An Efficient Geometric Localization Approach

for Distributed Sensor Networks\*

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Localization is a fundamental problem in wireless sensor networks. Many app- roaches, including range-based and range-free techniques, have been proposed to determine the optimal location for sensor nodes. This paper presents a simple range-free localization scheme that is based on received signal strength indicator (RSSI) geometric localization for wireless sensor networks. The node locations are computed by performing simple geometric calculations that rely on the specific approximate RSSI values with the position of a mobile beacon equipped with a global positioning system. The simulation results showed that the proposed scheme is efficient, and that the node positions can be determined accurately.

***Keywords:*** wireless sensor networks, localization, mobile beacon, mobile anchor, RSSI

**1. Introduction**

Wireless sensor networks have wide application in fields such as home, industry, environmental observation, military monitoring, and disaster relief [1]. Recent advances in wireless communications and electronics have enabled the development of small low- cost sensor nodes that communicate over short distances. Wireless sensor networks are comprised of several sensor nodes that communicate via wireless technology.

**2. Theoretical RSSI Model**

Recently, most of the proposed localization schemes are based on RSSI technique but the RSSI signal propagation models easily suffer from outer uncertain influences, such as signal fading, non-uniform spreading, and reflections. An RSSI-based approach therefore needs more data than other methods to achieve higher accuracy.

Assume that a sensor network consists of *N* nodes in total. Based on the path-loss model, the RSSI measured in dBm (decibels and referenced to 1mW) unit *Pij* for the signal transmitted from node *i* to node *j* can be expressed as

 🡨Equations should be typed in Mathtype (1)

for 1 ≤ *i* ≤ *N* , 1 *≤ j ≤ N*, and *i* ≠ *j*, (🡨symbol should be typed in this standard) where *P*0 is the RSSI measured in dBm at one meter distance, *dij* is the distance between node *i* and node *j* (*dij ≥* 1m), and the parameter *α* is distance–power gradient also known as pathloss exponent [8]. The independent and identically-distributed random variables *νij* ~*N*(0, *σν*2) represent log-normal shadow-fading effects in complex multipath environments, whereas the value of standard deviation (STD) *σν* depends on the characteristics of the specific environment. In the literature, pathloss measurements are usually considered to be reciprocal, *i.e.*, *Pij* = *Pji* for *i* = *j*, when the transmit powers are identical.

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**3. Design of the RGL Scheme**

This section explicitly details the processing of the proposed received signal streng- th indicator RSSI-based geometric localization (RGL) scheme. Specific problems regarding error analysis and approaches to avoiding obstacles are examined, and the proposed scheme is refined.

**3.1 Preliminaries**

Assume that the transmission range of each sensor node is a circle with radius *r*. Because real environments tend to be irregular, a minimal bounding rectangle (MBR) is adopted to implement the proposed scheme. Assume that the sensor nodes are deployed in a square with side *Range* (Fig. 1). The coordinates of the upper-left corner are set at (0, 0), and those of the lower-right corner at (*Range*, *Range*).

In RGL scheme, the mobile beacon is an anchor point with an accurately known position. Additionally, it is a self-propelled device that is equipped with a GPS. The bea- con adopts a predefined trajectory to traverse the deployed area.

Fig. 1. The coordinator plane of RGL. Fig. 2. Processing of locating a sensor node.

Next, as the beacon moves along a line toward a sensor node, it periodically broadcasts packets containing its localization and current path number. The path number is recorded the identity path with the same path number from a boundary side to the other. Besides, the path number is critical for accurately identifying its position.

**3.2 Mobile Anchor Path Planning**

In [12], two path-planning schemes were proposed for a mobile anchor node in a localization scheme, namely H-SCAN, V-SCAN and DOUBLE SCAN. In SCAN, the mobile anchor node traverses a single dimension (*e.g.*, the *x*- or *y*-axis). However, the collinearity of the beacon degrades the accuracy of the localization results. In DOUBLE SCAN, the collinearity problem is resolved when the mobile anchor moves in both the *x*- and the *y*-directions, but the energy overhead increases accordingly. An alternative path planning scheme named TRIANGLE was proposed for the mobile anchor node based on the trilateration localization scheme. The main advantage of the triangular trajectory is that it solves the collinearity problem.

Another typical trajectory that can be adopted for the mobile beacon is the random waypoint model (RWP) [3]. The beacon randomly selects a destination in the sensor field, and then moves to that location at a constant velocity. When the beacon arrives, it continues traversing to the subsequent destination at a constant speed by rotating its trajectory angle. In a normal state, RWP model is the typical trajectory route of a mobile beacon in RGL scheme. In Section 4, the five path plannings, H-SCAN, V-SCAN, DOUBLE SCAN, TRIANGLE and RWP, are employed to perform the comparison and evaluate the results in our simulations.

**3.3 Processing of the RGL Scheme**

The sensor nodes within the transmission range of the beacon receive and record the packet information into local memory. The beacon periodically broadcasts packets containing at least two main fields (*i.e.*, current path number and position) as it traverses at a constant velocity *v*. The beacon transmission interval time between two consecutive beacon messages is denoted as *t*. In each phase, the beacon moves a fixed distance *d*, which implies *d* = *v**t*.

As shown in Fig. 2, a sensor node’s real position is *p*3. When the beacon traverses a straight line, the largest RSSI value received by a sensor node corresponds with the point on the line that is closest between the beacon and sensor node. Theoretically, this point should be the projection of the node along the line. As the beacon is at position *p*2, the sensor node identifies the largest RSSI value by comparing with others receiving RSSI having the same path number from its local storage, and this position is denoted *RSSIMAX*. Furthermore, position *p*1 (*i.e.*, the position preceding *p*2, denoted *PreRSSIMAX*) must also be acquired. Subsequently, *h* indicates the distance from *p*2 to *p*3, which is derived from the maximal RSSI value, and *d* is the moving distance of mobile beacon from *p*1 to *p*2. In an ideal model, *RSSIMAX* (*i.e.*, *p*2) is assumed as the perpendicular intersection point of *d* and *h*. Thus, a right triangle can be constructed based on *d*, *h*, *p*1, *p*2,and *p*3 (Fig. 2).

Points *p*1(*x*1, *y*1), *p*2(*x*2, *y*2), and *p*3(*x*3, *y*3), and distances *d* and *h* can be expressed as the following bivariate quadratic equations:

 (2)

In Eq. (2), the values of (*x*1, *y*1), (*x*2, *y*2), *d*, and *h*, are known, whereas the values for (*x*3, *y*3) are unknown. Thus, the solution for *p*3 can be computed by Eq. (2), which obtains the two values (*x*3, *y*3) and (*x*3*'*, *y*3*'*), one of which is the correctly estimated position of a node.

**4. Performance Evaluation**

This section verifies the accuracy and reliability of the proposed scheme through simulation and comparison of the performance with several well-known schemes.

**4.1 Simulation Environment**

Using the RSSI scheme, the distance between the sensor node and a mobile beacon is measured by virtue of the received signal strength depends on the distance.

To determine the RSSI path-loss model for our simulation, we employ the theoretical RSSI model in Eq. (1) to calculate the receiving power. Then the converted distance in meters with the receiving power is obtained by the following equation from the IEEE 802.15.4 [23]

 (4)

where *Pt* is the transmit power and *Pr* is the receive power. The length of 8mis the longest length at which there is no reflection of a signal where has no walls and no obstacles.

The simulation was built using a MATLAB simulator. The collisions are not discussed under the assumption that they can be solved using MAC layer protocols, and the signals can be received only in LOS propagation. In simulation, we derived a transmit power value by a real distance in Eq. (4) and we can obtain a simulated distance by applied this transmit power value in Eq. (1). Each node was forced to remain active during the localization. The sensor nodes were deployed in an effective 300 × 300m area that was free from obstacles, and 100 sensor nodes were randomly deployed as a Gaussian distribution. In addition, the degree of irregularity (DOI) in the radio propagation model was applied in the simulation to determine whether the proposed scheme would be practical [16].

**4.2 Simulation Parameters**

The simulation parameters for the mobile beacon were the transmission radius *r*, results, the four path-planning traversing trajectories adopted for the simulation were SCAN, DOUBLE SCAN, TRIANGLE, and RWP.

**4.3 Metrics**

The following metrics were employed to evaluate the performance of the proposed localization scheme.

(A) Average localization error

Average localization error was estimated based on the mean error (ME). ME is defined as the mean difference between estimated location (*x*′, *y*′) and actual location (*x*, *y*) for all sensor nodes  where *N* denotes the total number of sensor nodes.

(B) Average execution time

Average execution time was defined as the time required to localize all sensor nodes

as where *ti* denotes the time required for node *i* to identify its location, and *N* denotes the total number of sensor nodes.

(C­) Average throughput

Average throughput is defined as the total number of packets transmitted by the mo-

bile beacon and received by all nodes where *pi* denotes the number of pac- kets received by node *i*, and *N* denotes the total number of sensor nodes.

(D) Average energy consumption

Most of the energy was consumed by the sensor node computations. The average energy consumption was defined as the total time for each node to compute its position

as where *ei* denotes the time required for node *i* to compute its location, and *N* denotes the total number of sensor nodes.

**4.4 Simulation Results**

The simulation results are discussed based on the following three factors: (1) steady state; (2) parameter observation; and (3) DOI affection.

(A) Steady state

Based on identical test conditions, 10 tests were randomly selected and conducted using different data sets and four path-planning schemes. Table 1 shows the experimental results.

(B) Parameters observation

Here, the various effects among the three parameters in Section 4.2 are discussed. First, the results are examined for the average localization error versus moving distance *d* = 3, 6, 9, 12, and 15 m, where *r* = 15m, and RWP was adopted with various DOI values (Fig. 7 (a)). In Fig. 7 (a), DOI = 0 represents an ideal environment without DOI.

**Table 1. The average localization errors by different path planning.**

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
|  | H-Scan | V-Scan | Double Scan | Triangle | RWP |
| 1 | 0.869 | 1.058 | 0.802 | 1.739 | 0.783 |
| 2 | 0.882 | 1.089 | 0.852 | 1.648 | 0.951 |
| 3 | 0.910 | 0.844 | 0.805 | 1.619 | 0.813 |
| 4 | 1.046 | 0.823 | 1.085 | 1.780 | 0.777 |
| 5 | 1.068 | 0.818 | 0.825 | 1.636 | 0.752 |
| Ave | 0.937 | 0.923 | 0.881 | 1.694 | 0.818 |

Subsequently, the simulations were examined regarding average localization errors versus the transmission radius *r* = 10, 15, 20, 25, and 30m (*d* = 3m, RWP was adopted with various DOI values; Fig. 7 (b)). The results showed that the average localization error gradually increased in conjunction with *r*. This shows that increasing the transmission radius to the cover maximal area increases the probability of RSSI errors, thereby reducing the localization accuracy.

Finally, the simulation results for the path-planning schemes were observed. The simulation was run to test the average localization error versus the traversing trajectories H-SCAN, V-SCAN, DOUBLE SCAN, TRIANGLE, and RWP (*r* = 15m, *d* = 3m, various DOI values as shown in Fig. 7 (c). The result revealed that the TRIANGLE trajectory was less accurate than the others. The reason is the probability of the sensor nodes receiving the packets from the beacon decreasing when the TRIANGLE trajectory is applied.

(C) DOI affection

Section 4.1 shows that the DOI model was practical. The simulations were performed for the average localization error versus the parameters and traversing trajectories, where DOI = 0.0, 0.2, 0.4, 0.6, and 0.8 (Figs. 7 (a)-(c)). No obvious difference was observed among the various DOI values. This occurred because the RSSI in the irregular region was temporarily missing, although a referable RSSI could be acquired if the signals fell into the regular region. Therefore, the DOI is incremental, and the ME is not obviously greater.

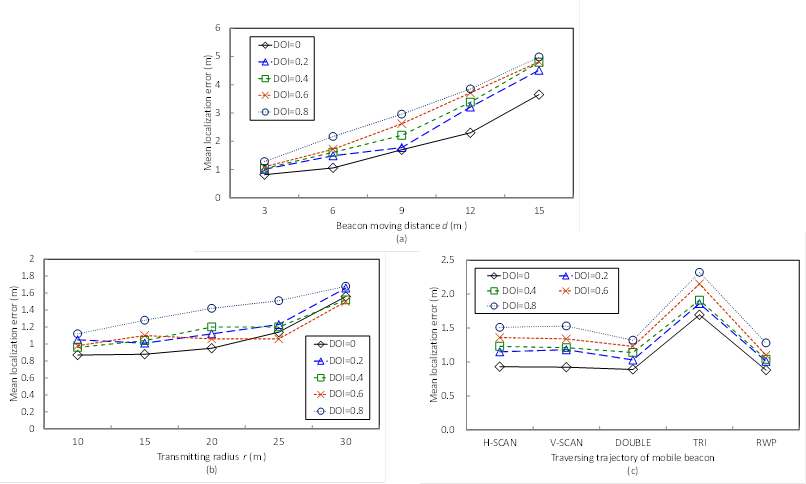


Fig. 7. Average location error versus metrics with different DOI (a) moving distance *d*; (b) radius *r*; (c) traversing trajectory.

**4.5 Scheme Evaluation and Comparison**

In this section, the performance is evaluated, and the proposed RGL scheme is compared with several well-known RSSI-based schemes that have been cited frequently. In TRI [7], the beacon information from the three vertices of the locating virtual triangle in which the node resides was used to calculate the location. A maximum-likeli- hood (ML) estimation method was applied to calculate 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 minimal average square error (MMSE) [15], which requires three or more sensor nodes to determine the target’s position. Guo proposed a scheme for estimating the position of a target by comparing the RSSI values on a sensor node, and exploiting the geometric relationship between the node and the trajectory of the mobile beacon. All three schemes employed a mobile-assisted localization approach.

(A) Effect of the average localization error

The simulation results in these schemes were evaluated based on the four metrics discussed in Section 4.3, and then compared with various parameters discussed in Section 4.4. Table 2 shows the effect of the metrics where *d* = 3, 6, 9, 12, and 15 m (*r* = 15m, RWP was adopted where DOI = 0). Table 3 shows the effect of the metrics when *r* = 10, 15, 20, 25, and 30m (*d* = 3m, RWP was adopted when DOI = 0). Table 4 shows the effect of metrics on the traversed trajectories SCAN, DOUBLE SCAN, TRIANGLE, and RWP). Guo’s scheme adopted the TRIANGLE only.

**Table 2. Performance for different moving speed ( *r* = 15m, RWP and DOI = 0).**

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Moving speed (m/sec) | | 3 | 6 | 9 | 12 | 15 |
| Beacon interval (sec) | | 1 | 1 | 1 | 1 | 1 |
| Average  location  error (m) | TRI | 1.71 | 1.92 | 1.95 | 2.06 | 2.27 |
| ML | 1.13 | 1.47 | 1.75 | \*1.82 | \*2.04 |
| Guo | 1.54 | 2.53 | 3.82 | 8.56 | 10.25 |
| RGL | \*0.82 | \*0.96 | \*1.74 | 2.32 | 3.65 |
| Average  execution  time (sec) | TRI | 7871 | 4384 | 3493 | 3214 | 2734 |
| ML | 7788 | 4291 | 3292 | 2323 | 2278 |
| Guo | \*5067 | \*3048 | \*2040 | \*2040 | \*1032 |
| RGL | 7460 | 4290 | 3756 | 4405 | 5416 |
| Average  throughput | TRI | 47.21 | 23.73 | 21.86 | 20.32 | 17.26 |
| ML | 50.73 | 24.95 | 20.03 | 16.52 | 15.86 |
| Guo | \*17.92 | \*10.46 | \*6.97 | \*6.92 | \*3.21 |
| RGL | 46.93 | 22.85 | 21.72 | 27.53 | 30.44 |
| Average  energy  consumption | TRI | 15.84 | 16.53 | 12.12 | 11.55 | 11.76 |
| ML | 12.46 | 12.84 | 12.44 | 10.96 | 10.64 |
| Guo | \*6.72 | \*6.29 | \*6.39 | \*6.45 | \*6.28 |
|  | RGL | 9.48 | 11.72 | 13.11 | 14.24 | 15.36 |

\* is the best value

The simulations were performed for these schemes to determine the average localization errors (Tables 2, 3, and 4). The simulation results showed that the RGL scheme nearly outperformed the other schemes based on the average localization error.

Table 2 shows that identical results were obtained for all schemes; specifically, the average localization error gradually increased in conjunction with the moving distance. However, the proposed RGL scheme outperformed the other schemes when *d* < 9 m. By increasing *d*, fewer RSSI values were received from the beacon, thereby reducing the localization accuracy. Guo’s scheme obtained similar results to those of the RGL. The TRI and ML schemes were less likely to be affected because both were more sensitive to the error caused RSSI value generally. For Guo’s scheme, when similar values were applied to *d* and *r*, the errors increased rapidly.

The simulation results in these schemes were evaluated based on the four metrics discussed in Section 4.3, and then compared with various parameters discussed in Section 4.4. Table 2 shows the effect of the metrics where *d* = 3, 6, 9, 12, and 15 m (*r* =15m, RWP was adopted where DOI = 0). Table 3 shows the effect of the metrics when *r* = 10, 15, 20, 25, and 30m (*d* = 3m, RWP was adopted when DOI = 0). Table 4 shows the effect of metrics on the traversed trajectories SCAN, DOUBLE SCAN, TRIANGLE, and RWP). Guo’s scheme adopted the TRIANGLE only.

Finally, Table 4 shows that all of these schemes obtained identical results; specifically, the average localization error was less likely to be affected by the any traversing trajectory except for TRIANGLE. Because Guo inherently adopts the TRIANGLE trajectory, the other three trajectories were ignored. The proposed RGL scheme was less accurate than Guo’s scheme for the TRIANGLE trajectory because the probability of the sensor nodes receiving packets from the beacon is lower; consequently, the accuracy was lower. However, when adopting the TRIANGLE scheme, the average localization error of the RGL scheme is comparable with that of Guo’s scheme.

(B) Effect of the average execution time

Tables 2-4 show the average execution time simulation results for all schemes. The TRIANGLE trajectory is inherently the shortest route; hence, the average execution time of Guo’s scheme is less than that of the other schemes. However, the average localization error is not the minimal relatedly. Otherwise, TRI, ML and RGL obtained similar average execution times, although those for RGL are more accurate.

Table 2 shows that increasing the constant velocity increases, the average execution time decreases. When the beacon packet transmission interval is fixed and the speed varies, the mobile beacon traverses a fixed distance to broadcast the packets. Table 3 shows that all of these schemes obtained identical results; specifically, the execution time gradually decreased when the transmitted radius increased. This occurred because a larger radius covers a greater area; thus, more nodes received the localization information.

**Table 3. Performance for different transmitting radius (*v* = 3m/sec, *t* = 1sec, RWP).**

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Radius range (m) | | 10 | 15 | 20 | 25 | 30 |
| Average  location  error (m) | TRI | 1.47 | 1.71 | 2.6 | 3.24 | 4.02 |
| ML | 1.04 | 1.13 | 1.43 | 1.62 | 2.87 |
| Guo | 1.63 | 1.54 | 1.65 | 1.67 | 1.62 |
| RGL | \*0.87 | \*0.82 | \*0.95 | \*1.14 | \*1.56 |
| Average  throughput | TRI | 35.76 | 47.21 | 66.74 | 89.23 | 116.73 |
| ML | 36.23 | 50.73 | 65.12 | 85.48 | 99.75 |
| Guo | \*10.54 | \*17.92 | \*21.37 | \*27.71 | \*37.07 |
| RGL | 34.91 | 46.93 | 64.86 | 85.38 | 90.12 |
| Average  energy  consumption | TRI | 15.39 | 15.84 | 12.78 | 14.91 | 15.63 |
| ML | 13.76 | 12.46 | 14.36 | 14.08 | 12.14 |
| Guo | \*6.28 | \*6.72 | \*6.78 | \*6.86 | \*6.96 |
| RGL | 10.72 | 9.48 | 9.52 | 10.2 | 10.76 |

\* is the best value

Similarly, Table 4 shows identical results for all schemes. Because the V-SCAN, H- SCAN, DOUBLE SCAN, and TRIANGLE trajectories have a fixed traversing time, the only remarkable difference was observed for RWP. Collectively, the simulation results in Tables 2, 3, and 4 show that the average execution time for the RGL scheme was superior to that of all of the other schemes except Guo.

(C) Effect of the average throughput

Tables 2-4 show the average throughput simulation results for the discussed schemes. Among the schemes, Guo’s scheme obtained the lowest average throughput (again, because it adopts only the TRIANGLE trajectory), although the average localization error is not the minimal relatedly.

Otherwise, TRI, ML and RGL obtained similar average throughput results, although the RGL is superior for localization accuracy. Table 2 shows that when *v* increases, the average throughput decreases, implying that the beacon traverses a greater distance to broadcast the packets; consequently, the sensor nodes receive fewer packets. Table 3 shows that all of these schemes obtained identical results; specifically, the throughput gradually increased in conjunction with the transmission radius. Again, this is attributed to the larger transmission coverage allowing a greater number of sensor nodes to receive packets from the mobile beacon. Table 4 shows that all of these schemes obtained similar results for all the trajectories except for RWP because the paths of the other trajectories are predefined. The simulation results in Tables 2, 3, and 4 show that the average throughput of the proposed RGL was superior to the others schemes except Guo.

**Table 4. Performance for different moving trajector (*v* = 3m/sec, *t* = 1sec and *r* = 12m).**

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Moving trajectory | | H-SCAN | V-SCAN | DOUBLE | TRI | RWP |
| Average  location  error (m) | TRI | 1.29 | 1.28 | 1.27 | 2.56 | 1.38 |
| ML | 1.04 | 1.1 | 1.42 | 1.56 | 1.45 |
| Guo | NA | NA | NA | \*1.38 | NA |
| RGL | \*0.93 | \*0.92 | \*0.89 | 1.49 | \*0.88 |
| Average  execution  time (sec) | TRI | 11181 | 11181 | 23762 | 3360 | 9752 |
| ML | 11181 | 11181 | 23762 | 3360 | 10324 |
| Guo | NA | NA | NA | 3360 | NA |
| RGL | \*11181 | \*11181 | \*23762 | \*3360 | \*9637 |
| Average  throughput | TRI | 48.97 | 48.97 | 98.14 | 14.71 | 40.54 |
| ML | 48.96 | 48.96 | 97.92 | 14.69 | 38.89 |
| Guo | NA | NA | NA | 14.66 | NA |
| RGL | \*48.57 | \*48.57 | \*97.14 | \*14.64 | \*38.01 |
| Average  energy  consumption | TRI | 20.16 | 20.16 | 43.41 | 9.26 | 20.04 |
| ML | 15.72 | 15.72 | 31.58 | 14.06 | 12.86 |
| Guo | NA | NA | NA | 6.68 | NA |
| RGL | \*14.44 | \*14.44 | \*29.52 | \*6.6 | \*12.64 |

\* is the best value

(D) Effect of the average energy consumption

Finally, Tables 2, 3, and 4 show the simulation results for the average energy consumption. Most of the energy was consumed by the sensor nodes computing the estimated position. However, all of these schemes employ quadratic equations to calculate the estimated position. Consider a complete localization estimation as a single operation. To provide an objective comparison, energy consumption is based on the number of reference nodes that are required to calculate a known position for every operation. For a single operation, the TRI scheme requires three reference nodes to calculate one operation, whereas the ML scheme requires eight reference nodes when a node was passing four times with different path numbers by a mobile beacon.

The results in Table 2 show that the energy consumption of the TRI and ML gradually decreased as the moving distance increased (both schemes require only a few reference nodes). Conversely, the RGL is difficult to localize and requires more time as the moving distance increases, thereby increasing the probability of the sensor node repeating localization. Table 3 shows that increasing the transmitted radius appears to exert no effect on energy consumption because the greater coverage allows the nodes to be completely localized, thereby slightly improving the time-efficiency, while causing a minor increase in error estimation. Tables 4 shows that among the trajectories, TRIANGLE achieved the fastest execution time; thus, the energy consumption is lower. Tables 2, 3, and 4 show that Guo obtained superior energy consumption results. However, if the RGL scheme adopts the TRIANGLE trajectory, the results are comparable (Table 4). This discussion shows that the performance and accuracy of the proposed RGL were superior.

**5. CONCLUSIONS**

In this paper, an efficient RGL scheme was presented for locating sensor nodes and achieving fine-grained accuracy by employing range-free and RSSI-based localization schemes. All computations were performed locally; thus, the mechanism is distributed, scalable, effective, and energy-efficient. The proposed technique is supported by a mobile beacon with a GPS. The beacon moves along a specific trajectory and periodically broadcasts information. Each sensor node receives the packets without interacting with other nodes for localization information. The distributed computation of node position involving elementary operations allows the system to operate while consuming minimal power. The experimental results were based on various parameters (*e.g.*, localization error, execution time, system throughput, and energy consumption), showing that the performance of the RGL scheme outperforms well-known RSSI-based schemes.

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