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DB-Sync: A Directional Beacon Assisted Time Synchronization Algorithm for Underwater Acoustic Wireless Sensor Networks

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Abstract: *As in all distributed systems, time synchronization plays a significant role in underwater sensor networks. Synchronization of clock values among the contributing nodes is one of the crucial prerequisites in addressing network related issues of Underwater Wireless Sensor Networks (UWSNs). The traditional terrestrial sensor network technologies like, the Global Positioning System (GPS) cannot be utilized proficiently for underwater scenarios due to its bandwidth limitations, channel complexities and network cost. All these together make the synchronization problem extremely challenging for UWSNs. Synchronization techniques assisted by a mobile beacon situated either on the ocean surface or along a predefined trajectory are intrinsically convenient, accurate at a reduced cost and energy supplies. In this paper, we propose a novel underwater synchronization approach based on directional beacons, called DB-Sync. The proposed approach employs directional signals, transmitted by an Autonomous Underwater Vehicle (AUV). The proposed scheme does not require the mutual communication between the AUV and the sensor nodes, thereby reducing the transmission energy consumption which is a non-trivial factor of sensor networks. The proposed scheme is analyzed using simulations and the results prove that our DB-Sync outperforms existing approaches in a precise, energy efficient fashion.*

Index Terms: *AUV, Directional Beacon, Energy Efficiency, Time synchronization.*

I. INTRODUCTION

Typically, an underwater wireless sensor network is constructed using a huge number of acoustically connected sensor nodes deployed at different depths, surface sinks and autonomous vehicles for exploring an area of interest [1]. Since, the underwater sensor nodes are subjected to passive mobility, they will not remain in a constant position for a long time. The autonomous vehicles can either travel on the ocean surface or dive and move under the water according to predefined paths [2]. Most of the UWSN algorithms depend on the assistance of mobile AUVs, since their paths can be easily monitored and controlled from a remote station. The acoustic antenna connected to the mobile AUVs emits beacon signals, which will be received by the sensor nodes. Directional antennas can be used to focus the beacon signal transmission in a particular region of exploration [3].

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Labeling of sensed information with time and location data is extremely essential in UWSNs, especially for applications like target tracking, disaster prevention and surveillance [4]. Most of the medium access and network protocols of UWSNs rely on the nodal clock values for their implementation. There are a quite large number of synchronization approaches available for terrestrial sensor networks, but regrettably they are hard to apply for UWSNs because of its exclusive challenges like passive mobility, energy constraints, limited bandwidth and variable channel characteristics [5].

Acoustic signal communications are considered as the most suitable technologies for UWSNs, since they offer a longer range at a shorter bandwidth. However, acoustic transceivers consume more energy than RF modems, and it is implicit from literatures that transmission of acoustic signal consumes ten times greater power than reception [6]. Henceforth, it is not advisable to use recurrent message exchanges for achieving underwater synchronization. Reduced signal transmissions not only improve energy efficiency of the system but also help to reduce the communication overhead. For synchronization purposes, even though the traditional Omni-directional antennas provide an extensive uniform coverage, directional antennas can be employed when the application is restricted to a specific region of interest.

In this paper, we suggest a novel directional beacon assisted underwater synchronization approach, called DB-Sync. Primarily, we describe the UWSN communication model for the proposed DB-Sync scheme. The AUVs at the beginning float on the ocean surface to receive the global timing values using the GPS. According to the system model, the AUVs provide directional beacon signals which contain their location and timing information. The underwater sensor nodes mutely receives the beacon signals, synchronizes themselves by computing the location and variable propagation delays. The mute listening approach, avoids the transmission of synchronization control messages, thus helps in reducing the communication overhead and energy consumption extensively. The rest of this paper is structured as follows. We initially discuss about the synchronization design challenges and the existing UWSN synchronization approaches in terms of their accuracy and energy efficiency in Section 2. In Section 3, we introduce the UWSN system model and present the definition of the synchronization problem. Our proposed DB-Sync scheme is described in Section 4. We assess the DB-Sync method based on the simulation results in Section 5. Finally, in Section 6, we provide the conclusion with some future directions.

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II. CHALLENGES AND RELATED WORK

The fundamental challenges for designing an UWSN time synchronization algorithm are: long and variable propagation delays and energy efficiency [7]. In acoustic communication based UWSNs, the signal velocity is regarded as 1500 m/s, which leads to very high communication delays. Also, the passive mobility experienced by the sensor nodes causes the variations in delays, both spatially and temporally. Utmost prevailing synchronization approaches estimate the propagation delay between two sensor nodes as half of the round trip time [8]. But, it is known that the delays on the way forth and back will not remain constant when the nodes are moving especially at high speeds, which affects the accuracy of the protocols.

In UWSNs, the main factor hampering the synchronization overhead is the constrained battery supply. Computation and communication are the two forms of energy consumption associated with sensor networks. Literatures reveal that, computation costs would be very less compared to communication in wireless sensor networks [9]. Hence, it is efficient to design an algorithm at a relatively high computational overhead compared to message transmissions.

Most of the existing UWSN synchronization approaches address the issue of long communication delays, but fail to consider either the channel variations or the energy constraints. In [10], a high delay tolerant synchronization approach is presented which uses one-way and two-way message exchanges for skew and offset corrections simultaneously. Even though, the scheme provides good energy efficiency, it fails to consider the mobility of UWSN nodes and hence assume constant delays in both way of the message exchanges thus makes the approach inaccurate.

A cluster based synchronization scheme for mobile UWSN is proposed in [11], assumes one-way propagation delay as half of the round trip time which is not the case in frequently varying UWSN channels. Mu-Sync performs the clock correction in two steps: the first step deals with the estimation of draft skew by the cluster head and the second step aims at correcting the clock skew followed by offset correction. In MU-Sync, the cluster head is accountable for the entire synchronization scheme and involves high control message transmissions.

In [12], a variable delay tolerant synchronization algorithm is presented, which uses the spatial correlation of nodal velocities to estimate the varying delays. The hierarchal approach requires link connectivity to a minimum of three anchors to implement the algorithm, which requires dense deployment of nodes thus increasing the network cost. Also, it is hard to obtain the accurate correlation model between nodes which in turn affects the accuracy of synchronization.

A Doppler shift based synchronization approach is provided in [13], which estimates the amount of Doppler spread due to relative movement of sensor nodes. The method is more accurate compared to existing schemes, due to the consideration of varying delays. But, the method fails to consider the skew effects while calculating the Doppler scaling factors, may lead to errors in velocity estimation thus affects the accuracy of the algorithm .

The most recent work, DA-Sync [14], is the first cross layer synchronization approach for mobile UWSNs. In this approach, the errors in D-Sync on calculating the Doppler scaling values are refined by Kalman filter based estimation algorithms. However, it provides good accuracy; the method involves more control message exchanges thus increasing the energy consumption of the network.

In this paper, we put forward a novel time-synchronization scheme, called DB-Sync, a directional beacon assisted protocol explicitly for passive mobile UWSNs, with high accuracy and high energy efficiency as its major design goals. The directional beacon signal emitted by the AUVs will be received by sensor nodes using "mute listening" approach in contrast to the control message exchanges as in traditional synchronization schemes. The sensors which are in the coverage range of directional beacons will compute their relative co-ordinates using the beacon information, and then the location values will be exploited to determine the Euclidian distances in turn the variable delays. The variable propagation delays are utilized to correct the clock values with high accuracy.

III. SYSTEM MODEL AND PROBLEM FORMULATION

This section defines the synchronization problem in sensor networks and elucidates the UWSN communication model for the proposed DB-Sync approach.

The sensor network model in underwater scenarios will differ according to the requirements of an application. The proposed UWSN model for DB-Sync is illustrated in Figure 1.

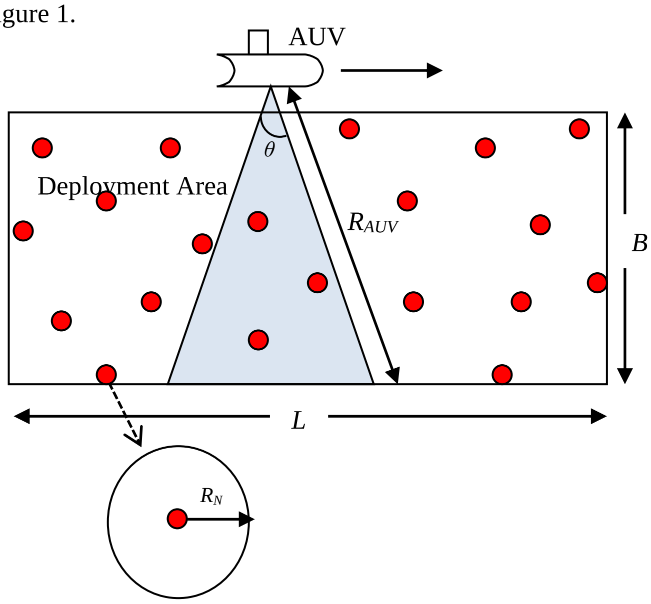

Figure 1: DB-Sync Communication Model

For our proposed algorithm, we assume a 4-dimensional UWSN [15], deployed in a specific area which is geometrically represented in our paper by a rectangle of length *L* and breadth *B*. The sensor nodes in our UWSN are assumed to have a slight degree of passive mobility. The sensor nodes are installed both on the ocean surface and at different depths using anchors. The nodes are assumed to have an Omni-directional antenna, with a uniform coverage range of radius R_N. The sensor nodes are also furnished with pressure detectors, which would help them to identify their depth i.e., the *z*-coordinates.

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The network consists of surface mounted AUVs which can either float on the sea surface or dive and move in the water as controlled by the predefined paths with uniform velocity. The AUVs are presumed to be well – synchronized and localized with the help of GPS receivers attached to them. The AUVs in our approach are facilitated with directional antennas, which will emit directional beacons of beam-width θ and radius R_{AUV}. The beacon format of AUVs is depicted in Figure 2 which contains the AUV's Id, beacon transmission time T_B, 3-dimensional AUV co-ordinates $(x_{AUV}, y_{AUV}, z_{AUV})$ at time T_B, depth of beacon and the beam-width.

AUV ID	x_{AUV}	y_{AUV}	z_{AUV}	T_B	θ	R_{AUV}

Figure 2: Beacon Frame Format

The AUVs will obtain their co-ordinates using GPS while floating on the surface and updates its location using the predefined trajectories as they move into the water. The AUVs will move along the length of the deployment region and broadcast the directional beacons in equal intervals of m seconds which would be received by the sensor nodes. The sensors acquired the AUV's information without mutual communication, thus our DB-Sync reduces energy consumption of control packet transmissions. The sensor nodes will determine their location using the beacon signals and use them to correct their clocks.

In distributed networks, time synchronization between two devices relies on estimating the skew and offset values, which determines the relation between the clocks of two nodes. Our DB-Sync is also a pair-wise synchronization approach, targets to synchronize the network node's clocks with the AUV beacon's timing.

Let T_N be the clock timing of sensor nodes, T_B is the reference time, δ and Δ stands for relative clock skew and offset respectively. Hence, the problem can be formulated as follows,

$$T_N = \delta * T_B + \Delta \qquad (1)$$

The synchronization algorithm aims at estimating the values of δ and Δ relative to the AUV's directional beacon.

IV. DESCRIPTION OF DB-SYNC

The former section details about the problem of time synchronization in UWSN and the system architecture to support the underwater sensor nodes synchronize themselves. To deal with the problem, we propose a pair-wise, energy efficient synchronization approach called, DB-Sync.

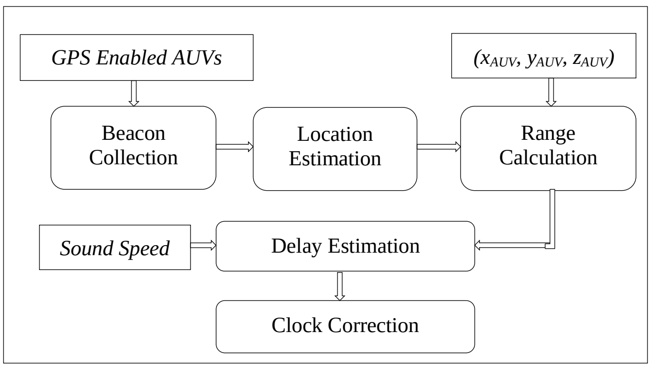

Figure 3: Stages of Proposed DB-Sync

The proposed DB-Sync algorithm implemented in every sensor node comprises of five stages as shown in Figure 3: Beacon Collection, Location Estimation, Range Calculation, Delay Estimation and Clock Correction.

A. Beacon Collection

The surface AUVs are the only sources of beacon signals in the proposed DB-Sync. The AUVs at first float on the sea surface collect the GPS information and then move along the deployment region as per the defined trajectories. The AUVs hold at each predetermined position, broadcasts the directional beacons with the parameters R_{AUV} and θ. There will be a uniform time interval of m seconds between two successive beacon transmissions. The sensor nodes fall in the taper of the directional beacons, mutely receives the beacon information.

B. Location Estimation

The nodes in our proposed DB-Sync architecture are assumed to be fixed with pressure sensors, using which they can calculate their z-coordinates. Consequently, the sensor nodes are required to estimate their 'x' and 'y' coordinates only.

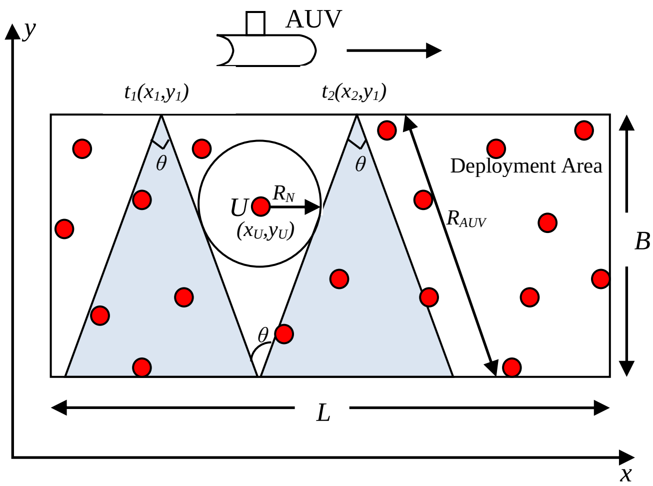

Figure 4: AUV transmission in DB-Sync

As shown in Figure 4, the surface AUV will emits its initial beacon at time t_1 with the x-y location (x_1,y_1) which will be received by the sensors in the taper of radius R_{AUV}.

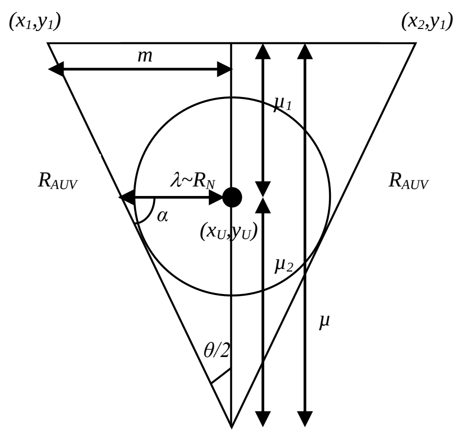

Figure 5: Location Estimation in DB-Sync

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The next beacon will be emitted at time $t_2 = t_1+m$, with the location (x_2,y_1). Instinctively, our DB-Sync uses the triangle models depicted in Figure 5 to obtain the location of node U, such that (x_U, y_U).

The sensor node's co-ordinates can be calculated using the following relations.

The x-coordinates can be calculated as,

$$x_u = x_1 + m \tag{2}$$

where $m = \frac{x_2 - x_1}{2}$

The y-coordinates can be calculated as,

$$y_u = y_1 - \mu_1 \tag{3}$$

The value of μ_1 can be calculated using the law of sines [16] as follows.

$$\mu_1 = \mu - \mu_2$$

$$\mu = R_{AUV} \cos\frac{\alpha}{2}$$

$$\alpha = 90^\circ - \theta/2$$

$$\frac{\mu_2}{\sin\alpha} = \frac{R_N}{\sin\theta/2}$$

$$\mu_2 = R_N(\sin\alpha)(\sin\theta/2)$$

The relative co-ordinates of sensor node U can be transformed into absolute co-ordinates.

C. Range Calculation

The co-ordinate values are then used to determine the distance between the sensor nodes and the beacon points. The Euclidian distance D_{UB1} between the sensor node U and the initial beacon point can be modeled as follows.

$$D_{UB1}{}^2 = (x_U - x_1)^2 + (y_U - y_1)^2 + (z_U - z_1)^2 \tag{4}$$

Where (x_U, y_U, z_U) and (x_1, y_1, z_1) are the 3-D co-ordinates of the sensor node U and the initial directional beacon point received from AUV respectively.

D. Delay Estimation

Most of the existing synchronization schemes assume the propagation delay as half of the round trip time, considering constant sound speed. But, in UWSN the sound velocity will not remain constant; it will vary with environmental conditions. DB-Sync employs the varying sound speed relation [17] to calculate the propagation delay, thus assures the applicability of the algorithm for mobile UWSNs and also enhances the accuracy of the synchronization scheme.

The sound speed relation with varying environmental conditions such as temperature T, salinity S and depth D is given as,

$$\begin{aligned} V_S(D,S,T) &= 1448.96 + 4.591T - 5.304*10^{-2}T^2 \\ &+ 2.374*10^{-4}T^3 + 1.340(S-35) + 1.630*10^{-2}D \\ &+ 1.675*10^{-7}D^2 - 1.025*10^{-2}T(S-35) - 7.139*10^{-13}TD^3 \end{aligned} \tag{5}$$

DB-Sync calculates the propagation delay as,

$$Delay_U = \frac{D_{UB1}}{V_S(D,S,T)} \tag{6}$$

E. Clock Correction

The sensor node U performs regression over received time stamps and the estimated delay values to correct their clock skew and offset. The node U can adjust its clock in such a way that,

$$T_N = T_B + Delay_U \tag{7}$$

Our DB-Sync can be applied to large-scale uniformly distributed mobile UWSNs. The method entirely depends on the surface AUVs, does not require any static anchors to be employed, thus reducing the deployment cost of the system.

V. PERFORMANCE EVALUATION

In this segment, we provide a detailed evaluation about the proposed DB-Sync using simulation results. The proposed method is analyzed by varying different metrics, namely beam-width, beacon intervals, number of nodes and sensing range. We perform the simulation with a maximum of 1000 sensor nodes uniformly deployed in an area of 300 m x 300 m x 500 m. We randomly select a node as node U, to be synchronized and select a random surface node as an AUV. The assumed AUV is assigned with a constant velocity of 1 m/s and the beacon intervals are varied from 1s to 3s. We have varied the sensing radius of the nodes from 1m to 1.5m for the simulation, and vary the beam-width from 5˚ to 50˚. The value of R_{AUV} is fixed as 500 m.

A. Impact of Beam-width

In directional beacon based approaches, the beam width is an important factor which along with the beacon depth determines the area of the beacon coverage. In our DB-Sync, we use a parameter called synchronization ratio to evaluate the significance of beam width. The synchronization ratio, SR can be defined as follows.

$$SR = \frac{N - Nerr}{N} \tag{8}$$

Where N is the total number of sensors in the beacon's range, $Nerr$ is the number of sensors with error values below a threshold.

The effect of beam width on synchronization ratio is shown in Figure 6. We set the value of R_N constant as 1.5 m, and vary the beam-width from 5˚ to 50˚ in steps of 5. The simulation results prove that the ratio improves with the beam width.

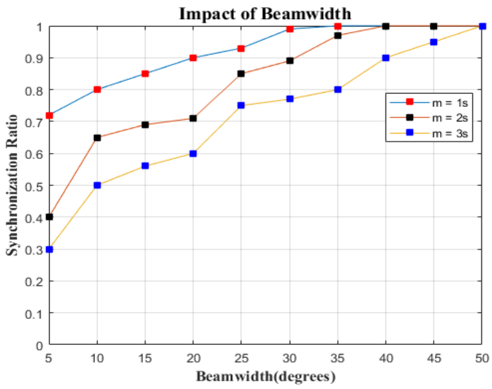

Figure 6: Impact of Beam-width

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As the angle reaches 40˚, the DB-Sync provides a synchronization ratio of 90 % irrespective of the beacon intervals.

B. Impact of Sensor Range

The sensing range of nodes is also a parameter, influencing the performance of DB-Sync. We analyze the effects of node's sensing range on synchronization ratio of DB-Sync which is depicted in the Figure 7. The range, R_N is varied from 1 m to 1.5 m keeping the beacon interval constant at 3 s. The analysis was performed for different beacon angles. It is observed that, as the value of R_N increases, *SR* also improves. This is because, as R_N becomes larger, more nodes will get the chances of receiving the directional beacons. For all the cases, the value of *SR* approaches 95% when R_N reaches 1.5 m which is considered as the adequate sensing range for the nodes.

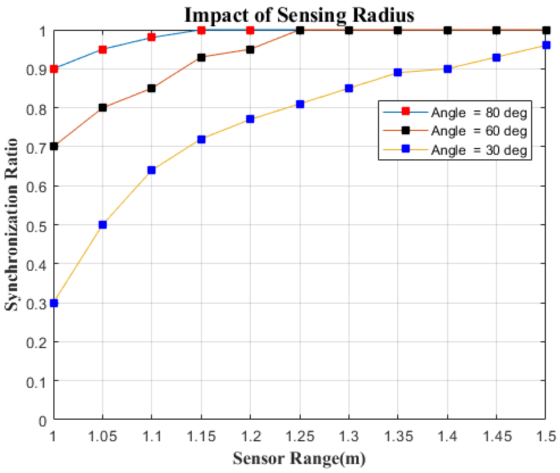

Figure 7: Impact of Sensing Range

C. Accuracy Analysis

Figure 8 validates the synchronization errors of the proposed DB-Sync and D-Sync. The results show that DB-Sync achieves more accuracy compared to D-Sync. DB-Sync exploits the effects of varying propagation delays by considering the sound speed relation based on environmental behaviors. The directional beacons are used to enhance the accuracy of the distance between nodes. The AUVs are allowed to move on the surface in order to acquire the real times GPS values. These techniques make DB-Sync more accurate than existing methods.

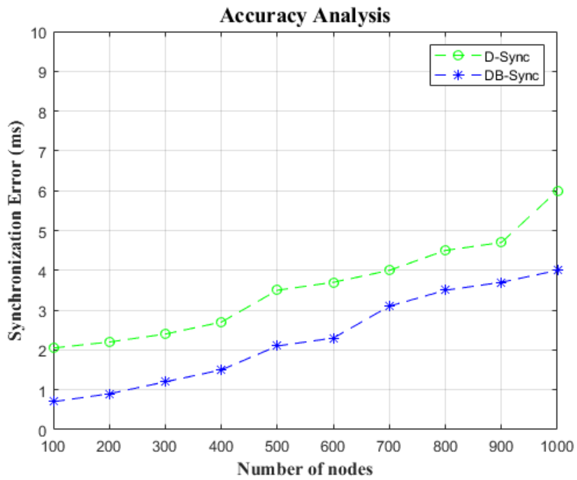

Figure 8: Accuracy Analysis of DB-Sync

D. Energy Efficiency Analysis

The improvement in energy efficiency achieved by DB-Sync in contrast to existing synchronization approaches is depicted in Figure 9. Here, we define the energy efficiency E_f as follows.

$$E_f = \frac{\kappa}{n\theta\tau} \tag{9}$$

Where n is the number of synchronizations required to achieve the acceptable error in a period of κ seconds at a beam-width θ beacon size τ. Here we fix the values of κ, θ and τ as 1µs, 45˚ and 40 bytes respectively. For a given error tolerance, E_f can be understood by calculating the value of n. The synchronization accuracy plays a major role in the calculation of synchronization times. A better accuracy scheme will have a lesser value for n, continuing that E_f will improve. The results prove that as the acceptable error increases, the synchronization schemes give better energy efficiency. However, DB-Sync performs well compared to other schemes.

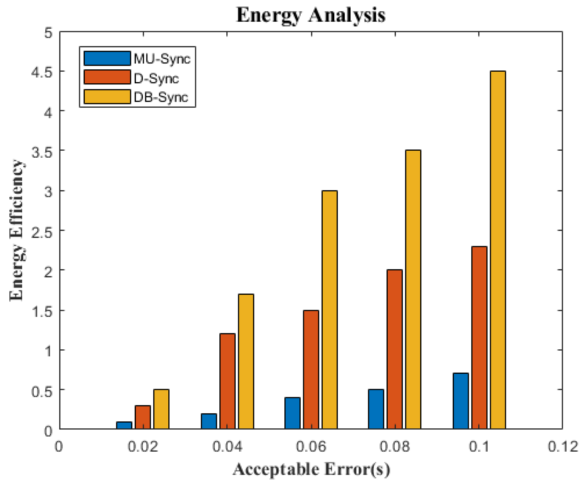

Figure 9: Energy Efficiency of DB-Sync

VI. CONCLUSION & FUTURE WORK

This paper addresses the problem of synchronization for mobile UWSNs using directional beacons. We proposed a pair-wise, energy efficient synchronization scheme which uses AUV's information to synchronize the nodal clocks. The method presents a "mute listening" approach for sensors, thus improving the energy efficiency of the system. The DB-Sync also considers the varying propagation delays to enhance the accuracy. Finally, we evaluate the performance of the proposed DB-Sync in terms of synchronization error, synchronization ratio and energy consumption.

In future, we plan to test the DB-Sync in real time underwater test beds and also like to extend the performance of the algorithm by studying the different AUV trajectories.

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