Postprint of Localization Algorithm Based on Secondary Grid Scanning and Anchor Node Decremental Grid Scanning

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Abstract

To enhance the localization accuracy of wireless sensor networks, further improvements are proposed based on the Grid-Scan algorithm. The method first employs a two-stage grid scanning process to determine an initial localization point and generate a reduced localization region. Within this contracted region, distances between neighboring anchor nodes and the initial localization point are converted into theoretical signal strength values. These theoretical values are then compared with the actual signal strength received by neighboring anchor nodes from the unknown node, enabling a conditional decrement of anchor nodes. This process yields a decremental anchor node grid scanning rule that ultimately determines the estimated position of the unknown node. Comparative simulation experiments demonstrate that the improved localization algorithm enhances localization accuracy to a certain extent.

Full Text

A Localization Algorithm Based on Two-Stage Grid Scanning and Anchor Node Decremental Grid Scanning

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Abstract: To improve the positioning accuracy of wireless sensor networks, this paper proposes further improvements to the Grid-Scan algorithm. The method first employs two-stage grid scanning to determine an initial location estimate and generate a reduced positioning region. Within this reduced region, distances between neighbor anchor nodes and the initial location estimate are converted to theoretical signal strength values, which are then compared with the actual signal strength received from the unknown node. This comparison enables a conditional decrement of neighbor anchor nodes, yielding a decremental anchor node grid scanning rule that ultimately determines the estimated position of the unknown node. Simulation experiments demonstrate that the improved localization algorithm enhances positioning accuracy to a certain extent.

Keywords: wireless sensor networks; Grid-Scan algorithm; two-stage grid scanning; signal strength; decremental

0 Introduction

Many applications and protocols in wireless sensor networks (WSN) rely on node location information, making node localization one of the core supporting technologies of WSN [1]. Localization refers to determining the positions of unknown nodes based on a subset of nodes with known locations (anchor nodes) [2]. Current localization algorithms can be categorized into range-based and range-free algorithms according to whether they require actual distance measurements between nodes during the positioning process [3].

Range-based localization algorithms calculate the distance or direction between unknown nodes and neighboring beacon nodes through communication, enabling node self-localization [4]. Classic algorithms include Received Signal Strength Indication (RSSI)-based ranging, Time of Arrival (TOA)-based ranging, and Time Difference of Arrival (TDOA)-based ranging [5,6]. These algorithms typically achieve high positioning accuracy through precise distance or angle calculations but consume significant node energy, impose stringent hardware requirements, and substantially increase network computational and communication costs [7,8]. To address these limitations, numerous range-free localization algorithms have been proposed, with typical examples including the Approximate Point-in-Triangulation (APIT) test, centroid algorithm, and DV-Hop algorithm [9,10]. Range-free algorithms leverage node proximity relationships and connectivity for localization, offering low cost and positioning accuracy sufficient for most applications with high cost-effectiveness, thus gaining wide adoption. Among them, the Grid-Scan algorithm is a typical range-free localization algorithm proposed within the APIT framework, which divides the target area into square grids and selects the most appropriate grid to calculate its centroid as the estimated position of the unknown node. Scholars have conducted extensive improvement work on range-free localization algorithms [11]. Reference [12] utilized connectivity constraint information between unknown nodes and anchor nodes within two-hop range, introducing distant nodes for secondary grid scanning to effectively improve positioning accuracy. This paper optimizes the initial estimated position through two-stage grid scanning, compares actual received signal strength with theoretical signal strength values, derives an anchor node decrement rule, and employs anchor node decremental scanning to reduce the localization region, thereby decreasing localization error to a certain extent.

1 Grid-Scan Algorithm Description

The Grid-Scan algorithm is a typical range-free localization algorithm proposed within the APIT framework [13]. The algorithm consists of three steps [14]:

a) **Network Deployment:** Unknown nodes to be localized search for all anchor nodes within their communication range and record the ID and coordinate information of discovered anchor nodes, which are referred to as neighbor anchor nodes.

b) **Estimative Rectangle Generation:** The intersection of communication circles of all neighbor anchor nodes of unknown node O is approximated by its circumscribed rectangle, yielding the Estimative Rectangle (ER). As shown in [Figure 1: see original paper], the four sides of ER are parallel to the x-axis and y-axis. The size of ER is determined by Equation (1).

c) **Grid Partitioning and Unknown Node Coordinate Calculation:** Let the grid edge length be l, the length of ER be $L \times l$, and the width be $W \times l$. Then ER can be represented as a collection of $L \times W$ grids, as shown in Equation (2). All grids in the network are initially assigned a value of 0. If both grid G_m in ER and its center C_m are located within the communication range of N neighbor anchor nodes, then grid G_m is assigned a value of N. The region composed of all grids with the maximum value in ER corresponds to an estimated region E_j for an unknown node. As shown in Figure 1: see original paper, the region composed of grids with the maximum value is the estimated region E_j. Finally, the centroid of this estimated region E_j is calculated to localize the unknown node.

2.1 Algorithm Principle

Through research on the Grid-Scan localization algorithm, this paper observes that in randomly generated network topologies, the actual position of an unknown node may lie within a circle centered at the estimated position with a radius equal to the distance to neighbor anchor nodes. By performing secondary grid scanning, a new initial estimated position is obtained, and conditional decrement of neighbor anchor nodes is achieved, completing the algorithmic improvement.

2.2 Two-Stage Grid Scanning Method

First, the initial position estimate of an unknown node is obtained from neighbor anchor node location information. Then, using the coordinate information of the nearest anchor node and the initial position estimate, a smaller and more precise position estimation region for the unknown node is derived. Secondary grid scanning of this region yields a new initial estimated position. The two-stage grid scanning algorithm consists of three phases:

2.2.1 Initial Position Estimation

Let the number of neighbor anchor nodes for an unknown node be N. After rasterizing the monitoring region and completing grid assignment within the unknown node' s ER region using the traditional Grid-Scan algorithm, all grids in region E_j assigned with value N are obtained, yielding the initial position estimate coordinates (x_{t0}, y_{t0}).

2.2.2 Relocatability Determination

Since the two-stage grid scanning algorithm utilizes only the nearest anchor node, situations may arise where relocation is impossible. Therefore, it is necessary to determine whether an unknown node can be re-localized. The signal strength from all neighbor anchor nodes to the unknown node is calculated. Let the signal strength received by the unknown node from all neighbor anchor nodes be RSS, and the anchor node corresponding to the maximum signal strength RSS_u in RSS is identified as the nearest anchor node. The distance $dist$ from the initial position estimate to the nearest anchor node is calculated using Equation (3).

Scanning is performed with the nearest anchor node as the center and the distance between the nearest neighbor anchor node and (x_{t0}, y_{t0}) as the radius. This radius is converted to a signal strength value using Equation (4). When the signal strength value received by the nearest neighbor anchor node from the unknown node is greater than the signal strength value derived from the distance between the nearest neighbor anchor node and the initial position estimate point, the unknown node is determined to be within the communication circle centered at the nearest anchor node with radius equal to the distance between the nearest neighbor anchor node and (x_{t0}, y_{t0}). Satisfying this condition indicates that the unknown node is relocatable. When $RSS_u > RSS_e$, the unknown node is deemed relocatable; conversely, when the signal strength value received by the nearest neighbor anchor node from the unknown node is less than or equal to the signal strength value derived from the distance between the nearest neighbor anchor node and the initial position estimate point, the unknown node is determined to be outside the communication circle, i.e., when $RSS_u \leq RSS_e$, the unknown node is deemed non-relocatable.

2.2.3 Localization Region Reduction

For relocatable unknown nodes, two-stage grid scanning is performed. The distance D from all grid centers C_m in region E_j to the nearest anchor node is calculated using Equation (5). When $d_m > dist$, the corresponding value in $Grid$ remains unchanged; when $d_m < dist$, the grid value corresponding to d_m in $Grid$ is set to $N+1$. The collection of grids assigned value $N+1$ is denoted as $Gridmap$, which generates a new estimated region EN_j. The centroid of EN_j is calculated to obtain the optimized initial estimated position.

As shown in [Figure 2: see original paper], assume an unknown node has three neighbor anchor nodes A_1, A_2, and A_3 with intersection region E_j, where A_1 is the nearest anchor node. The initial position estimate is obtained within region E_j, yielding $Grid$ with grids assigned value 3. Using the distance $dist$ from the initial position to A_1 as the radius, grid scanning of region E_j produces estimated region EN_j, where grid values are incremented by 1 from their values in $Grid$. The collection of grids in region EN_j assigned value 4 is denoted as $Gridmap$, from which the re-localization coordinates are calculated.

2.3 Decremental Anchor Node Scanning Method

The decremental anchor node scanning method using the initial algorithm's estimated position as the initial centroid is denoted as NGrid-Scan algorithm, while the method using the two-stage grid scanning estimate as the initial centroid is denoted as TNGrid-Scan algorithm.

In practice, the monitoring region is first rasterized. Let the neighbor anchor nodes of an unknown node be AN, and let the maximum-valued grid within ER obtained through the initial algorithm or two-stage grid scanning be C, as shown in Equation (6). Let the centroid coordinates of C_h be (x_{Ch}, y_{Ch}), the centroid coordinates derived from C be (x_f, y_f), the grid edge length be l, and the anchor node matrix be AN, as shown in Equation (7).

The distance NF between neighbor anchor node AN and (x_f, y_f) is calculated using Equation (8). Substituting NC_i into Equation (3.1) yields the theoretical signal strength value $RSSN$ received by neighbor anchor node N_i at coordinates (x_f, y_f), as shown in Equation (9).

In practical scenarios within a network calibrated by BP neural networks, when the signal strength RSS_{ji} received by neighbor anchor node N_i from unknown node U_j satisfies $RSS_{Ni} > RSS_{ji}$, that anchor node is discarded. When the theoretical signal strength $RSSG_{hj}$ obtained by substituting the distance between grid C_h and anchor node into Equation (3.1) satisfies $RSSG_{hj} > RSS_{Ni}$, the value of grid C_h is assigned once more, and a surrogate node is generated for the next round of anchor node decremental scanning. This yields the grid $Grip$ after anchor node decremental scanning assignment, as shown in Equation (10). The elements of $Grip$ originate from C, with the number of elements in $Grip$ being less than or equal to that in C. As shown in [Figure 3: see original paper], grids assigned value 7 represent the maximum-valued grids obtained through neighbor anchor node decremental scanning. The centroid of these maximum-valued grids is calculated as the final localization point of the algorithm.

3.1 Experimental Design

The experiments in this paper are conducted on the MATLAB platform. The number of nodes is set to $Node$, and random topology scenarios are generated within a 100×100 m monitoring region. Node communication radius is r, grid edge length is l, node transmission signal power $P_T = 0$ dB, reference distance

$d_0 = 1$ m, path loss power at reference distance $P_L(d_0) = 55$ dB, and path loss exponent $\eta = 4$. The proposed two-stage grid scanning and anchor node decremental grid scanning localization algorithm is abbreviated as TNGrid-Scan. For comparison, the initial grid scanning algorithm, two-stage grid scanning algorithm, anchor node decremental grid scanning localization algorithm, the algorithm from reference [12], and the algorithm from reference [15] are abbreviated as Grid-Scan, TGrid-Scan, NGrid-Scan, SGrid-Scan, and VGrid-Scan, respectively. The VGrid-Scan algorithm adopts the anchor node communication radius setting method from reference [15], configured as 0.7 times the node communication radius.

The normalized average relative localization error of unknown nodes in the network is calculated using Equation (11), where (x_{es}, y_{es}) represents the localization coordinates of an unknown node, (x_t, y_t) represents the actual coordinates of an unknown node, r represents the node communication radius in the network, n_u represents the number of localizable unknown nodes, and k represents the number of randomly generated network deployments (normalization iterations). In the experiments, the normalization iteration count $k = 100$, meaning 100 random node deployments are generated, and n_r is the number of localizable nodes.

To ensure comparability of simulation errors for the improved algorithm, each randomly generated network topology scenario is provided to all six algorithms for simulation, ensuring that localization error calculations are performed under identical environmental conditions and enhancing the reliability of experimental data comparisons.

3.2 Influence of Communication Radius on Localization Error

Equation (1) demonstrates that node communication radius can affect the size of the unknown node' s circumscribed rectangle, thereby influencing the number of neighbor anchor nodes. With $Node = 200$, anchor node count = 40, and grid edge length $l = 2$ m, the simulation results are shown in [Figure 4: see original paper].

As illustrated in [Figure 4: see original paper], the localization error of all algorithms decreases as communication radius increases, with anchor node decremental algorithms demonstrating significantly better accuracy improvement and lower error than other methods. The TNGrid-Scan algorithm reduces localization error by an average of 0.614% compared to NGrid-Scan, 6.863% compared to TGrid-Scan, 7.7% compared to VGrid-Scan, 10.95% compared to Grid-Scan, and 5.17% compared to SGrid-Scan.

3.3 Influence of Anchor Node Count on Localization Error

Anchor node density affects the number of neighbor anchor nodes, which in turn influences the size of the estimated region E_j. With $Node = 200$, node communication radius $r = 20$ m, and grid edge length $l = 2$ m, the simulation results are shown in [Figure 5: see original paper].

As depicted in [Figure 5: see original paper], the localization error of all algorithms gradually decreases as anchor node count increases. The TNGrid-Scan algorithm reduces localization error by an average of 0.634% compared to NGrid-Scan, 5.62% compared to TGrid-Scan, 6.36% compared to VGrid-Scan, 9.63% compared to Grid-Scan, and 5.03% compared to SGrid-Scan.

3.4 Influence of Node Count on Localization Error

Total node count is a crucial parameter for measuring network density. Therefore, the impact of total node count on the localization performance of the six algorithms is simulated. With node communication radius $r = 20$ m, anchor node count $= 0.2N$, and grid edge length $l = 2$ m, the simulation results are shown in [Figure 6: see original paper].

As shown in [Figure 6: see original paper], as node count increases and network density grows, the localization error of all algorithms decreases accordingly. The TNGrid-Scan algorithm reduces localization error by an average of 0.71% compared to NGrid-Scan, 5.27% compared to TGrid-Scan, 6.14% compared to VGrid-Scan, 9.32% compared to Grid-Scan, and 3.91% compared to SGrid-Scan.

3.5 Influence of Grid Edge Length on Localization Error

The Grid-Scan algorithm' s localization principle indicates that grid edge length affects the number of grids on the edge of estimated region E_j, thereby influencing the centroid position of E_j. With $Node = 200$, anchor node count $= 40$, and node communication radius $r = 20$ m, the simulation results are shown in [Figure 7: see original paper].

As illustrated in [Figure 7: see original paper], the localization error of all six algorithms decreases as grid edge length decreases. The TNGrid-Scan algorithm reduces localization error by an average of 0.94% compared to NGrid-Scan, 2.87% compared to TGrid-Scan, 5.50% compared to VGrid-Scan, 6.41% compared to Grid-Scan, and 3.89% compared to SGrid-Scan. As grid edge length increases, the localization errors of all algorithms converge, though TNGrid-Scan consistently maintains superior positioning accuracy.

4 Conclusion

This paper optimizes the initial localization of unknown nodes through two-stage grid scanning, then derives an anchor node decremental scanning rule by comparing theoretical signal strength values with actual received signal strength.

Through conditional decrement of neighbor anchor nodes, the localization region for unknown nodes is reduced, ultimately achieving the two-stage grid scanning and anchor node decremental grid scanning localization algorithm, which effectively decreases localization error. Simulation results demonstrate that under varying conditions of communication radius, anchor node count, node count, and grid edge length, the proposed algorithm consistently reduces the average relative localization error.

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