A Hybrid Range-free Localization Algorithm for ZigBee Wireless Sensor Networks

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Abstract: Localization is one of the key aspects of wireless sensor networks (WSNs) that has attracted significant research interest. A wide variety of proposed approaches regarding the research topic has recently emerged; however, the majority of the existing approaches are limited by at least one of the following restrictions: inaccuracy, high cost, fast energy depletion, inappropriate indoor performance, or the requirement of an additional positioning hardware. In this paper, we present the research and development of a hybrid range-free WSN localization system, using the hop-count and received signal strength (RSS) methods. The proposed system is reliable and efficient indoors in terms of localization accuracy, cost and power consumption. Reference and target nodes have been designed and implemented, while real experiments have been carried out to assess the proposed system’s efficiency.

Keywords: Localization, Tracking, ZigBee, Wireless Sensor Networks (WSNs).

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1. Introduction

Wireless Sensor Networks (WSNs) are spatially distributed sensor nodes to observe physical or environmental conditions, such as temperature, humidity, sound and gas levels. Although research and development work regarding WSNs was initially motivated by military applications, WSNs are nowadays deployed in wide-ranging applications including surveillance, industrial, environmental monitoring and agricultural systems [7, 11, 14, 16]. A sensor network is a group of sensor nodes organized into a cooperative network, whereas a sensor node is low in cost, small in size and communicates over short distances. Generally, each sensor node consists of four subsystems, as follows:

- **Controller Subsystem**: includes a general-purpose processor and optimized embedded applications.
- **Communication Subsystem**: bit or byte stream data are transmitted, using a short radio transceiver, as radio waves.
- **Sensing Subsystem**: environmental conditions are sensed by a various types of sensor devices (light, humidity, temperature etc.).
- **Power Supply Subsystem**: contains an energy source that feeds the communication subsystem, on-board sensors and the controller subsystem.

Previous works have focused on various aspects of WSNs, such as routing protocols, network design, hardware design, data gathering and location tracking [1, 2, 4]. Location tracking involving WSNs has received much attention recently, driven by the requirement to accomplish efficient localization accuracy with the lowest possible cost.

In WSNs, location tracking systems can be either range-based or range-free. In range-based localization systems, an additional device needs to be attached to each sensor node (reference or mobile target) in order to perform the localization process. The related methods involve RSS, Time Of Arrival (TOA), Angle Of Arrival (AOA) and Time Difference Of Arrival (TDOA). Examples of range-based technologies include radio frequency identification, camera, Global Positioning System (GPS), ultrasonic and infrared devices. However, applying an extra device to each reference node or mobile target node introduces two significant concerns: first, an additional cost is involved; and, second, high power consumption is necessitated when GPS, camera or ultrasonic sensors are employed in the localization system.

On the other hand, range-free localization methods locate mobile targets without prior information about the distance and the node’s angle of position. Range-free methods are more appropriate for low-power and low-cost WSN applications, but they are inappropriate in terms of positioning accuracy.

As discussed above, TOA, TDOA and AOA localization systems require complicated calculations, in addition to the requirement of attaching extra hardware to each sensor node to perform the time synchronization system, while RSS localization methods involve low-cost, simple operations, without any requirement to install an extra positioning device. Therefore, RSS systems are relatively simple and cheap compared to TOA, TDOA and AOA methods.
The RSS function is defined as the voltage measured by the receiver’s circuit, where the signal strength values are obtained directly by each receiver throughout data communication, without causing extra energy or bandwidth requirements. However, the received signal values are affected by walls and obstacles, which significantly exacerbate the positioning error.

In sensor network applications, sensor nodes are scattered randomly over a geographical area, such that a large number of reference nodes may cover a certain geographical area. In such a scenario, the mobile target node may be covered by a large number of reference nodes (i.e., > 4), which may exacerbate the localization error. Figure 1 depicts the concept of WSN localization, where the mobile target node (node with an unknown location) is covered by five reference nodes (nodes with known locations).

![Figure 1. Localizing a mobile target through distributed sensor nodes.](image)

In this paper, a hybrid range-free localization system is proposed and subjected to practical experimentation using ZigBee sensor nodes. The proposed system consists of two subsystems: hop-count and RSS. The former is used to identify the mobile target’s area (Area A), while the latter computes the mobile target’s location more precisely (the precise location in the predefined Area A). The integration of the above two systems (hop-count and RSS) will represent major enhancement over employing each one separately.

The rest of this paper is organized as follows. In section 2, we discuss the relevant existing localization approaches, while section 3 presents the proposed hybrid localization system. In section 4, we present the implementation and evaluation of the proposed system, then we conclude the presented work in this paper and discuss our future work in section 5.

2. Related Works

Recently, several positioning and tracking systems for sensor networks have been researched and addressed [5, 9, 17]. In this paper, the hop-count and RSS systems are considered and discussed.

First, the RSS based localization systems are discussed. Although sensor networks were not designed for positioning purposes, measuring the signal strength values for each packet received can offer positioning information on target nodes with unknown location information. LAURA [18] is an indoor RSS-based localization system, which uses a practical filter for tracking the location of patients and observing services inside nursing institution. In [15], the authors proposed an indoor positioning and tracking system using wireless and PIR sensory fusion systems, as well as a localization algorithm called the WPIR inference algorithm, which determines the fused location from both PIR and RSS localization systems.

An RSS fingerprinting indoor localization system, which was tested using ZigBee WSNs is proposed in [8], while a hybrid RSS positioning system, based on the divide-and-conquer strategy, is presented in [10].

The novel RSS-based tracking system proposed in [3] is based on triangulating the RSS values, in addition to estimating the noise of indoor environments in order to improve localization accuracy.

Second, hop-count systems are considered. A cost-effective localization solution is proposed in [13] involving two improved algorithms were proposed (selective 3-anchors DV hop and checkout DV hop). The checkout DV hop system calculates the target node position based on the nearest anchor, whereas the selective 3-anchors DV hop selects the three best anchors to enhance localization accuracy.

In [12], the authors proposed a range-free localization system based on the hop-count algorithm. In this work, two reference nodes were installed at corners of a square monitored region, in which sensor nodes with the same minimum hop counts were located next to corner nodes to form a zone. The location of the target nodes was then estimated and adjusted according to their relative location in the zone. The work presented in [19] includes a fine-grained hop-count-based localization algorithm, where the hop-count information is estimated first, after which the Apollonius circle method is employed to achieve initial position estimation, followed by enhancement of localization accuracy using the confidence spring model.

3. Hybrid Range-free Localization System

In this section, the proposed hybrid localization approach is presented, where the hop-count and RSS systems are introduced and discussed.

First, the hop-count system is discussed. The principle of the hop-count system is presented in Figure 2. In diverse sensor network applications, sensor nodes are deployed with high density, such that each mobile target node is covered by a fairly large number of reference nodes, which may exacerbate the localization error for such applications. Therefore, a
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A hop-count method is implemented in order to locate the area of the target node.

Secondly, the RSS method is employed to compute the distance between the transmitter (target node) and the receiver (reference node) by utilizing a signal propagation model in order to translate the signal strength to a distance measurement. This involves the use of previous knowledge about the reference nodes’ positions and the deployment of a geometry method to estimate the location of mobile target nodes. Figure 3 depicts the concept of triangulating the mobile target’s location based on an RSS system.

The process of combining the hop localization system with the RSS system will increase localization accuracy. The proposed localization system is composed of four phases. In the first phase, the mobile target node broadcasts a “hello” packet in a single-hop communication. In the second phase, every reference node that receives a “hello” packet will transmit a localization packet, which includes the RSS value obtained from a mobile target node and its location information, to the mobile target node. In the third phase, the mobile target node estimates the area in which the mobile target is located by using the hop-count system, after which the mobile target estimates its current location more accurately using the RSS system. Finally, in the fourth phase, the estimated localization information is transmitted to the sink node. The flow chart for the hybrid localization system is presented in Figure 4.

Algorithm 1: Code runs on the mobile target node

1: let $M$ be a mobile target node
2: let $R_M$ be the set of reference nodes that hear $M$
3: let $\text{sink}$ be the sink node
4: let $\text{RSS}_{(r_i,M_j)}$ be the RSS value obtained from $r_i$
5: let $r_{(x,y)}$ be the 2-D coordinates for reference node $r$
6: let $M_{(x,y)}$ be the estimated location for $M$
7: $M$ broadcasts ‘hello’ in a single hop communication
8: loop: $\forall R_M$
9: if $(\text{RSS}_{(r_i,M_j)} \geq \theta_{\text{rss}})$
10: let $\alpha_i = \text{RSS}_{(r_i,M_j)}$
11: $i++$
12: end if
13: end loop
14: $M$ estimates its current location using $\alpha_i$
15: $M$ transmits its current location to sink node
16: Go to 6
17: end

In order to minimize the power consumption for the proposed localization algorithm, a localization function $f(l)$ is introduced and presented in Equation (1). The mobile target node needs to compare the RSS values obtained from every reference node that communicates with the mobile target node in a single hop. If the obtained RSS value is less than a certain
threshold (Equation (2)), then the RSS value is ignored and will not be taken into consideration in the localization process; otherwise, the RSS value will be saved and then employed in the localization process.

\[
f(i) = \begin{cases} 1: & \text{RSS}_{r_i, M_j} \geq \theta_{\text{rss}} \\ 0: & \text{RSS}_{r_i, M_j} < \theta_{\text{rss}} \end{cases}
\]  

(1)

\[
\text{RSS}_{r_i, M_j} \geq \theta_{\text{rss}}
\]  

(2)

\[
\theta_{\text{rss}} = \frac{\sum_{i=1}^{n} r_i}{n}
\]  

(3)

where \( r_i \) is the reference node number \( i \), and \( n \) is the total number of reference nodes set in the range of the mobile target node \( M_j \).

On the other hand, when using the hop-count localization system, the mobile target needs to transmit a single packet periodically (for instance, every 30 s) to the sink node in order to estimate its current area (the location area of mobile target, for instance, Area A). However, this increases the level of power consumption, given that more than one packet will be transmitted to the sink node via multi-hop communication, while the mobile target remains in the same precomputed area (Area A). Therefore, to minimize the total number of multi-hop messages, the mobile target node estimates its current location area every \( t_{\text{mh}} \) period of time, where \( t_{\text{mh}} \) is calculated using Equation (4).

\[
t_{\text{mh}} = \frac{s}{i}
\]  

(4)

where \( s \) is the average speed of the mobile target (about 5 km/h) and \( i \) is the intensity of the reference nodes in the localization area. Algorithm 2 shows the code runs on the reference node, while Algorithm 3 presents the code runs on the sink node.

Algorithm 2: Code runs on the reference node
1: let \( R \) be the set of reference nodes in the ZigBee network
2: let \( M \) be a target node
3: while (\( M \) communicates to \( r \) in one hop)
4: \( r \) transmits its current location to \( M \) every \( t_{\text{mh}} \)
5: end while
6: end

Algorithm 3: Code runs on the sink node
1: let \( R \) be the reference nodes in the ZigBee network
2: let \( M \) be a target node
3: let \( s \) be the sampling frequency rate
4: let \( \text{sink} \) be the sink node
5: every (sf)
6: sink node requests localization information from \( M \)
7: the estimated \( M_{\text{est}}((x,y)) \) is displayed to end-user
8: end

4. Experimental Evaluation

This section presents the experimental test bed used to implement the hybrid localization system. In addition, the results obtained from real experiments are presented and discussed.

4.1. Experiment setup

As presented in Figure 5, the experimental test bed (12×8 m) is composed of a single target node and nine reference nodes. The reference nodes are nodes with predefined 2D position coordinates, whereas the mobile target node is a sensor node with unknown 2D coordinates.

The XBee Series 2 module has been employed to implement the target and reference nodes, as it is an efficient in terms of cost and power consumption. Each sensor node (reference/mobile target) consists of a ZigBee transmission module and the ATTiny85 microcontroller, which is an energy-efficient module that is able to process and handle localization information. The designed reference node model is presented in Figure 6.

![Figure 5. Experimental test bed localization area.](image)

![Figure 6. Reference node model.](image)

In all experiments, the ZigBee protocol is adopted as a communication protocol. ZigBee is used to design personal area networks for home automation and remote control applications with low cost, low power consumption and low data rate wireless communication standards. In the ZigBee protocol, a sensor node can operate as either a Full Function Device (FFD) or a Reduced Function Device (RFD). An FFD has the role of initiating network formation and multi-hop routing of messages, whereas an RFD is intended for low-power operations [6].
In the experimental test bed, the mobile target node and reference nodes were implemented as an FFD. Table 1 shows the experimental test bed parameters.

Table 1. Experiment parameters.

<table>
<thead>
<tr>
<th>Parameter name</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of nodes</td>
<td>9</td>
</tr>
<tr>
<td>Average number hops</td>
<td>2</td>
</tr>
<tr>
<td>Experiment time</td>
<td>10 min</td>
</tr>
<tr>
<td>Sampling rate</td>
<td>5 s</td>
</tr>
<tr>
<td>Communication protocol</td>
<td>ZigBee</td>
</tr>
<tr>
<td>TX energy</td>
<td>0.46 mA</td>
</tr>
<tr>
<td>RX energy</td>
<td>0.47 mA</td>
</tr>
<tr>
<td>Transmission range</td>
<td>Very low (≈7 m)</td>
</tr>
</tbody>
</table>

### 4.2. Results

This section presents the evaluation findings for localization accuracy and power consumption under three different scenarios: namely, hop-count, RSS and hybrid. First, the positioning accuracy is estimated for the aforementioned three scenarios, where the localization error is tested in six different positions. In the localization experiment, the mobile target node is placed in different locations with known 2D coordinates (reference points), after which the mobile target node’s location is estimated (estimated location) based on the three scenarios. As shown in Figure 7, the hop-count system presents a high localization error (2.64 m) compared to the RSS and hybrid systems. This is explained by the fact that the hop-count system can only determine the presence of a mobile target node based on the adjacent reference nodes, which hear the mobile target node.

On the other hand, the implemented RSS system offers an average position error of 2.31 m as shown in Figure 8. This is because, in some cases, the mobile target node triangulates its location using more than three reference nodes, which exacerbates the localization error, while the proposed hybrid localization algorithm offers an average positioning error of 1.42 m, as presented in Figure 9. Hence, the proposed hybrid localization system offers better localization accuracy than the RSS-based and hop-count positioning methods.

Secondly, the power consumption is evaluated. The total numbers of exchanged packets is estimated in order to evaluate the total energy consumption for reference nodes. The average number of exchanged packets \( m_{\text{packets}} \) is estimated using Equation (5).

\[
\text{Equation (5)}
\]

When conducting real experiments, the total number of exchanged messages in the hop-count system is almost equal to the exchanged messages in the RSS system, as presented in Figure 10, given that each reference node that hears the target node will transmit a localization packet to the sink node. The RSS system requires more energy than the hop-count system because, unlike the hop-count system, the RSS reference nodes are required to process localization information before transmitting it to the sink node.

The hybrid system proposed in this paper offers the minimum number of exchanged messages among reference nodes. This is because the target node triangulates its current location based on three references nodes, even if the target node is in the range of more than three reference nodes. Moreover, the hybrid system offers low power consumption, since a low number of messages will be exchanged. Figure 11 presents the average power consumption for each reference node in the three scenarios.
Table 2 presents the average localization error, number of exchanged packets and power consumption for the three systems. The hop-count algorithm presents the highest localization error, since the mobile target’s location is estimated using the number of hops between the sink node and the mobile target node.

Table 2. Comparison of the hop-count, RSS and hybrid algorithms.

<table>
<thead>
<tr>
<th>Localization algorithm</th>
<th>Localization error (meter)</th>
<th>Power consumption</th>
<th>No. # of exchanged packets</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hop-count</td>
<td>2.64</td>
<td>1908 mA</td>
<td>254</td>
</tr>
<tr>
<td>RSS</td>
<td>2.31</td>
<td>1256 mA</td>
<td>238</td>
</tr>
<tr>
<td>Hybrid</td>
<td>1.42</td>
<td>1194 mA</td>
<td>164</td>
</tr>
</tbody>
</table>

5. Conclusions and Future Work

In this paper, a hybrid range-free localization approach for ZigBee WSNs has been proposed, implemented and tested. The proposed system has been validated using real experiments, with the results proving that the use of the hybrid range-free system offers better localization accuracy than when using the RSS system or hop-count system individually. The proposed hybrid system is efficient in terms of localization accuracy, power consumption and cost. There is no requirement to employ any additional sensor device for reference or mobile target nodes, which in turn minimizes the total cost for WSN localization systems. In terms of future work, we intend to improve the localization accuracy by adopting other efficient localization methods.

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References


