Hybrid Localization Algorithm of Mobile Nodes in Wireless Sensor Networks

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Abstract —To improve algorithm compatibility and reduce localization errors and node energy consumption, a hybrid localization algorithm of mobile nodes in wireless sensor networks (HLA) is proposed. In HLA, each mobile node analyzes the locations and number of adjacent stationary nodes. When a mobile node has detected that more than two adjacent stationary nodes exist, it will use energy localization algorithm to calculate its location coordinates. In other cases, the mobile node will use Beidou module to obtain its location coordinates. In the energy localization algorithm, maximum likelihood estimation algorithm is used to calculate energy location coordinates with RSSI values. And Kalman filter is used to filter the energy location coordinates. Finally, the current HLA location coordinates can be calculated based on movement distance and HLA location coordinates at last time. Simulation results show that whether in the area of 10m*10m or 20m*20m, our HLA can improve localization accuracy and control localization error within preferred range. Under certain conditions, our HLA outperforms Centroid Localization Algorithm (CLA) and Beidou Localization Method (BLM).

Index Terms—Wireless sensor networks, mobile node, Hybrid localization, localization error

I. INTRODUCTION

With the rapid development of digital electronic technology, wireless communication technology, microelectromechanical technology and other technologies, low-cost Wireless Sensor Networks (WSNs) have been an unprecedented development [1]. In WSNs, a large number of micro-computing devices (sensor nodes) have limited resources such as limited storage space, wireless transceiver of short distance and small battery capacity. According to different application environment, many sensor nodes use different sensors to monitor the interest environment (such as temperature, humidity, pressure), transmit perception data to a specific device (sink node) with cooperative manner (typical multi-hop). According to the received sensor data, sink node or base station node analyzes the phenomenon or event which may exist, reports and further routes data to a remote user or monitoring center database by conventional infrastructure (such as the internet network) [2]. WSNs have been applied in the field of disaster rescue, remote monitoring, military, smart city, etc. and have broad application prospect [3], [4].

In many applications of WSNs, sink nodes or some sensor nodes are mobility. But only when the mobile node gets its location clearly, it can move effectively. At present, the research on localization algorithm of mobile node in WSNs has achieved some results. Reference [5] proposes a clustering localization algorithm. The algorithm divides WSNs into cluster head nodes and connecting clusters composed of multiple sub-nodes. The mobile sub-nodes receive RSSI (received signal strength indication) values of adjacent nodes, range the RSSI values from high to low, choose locations of nodes with high RSSI values, and use centroid localization algorithm to calculate its location coordinates. Reference [6] proposes an energy-saving localization method based on mobile beacon for WSNs. The anchor moves along the trajectory which covers all nodes, and broadcasts its location coordinates. Non-located node receives the location information of multiple anchors, uses energy localization algorithm to obtain its location coordinates. Reference [7] proposes Monte Carlo localization algorithm based on temporary anchor nodes. The algorithm selects the node of high accuracy location as temporary anchor node to locate other nodes. Reference [8] proposes grid-based localization algorithm. In the algorithm, mobile reference node moves along the grids, and broadcasts its own information packets. Non-located node receives the information of mobile reference nodes and uses trilateral localization algorithm to determine its location coordinates. Reference [9] proposes location prediction algorithm of indoor mobile node. The algorithm establishes path planning model, uses maximum likelihood estimation to obtain target's location, and predicts its next location based on the model and previous location prediction results. But the references [5]-[9] assume that each anchor knows their own location information. If mobile nodes can not find more than 3 anchors, the algorithms are not applicable and the nodes can't get their locations. In the reference [10], sensor nodes use synchronization prediction of loose time and time location equation to calculate their current location coordinates. Meanwhile, currently Global

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Positioning System (GPS) module occupies the main body in Chinese market. Satellite localization accuracy of Beidou is little different from GPS, but its anti-interference ability is better than GPS's. However, the working currents of the two modules are tens of milliamps. Compared with power supply capacity of the mobile node, they are relatively high.

In summary, the contributions of this paper are as follows. First, energy localization algorithm is proposed. Namely, maximum likelihood estimation algorithm is used to calculate energy location coordinates with RSSI values of communication links. Kalman filter is used to filter the energy location coordinates. HLA location coordinates at current time are calculated based on movement distance and HLA location coordinates at last time. The energy localization algorithm can improve localization accuracy and reduce energy consumption of nodes. Second, a hybrid localization algorithm of mobile nodes in WSNs is proposed. The algorithm combines Beidou localization with energy localization. Namely, if there are more than two anchors surrounding mobile node, the mobile node closes Beidou module, uses energy localization algorithm to calculate its own location coordinates. Else it uses Beidou module to obtain its location coordinates. HLA can be applied whether there are adjacent anchors. The compatibility of HLA is strong.

The remaining parts of paper are organized as follow. In Section 2, the principle of HLA which includes energy location calculation, Kalman filter design and HLA location calculation is presented. In Section 3, the implementation steps of HLA are proposed. In Section 4, the simulation results are presented. In Section 5, the paper is concluded.

II. Principle of HLA

In HLA, assume that in the WSNs, there are mobile nodes and several stationary anchors which know their own locations; all mobile nodes install Beidou modules and displacement sensors. All anchors install Beidou modules; all nodes have limited energy and unified energy model [11].

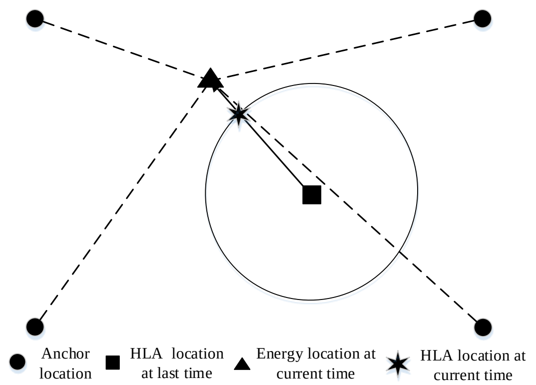

Fig. 1. Principle of HLA.

When there are less than three adjacent anchors, mobile node opens Beidou module to obtain its location coordinates. If mobile node monitors that there are more than two adjacent anchors, it closes power supply of Beidou module, and records current movement distance through displacement sensor. According to the RSSI values and movement distance, mobile node calculates its current location coordinates. As shown in Fig. 1, the square symbol represents HLA location at last time. The radius of the circle is self-measured movement distance of the mobile node from the last time to current time. The location (triangle symbol) at current time is intersection point of the circle and the line. As mentioned above, the key of the HLA for mobile node is to propose energy localization algorithm in the small area, reduce energy consumption of mobile nodes and guarantee localization accuracy. The energy localization algorithm includes energy location calculation, Kalman filter design and HLA location calculation. The specific principles of the three contents are as follows.

A. *Energy Location Calculation*

When a mobile node receives a broadcast packet of anchor, it obtains the location coordinates of anchor and RSSI value of the link communication. According to the RSSI value, distance between two nodes is calculated.

$$d = 10^{(A\text{-}RS)/(10Loss)} \tag{1}$$

where d represents distance between two nodes, RS represents received signal strength value, parameter A represents absolute value of received signal strength at 1m from transmitter. Its value range is 20-40. Parameter $Loss$ represents path loss exponent, namely decay rate of signal energy. Its value range is 2-8 and it is usually experience value based on actual measurement. The analysis of actual measurement value shows that when the communication distance increases, average decline rate of received signal energy reduces. Therefore, the larger RSSI value is, the more accurate converted distance value is.

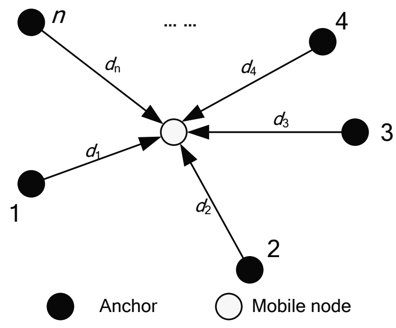

Fig. 2. Principle of maximum likelihood estimation algorithm.

When mobile node has known the location coordinates of more than two adjacent anchors and the distances to the anchors, maximum likelihood estimation algorithm is used to calculate its own coordinates. As shown in Fig. 2, there are No.1, No.2, No.3 until No.n sensor nodes. The distances to the mobile node d_1, d_2, d_3, ⋯⋯, d_n are obtained by (1). The distance equations from each anchor to the mobile node are

$$(x_1 - x^R)^2 + (y_1 - y^R) = d_1^2 \\ \vdots \qquad \vdots \\ (x_n - x^R)^2 + (y_n - y^R) = d_n^2 \tag{2}$$

where (x^R, y^R) represents energy location transverse and vertical coordinates by maximum likelihood estimation algorithm. (x_1, y_1) , (x_2, y_2) …… (x_n, y_n) represents anchor coordinates.

Each adjacent two equations subtract and (3) is obtained.

$$2\begin{bmatrix} x_n - x_1 & y_n - y_1 \\ \vdots & \vdots \\ x_n - x_{n-1} & y_n - y_{n-1} \end{bmatrix}\begin{bmatrix} x^R \\ y^R \end{bmatrix} = \begin{bmatrix} (d_1^2 - d_n^2) - (x_1^2 - x_n^2) - (y_1^2 - y_n^2) \\ \vdots \\ (d_{n-1}^2 - d_n^2) - (x_{n-1}^2 - x_n^2) - (y_{n-1}^2 - y_n^2) \end{bmatrix} \tag{3}$$

The (3) is solved and energy location coordinates (x^R, y^R) of mobile node are obtained.

B. Kalman Filter Design

Between two unknown stationary nodes, the distance calculated by received signal energy contains random fluctuation. Therefore, Kalman filter is used to filter out precise distance value [12]. According to the theory proposed by K. P. Schwarz, dynamic navigation and location data are suitable for constant velocity and acceleration model. Then assume that state vector $[x, v, a]^T$ is composed of displacement, velocity and acceleration in the horizontal or vertical direction. The corresponding discrete time state space model is

$$X_{k+1} = F_k X_k + \Gamma_k W_k \tag{4}$$

where X_k represents estimated value of system state vector at time k, W_k represents process noise, F_k represents state transition matrix, Γ_k represents process noise parameter. F_k and Γ_k are expressed as

$$F_k = \begin{bmatrix} 1 & \Delta T & \Delta T^2/2 \\ 0 & 1 & \Delta T \\ 0 & 0 & 1 \end{bmatrix}, \ \Gamma_k = \begin{bmatrix} \Delta T^3/6 \\ \Delta T^2/2 \\ \Delta T \end{bmatrix} \tag{5}$$

where ΔT represents sampling time.

The establishment of observation equation is

$$Z_{k+1} = H_k \mathrm{X}_{k+1} + \mathrm{V}_{k+1} \tag{6}$$

where H_k represents measurement matrix $[1 \quad 0 \quad 0]$, V_{k+1} represents measurement noise, Z_{k+1} represents measurement value at time k+1.

The steps of Kalman filtering algorithm are as follows.

Step 1: parameters such as X_0, P_0, k=1 are initialized.

Step 2: system state vector at time k+1 are predicted in advance.

$$X_{(k+1/k)} = F_k X_k \tag{7}$$

Step 3: measurement value at time k+1 is predicted in advance.

$$Z_{(k+1/k)} = H_{k+1} X_{k+1/k} \tag{8}$$

Step 4: covariance matrix of prediction error at time k+1 is calculated. Gain matrix is calculated.

Step 5: estimated value of system state vector at time k+1 is calculated. Filtering error covariance matrix of state vector is calculated.

Step 6: k=k+1, return to step 2.

Steps 1-6 are executed repeatedly and energy location coordinates is filtered.

C. HLA Location Calculation

Because wireless propagation signal is affected by environmental factors (temperature, humidity, atmospheric pressure, etc.) and has large noise in practical application. It leads that sometime signal strength attenuation doesn't conform to theoretical change, and affects energy localization accuracy. Thus the energy location coordinates is needed to be modified.

When mobile node closes Beidou module, it knows the last HLA location coordinates (x_{k-1}^s, y_{k-1}^s) and current energy location coordinates. The movement distance S from time k to time k+1 is obtained according to displacement sensor or other sensors. And HLA location coordinates (x_k^s, y_k^s) at current time is calculated by following method.

The mobile node is on the circumference of the circle whose center is (x_{k-1}^s, y_{k-1}^s) and radius is S. Because energy location coordinates have localization error, it is not on the circumference, but connection line between (x_{k-1}^s, y_{k-1}^s) and (x_k^R, y_k^R) represents the movement direction of the mobile node. Therefore, intersection point coordinates of the circle and line is HLA location coordinates (x_k^s, y_k^s) of the mobile node at current time. The calculation method of (x_k^s, y_k^s) is as follows.

When $x_k^R = x_{k-1}^s$ and $y_k^R = y_{k-1}^s$, then $x_k^s = x_{k-1}^s$ and $y_k^s = y_{k-1}^s$.

When $x_k^R = x_{k-1}^s$ and $y_k^R \neq y_{k-1}^s$, then $x_k^s = x_{k-1}^s$ and $y_k^s = \begin{cases} y_{k-1}^s + S, if \ y_k^R > y_{k-1}^s \\ y_{k-1}^s - S, if \ y_k^R < y_{k-1}^s \end{cases}$.

When $x_k^R \neq x_{k-1}^s$ and $y_k^R = y_{k-1}^s$, then $y_k^s = y_{k-1}^s$ and $x_k^s = \begin{cases} x_{k-1}^s + S, if \ x_k^R > x_{k-1}^s \\ x_{k-1}^s - S, if \ x_k^R < x_{k-1}^s \end{cases}$.

When $x_k^R \neq x_{k-1}^s$ and $y_k^R \neq y_{k-1}^s$, the line between two points (x_k^R, y_k^R) and (x_k^R, y_k^R) is

$$y = \frac{y_{k-1}^s - y_k^R}{x_{k-1}^s - x_k^R}(x - x_{k-1}^s) + y_{k-1}^s \tag{9}$$

where x and y are independent variables. The circle equation is

$$\sqrt{(x-x_{k-1}^s)^2+(y-y_{k-1}^s)^2}=S \tag{10}$$

Let $\dfrac{S}{\sqrt{(y_{k-1}^s-y_k^R)^2/(x_{k-1}^s-x_k^R)^2+1}}=A$, and (9) is token into (10). According to the location relationship of (x_k^R, y_k^R) and (x_{k-1}^s, y_{k-1}^s), HLA coordinates (x_k^s, y_k^s) at current time is calculated through (11) and (12).

$$x_k^s=\begin{cases} x_{k-1}^s+A, if\ x_k^R>x_{k-1}^s \\ x_{k-1}^s-A, if\ x_k^R<x_{k-1}^s \end{cases} \tag{11}$$

$$y_k^s=\begin{cases} y_{k-1}^s+A\times(y_{k-1}^s-y_k^R)/(x_{k-1}^s-x_k^R), if\ y_k^R>y_{k-1}^s \\ y_{k-1}^s-A\times(y_{k-1}^s-y_k^R)/(x_{k-1}^s-x_k^R), if\ y_k^R<y_{k-1}^s \end{cases} \tag{12}$$

III. Algorithm Implementation

HLA is a distributed algorithm. Anchors and mobile nodes execute their own algorithms.

HLA in anchors is simple. When the network starts, each anchor opens Beidou module, reads latitude and longitude values, converts them into earth coordinates, uses Kalman filter and stores processed data in the cache. When one anchor receives location information query packet of mobile node in its 1 hop communication range, it feeds back its own location, node address and other information to the mobile node.

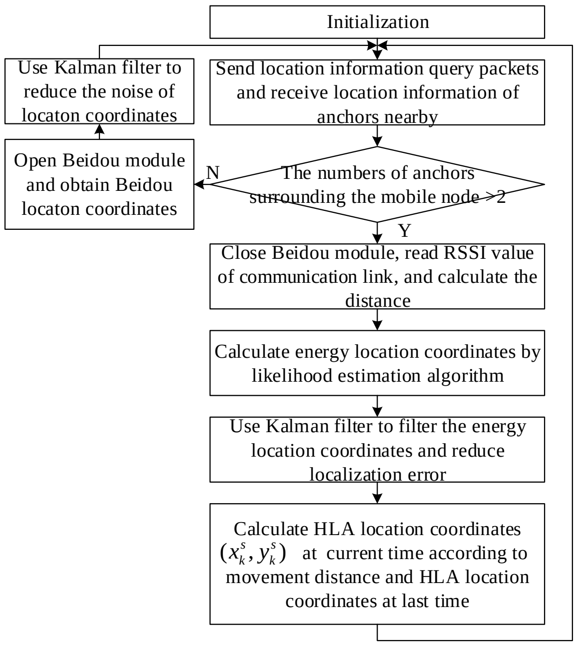

Fig. 3. Work flow chart of mobile nodes.

As shown in Fig. 3, when the network starts, specific steps of HLA in mobile node are as follows.

Step 1: mobile node transmits location information query packet to anchors in the vicinity, receives location information of anchors, and judges whether there are more than two adjacent anchors. If it exists, go to step 2, else if not, mobile node uses its Beidou module and Kalman filter to obtain its own location coordinates.

Step 2: mobile node closes Beidou module, sends location information query packets, receives feedback packets, and obtains RSSI values of communication links.

Step 3: mobile node calculates the distance between two nodes by (1), calculates energy location coordinates by likelihood estimation algorithm, uses Kalman filtering algorithm to filter the energy location coordinates and reduce localization error.

Step 4: mobile node obtains movement distance *S*, calculates intersection point coordinates of the circle whose center is (x_{k-1}^s, y_{k-1}^s) and radius is S and the line from (x_{k-1}^s, y_{k-1}^s) to (x_k^R, y_k^R), obtains HLA location coordinates (x_k^s, y_k^s) at current time. Then go to step 1.

The steps 1-4 are executed repeatedly, until energy of mobile node is exhausted.

IV. Algorithm Simulation

A. *Experimental Data Acquisition*

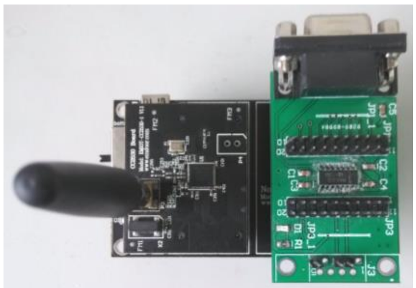

Fig. 4. Wireless node

Fig. 5. Beidou module UM220-III

In the experiment, four wireless nodes with Beidou modules UM220-III are distributed on the four corners of the square area. The trolley with wireless node and Beidou module moves along the designated path. As shown in Fig. 4 and Fig. 5, experiment data of related RSSI values and Beidou location coordinates are obtained by the wireless nodes and Beidou modules. The wireless node mainly uses chip CC2530F256. CC2530F256 is a system-on-chip. It includes RF transceiver, 8051 MCU, 256K programmable memory, 8KB RAM and other modules and is applied in 2.4GHz IEEE 802.15.4 system, Zigbee and RF4CE applications. It builds in received signal strength indicator. The eight signed RSSI values can be directly read from related register or received packet.

As shown in Fig. 5, UM220-III of Beijing Unicorecomm Science Technology Limited Corporation is a high-performance GNSS module of dual system. It is also multi-frequency SoC chip, and supports two frequency points such as BD2 B1 and GPS L1 [13]. To obtain the only Beidou location data, only BD2 B1 of the module is used.

B. Comparison Algorithms and Simulation Parameter Selection

When the number of adjacent anchors is less than 3, Beidou location coordinates are directly used. Because Beidou localization performance is known in public, its comparison is not needed. Therefore, HLA, BLM and CLA are compared when the number of adjacent anchors is not less than 3. BLM uses Beidou model UM220-III. The latitude and longitude values are output through serial port. The earth's absolute coordinates are calculated by following equations.

$$\begin{aligned} x^B &= r \times \cos\phi \times \cos\lambda \\ y^B &= r \times \cos\phi \times \sin\lambda \end{aligned} \tag{13}$$

where x^B and y^B represent earth horizontal and vertical coordinates, r represents radius of earth, ϕ represents latitude value, λ represents longitude value. Because x^B and y^B are earth absolute coordinates, they are converted into relative coordinates in the simulation, and Beidou location coordinates are obtained. CLA sorts out received RSSI values by mobile node, preferentially selects the three anchors with highest RSSI values, and executes weighted centroid calculation through (14) and (15).

$$x_z = \frac{\dfrac{x_1}{d_1+d_2} + \dfrac{x_2}{d_2+d_3} + \dfrac{x_3}{d_2+d_3}}{\dfrac{1}{d_1+d_2} + \dfrac{1}{d_2+d_3} + \dfrac{1}{d_2+d_3}} \tag{14}$$

$$y_z = \frac{\dfrac{y_1}{d_1+d_2} + \dfrac{y_2}{d_2+d_3} + \dfrac{y_3}{d_2+d_3}}{\dfrac{1}{d_1+d_2} + \dfrac{1}{d_2+d_3} + \dfrac{1}{d_2+d_3}} \tag{15}$$

where (x_z, y_z) represents location coordinates of mobile node in CLA.

According to the analysis of above algorithms, in the simulation, the following parameters are selected to calculate location coordinates and localization errors. Path loss exponent $Loss$ is 4.6. System state vector X_0 is the first observation value. Covariance matrix P_0 of estimated error is $[1\ 0\ 0; 0\ 1\ 0; 0\ 0\ 1]$. Parameter Γ_K is 1. Q_k and R_k are the covariances of rand Gauss noise. Sampling time ΔT is 1s.

C. Analysis of Simulation Results

The location coordinates, trajectories and localization errors of mobile node in 10m*10m area are analyzed. In the area, four anchors are separately distributed on the coordinates (0 0), (0 10), (10 0) and (10 10). Mobile node moves along the trajectory (2 2)-(8 2)-(8 8)-(2 8)-(2 2). The movement speed is 0.1m/s. As shown in fig.6, green line through cross symbols (BLM coordinates) is Beidou trajectory. Blue line through dot symbols (CLA coordinates) is centroid trajectory. Compared with real mobile trajectory (black line through rectangular symbols), both Beidou trajectory and centroid trajectory are poor and no characteristic of rectangular trajectory.

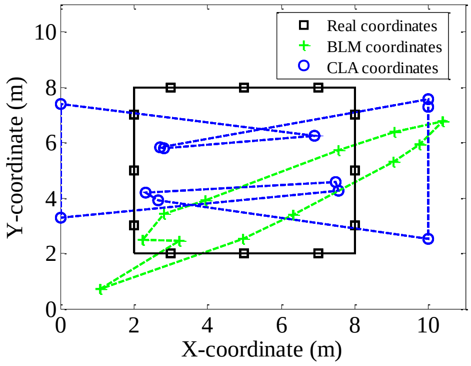

Fig. 6. Coordinates and trajectories of BLM and CLA in 10m*10m area

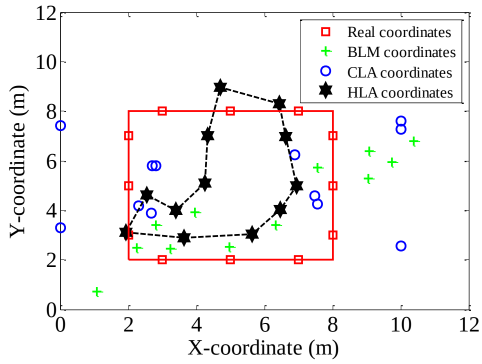

Fig. 7. Coordinates and trajectory of HLA in 10m*10m area

As shown in Fig. 7, black line through five-pointed stars is HLA trajectory. Compared with centroid trajectory and Beidou trajectory, localization accuracy of HLA is better and mobile trajectory is closer to real mobile rectangular trajectory.

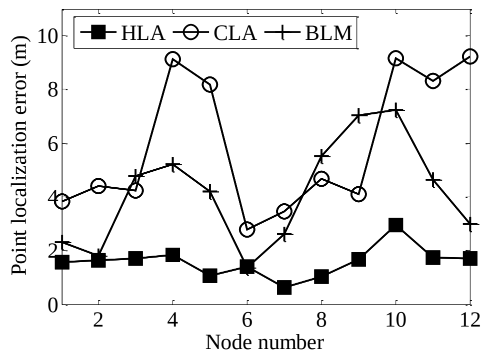

Fig. 8. Point localization error comparison in 10m*10m area

Defined point localization error is

$$error_p = \sqrt{(x_s^p - x^p)^2 + (y_s^p - y^p)^2} \tag{16}$$

where (x_s^p, y_s^p) represents measurement coordinates of p point. (x^p, y^p) represents real coordinates of p point. As shown in Fig. 8, localization errors of 10 points in HLA are obviously smaller than point localization errors in CLA and BLM. It is the reason that when there are four anchors in the 10m*10m area, HLA uses Kalman filter to reduce measurement noise of link energy and uses movement distance to modify the energy location coordinates. Therefore, point localization error in HLA is smaller. Although location coordinates of some points in CLA and BLM are just in the vicinity of real points, data measurement error of BLM is larger and CLA is simple. Therefore, error curves of the two algorithms fluctuate and their point localization errors are higher.

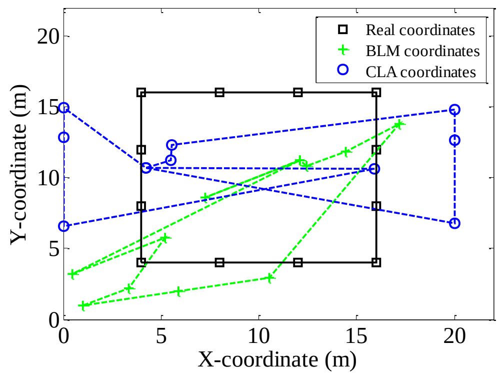

Fig. 9. Coordinates and trajectories of BLM and CLA in 20m*20m area

Secondly, location coordinates, trajectories and localization errors of mobile node in 20m*20m area are analyzed. In the area, four anchors are separately distributed on the coordinates (0 0), (0 20), (20 0) and (20 20). Mobile node moves along the trajectory (4 4)-(16 4)-(16 16)-(4 16)-(4 4). The movement speed is 0.4m/s. As shown in fig.9, when the area became larger, compared with real mobile trajectory, the trajectory through BLM coordinates (green line through cross symbols) and the trajectory through CLA coordinates (blue line through dot symbols) are not ideal. Their localization effect is poor.

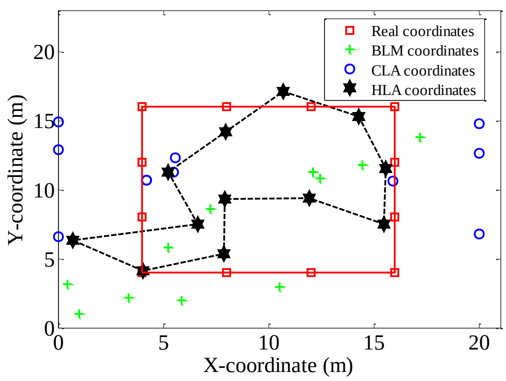

Fig. 10. Coordinates and trajectory of HLA in 20m*20m area

As shown in Fig. 10, when the area becomes larger, the trajectory through HLA coordinates (black line through five-pointed stars) is not affected. It is closer to the real trajectory than trajectories of CLA and BLM. Its location effect is more ideal.

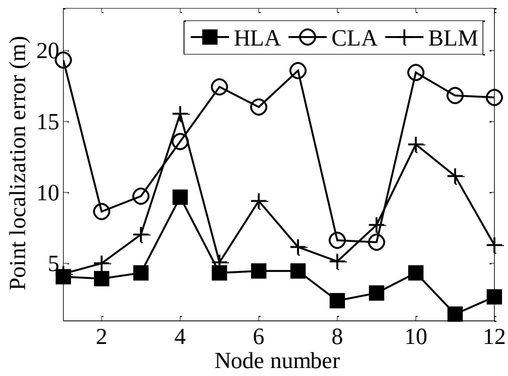

Fig. 11. Point localization error comparison in 20m*20m area

As shown in Fig. 11, when the area becomes larger, point localization errors of HLA become larger. But in HLA, energy localization algorithm is used to calculate the location coordinates of mobile node. It reduces localization error and improves localization accuracy. Therefore, point localization error of HLA is lower than point localization errors of CLA and BLM.

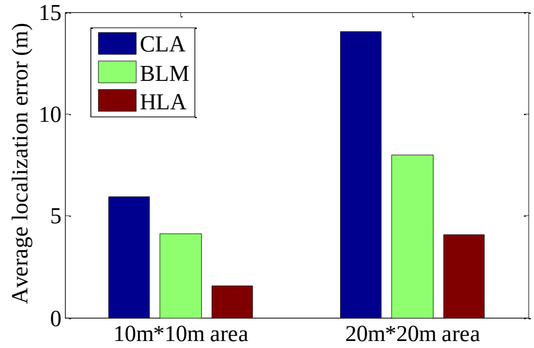

Fig. 12. Average localization error comparison in 20m*20m area

Average localization error is defined as average point localization error of 12 points. As shown in Fig. 12, whether in 10m*10m area or 20m*20m area, average location error of HLA is lower than average localization errors of CLA and BLM. In 10m*10m area, average location error of CLA is 3.79 times average localization error of HLA. Average location error of BLM is 2.63 times average localization error of HLA. In 20m*20m area, average location error of CLA is 3.43 times average localization error of HLA. Average location error of BLM is 1.96 times average localization error of HLA.

V. CONCLUSION

Combining Beidou localization technology with energy localization technology, a hybrid localization algorithm of mobile node for wireless sensor networks is proposed. Firstly, algorithm assumptions and switching condition between Beidou localization and energy localization are proposed. Secondly, when there are more than two adjacent anchors, mobile node uses calculation method of energy location coordinates, Kalman filter and calculation method of HLA coordinates to reduce localization errors. Thirdly, implementation steps of HLA are presented. Finally, simulation parameters are listed and the performance of HLA, CLA and BLM in 10m*10m area and 20m*20m area are respectively compared.

In short, based on the locations and the number of adjacent anchors, HLA uses different localization algorithms and improves algorithm compatibility. When there are more than two anchors surrounding the mobile node, HLA controls localization error within preferred range, improves localization accuracy and closes Beidou module to reduce energy consumption of nodes. But HLA assumes that all nodes install Beidou modules, which means an increase in system cost. Therefore the further study direction is to use the mobility of anchor installed Beidou module, study on localization algorithm of stationary nodes which don't install Beidou module to reduce system cost and energy consumption.

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