New Hybrid RSS-based Localization Mechanism For Underwater Wireless Sensor Networks

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Abstract—Localization is an important stage in Wireless Sensor Networks (WSNs) in order to make the collected information meaningful. For Underwater Wireless Sensor Networks (UWSNs), received signal strength (RSS) has been used for distance measurement through the state-of-the-art Lambert function [1]. In this work, a hybrid RSS-based localization mechanism is presented which is comprised of three different stages including initialization, distance measurement, and position estimation. The simulation results, from comprehensive simulations, demonstrate the accuracy and efficiency of the hybrid localization mechanism compared to other existing distance measurement technique like Time of Arrival.

Keywords—Acoustic distance measurement; Lambert W; Received Signal Strength; RSS; Time of Arrival; Underwater localization

1 Introduction

The Underwater Wireless Sensor Networks (UWSNs) are envisioned for oceanographic applications such as data collection, pollution monitoring, offshore exploration, disaster prevention, assisted navigation, and tactical surveillance applications [2]. Due to the potential of oceanographic applications, UWSN is gaining popularity among researchers, but unlike terrestrial WSN (TWSN), there are less literature and works devoted to this area so far. UWSNs work in a collaborative task among different kinds of nodes to collect the data from sea-bed and convey it to an onshore station for further processing. In this scenario, sinks are mostly on the sea surface established as buoy for relaying data to the base-station via satellite or long-range radio frequencies.

Localization is an important matter in underwater likewise other sensor networks. However, it could be more complicated compared to the terrestrials in terms of protocol design because it might be difficult or impossible to recover the network nodes in most of cases after deployment. Existing underwater localization works are not many if compared to the terrestrials while it requires specific consideration due to three fundamental differences [3]:

- Radio is not suitable for aquatic communication because of highly limited propagation (50 - 100 cm).
- The switch from radio frequency (RF) to acoustics wave change the physics of communication from speed of the light ($3x10^8 m/s$) to the sound velocity ($1.5x10^3 m/s$).
- Energy consumption of Underwater WSN might be different from Terrestrial WSN caused by the sensors size and irregular data transfer intervals.

Basically, there are four different distance measurement techniques for wireless communications including Time Difference of Arrival (TDoA), Time of Arrival (ToA), Received Signal Strength (RSS), and Angle of Arrival (AoA). TDoA uses two different transmission-media like radio frequency (RF) and acoustic wave and estimates the distance using different arrival times due to different dissemination velocities [4]. Since RF is not applicable in aquatic environment because of extremely limited propagation [3], then TDoA is not suitable for UWSN. On the other hand, AoA relies on a direct line-of-sight (LOS) path from a transmitter to a receiver, then a multi-path component may appear as a signal arriving from an entirely different direction and can lead to very large errors in AoA measurements [5]. Observing the existing underwater works, ToA is widely employed in existing localization works for distance measurement, although it demands precise synchronization among nodes [3]. Thus far, RSSI could get less attention as another alternative to measure distance.

We proposed a new localization mechanism which is based on Received Signal Strength (RSS). Wireless devices are generally able to measure the power of received signals which can be used for RSS-based distance measurement. In contrast to ToA techniques, they do not demand synchronization. However, finding accurate inverse function could be a challenging task to extract the distance upon transmission loss. We have used the result of our previous work as an efficient and robust computational method through the Lambert function [1] . Accordingly, a hybrid localization mechanism is developed which gives an accurate estimation of sensors positions.

The localization is divided in three separate steps in-

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cluding initialization, distance calculation, and position estimation. In initialization, sensor nodes store received signal strength of beacons. Sensors send those information back to sink where the distances are measured. Finally, the sink calculates the position of sensors. The developed localization helps sensor nodes to have a coarse location estimation and it extracts the accurate position by using the sink as a powerful node. This algorithm is considered a new hybrid computation method which is distributed as well as it is centralized.

A mathematical evaluation showed that the distance function calculates an accurate distance with only 5 iterations. Furthermore, the simulation results proved that the proposed hybrid RSS-based localization is more accurate compared to the ToA-based localizations and it is also more reliable as the calculation is less vulnerable to the possible errors.

This paper is organized as follows: The existing distance measurement techniques as well as their drawbacks are briefly introduced in Section 2. Section 3 briefly explains transmission loss and the Lambert calculation in underwater environment. In Section 4, our hybrid localization mechanism is presented in details. The simulation scenarios are defined in Section 5 which it is followed by the results in Section 7 Finally, The paper is concluded in Section 8.

2 Related Works

There are fine-grained and coarse-grained localization categories [6] in UWSNs as the basic techniques are similar to TWSNs. Likewise, the way of choosing a particular technique for localization, either fine-grained or coarse-grained, depends on applications. For instance, the applications like disaster prevention may not need precise coordinates of nodes while oil pipes leakage or underwater construction activities demand more accurate location. Accordingly, the methods are generally discussed in two categories as coarse-grained and fine-grained.

In terms of coarse-grained estimation, [7] has developed an area localization scheme (ALS) which divides the operational field to few subsections. In this work, 2D architecture is targeted while there are four beacons around the field and they send beaconing messages via different power-levels. Each sensor node saves a record like $< P_{b_1}, P_{b_2}, P_{b_3}, P_{b_4} >$ from the power levels that receives from each beacons. However, the accuracy of this work may satisfy the requirement of some applications but the sections are not well separated because the acoustic wave propagation is not circular. The authors have attempted to improve the accuracy of their work by increasing the number of beacons to 8 [8]. However, the main drawback could be the cost of adding many beacons as they are more expensive and the deployment of such nodes might be costly. To solve the beacons deployment problem, [9] has proposed the idea of Detachable Elevator Transceivers (DETs). In such manner, the beacons are established above the surface as buoys and DETs get the positioning information from the beacons and disseminate their positions. The nodes only save the received power-levels and based on the power-levels they extract a rough area of where they are. The method can obtain better accuracy compared to the work of [7] and [8], but it may have same problem with the work of [10] in terms of reliability due to the underwater currents and cost of devices.

On the other hand, to have a fine-grained location data, [11] has proposed a ToA based method that uses one Autonomous Unmanned Vehicle (AUV) as beacon node. The AUV gets the coordinates via GPS above the sea surface and dives to the depth to disseminate the coordinates through the unknown nodes. A dynamic 3D infrastructure is considered in this work. Despite of good idea, localization duration takes hours, while Doppler shift and synchronization might degrade the accuracy. Moreover, the authors have presented another multi-stage localization mechanism that use dive and rise (DNR) beacons [10]. DNR beacons are able to ascend and descend in the water column to get the coordinates from GPS and broadcast to the network. However, the idea of using few DNRs fulfills the localization function faster than the first mechanism, but it could be expensive if the number of DNRs increases. Besides, beacon movement and synchronization may still decrease the accuracy, also there could be some inaccuracy because of underwater currents. [12] further proposed a method which does both localization and synchronization at same time. A static 3D architecture is being used while beacons are established above the surface and the field is partitioned to some octahedron cells. Each cell has only one sensor with distinct number of neighbors. Establishing such structures might look difficult concerning the underwater conditions. In this area, [13] divided the localization mechanism to three steps including distance estimation, position computation, and localization algorithm. To perform the distance estimation, they used ToA technique in a static 2D architecture for distance estimation. Also trilateration is manipulated for position estimation. The localization algorithm is based on static architecture while 3 beacons are employed in that work. The work shows reliable architecture and accurate result, however, it should be tested for the possible errors of synchronization. In terms of ToA based methods, [14] proposed another work which has assigned a unique ID to each sensor node before deployment. [15] have presented the localization algorithm with merging segmented maps (LaMSM) for UWSNs. The mechanism is based on multidimensional scaling (MDS) which is already used in terrestrial localization [16]. Their method is constructed on the segmented maps of the nodes which are in their communication range. Similar to [16], [15] needs many broadcasting between sensor nodes to building the map as each node should be aware of all information of itself. [17] proposed a depth-based method to cover the inhomogeneous nature of sea water. By using Fermats' Principle and calculus of variation, they reconstructed the slanted path and removed the bias via maximum likelihood estimator and Cramer Rao Bound methods. Recently, Silent positioning is developed by [18] which is a return-trip ToA-based localization. Silent positioning system relies on Time of Arrival from sensor to four beacons. However, they used a ping-pong style to compensate the synchronization issue, but the delay required for handling the signal in the second sensor [5] is ignored. Apart from the discussed works so far, [19] has introduced a hybrid localization by using ToA and AoA simultaneously. They have extracted the difference of arrival time according to the receiving time of signal to two surface reference nodes. Despite the novelty of idea, implementing such AoA measurement based on expensive antenna arrays for each individual sensor node is very costly. More than that, it needs precise synchronization between reference nodes with regards to ToA.

2.1 Underwater Synchronization

The aim here is not to analyze the existing underwater synchronization work, but to introduce the challenges that affect distance measurement accuracy. Synchronization is widely studied in terrestrial sensor networks, taking wireless communication between sensor nodes as instantaneous. Electromagnetic (EM) transmission is at light speed, so the travel time for short distances can be neglected. Acoustic wave propagation is five orders of magnitude slower than EM [20]. The major error in synchronization is non-deterministic estimation of message delivery, with errors originating [20] in: send time, access time, interrupt handling time, transmission and reception time, propagation time, encoding and decoding time, byte alignment time, and receive time.

Furthermore, synchronization accuracy degrades over time [20], [21], exactly after the synchronization procedure stops. Accordingly, in UASNs, precise time synchronization is hard to achieve due to the characteristics of sound travel in the water [20]. Therefore, the new RSS-based measurement technique, presented in this paper, does not rely on synchronization.

3 Underwater Acoustic Transmission Loss

Acoustic transmission loss in water is classified as spreading loss, including spherical and cylindrical, and attenuation loss consists of absorption, duct leakage, scattering and diffraction [22]. Generally, attenuation parameters relate to the medium (salinity, acidity, pressure, and temperature) and environment (air bubbles, sediment absorption, surface reflection and scattering). In our work, we only consider the medium parameters. Moreover, spherical spread fits the measured data in many cases either [22]. Accordingly, the general TL equation would be

$$TL_{total} = TL_{sph} + TL_{cyl} + 10^{-3}\alpha\, Dist. \quad (1)$$

where α is absorption coefficient in sea water. We have used Thorp model [23] as absorption coefficient model. Eq. 1 can be inverted through the Lambert function in order to calculate distance X as follows

$$Dist = \frac{20000 \times W\left(\frac{\ln(10)}{20000}\alpha e^{\lambda TL}\right)}{\alpha \ln(10)}, \quad (2)$$

where TL represents the transmission loss measurable by receiver and W are the Lambert function weights available by the Halleys method

$$w_2 = w_1 - \frac{w_1 e^{w_1} - Y}{e^{w_1}(w_1+1) - \frac{(w_1+2)(e^{w_1}-Y)}{2w_1+2}} \quad (3)$$

$$= 0.031097128121345300 \quad (4)$$

The complete derivation and mathematical proof can be found in [1].

4 Hybrid RSS-based Localization

Localization is significant in wireless sensor networks either for application needs or other protocol demands. The quality of the location information is dependent on the application requirements. Apart from granularity resolution of the estimated position, the localization methods can be divided to two categories according their computation circumstance including distributed and centralized. Distributed generally means that each sensor computes its location by using its own resources and save that coordinates. Where in centralized, they mostly assume that sensors communicate to the beacons or the sink in one-hop communication, and their position can be calculated by beacons or sink. The literature review in Section 2 has shown that most of the proposed methods are established on the distributed computations rather than centralized. However, such methods may decrease the network life-time due to the limited resources on sensor nodes. Accordingly, A hybrid computation mechanism is developed in this research that can cope both demands, i.e. sensor nodes will get some location information via minimum energy usage and the network can obtain an accurate position estimation by further processing on the received information from sensor nodes on a third agent like sink or base-station. The new localization mechanism is divided to three stages as follows:

1) Initialization
2) Distance measurement
3) Position Estimation

Each stage is described in details as follows along with the proposed algorithms. In this mechanism, both centralized and distributed computations are manipulated.

4.1 Initialization

First, sensor nodes obtain a raw location knowledge while beacons, deployed on the corners of the network field, send beaconing signals periodically and sensors save the received signal strength in a record. This step covers the distributed aspect of localization in order to make sensor nodes location-aware via some preliminary location information and the idea is similar to work in [7]. However, the location information in their works is comprised of four integer numbers according the different power levels, in our work, the exact value of the received signal strength saves and it will be used later to extract a fine-grained estimation. Algorithm 1 represents the pseudo code of the initialization step.

Algorithm 1 Initialization

```
Beacon_No = 4;
Raw_Loc[1..Beacon_No] = 0;
while Beaconing_Time do
    for iteration = 1 to Beacon_No do
        Receive_Signal_Strength = Beaconing_Signal;
        if (Raw_Location[i] == 0) then
            Raw_Loc = Received_Signal_Strength;
            else if (Raw_Loc[i] < Received_Signal_Strength)
            Raw_Loc = Received_Signal_Strength;
        end if
    end for
end while
```

According the algorithm, each sensor node receives signals from all four beacon nodes during a period of time. For the purpose of simplicity, it is assumed that beacons are synchronized or they can transmit acoustic waves in different channels, so there are no interferences between beacon nodes. Therefore, each sensor keeps a record as $< Raw\_Loc_{B1}, Raw\_Loc_{B2}, Raw\_Loc_{B3}, Raw\_Loc_{B4} >$ where each field indicates the received signal strength from a particular beacon. All nodes save the received signal strength from beacons for the first time. However, regarding the situation that each sensor receives several signals from same beacon, the sensor node save higher signal strength which has lower transmission loss. Because it is supposed that a signal with higher strength is arrived to the node in a straight line with minimum errors due to sea-bottom reflection or noises. This record is denoted in a shorter form as $Raw\_Location\_Record$ in the sequel. In this manner, when a sensor detect a phenomenon, it disseminates a packet that might consist of descriptive data for the detected event and attaches the $Raw\_Location\_Record$ to the packet. This data will arrive at the beacons and later on to the sink through a multi-hop communication. Although the $Raw\_Location\_Record$ can be used in such protocols that may need location information, but it will be sent to the sink or base station for further processing and deriving the fine-grained coordinates. The requirement of multi-hop communication is not considered in this research as it is out of the scopes. So, the rest of the localization process is comprising of the distance measurement and position estimation will be fulfilled in the sink or onshore base-station.

4.2 Distance Measurement

The phase is considered to be conducted in a powerful node like sink or onshore base station where there are no resource limitations like power, process-ability, and memory. Once the sink receives $Raw\_Location\_Record$, calculates distances from the beacons through Eq. (2). The distances would be further used in position estimation phase using bilateration techniques.

4.3 Position Estimation

The process of approximating the position for each sensor node is divided into two parts including bilateration and refinement. The explanation of each particular part comes as follows:

4.3.1 Bilateration

It is a well-known approach to find coordinates of an unknown point according the available information including coordinates of two reference points and the distances of the unknown point from each reference points. Bilateration equations for the beacons are represented by Eq. 5.

$$\begin{cases} Eq1: (X_{B1} - X_U)^2 + (Y_{B1} - Y_U)^2 = Dist_{B1} \\ Eq2: (X_{B2} - X_U)^2 + (Y_{B2} - Y_U)^2 = Dist_{B2} \\ Eq3: (X_{B3} - X_U)^2 + (Y_{B3} - Y_U)^2 = Dist_{B3} \\ Eq4: (X_{B3} - X_U)^2 + (Y_{B3} - Y_U)^2 = Dist_{B4} \end{cases} \quad (5)$$

where X_U and Y_U represent the targeted coordinates; (X_{B1}, Y_{B1}), (X_{B2}, Y_{B2}), (X_{B3}, Y_{B3}), and (X_{B4}, Y_{B4}) present the coordinates of four beacons; $Dist_{B1}$, $Dist_{B2}$, $Dist_{B3}$, and $Dist_{B4}$ are respectively the distances between unknown node and each beacons. As there are four equations, then there are multi values for X_U and Y_U. To have an accurate estimation, it requires a comprehensive evaluation of all possible values for X and Y. Therefore, two different combinations are organized to generate all possible pairs of X and Y.

1) Combination of equations: As mentioned above, bilateration is a method of finding coordinates based on two reference points and the respected distances from one unknown node. Considering that there are four reference points available in this case, then bilateration has to be applied for each pairs of them. As there are $\frac{n(n-1)}{2}$ states for n objects (n is the number of equations here). Therefore, bilateration method has to be applied for six pairs of reference nodes.
2) Combination of X and Y values: From the bilateration results, There are two X and Y values for each pair of equations. Hence, a combinations of all X and Y, from Eq. (5), are produced. Accordingly, there are totally 24 pairs of different X and Y values.

Once all possible values are extracted, the right coordinate has to be determined. The process of determining the right value for X and Y is called refinement.

4.3.2 Refinement Algorithms

The multivalued nature of Euclidean method and combinations of those values require a refinement for determining more accurate position. The process of refinement is divided into two different stages similar to the combination stage which are simply called first and second refinements.

1) First Refinement: There is a possibility that the values of X and Y indicate a position out of the field. Therefore, as first step, all X and Y values which are outside the boundaries of the field are eliminated. It causes lesser comparisons later and makes the position estimation more reliable. This approach would be conceivable since it is assumed that the nodes are static and they are deployed in a field surrounded by the beacon nodes.

Algorithm 2 Second Refinement

```
Receive First_Refined_Coordinates, Beacon_Info, RSS;
for i=1:size(First_Refined_Coordinates) do
    for j = 1 : 4 do
        Dist_XY(i,j)=Calculate_Distance((X,Y),Beacon_Info(j));
        New_SS(i,j)=Calculate_Signal_Strength(Dist_XY);
    end for
end for
for m=1:size(New_SS) do
    for n = 1 : 4 do
        Error=Error + sum(abs(New_SS(m,n) - RSS(m,n));
    end for
    Add Error to First_Refine_Coordinates(m);
    Error = 0;
end for
length=size(First_Refine_Coordinates);
Sorted_Coordinates=sort(First_Refine_Coordinates based-on Errors);
Final_X=average(Sorted_Coordinates(1:round(length/4),X);
Final_Y=average(Sorted_Coordinates(1:round(length/4),Y);
Final_Coordinates=(Final_X,Final_Y);
```

2) Second refinement: Once all the unexpected values are deleted from the available choices, the second refinement is being started to determine the most probable value of X and Y. The detail of the second refinement is presented in Algorithm 2. As can be seen, the distances among all available pairs and beacons are calculated. According the calculated distances, it is possible to measure the signal strength for each particular distance. So the new signal strength (denoted by New_SS in Algorithm 2) is now calculated and the Received Signal Strength (denoted by RSS there) is available from initialization step (see Section 4.1), then the existing errors among all New_SS values and RSS are measurable. The coordinates values are sorted on ascending order of errors. Thereafter, the extensive study on different data sets showed that the most proper value can be reached by calculating the average of first 25% of data set which have least errors.

This new method gets benefit of unlimited resources of the sink node and extracts the coordinates through a reverse solution. There are some advantages of this kind of mechanism design which are briefly summarized as follows:

1) The initialization section supports the distributed concept of localization by preparing raw location information for each sensor node in the field. As this raw information may be needed by other protocols.
2) There is no extra cost on sensor nodes like repetitive send and receive signals, special instruments, and extra process or memory.
3) As the sink fulfills all derivation and repetitive works and it is assumed that there is no resource limitation there, it is possible to design more complicated refinement methods to obtain more accurate values.

Extensive simulation scenarios are organized for verifying this algorithm which are explained in the next section.

5 Localization Scheme Simulation

To evaluate the effectiveness of the designed components as well as whole localization mechanism, variety of simulations are organized. As discussed in Section 3, there two are groups of factors which affect the acoustic wave propagation in underwater while this work considers both in terms of simulation including transmission medium and environment factors. The former one, consists of temperature, salinity, pressure, and acidity, covers through the absorption coefficient. However, to consider the later one, Gaussian random number generation is being employed for generating random errors (noise) on the original data. Unlike the existing works, the generated errors and simulation scenarios are very comprehensive in this work. The errors are varying from 0% which represents an ideal environment to 10%. Besides, it is considered that errors affect on the received signal strength from one beacon up to four beacons. Therefore, total generated error varies from 0% up to 40%. So the simulations are organized in the following order:

1) One Beacon Error: In this step, it is assumed that errors affect on received signal strength from only one beacon. The simulation is ran for different amount of errors between 0 to 10% while the standard deviation of error is $\pm 5\%$. The specific beacon is being selected randomly.
2) Two Beacons Errors: The affected errors are extended to two beacons in same time in this step. It is considered that error happens on the received signal strength of two beacons. So similar to one beacon error, errors vary from 0 to 10% but for received signals of two beacons. Hence, the standard deviation of total error is still $\pm 5\%$ in this stage, but total generated error is 10%. The presented pseudo code can also manage the error generation for this stage.
3) Three Beacons Errors: In this scenario, three out of four beacons are randomly selected that their

transmitted signals could be affected via errors. So there are three inaccurate received signals by sensor nodes. The error variation is similar to the last two scenarios which increase up to 10% for the received signal from each of those three beacons. Therefore, the standard deviation of generated error is $\pm 5\%$ while total error is 15%.

4) Four Beacons Errors: Finally, the designed localization mechanism is tested for the affected received signal strength from four beacons. In this step, it is assumed that all signals are received with errors which might be caused from environment factors. The errors variation alters up to 10% which is between -5 to $+5\%$. So the standard deviation of maximum generated errors is $\pm 5\%$ for each node in the last simulation scenario but the total error is 20%. While all error generations are managed by same manner. Algorithm 3 presents that how a beacon selects and error adds to the original received signal strength.

Algorithm 3 Error Generation

```
receive No_Beacons, Org_RSS, Err_Percent;
Selected_Beacons=random(1, 4, No_beacons);
for i=1:all Nodes do
    for j=1:all Beacons do
        Percent=Org_RSS(i,j)*(Err_Percent/100)*Selected_
        Beacons(i,j)/2;
        Err(i,j)=randint(1,1, 2*Percent+1) - Percent;
        Err_RSS(i,j)=Org_RSS(i,j) + Err(i,j);
    end for
end for
returen Err_RSS;
```

5.1 Existing Techniques

The fine-grained localization methods for underwater environment are based on Time of Arrival. For the reason of comparison, ToA is being simulated in this work since it is the basis for the existing localization works so far. The major problem for the existing works in underwater area is that they mostly assume ideal environment without any sound velocity variation and they simply assume that the nodes are synchronized. As it is discussed in Section 2.1, synchronization is a big challenge in sensor networks especially in the case of underwater sensor networks. Therefore, a wide range of simulations are set up in this research to analyze the accuracy of ToA-based techniques. Furthermore, to increase the reliability of results, both techniques are simulated in the same proposed localization mechanism including same position estimation and refinements. Likewise the simulation scenarios in Section 5, there are four different error generations. The generated error is based on the synchronization delays which are discussed in Section 2.1. Consequently, the error values vary from 0 to 0.1 sec delay by 0.01 increment in each step. However, the error could be increased up to 0.18 sec while all errors are obtained immediately after synchronization stage. So the scenarios are considered as follows:

1) One Beacon Error: In this case, it is assumed that only one beacon is not synchronized with receiver node. Therefore, the delay error varies from 0 to 0.1 sec with a standard deviation of ± 0.05 sec.
2) Two Beacons Errors: If there are two unsynchronized beacons with the receiver node, then the error can affect on two arrival times. Therefore, the errors are generated randomly in terms of delay time by the standard deviation of ± 0.05 sec for each beacons. The total error has ± 0.1 sec variation.
3) Three Beacons Errors: The possible errors are extended to the arrival times from three beacons. The delay time varies from 0 to 0.1 sec. Then the total generated error could be 0.15 sec while the standard deviation of error for each particular beacon is ± 0.05 sec.
4) Four Beacons Errors: The last scenario studies the possibility of having delay time on all arrival times. In this case which is the worst case, the generated errors follow the same behavior in terms of values. However, the total generated error on the calculation grows up to 0.2 sec, but the each node has only the ± 0.05 sec standard deviation of errors.

Obviously, the simulation scenarios cover most of error conditions and give a comprehensive insight into the error toleration of those distance measurement techniques. The results of simulations are presented and analyzed in the next section and both techniques are discussed according to the obtained results.

6 Result

The result of simulations, both RSS-based and ToA-based techniques, are presented in two separated subsections and accordingly we discuss the result at the end of this section. Moreover, the results are obtained while each scenario is repeated for 10 times because not much variation is being observed.

6.1 RSS-based Localization Simulation Results

There are four different simulation scenarios according to the source of errors including one beacon error, two beacons error, three beacons error, and four beacons error. Tables 1, 2, 3, and 4 present the average obtained results from all repeated simulations for all four scenarios. The tables show that the localization algorithm approximate accurate position in terms of ideal environment. As can be seen in Table 1, the new RSS-based localization mechanism can cope with the error received from only one beacon with three correct RSS from other beacons. The average error increased from 1.1 $\mu meter$ for an ideal environment to 4.695503 $meter$ in the case of existing 10% error occurring on the beacon. The obtained accuracy could be acceptable in many applications. Table 2 represents the results of two beacons error simulations. It can be seen that the error produced from two beacons generated overall error of almost four

TABLE 1
Total Results for One Beacons Error Using RSS Mechanism

	0%	1%	2%	3%	4%	5%	6%	7%	8%	9%	10%
Minimum Errors	0.0	0.000001	0.000001	0.000001	0.000001	0.000001	0.000001	0.000001	0.000001	0.000001	0.000001
Maximum Errors	0.000145	8.372887	15.189179	22.458929	27.372282	32.815336	40.229481	47.979995	55.560708	71.543648	69.379365
Mean Errors	0.000011	0.525717	1.178888	1.651087	2.054959	2.129891	2.554821	3.078772	3.818973	3.892772	4.695503
STD Errors	0.000012	1.370640	2.747879	3.911194	4.503551	5.237535	5.821420	7.521040	8.455174	9.515943	10.733185

TABLE 2
Total Results for Two Beacons Error Using RSS Mechanism

	0%	1%	2%	3%	4%	5%	6%	7%	8%	9%	10%
Minimum Errors	0.0	0.001069	0.029623	0.020537	0.026225	0.012714	0.068862	0.055409	0.066332	0.043587	0.026935
Maximum Errors	0.000145	46.625749	37.555894	57.357989	78.653390	84.646437	112.370825	103.259812	141.812124	123.054442	136.335776
Mean Errors	0.000011	3.839385	7.471701	11.227395	14.637962	17.858888	20.876378	23.920124	26.773099	28.815548	31.291678
STD Errors	0.000012	4.367492	6.321917	9.690167	12.908883	15.158915	18.078578	19.594607	21.959973	23.377652	25.461796

TABLE 3
Total Results for Three Beacons Error Using RSS Mechanism

	0%	1%	2%	3%	4%	5%	6%	7%	8%	9%	10%
Minimum Errors	0.0	0.359216	0.479694	0.587597	1.002730	1.212758	0.649355	1.443040	1.139166	1.989461	2.307758
Maximum Errors	0.000145	74.794418	195.186453	186.447123	178.855346	197.237587	197.679428	187.508711	206.153325	189.024555	195.010780
Mean Errors	0.000011	5.814226	11.979003	17.634366	23.647306	28.845735	34.105747	40.354979	43.188692	48.608537	52.115845
STD Errors	0.000012	6.449714	15.620786	17.242338	20.505061	23.963838	27.403823	30.111980	31.820948	33.656818	35.423996

TABLE 4
Total Results for Four Beacons Error Using RSS Mechanism

	0%	1%	2%	3%	4%	5%	6%	7%	8%	9%	10%
Minimum Errors	0.0	0.872670	1.134199	1.352676	0.995907	2.759724	2.209110	2.310711	3.299945	2.850878	3.174703
Maximum Errors	0.000145	51.710014	172.431377	157.169221	326.787322	264.499183	334.911709	289.432459	295.311484	252.233716	347.042930
Mean Errors	0.000011	7.003154	15.641568	22.401105	32.272985	38.846561	48.297108	53.333921	60.695749	65.205151	72.393619
STD Errors	0.000012	5.596661	15.309967	17.241329	30.339329	29.747229	39.377425	36.795335	37.394128	39.122972	45.707778

times greater compared to the last scenario. For instance, a 10% error from one beacon produces 4.695503 meters error while a 5% error from two beacons can generate 17.858888 meters error.

The error values are expanded in the third and fourth scenarios where the errors are generated via three and four beacons, however, the incremental errors are almost constant. The results are shown in tables 3 and 4. It is shown that the error increases is around $20\ meters$ per each scenario if increment is made from 2 to 4 beacons. While the standard deviation increases by $10\ meters$ for each scenario. It means that when error happens on only one beacon it is possible to get acceptable results whereas if errors happen on more than one beacon, the accuracy will be dramatically degraded. It is also shown that error produced due to noises increases with a constant value. In the next section, the obtained results from ToA-based localization mechanism is presented and analyzed.

6.2 ToA-based Localization Accuracy Results

Time-of-Arrival is another distance measurement technique which is widely used in underwater wireless sensor network localizations. The approach is dependent on acoustic wave propagation velocity and the accuracy of such techniques is completely determined by the quality of synchronization which is discussed in Section 2.1.

Tables 5, 6, 7, and 8 present the results in terms of ToA-based localization mechanism. The results show that there are some position estimation errors even in the ideal environment. However, it can be ignorable in most of applications. Table 5 shows the synchronization error occurred from only one beacon and the accuracy of such methods is sufficient even with $0.1msec$ delay. However, the error is increased when there are synchronization delays from two beacons as it can be seen from Table 6. It shows that the delay produce up to $49.087859\ meters$ average estimation error while standard deviation of error is also high which is around $40.912396\ meters$.

This situation is expanded to the third simulation scenario where the average errors are increased almost up to 2 times of two beacons error in the worst case when there are $0.1\ msec$ synchronization delay from three beacons. In this case, standard deviation is still high around $44.910707\ meters$ that shows the estimated values are more dispersed because of synchronization errors. The result of three beacons error is represented in Table 7. However, in the last scenario, the synchronization delay from four beacons has less error generation compared to two and three beacons scenarios as the results show in Table 8.

7 Comparison with Existing Techniques

Based on the simulation results, RSS and ToA-based techniques are compared in this section. Figures 1a and 1b present the total average errors of both techniques including Received Signal Strength and Time-of-Arrival. As can be seen in those figures, the new RSS-based mechanism generally achieve better as accuracy compared to the results of ToA-based approach. However, there is a point which it can be seen in Figures 2a and 2b in terms of standard deviation of errors behavior. The standard deviation of such time-based

TABLE 5
Total Results for One Beacons Error Using ToA Mechanism

	0	0.01	0.02	0.03	0.04	0.05	0.06	0.07	0.08	0.09	0.1
Minimum Errors	0.000067	0.000091	0.000077	0.000067	0.000070	0.000066	0.000067	0.000059	0.000060	0.000066	0.000075
Maximum Errors	0.001036	11.271598	18.725498	25.374619	34.999543	44.297050	54.163230	56.395861	55.442227	78.001236	90.866997
Mean Errors	0.000513	0.404678	0.870272	0.920895	1.474866	1.717529	2.027273	1.951900	1.941413	2.946702	3.244457
STD Errors	0.000199	1.480887	2.867293	3.426876	4.814403	5.946720	6.935659	7.060553	7.029694	10.200098	10.559761

TABLE 6
Total Results for Two Beacons Error Using ToA Mechanism

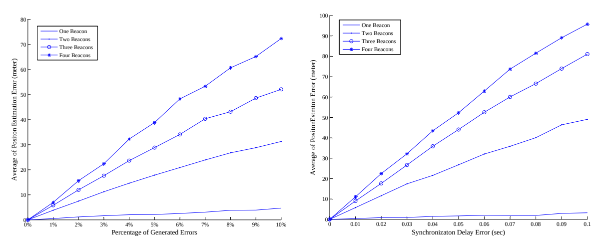
	0	0.01	0.02	0.03	0.04	0.05	0.06	0.07	0.08	0.09	0.1
Minimum Errors	0.000067	0.000200	0.000216	0.000306	0.000290	0.000381	0.000479	0.032293	0.000679	0.000783	0.000784
Maximum Errors	0.001036	55.138918	62.793640	92.679217	72.398628	119.449318	134.878990	139.862132	143.587482	166.721561	170.173832
Mean Errors	0.000513	5.781973	11.617062	17.437869	21.583570	26.785789	32.061299	35.859806	40.085442	46.378091	49.087859
STD Errors	0.000199	5.859496	9.959610	14.866081	17.756839	22.527829	26.164950	30.684279	33.967162	38.027516	40.912396

TABLE 7
Total Results for Three Beacons Error Using ToA Mechanism

	0	0.01	0.02	0.03	0.04	0.05	0.06	0.07	0.08	0.09	0.1
Minimum Errors	0.000067	0.673804	0.317610	1.087181	1.096793	1.153255	1.389423	1.599626	2.049219	2.275899	2.163936
Maximum Errors	0.001036	62.055211	135.565906	122.558521	208.349384	205.214051	203.064452	211.223949	207.119629	212.719591	212.039734
Mean Errors	0.000513	9.045163	17.642940	26.698954	35.872390	44.078696	52.545194	60.084563	66.615453	73.970804	81.084666
STD Errors	0.000199	5.879861	13.753461	16.079426	24.040389	26.716294	29.799622	34.851913	36.843168	40.973798	44.910707

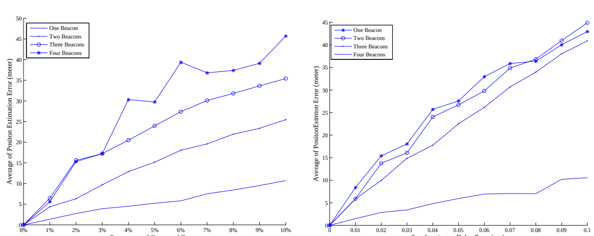
TABLE 8
Total Results for Four Beacons Error Using ToA Mechanism

	0	0.01	0.02	0.03	0.04	0.05	0.06	0.07	0.08	0.09	0.1
Minimum Errors	0.000067	0.776429	1.842221	1.762086	2.516809	4.131441	4.619089	5.965190	7.155262	8.039497	7.740380
Maximum Errors	0.001036	107.849784	166.889461	176.582426	229.082363	207.889861	260.641873	272.653405	219.085555	260.845219	221.528687
Mean Errors	0.000513	11.068313	22.461528	32.206981	43.465992	52.309373	62.968495	73.732201	81.530068	89.102890	95.801855
STD Errors	0.000199	8.385139	15.412854	18.048364	25.709434	27.590203	32.960232	35.880590	36.403353	40.045546	42.971137



(a) Received Signal Strength (b) Time of Arrival

Fig. 1. Arithmetic Mean Errors of Simulation Results



(a) Received Signal Strength (b) Time of Arrival

Fig. 2. Standard Deviation Errors of Simulation Results

methods is dramatically increased when sensor nodes receive synchronization delay error from two beacons or more. In this case, the RSS-based results have a normal incremental behavior for different errors.

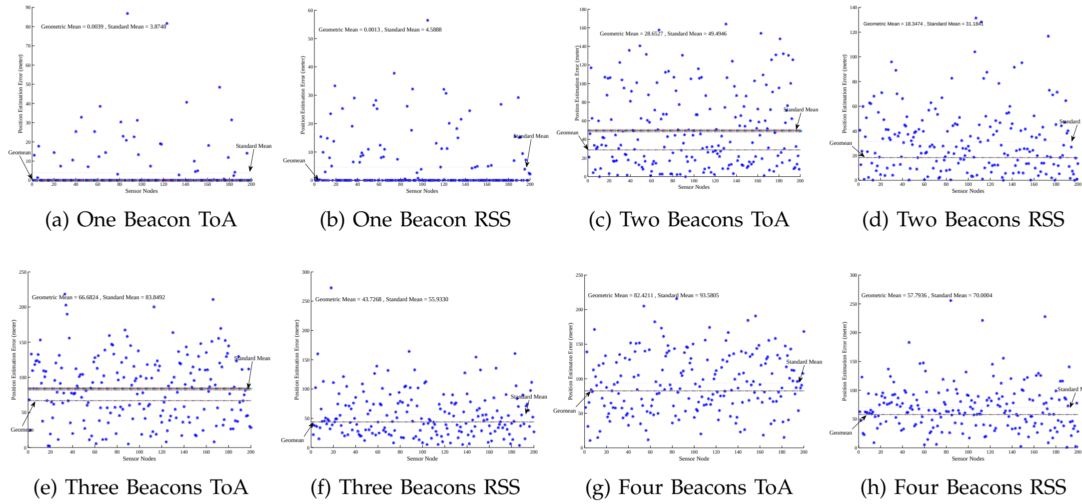
Furthermore, it can be observed in the tables that even in the ideal environment the RSS-based localization can get an accurate position while the the ToA-based methods have some errors. To have a minutely analysis, few sample of error distributions are presented in Figure 3. These samples are extracted from only one of the simulation results, but based on the data observations, it can be extended to all simulation. The sub-figures show the quality of position estimation errors related to RSS and ToA approaches for the worst case in each scenario, it means 10% for RSS and $0.1\ msec$ for ToA from one beacon to four beacons. Geometric mean is being employed to get more accurate average of the results using (6).

$$Geometric\ Mean = \sqrt[n]{\prod_{i=1}^{n} x_i} \qquad (6)$$

where n is the number of sensor nodes in this case. Subfigures in Figure 3 show that the RSS-based mechanism can achieve better accuracy in all conditions. It is shown that the geometric mean of error of localization using the RSS-based distance measurement is one-third of the ToA-based methods when there is 10% errors from one beacon. Likewise, it is more accurate in other conditions. There are two points in the sub-figures which are:

1) ToA-based calculation has more scattered error distributions compared to RSS-based approach.
2) RSS-based calculation could achieve better accuracy as its geometric mean is less than ToA method in all cases.

It can be concluded that the sensitivity of ToA-based methods against synchronization errors might be higher than the new RSS-based localization against the environment noises. It could be conceivable because of the



(a) One Beacon ToA (b) One Beacon RSS (c) Two Beacons ToA (d) Two Beacons RSS

(e) Three Beacons ToA (f) Three Beacons RSS (g) Four Beacons ToA (h) Four Beacons RSS

Fig. 3. Error Distribution of Different Simulations

nature of calculations where distance calculates via a linear equation in the case of ToA. Therefore, any change of values directly influence on the results. On the other hand, the RSS calculates the distance via an exponential equation and changing value may have less effect on results compared to the linear equations. Finally, the simulation results show that the new RSS-based localization can produce more accurate position estimation without any extra demand such as time synchronization or large number of beacons.

8 Conclusion

A new RSS-based localization is proposed which is hybrid in terms of the positioning process. Three steps localization mechanism, comprised of initialization, distance measurement, and position estimation, is developed to support distributed aspect of such mechanism throughout the network field as well as it is centralized to preserve the energy. The results, achieved by extensive simulations, show that the proposed RSS-based localization is more accurate and less vulnerable to environment errors compared to ToA-based approaches.

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