measurement-demand message. If RSSI exceeds the preset threshold value, a sensor node transmits the target ID and sequence number to the sink node.
4. The sink node collects the ID and sequence number of the target, and the ID and RSSI of each sensor node, and transmits these data to the PC by serial communication. If three or more RSSI values with the same target ID and sequence number are collected, the target's position can be estimated by the PC.

4 Experimental results

We conducted an experiment to investigate the relationship between the measured RSSI value and the distance between nodes. All of these measurements were performed in the passages and conference rooms at Osaka University. For various different distances between the target and sensor nodes, we transmitted a packet from the target and collected the RSSI values acquired from the sensor by the sink node. We performed ten measurements for each position and took the average as the measured RSSI value. We then computed an approximate expression from these measured values using the least-squares method. The results of measurements in a passage and conference room are shown in Fig. 4. Expressing the distance as x [m] and the measured signal strength as y [dBm], we obtained the following relationships:

- In a passage

$$y = -8.93\ln(x) - 51.6 \qquad (12)$$

- In a conference room

$$y = -13.3\ln(x) - 47.0 \qquad (13)$$

We experimented on our position-estimation system in a conference room in the university. We installed 20 sensor nodes in the conference room (area: 7.08 m $\times$ 10.60 m), and we measured six targets in this room. The positions of these sensor nodes and targets is shown in Fig. 5.

The experimental procedure was as follows. First, we set the same value for the RSSI threshold in all the sensor nodes. Next, we set up the target node in the place whose position was to be estimated and transmitted the measurement demand message from the target. If the sink node received three or more RSSI report messages from the sensor nodes, it performed target position estimation. The measurement demand message was transmitted five times per second and the estimated distance was averaged. We can obtain the relationships between the RSSI threshold and the number of data that can be collected by using Equations (11) and (13). We had to set the RSSI threshold to an integer because of the limitations of the ubiquitous device. Table 2 shows the number of data that were predicted to be collectable for various RSSI thresholds.

The relationship between the predicted and actually obtained data collection numbers are shown in Figure 6. The difference between them increased as the RSSI threshold was reduced. The cause of the difference might be the limitation on the number of retransmissions in IEEE 802.15.4, which is five. Next, the relationships between the predicted data collection number and the position estimation error for six targets are shown in Figure 7. The number of data in which the estimation error could be reduced was seven or less, though the result depended on the position of the target. Even if more data were collected, the estimation error could not be reduced. These experimental results

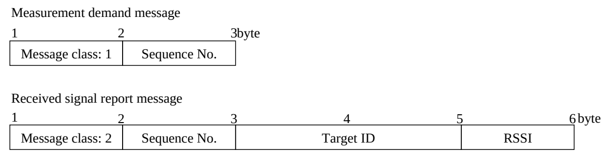
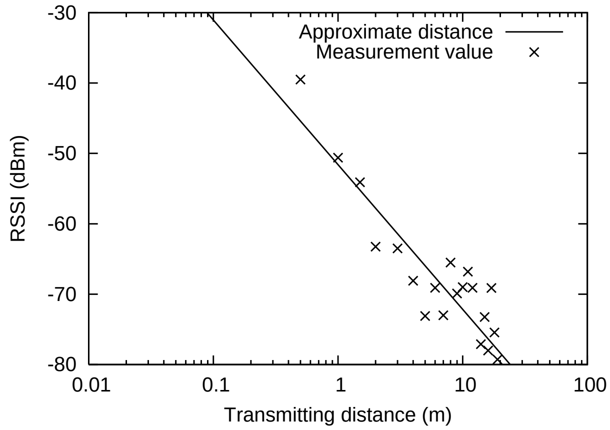
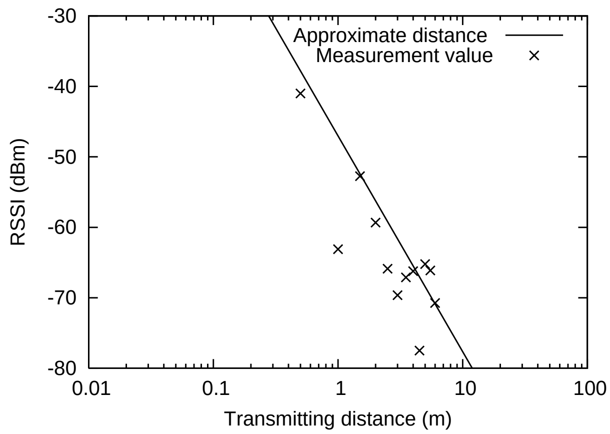


Figure 3. Packet formats of localization system.



(a) Passage



(b) Conference room

Figure 4. Relationship between communication distance and RSSI value.

show that when the installation density of sensor nodes was set to 0.27 nodes/m^2, the position estimation error could be reduced to 1.5-2 m.

5 Conclusion and future work

We have implemented a localization system that uses RSSI in a sensor network based on the ZigBee standard. The collected numbers of data could be controlled by changing the RSSI threshold. We evaluated the system's position estimation accuracy. In the experimental environment, the number of sensors and target nodes was limited, so the number of collected RSSI data was not very large. It is therefore necessary to verify the practicality of our technique for sensing the positions of more targets with a large number of sensors. Furthermore, to achieve an autonomous system, it would be preferable if a sensor node could decide an appropriate threshold automatically by judging its wireless environment through the mutual exchange of RSSI information.

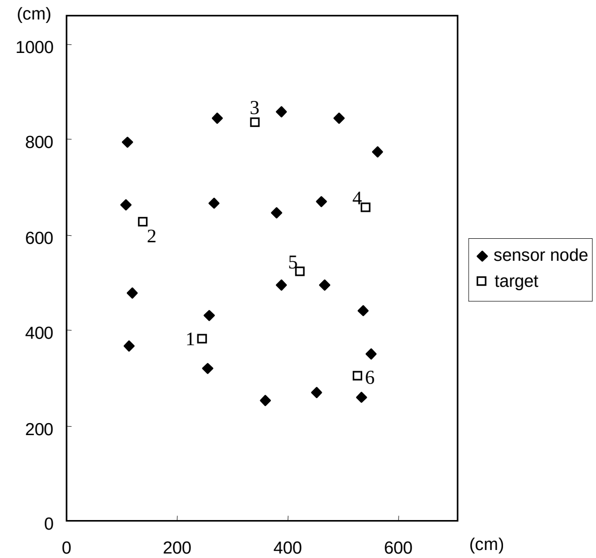


Figure 5. Positions of sensor nodes and targets in the conference room.

Table 2. Predicted numbers of collectable data for various RSSI thresholds.

RSSI threshold (dBm)	Number of collectable data
-58	4.4
-59	5.1
-60	5.9
-61	6.8
-62	7.9
-63	9.2
-64	10.7
-65	12.5

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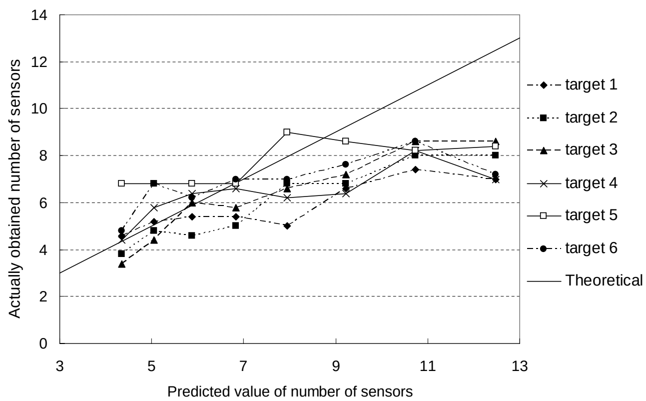

Figure 6. Relationship between predicted and actual numbers of collectable data.

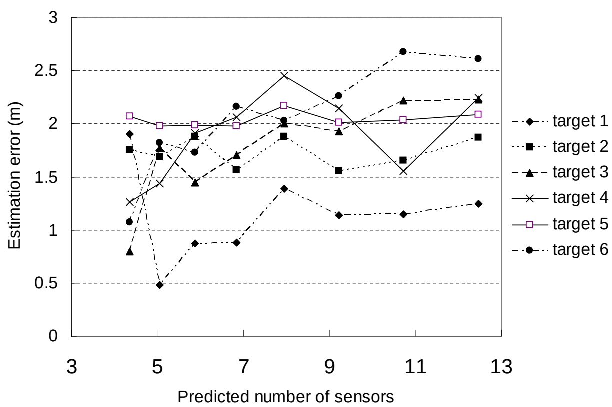

Figure 7. Relationship between predicted number of collectable data and position estimation error.

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