Target Localization in Wireless Sensor Network based on Time Difference Of Arrival

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Abstract — One of the most prominent challenges in Wireless Sensor Network (WSN) is target localization. As majority of the decisions made in navigation and path planning are dependent on current information available, target localization is one of the fundamental requirements. This paper presents accuracy studies on target localization using the Time Difference of Arrival (TDOA) method. An evaluation of the TDOA is presented through a random reference node by using four stationary sensors in a sensor network. Some of the fundamental advantages in the presented method are its simplicity through requiring only four reference nodes, tolerating errors in node positioning and time differences. Simulations results show that proposed TDOA method outperforms the centroid TDOA method in different test environments, with an average localization error of 2.36 m.

I. INTRODUCTION

A wireless sensor network (WSN) is a group of sensor nodes (few - several hundreds) distributed in organized or random patterns in the environment. Every single node consists of a power source derived from a battery or transducer to convert the energy from collection data to electrical signals. The on-board computer processes the data, and the radio transceiver makes the connection among existing sensor nodes [1]. Broadly speaking, these WSNs can communicate wirelessly, assist in gaining intelligence, thus leading to the development of smart environments.

Alongside the progress in technology, the sensor nodes have seen an enormous growth in the recent years to become smaller, lighter, and economical, leading to versatile applications. Some of the parameters typically monitored through sensor nodes are speed, humidity, sound, vibration, wind, temperature, localization, pollution level, chemical concentrations, light, mechanical stress level, and vital body actions [2]. On the other hand, some applications of sensor nodes include traffic monitoring, medical device monitoring, industrial automation, air traffic control, robot navigation, target detection and controlling etc. Overall, WSN could be used to collect data, communicate wirelessly, and operate in harsh conditions.

WSNs have received momentous attention in recent years from the enormous potential in applications [3]–[5]. While the sensor networks are promising in solving many problems, one of the fundamental challenges that still exists is target localization. Target localization systems play a crucial role in many context-aware applications providing positioning data, and have led to design of many practical applications such as automation systems in smart buildings, navigation systems for the blind [6]-[7], autonomous navigational robots [8]-[10]. From this multitude of applications, there has been a lot of progress in indoor positioning systems to provide crucial information for localization, tracking, and navigation, where the global positioning system is typically infeasible due to its inaccuracy while operating indoors.

In the recent years, numerous localization algorithms have been proposed using different technologies such as ultrasonic [11], infrared [12], and received signal strength [13], and different methods such as Time of Arrival (TOA), Time Difference of Arrival (TDOA), Angle of Arrival (AOA), and Received Signal Strength Indicator (RSSI). Of the several methods that exist for target localization, TDOA is one of the fundamental and most popular methods. Here, typically several sensors are placed at different locations, synchronized with respect time and read the time of emission to calculate the difference between two TOA measurements. Answering the challenges in WSN, this paper presents a new method of target localization using TDOA method, and is outlined as follows. Section II presents the previous work on target localization, and section III explains the new and improved TDOA localization algorithm. Section IV validates the algorithm through simulation results, and conclusions are presented in Section V.

II. PREVIOUS WORK

Of the several methods used for target localization, RSSI [13] is an indicator of the received signal strength at the sensor nodes. It can provide a relative estimation of the distance to the target, and its implementation is classified into two types based on the techniques used: range-free [14], and range-based [15]. The range-free method uses the connectivity data to identify the position of the nodes, without accounting for the distance to the target. On the other hand, range-based method uses RSSI to estimate the position with respect to the nodes, thus estimating its distance between the sensor node and the target. While it is one of the fundamental methods, it is not reliable due to its
dependence on angle of measurement and environment noise [13].

Angle of Arrival (AOA) is one other method, and operates based on the angles between the known anchor nodes and unknown target nodes [16]. The AOA method differs from RSSI through estimating the direction of the sensors, rather than their relative distance. Similar to RSSI, the AOA is classified into two types. The first method employs an array of sensors, and signal processing techniques to estimate the angle between the sensor nodes and the target. The second method employs a combination of RSSI and AOA to better estimate the position (distance and angle) of the target with respect to the sensor nodes. As AOA is not sufficient to estimate the position, this method is typically used in combination with RSSI or TOA methods for target localization. In addition, it suffers from the limitation of requiring multiple antennas and sensor nodes, thus increasing the cost of implementation [17].

Time of Arrival (TOA) is one other method that operates based on estimating the distance between the sensor and target nodes with the presumption that this distance is directly proportional to the propagation time. While this method can deliver promising results, it suffers from two major limitations. First, all sensor nodes and target systems must be precisely synchronized at the microsecond level. Second, all signals transmitted must have a timestamp incorporated in them to accurately estimate the distance travelled. These challenges in TOA method can be overcome using the Time Difference of Arrival (TDOA) method where the difference in signal arrival time at different sensor nodes is used for target localization. The TDOA measurement defines a hyperbolic area with the possible location of target with two paired sensors as foci. Based on the previous research and challenges in choosing the right parameters for the TDOA method, this paper presents a new methodology behind choosing the right number of sensors to accurately estimate the target position, while at the same time compares the results to existing literature.

III. TDOA ALGORITHM TESTING

The proposed TDOA method for target localization is based on intersecting coordinates of hyperbolas. To get a clear understanding, first let’s consider a hyperbola with the transverse axis aligned with y-axis as in Fig. 1 with the characteristic equations as in (1)-(3), where $a$ is the distance from the center to either vertex, $b$ is the length of perpendicular segment between each vertex and the asymptotes, and $c$ is the distance from center to the either focus points. For any point $P(x,y)$ on either vertex, the absolute difference between the eccentricity $|d_1-d_2|$ is always equal to twice the distance between center and the vertex. The proposed TDOA method works based on the presumption that target is located somewhere on the hyperbola, and uses the intersection of two or more hyperbolas to perform localization.

\[
\sum_{a}^{i} + \sum_{b}^{j} = c^2 = \frac{V \Delta t}{2},
\]

Consider a region where nodes $(N_1, N_2, N_3,..)$ are located at random locations $((x_1,y_1),(x_2,y_2),(x_3,y_3),..)$ as in Fig. 2. When the target initiates its search routine for sensor nodes in its vicinity, it marks the time of arrival of each node in its sensing radius as $T_1, T_2, T_3,..$. Once this information is obtained, target designates the node with lowest TOA as reference node, and draws hyperbolas between the reference nodes and three other nodes. For the example presented in Fig. 2, $N_1$ was identified to be the reference node, and hyperbolas were drawn between $N_1 - N_2$, $N_1 - N_3$, and $N_1 - N_4$. Per the hyperbola characteristic eqs. (1)-(3), if $T_1$ and $T_2$ were TOA to $N_1$ and $N_2$, distance between vertexes to center can be computed as in (4), where $V$ is the speed of target signal. Further, based on the location of $N_1$, and $N_2$, distance between the nodes $c$, and length of perpendicular segment from each vertex to the asymptotes $b$ can be computed as in (5)-(6).

\[
a = \frac{T_2 - T_1}{2} = \frac{V \Delta t}{2}
\]
With this foundation, consider a two dimensional area $(x,y)$ with four sensor nodes $(N_b, N_c, N_d, N_f)$ and their respective signal time of arrival from the target being $T_{ba}, T_{bc}, T_{bd}$, and $T_{db}$ respectively. If $T_d$ is the lowest of all, the time difference of arrival between $N_d$ and other nodes can be calculated as in (7)-(9), and the distance between the nodes can be calculated as in (10)-(12).

$$c \cdot \frac{D}{2} = \frac{(x_2-x_1) + (y_2-y_1)}{2}$$

$$b = \sqrt{c^2 - a}$$

$$T_{da} = T_{ba} - T_a$$

$$T_{db} = T_{bc} - T_b$$

$$T_{dc} = T_{bd} - T_c$$

$$\sqrt{(x_A-x_A)^2 + (y_A-y_A)} = V \cdot T_a$$

$$\sqrt{(x_B-x_B)^2 + (y_B-y_B)} = V \cdot T_b$$

$$\sqrt{(x_C-x_C)^2 + (y_C-y_C)} = V \cdot T_c$$

Solving (10) and (11) for target location yields (13)-(15), and solving (11) and (12) yields (16)-(18). Finally, by solving equation (16) and (17), intersection point of hyperbolas, and target location $(x, y)$ can be estimated as in (19)-(20).

$$y = k_1x + b_1$$

$$k_1 = (T_{dc}x_c - T_{da}x_d) / (T_{dc}y_c - T_{da}y_a)$$

$$b_1 = \frac{T_{db}(x_A^2 + y_A^2) - T_{ba}(x_B^2 + y_B^2)}{2T_{ba}y_a - 2T_{da}y_d} \cdot V \cdot T_{ba}T_{da}(T_{db} - T_{ba})$$

$$y = k_2x + b_2$$

$$k_2 = (T_{da}x_A - T_{db}x_B) / (T_{da}y_A - T_{db}y_B)$$

$$b_2 = \frac{T_{dc}(x_A^2 + y_A^2) - T_{db}(x_B^2 + y_B^2)}{2T_{db}y_b - 2T_{dc}y_c} \cdot V \cdot T_{db}T_{dc}(T_{dc} - T_{db})$$

$$x = (b_2 - b_1) / (k_1 - k_2)$$

$$y = k_1x + b_1$$

IV. SIMULATION AND RESULTS

Effectiveness of the proposed algorithm has been tested through numerous simulations, and comparison with the centroid method [18] at different conditions (number of sensor nodes, sensing radius, and environment noise). The test environment is an area of 250x250 m² with the target moving in a random pattern with the signal’s propagation speed at 340 m/s.

In the first test, 400 sensor nodes were placed at random locations, environment noise set at 10%, and the target starting coordinates set to (0,5). Then, target localization algorithm as proposed in previous section was implemented, and results obtained are presented in Fig.3. Here, the actual target movement pattern is marked in black line, estimated location per the centroid method is marked with blue line, and the estimated location per the proposed method is marked in red line. At every instance, the target reads all the sensor nodes in its radius, identifies the nodes with lowest TOA, and performs localization per eqs. (13)-(20). Accordingly, results from the proposed method are evaluated through Fig. 4, where the difference between actual and the estimated location is presented. While the centroid method (blue line) estimated the target location with an average of 11.2m, the proposed method (blue line) has shown a significant improvement with an average of 2.36m.

Figure 3. Test environment of WSN with moving target.

Figure 4. Comparison of localization error in the test environment
obtained have shown that the proposed algorithm outperforms the centroid method with an average accuracy of 6.01m in comparison to 20.32m. Further tests were performed with environment noise set to 100%, sensing radius set to 30m, and varying the number sensor nodes between 400 to 600. Results obtained in Fig. 6 shows that the proposed algorithm outperforms centroid method with an average localization accuracy of 8.01m in comparison to 15.34 m.

Future work in this research involves identifying the ideal pattern for sensor node distribution, placement of different antenna patterns to increase localization accuracy by two folds.

REFERENCES