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RESEARCH ARTICLE

A Novel Positioning Technique for 3D Underwater Sensor Networks

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Abstract— ***Positioning or Localization, that is, determining the location of every sensor is important and the process aims to have the maximum percentage of localized nodes whether stationary or in motion. This paper elaborates the idea of mining applications in the underwater scenario and also highlights the basic differences between terrestrial sensor networks with the underwater paradigm while exploring the different positioning approaches that are relevant to underwater sensor networks as well as the challenges in meeting the requirements posed by emerging applications. We propose a new algorithm which uses the (mining counter-measure) MCM applications through of an UUV-guided positioning system in an UW-ASN. Also, we have compared with the other related work previous done on this very same field and we have proved that our work yields better results than the previous work done and the performance analysis through various MATLAB simulations have been shown.***

Key Terms: - Underwater Wireless Acoustic Sensor Networks (UW-ASNs); Acoustic Communication; Terrestrial Wireless Sensor Networks (TWSNs); Radio Frequency (RF); Localization; Anchor Node; UA (Underwater Acoustic) Node; Surface Buoy; MCM

I. INTRODUCTION

Wireless underwater acoustic networking is the enabling technology for the applications such as oceanographic data collection, pollution monitoring, offshore exploration, disaster prevention, assisted navigation and tactical surveillance technologies and in collaborative monitoring missions [1] [2] [3].

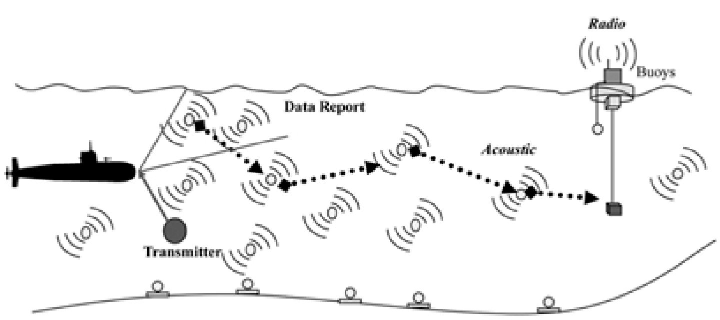


Fig. 1: Underwater Sensor Network

Wireless networking technologies have experienced a considerably development in the last fifteen years, not only in the standardization areas but also in the market deployment of a bunch of devices, services and applications. Recently, wireless sensor networks have been proposed for their deployment in underwater environments where a lot of applications like agriculture, pollution monitoring, offshore exploration, etc. would benefit from this technology [4][5].

Despite having similarities with TWSNs, UWSNs exhibit several architectural differences with respect to the terrestrial ones, which are mainly due to the transmission medium characteristics (sea water) and the signal employed to transmit the data (acoustic ultrasound signals) [6]. Then, the design of appropriate network architecture for UWSNs is seriously hardened by the conditions of the communication system and, as a consequence, what is valid for TWSNs is perhaps not valid for UWSNs. Fig. 1 shows the underwater sensor network in which the underwater sensor nodes communicate and send the sensed data report from an AUV or any other moving vehicle to the buoys at sink. The AUVs receive the information from the transmitters. Maintaining all established connections becomes complicated in unstable underwater channel. Underwater sensor networks or underwater acoustic wireless sensor networks mainly differ in the communication media employed for information transmission. The work described in [7] reviews the physical fundamentals and engineering implementations for efficient information exchange via wireless communication using physical waves as the carrier among nodes in an underwater sensor network. The physical waves include sound, radio, and light. Based on the comparative study, one can select carriers for underwater sensor networks that enhance the communication efficiency in specified underwater environment.

II. POTENTIAL APPLICATIONS

The application of WSNs in the underwater domain has huge potential for monitoring the health of river and marine environments [8]. A sensor network deployed underwater can be used to monitor physical variables such as water temperature and pressure as well as variables such as conductivity, turbidity and certain pollutants [9] [10].

Navy Applications: The unmanned underwater vehicle (UUV) provides strategic and operational advantages to the Navy and security forces by reducing the cost and human risk significantly in the MCM operations, as well as by extending the reach of information, surveillance and reconnaissance. MCM operations are conducted by the Navy to estimate the location and destruction of the naval mines [11]. These UUV systems can be launched off the naval platform, offer significant protection against major threats such as naval mines.

III. RELATED WORK

In this paper, we have emphasized on the problem of Localization or Positioning. In underwater environment, sensor nodes need to justify their own locations because they may be drifted by water currents [12]. Moreover, some kinds of measured information are meaningless without location information. We need to introduce a new localization method which operates undersea with the least use of GPS. In underwater situation, sensor nodes can easily measure their depth with hydraulic gauge. Localization is the prominent problem and its solution is the need of the hour as it directly relates with other problems like Channel Assignment and Cluster-head Selection in homogeneous UW-ASNs in the circumstances in which the Figure 2 scenario is considered.

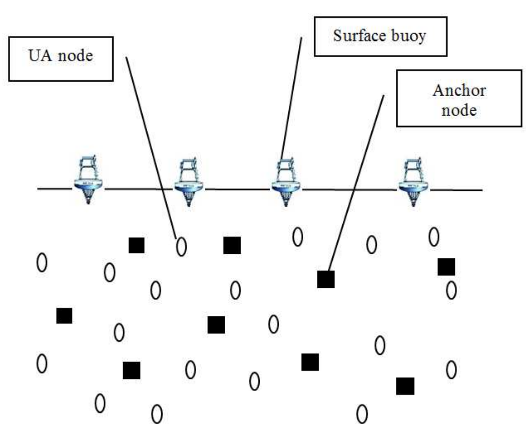


Fig. 2: Underwater Sensor Network Architecture

In general localization method in water, sensor nodes identify their positions based on distances from some anchor nodes (in common language, landmarks). There are many Localization or Positioning schemes deduced.

A. Distributed positioning approach

1. Estimation-based schemes:

   a. Dive 'N' Rise Localization (DNRL) [13] is a distributed estimation-based localization scheme. Its main usage is in the field of mobile UW-ASNs. The procedure it applies enables the Dive 'N' Rise (DNR) Beacons (or localized) to descend and ascend in the water column. DNRL uses one-way ranging ToA (Time of Arrival) technique and uses lateration.
   b. Multi-Stage Localization (MSL) [14] is an extension of DNRL which includes an iterative phase. DNR beacons are not propelled and use successfully localized nodes as a beacon which is unable to ascend or descend but allowed to send self-coordinates.
   c. AAL (AUV-Aided Localization) [15], LDB (Localization with Directional Beacons) [16] and LSL [17] and LSLS (Large-Scale Localization Scheme) [18] are other estimation-based schemes.

2. Prediction-Based Schemes: They are the schemes which estimate the localization by using the nodes' previous coordinates and mobility patterns. In [19], the authors make use of the hierarchical architecture of [20] and idealize a new concept of Scalable Localization with Mobility Prediction (SLMP) for mobile UW-ASNs.

B. Centralized positioning approach

1. Estimation-Based Schemes:
   a. MASL (Motion-Aware Self Localization) [21] aims to provide accurate localization by addressing inaccurate distance estimates in mobile UW-ASNs. MASL involves a scenario in which each node collects its location and its neighbour's locations also and then it forwards to an AUV or UUV.
   b. Area-based Localization Scheme (ALS) [22] gives the estimate of the area where the sensor node resides rather than its set of coordinates. The anchor nodes partition the region into non-overlapping areas by sending messages at varying transmission power levels. ALS is less energy efficient than other silent localization protocols such as Underwater Positioning System (UPS) [23] approach.
2. Prediction-based Schemes: These involve approaches such as Collaborative Localization (CL) is explained in [24]. The author uses this approach for the fleet of underwater drifters. It assumes a scenario in which underwater sensors are responsible for collecting data from the depths of the oceans and carrying them to the surface.

IV. PROPOSED WORK

The problem of localization is taken very seriously these days as new algorithms and schemes are now being researched and found out to overcome the situation when several nodes are there in the underwater scenario looking to be localized with minimum error and maximum localization success.

A. Underwater Acoustic Network Scenario and Assumptions

We contemplate a three dimensional (3D) underwater acoustic network scenario in which the sensor nodes are floating at different levels. As shown in Fig. 3, the UUV is moving in a straight line set beacon points at different time intervals and as per the situation demands, some sensor nodes encountered in the path of the UUV can also be given the responsibility of being a temporary beacon point so that keeping the sparse 3D sensor network in mind, the nodes beneath the level at which the UUV is moving and also above that level can be localized with more efficiency. So to enhance the localization success, we need to ponder the scenario illustrated in Fig. 3 and also cogitates the algorithm named UUV – Enabled Positioning Scheme (UEPS) shown in Table 1. In the figure below, the nodes S_2 and S_3 have been localized at different situations. The node S_1 is the node which is not accurately localized and hears the directional beacon beam from only one beacon point, whereas the other nodes S_2 and S_3 hear the directional beacon beam from two beacon points at different height H respectively. The scenario shown in Fig. 3 is majorly devised to play the fulcrum role in the Navy MCM (mine counter-measure) operations. First of all, the MCM operation is conducted by the naval forces which search for any underwater naval mines which may be floating in the middle of the ocean 3D volume or may be at the bottom of the ocean or the ocean floor.

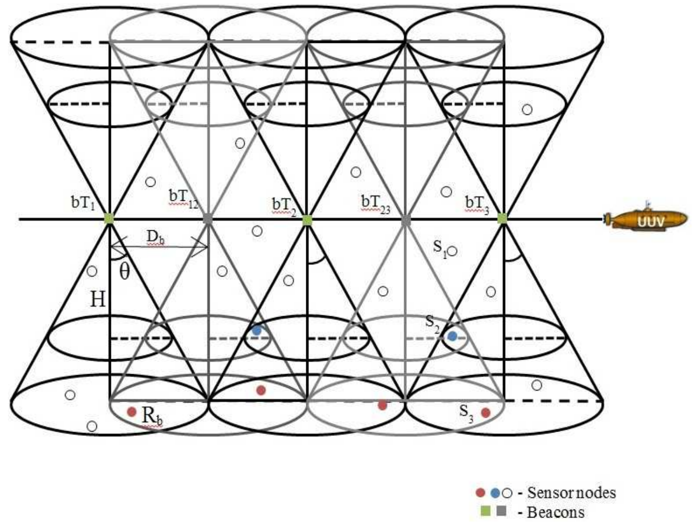


Fig. 3: 3D UW-ASN scenario involving the UUV, beacons and sensor nodes

B. Proposed UEPS Algorithm

In the Fig. 3 shown above, the UUV is moving on a straight-line path setting the beacon points at different time intervals such as bT_1, bT_2 and bT_3. The geometric cone formed by the directional antennae of the beacons. We also see in this figure, the two different beacons – the beacons set by the UUV and the other ones are the temporary beacons, i.e. the responsibility given to a sensor node being encountered in its straight-line path. The height of the cone is H, its radius is R_b, and its beacon angle is θ. The depth of a node can be directly measured by a cheap pressure sensor, which is denoted as *H*. The key challenge to position a node's location is thus to determine its 2D position at the fixed depth (the node is denoted as *S*). This scenario can be used in MCM operations conducted by the Navy. If the density of the 3D underwater volume is increased, the one-third of the maximum transmission range of the UUV model used and the trade – off between the transmission range and the attenuation of the denser medium of the ocean deep is taken. Now further, we will be elaborating our 3D UW-ASN architectural scenario. The fact that when the UUV sends a directional beacon towards the sensor field, those nodes who have heard the beacon actually fall in the conical beacon beam and the beam forms different circles with different *H*. With a fixed depth *H*, the centre of the circle is *(x, y, H)*, and the radius of the circle is

$$R_b = \tan\left(\frac{\theta}{2}\right) \times \Delta H \quad (1)$$

Here θ is the angle of the conical beacon whose height is $\Delta H = | H_U - H |$. Thus, when UUV wanders at fixed depth of water sending beacons, we could map the nodes from 3D to 2D with those determined circles. For example, when node *S* falls in the circle of depth *H* (or the circle covers *S*), *S* can receive beacons from *H* from the UUV, and thus can roughly estimate its position from the coordinate *(x, y, H)*. This basic scheme, however, would introduce a relatively large error, because *S* can be actually at the border of the circle. We first define the *Initially-heard beacon point* and the *Finally-heard beacon point* in those series of beacons. As shown in Fig. 4, the UUV's movement trajectory is the broken line. Sensor node *S* hears the beacons when UUV sends them at points from $I(x_1, y_1)$ to $F(x_2, y_1)$ and we define these points as beacon points. UUV sends a beacon at point $I(x_1, y_1)$, and this beacon is the first beacon is the first beacon which the sensor *S* hears we define this point as the Initially-heard beacon point. UUV moves in a straight broken line paralleled with *x*-axis. We assume that the node *S* is positioned on the top side of the UUV's current moving trajectory. *I* is node *S*'s the *Initially-heard beacon point* and *F* is node *S*'s the *Finally-heard beacon point* with corresponding coordinates (x_1, y_1), (x_2, y_1) respectively. The distance between *S* and *I* or *F* is R_b calculated using Equation (1). The position of *S* is thus calculated as,

$$\begin{cases} x = \frac{x_1+x_2}{2} \\ y = y_1 + \sqrt{{R_b}^2 - \left(\frac{x_1-x_2}{2}\right)^2} \end{cases} \quad (2)$$

The node's position can thus be determined by the Initially-heard beacon point and the Finally-heard beacon point, the UUV sends beacons discretely with time intervals, nodes in the small area will share the same Initially-heard beacon point.

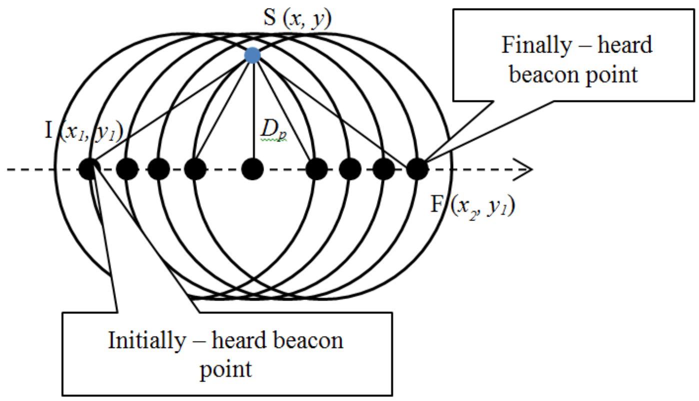
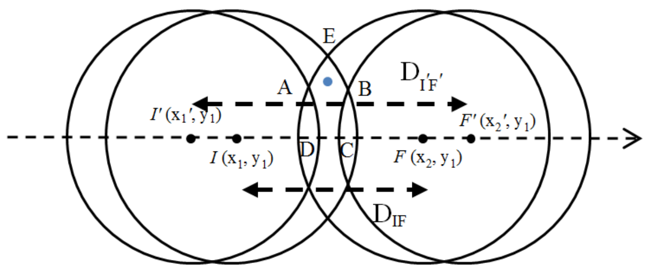


Fig. 4: Positioning using the Initially-heard and Finally-heard beacon points.

Now as shown in Figure 5, we define the *mobile anchor point I'* before the *Initially-heard beacon point I* as the *pre-heard beacon point* of *I* and the *mobile anchor point F'* post the *Finally-heard beacon point* of *F*. The distance between two adjacent mobile anchor points which we called *beacon-beacon distance* is defined as D_b. If we include the beacon interval t and the speed of UUV v_U in the beacon sending by the UUV, then the node can calculate D_b as $D_b = bT \times v_U$. We also define the distance between I and F is D_{IF}, this is due to the fact that the UUV moves in a straight line paralleled with x-axis, hence $D_{IF} = |IF| = |x_2 - x_1|$. We also define the distance between I′ and F′ as D_{IF}', hence the relation between D_{IF} and D_{IF}' is $D_{IF}' = |I'F'| = |IF| + 2D_b = D_{IF} + 2D_b$. Four circles centred at I′, I, F, F′ with radius R_b form the intersection area. With different D_{IF}', the intersection will have different shape as shown in figure 5. Now, here is the case where $D_{I'F'}=|I'F'| \geq 2R_b$ as shown in figure 5. When computing the positions of the nodes in the intersection area, they have the same characters, and we compute *S*'s coordinate (*x, y*) as follows:

$$\begin{cases} x = \frac{x_1+x_2}{2} \\ y = y_1 + \frac{\sqrt{{R_b}^2 - \left(\frac{x_1-x_2}{2}\right)^2}}{2} \end{cases} \quad (3)$$

We, therefore, present our UEPS algorithm in Table 1. The UUV moves parallel to the x-axis as per the bottom-up approach (shown in figure 3), with a constant speed v_U over the 3D sensor deployment volume.



$D_{I'F'} = |I'F'| \geq 2R_b$

Fig. 5: Sensor node (blue dot) lies in a small area ADCBE.

When a sensor node receives a beacon successfully, the timer *T* is increased by *bT*, which is the time interval between the two beacons set by the UUV travelling in a straight line as illustrated in the underwater sensor network architecture and scenario shown in figure 3. When the node receives the next beacon, it stores the UUV's new position coordinates *x*, *y* and increase the time *T*. After that, it checks whether the difference between *y* and *y1* is greater than or equal to D_p. If this value is true, which means that the UUV has moved to the estimated position of the sensor node, it stops receiving beacon signal in poscalc() procedure and then it calculates the sensor node's position using the Equation (3) according to the case we have considered i.e. $D_{I'F'} \geq 2R_b$. Since UEPS is divided into different procedures or sub-routines, it is a distributed algorithm.

Table 1: UUV – Enabled Positioning Scheme (UEPS) Algorithm
func START
Initialize *H*, height of the UUV, *T*, the time factor as initial points and Rec1st as False
return True
end func
func BeaconRcvd()
if Rec1st = = False then
Rec1st ← True
1stBeaconRcvd()
else
NxtBeaconRcvd()
end if
return True
end func
func NxtBeaconRcvd()
Initialize x_1, y_1, bT, v_U, θ, H_U, D_P
$R_b \leftarrow \tan(\theta/2) \times (H_U - H)$
$bT_m \leftarrow 2R_b / v_U + 1$
$T \leftarrow T + bT$
return True
end func
func NxtBeaconRcvd()
Initiallyize x_2 and y_2.
$T \leftarrow T + bT$
if $\| y - y_1 \| \geq D_P$ **then**
poscalc() // Function to calculate node's position
end if
chtime() //Check the time factor
return True
end func
func poscalc()
if $T > bT_m$ **then**
poscalc()
end if
return True
end func
func poscalc()

```
Initialize UUV transmission range value T_u as 2.35, 2.1 and 2 km.
  R_b ← tan (θ/2) × (H – H_U)
  D_I'F' ← (x_2 – x_1) + 2bT v_U
  if D_I'F' ≥ 2R_b then
     Equation (3) computes x & y, the node's location
     Equation (6) computes the localization success
  end if
  Turn off the receiver
  return True
end func
```

V. PERFORMANCE ANALYSIS

We analyse the performance of our UEPS algorithm through MATLAB simulations. About a thousand sensor nodes are randomly deployed in 500m × 500m × 500m 3D volume. The UUV follows a pre-defined trajectory as shown in figure 3 at a fixed depth with a constant speed over the 3D underwater sensor network deployment volume, and the mounted transducers on the UUV has the fixed acoustic radiating power to reach the farthest nodes that may be deployed on the bottom of the 3D volume or space. We set the speed of UUV 1.54 m/s (approx. 3 knots). Our metrics for performance analysis are beacon intervals (*bT* values in seconds) and beacon angle (θ in degrees). To measure the hit percentage of localization i.e. how much the nodes are localized, we use the localization success percentage, which is defined as

$$L_s = \log_{10}(T_u) \times e^{P(bT)} \tag{6}$$

Here, L_s is the percentage of localization success, T_u is the transmission range of the UUV and *P(bT)* is the probability of beacon intervals for the localization of sensor nodes deployed in the three-dimensional underwater scenario volume. The performance metrics for this equation is shown in Table 2. The P(bT) here can be taken in the range 50 – 95 % and 50 – 80 % because of the two main scenario properties – high percentage of naval mines and low percentage of naval mines to be destroyed. So we can see that in the best case the maxima value of the localization success can be up to 96% and in the worst case, the maxima can reach up to 85 %. Therefore UEPS gives the coordinates of the to-be-positioned nodes with a relatively high localization success.

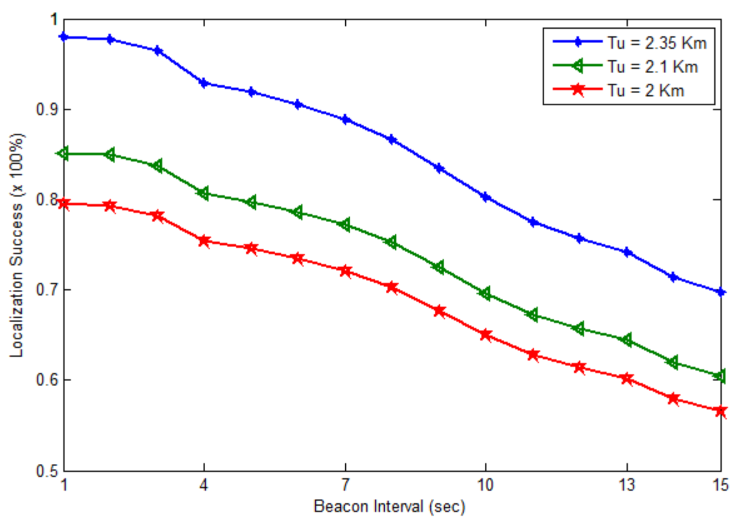


Fig. 6: Different Localization Success line graphs by varying T_u

In figure 6 above, we show the localization success for different beacon intervals. We fluctuate the probability of frequent beacon intervals *P(bT)* where bT = 1s to 15s. As we see from equation (6), the localization success depends on beacon intervals *bT* and the transmission range of the UUV T_u. The logarithmic value of order 10 is taken because of the fact that the 3D volume space is always measured in the orders of 10. In the Fig. 6, we set the range of T_u value from 2 – 2.35 km because of the fact that we are using REMUS 6000 UUV which has the maximum transmission range up to 6 km. To reduce the network overhead and power consumption of the UUV for higher network lifetime, we reduced the transmission capability so that it can be quite adequate for the current scenario of MCM operations in small 3D volume. So, we randomly selected about one-third of the maximum transmission range i.e. 2 km as the lower bound and 2.35 as the upper bound.

We also observe that when T_u is at 2.35 Km, we obtain the localization success at approximately 98% and when T_u is 2.1 Km, the localization success reduces to 85% and then further reduces to 80% when T_u is 2 Km. This is because within the value range from 2 – 2.35 Km, the UUV gets the opportunity to send and receive more and more localization messages in a dense underwater sensor network. We have increase the density so as to improve the localization success used in the MCM applications. As we decrease Tu to 2 Km, we also observe a substantial decrease in the localization success and hence the less number of nodes would be localized or positioned in a given specific time frame.

Metric	**Value / Range**
UUV Transmission Range, T_u	2.00 - 2.35 Km
Beacon Interval, *bT*	1 - 15 sec
Probability of Frequent Beacon Intervals, *P(bT)*	50 – 95% or 50 – 80%

Table 2: Performance Metric used in the positioning scheme

The performance metrics used here in the simulation are mentioned in Table 2 above. From the result obtained, ranging the value of T_u as 2.35 Km, 2.1 Km and 2 Km, we observe that the localization success decreases as we increase the beacon interval. This is because as the beacon interval increases i.e. the probability of frequent beacon intervals increases, the *beacon-beacon distance* D_b increases and it goes more out of the UUV's transmission range T_u.

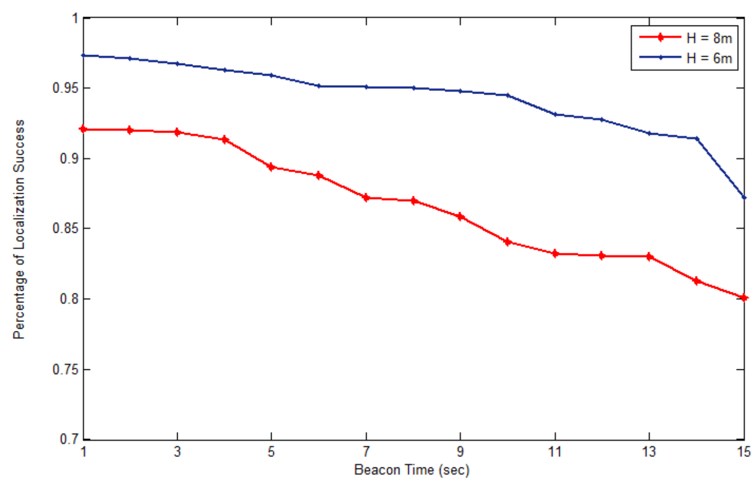


Fig. 7: Previous Work by varying the height above the to-be-positioned node, H

From the illustration of the figure 7 above, the related work in this field has been done by varying the height of the beacon conical beam on the to-be-positioned node done by the authors in [22]. When the height is 6 meters, which is the appropriate height for the REMUS class UUV for better localization success, the highest localization success achieved is at 97% when the beacon time interval is 1 second. But as this beacon time increases, the localization success plummets gradually. When H is at 8 meters, the base of the conical beam is larger due to the larger radius (see equation (1)) and hence the localization success is reduced considerably even when the beacon time is at 1 second i.e. at 93%. We also see quite a zig – zag form in red line throughout and in blue line after the beacon time is 13 seconds. Keeping in mind the equation (7), we have already discussed that the beacon interval *bT* is directly proportional to the beacon – beacon distance D_b. Therefore, by increasing the upper bound of the probability *P(bT)*, the localization success also increases.

VI. Conclusion

The proposed scenario and its associated algorithm have a great significance in the field of Navy MCM operations which require a denser deployment of the UW-ASN including small number of UUVs. The previous work done was by considering the height of the conical beacon beam over the sensor nodes for better positioning percentage and we have devised a new UW-ASN scenario and used the transmission range of UUV as a useful parameter that clearly determines the localization success and thus proves better approach than the previous work done.

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