# Enhancement of MU-Sync: A Time Synchronization Protocol for Underwater Mobile Networks

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***Abstract*—In this paper, we propose a cluster-based synchronization algorithm for underwater acoustic sensor networks based on MU-Sync, called EMU-Sync. Time synchronization is an important part of many services. Although many time synchronization protocols for terrestrial wireless sensor networks have been well-developed, none of them can be applied directly in underwater wireless sensor networks. The challenges of time synchronization in underwater wireless sensor networks are long propagation delay, sensor node mobility, and energy consumption. EMU-Sync is designed to improve the performance of MU-Sync while able to maintain its low complexity. This is possible by allowing the cluster head to calculate the skew and the offset from the view of both a cluster head and a neighboring node. Simulation results confirms that EMU-Sync offers better performances than MU-Sync in both accuracy and energy efficiency.**

***Keywords*—Time Synchronization, Underwater acoustic sensor networks, Mobility, Sensor networks,**

## I. INTRODUCTION

In recent years, underwater wireless sensor networks have attracted great interest from researcher and industry to be studied and implemented in some application such as tsunami monitoring, environment monitoring and underwater exploration [1, 2]. However, implementation of underwater wireless sensor networks faces a main challenge namely time synchronization. Time synchronization is an important part of underwater communication since most of protocols in underwater network require time synchronization for the operation. Furthermore, most of localization algorithms need to have time synchronization. The clock in each sensor can drift due to the pressure, corrosion, temperature, voltage battery etc. It causes in the needs of time synchronization. The existing time synchronization methods for the terrestrial networks cannot be applied directly to the underwater environment because of long propagation delay, node mobility and energy consumption.

Many time synchronization protocols have recently been proposed for underwater wireless sensor networks such as Time Synchronization for High Latency Acoustic Networks (TSHL) [3], MU-Sync [4], Mobi-Sync [5], D-Sync [6], and DA-Sync [7]. Although these protocols are designed to solve the issue of long propagation delay or mobility of the sensor nodes, they still face some other problems. For example, TSHL works well in static underwater networks but it has the poor performance in the mobile underwater networks. On the other hand, MU-Sync is simple to be implemented in the mobile underwater networks. However, it results in incorrect in the calculation of the propagation delay leads to low accuracy and low energy-efficiency. D-Sync and DA-Sync are highly complex since they require the calculation of the Doppler shift.

The rest of this paper are organized as follow. In Section II, we discuss the challenges in time synchronization. Then we review some related work in Section III and describe EMU-Sync in detail in Section IV. Next, the simulation and results is shown in Section V. Finally, we give our conclusion in Section VI.

## II. CHALLENGES

Any device with clock system may not provide the actual time correctly due to errors. It leads to the needs of time synchronization. To obtain a perfect time synchronization in mobile underwater, there are two main challenges. The first challenge is long and dynamic propagation delay that makes the calculation of time propagation delay become difficult. Second, since the nodes rely on battery power for operation, the synchronization should consume low energy.

### *A. Long & Dynamic Propagation Delay*

Most of acoustic underwater time synchronization algorithms utilize the technique of two-way message exchange in the message delivery time which causes several uncertainties such as sending time, access time, propagation time, receive time, etc. In these uncertainties, propagation delay is the major barrier because of low speed of acoustic underwater signal and the motion of nodes in the water. For these reasons, there is no way to find out real propagation delay hence the error still exists.

### *B. Energy consumption*

Energy is required to operate the system. In underwater environments, it is difficult to recharge or replace the battery. Therefore, the design of energy efficient protocols for underwater wireless sensor networks is important. In the underwater wireless sensor networks, energy is used for computation and communication including time synchronization

process. Hence, a simple communication procedure, i.e. small number of message exchanges is required to reduce the energy consumption

## III. RELATED WORK

In recent years, there is growing interest in time synchronization for underwater wireless sensor networks. However, the research is still limited. From literatures, TSHL [3] is designed to estimate skew and offset by using one-way and two-way communications respectively for the high latency networks. However, a common assumption of the constant propagation delay during the message exchanges in static networks is not applicable in mobile networks. MU-Sync [4] is a cluster-based protocol, in which the cluster head is responsible for starting the time synchronization process and for calculating the skew and offset for all nodes within the cluster. MU-Sync performs twice linear regression. For the first linear regression , the cluster head estimates skew to reduce the effect of skew during the processing time of the neighboring node. For the Second linear regression, the skew and offset are estimated. Although, MU-Sync is designed to solve the long and dynamic propagation delay, the calculation of propagation delay from half of the round trip time is inaccurate.

Mobi-Sync [5] is different from the previous methods. The Mobi-Sync structure consists of three types of nodes, namely surface buoy, super node and ordinary node. The surface buoys are equipped with GPS to obtain the global time. The super nodes are assume to be able to communicate with surface buoys in real time. In practice, this assumption is not realistic. The ordinary nodes will synchronize with the super nodes by spatial correlation of velocity of the super nodes. To achieve good time synchronization, it required minimum three or more super nodes. D-Sync [6] and DA-Sync [7] utilize the Doppler shift to estimate velocity of the nodes. In D-Sync, the estimated velocity is used for estimating the propagation delay. Since there is error in the estimated velocity, it will certainly result in error in the estimation of the propagation delay. On the other hand, DA-Sync the estimated velocities are leveraging by Kalman filter before used in the propagation delay estimation. However, the leveraging process requires a good precision in the velocity measurement. This is difficult to archive.

Although, Mobi-Sync, D-Sync and DA-Sync are more efficient than MU-Sync, they require complex computation and have their own limitation. On the other hand, MU-Sync is simpler and require less computation. All of the contents above leads to the proposed algorithm called “Enhance MU-Sync (EMU-Sync)” which is a cluster based synchronization algorithm for underwater acoustic sensor networks based on MU-Sync. The design algorithm reduces the error of skew and offset by calculating both cluster head and neighboring node.

## IV. EMU-SYNC

The EMU-Sync (Enhanced MU-Sync) is an improved MU-Sync protocol. As stated in Section III that MU-Sync is a simple but low accuracy protocol. This inaccuracy is mainly caused by the assumption that the one-way propagation delay of each direction during the message (a REF packet) exchange are the same which is rarely true for mobile underwater network. As a result, the estimation of skew and offset of

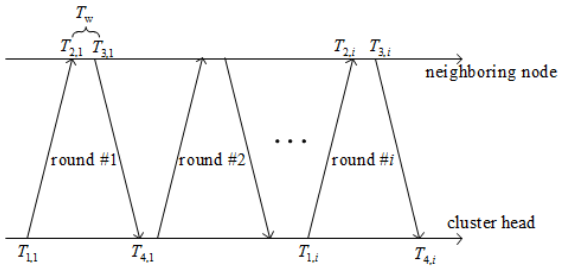


Fig. 1: Message Exchange

MU-Sync is only correct for the following conditions: 1) when the cluster head is static while the neighboring node can be static or mobile, 2) Both cluster head and neighboring node are mobile in the same speed and direction. For other cases, cluster head is mobile and neighboring node is static and both neighboring node and cluster head are mobile in different speed and different direction, the estimation of skew and offset is incorrect since estimation of the propagation delay from half of the round trip time is incorrect.

EMU-Sync can alleviate the above-mentioned problem of MU-Sync by calculating the skew and offset by averaging the estimated skew and the estimated offset from both neighboring node and cluster head at cluster head side. The estimation error can be reduced by taking the average of the estimated skew and offset.

In general, time synchronization use two parameters namely skew and offset as equation

$$T = at + b, \tag{1}$$

where $T$, $t$, $a$ and $b$ are local time, global time, skew and offset respectively.

The EMU-Sync is designed to solve the problem from the worst case by calculating skew and offset of both the cluster head and neighbor node at cluster head. As in step 1 of Fig. (1), in step 1 the cluster head sends a synchronization message at time $T_1$ ,then a neighboring node receives the synchronization message at time $T_2$. In step 2 a neighboring node sends the synchronization message at time $T_3$, then the cluster head receives the synchronization message at time $T_4$ and repeat the same procedure for $n$ round. Time stamp of each node is its local clock that can be expressed as equation (1).

$$T_1 = a_{\mathrm{c}} t_1 + b_{\mathrm{c}}, \tag{2}$$
$$T_2 = a_{\mathrm{n}} t_2 + b_{\mathrm{n}}, \tag{3}$$
$$T_3 = a_{\mathrm{n}} t_3 + b_{\mathrm{n}}, \tag{4}$$
$$T_4 = a_{\mathrm{c}} t_4 + b_{\mathrm{c}}, \tag{5}$$

where $a_{\mathrm{c}}$ and $b_{\mathrm{c}}$ are the skew and the offset of cluster head while $a_{\mathrm{n}}$ and $b_{\mathrm{n}}$ are the skew and the offset of the neighboring node, respectively. The global time, $t_2$ and $t_4$ can be represented as equation (6) and (7)

$$t_2 = t_1 + d^{\mathrm{c}\to\mathrm{n}}, \tag{6}$$
$$t_4 = t_3 + d^{\mathrm{n}\to\mathrm{c}}, \tag{7}$$

where $d^{c\to n}$ and $d^{c\to n}$ are the propagation delay from a cluster head to a neighboring node and from a neighboring node to a cluster head, respectively. Since the propagation delay from step 1 and step 2 are unknown and unequal, we assume the propagation delay can calculate from half of the round trip time in each round as

$$d_i^{c\to n} = d_i^{n\to c} = \frac{(T_{4,i} - T_{1,i} + \frac{(T_{2,i}-T_{3,i})}{\hat{a}})}{2}, \quad (8)$$

where $i$ denotes the message exchange round number. Similarly to MU-Sync, $\hat{a}$ is the skew estimation obtained from the first linear regression with Least Mean Square (LMS) operation. To reduce the effect of node's mobility, the propagation delays obtained from (8) are subtracted from the $T_{2,i}$ and $T_{4,i}$. The cluster head then applies second linear regressions over the data points obtained from the previous step. Instead of performing a second linear regression over the data points $(T_{1,i}, T_{2,i})$ to obtain the estimated skew and offset of the neighboring node based on a perspective of a cluster head, EMU-Sync performs linear regressions to obtain the estimated skew and offset of the neighboring node based on the perspective of both a cluster head and a neighboring node which are denoted as $\hat{a}_{n,c}$, $\hat{b}_{n,c}$, $\hat{a}_{c,n}$ and $\hat{b}_{c,n}$, respectively.

To reduce the effect of the assumption $d_i^{c\to n} = d_i^{n\to c}$ in MU-Sync, we obtain the final estimated skew and offset by

$$\hat{a}_n = \frac{(\hat{a}_{n,c} + \frac{1}{\hat{a}_{c,n}})}{2}, \quad (9)$$

$$\hat{b}_n = \frac{(\hat{b}_{n,c} - \hat{b}_{c,n})}{2}, \quad (10)$$

where $\hat{a}_n$ and $\hat{b}_n$ are the average estimate skew and offset respectively. Finally, cluster head broadcasts these value to its neighboring nodes so that each can keep itself synchronized with each others.

## V. SIMULATIONS AND RESULTS

### A. Simulation setup

In our simulation, the nodes are placed randomly according to uniform distribution and are allowed to move randomly within an area of 1000 x 1000 m. The movement model of a node is the same as the one used in [4]. The speed of sound underwater is assumed to be constant at 1500 m/s and there is no skew variation and no packet collision during message exchanges. As suggested in [8], the non-deterministic errors are modeled using Gaussian distribution, with a receive jitter of 15$\mu$s. Unless specified otherwise, the following set of parameters are used in the simulations:

- Clock skew is 50 ppm.
- Clock offset is 800 ppm.
- The duration a node takes before responding to a REF packets ($T_w$) is 0 s.
- Maximum speed of a sensor node ($V_{max}$) is 2 m/s.
- The number of REF packets used to perform linear regression is 25.
- The time interval between two successive REF packet is 5 s.
- Clock granularity is 1$\mu$s.

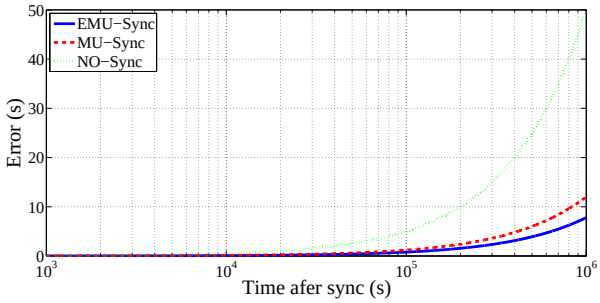


Fig. 2: The error in time estimate VS the time elapsed since synchronization.

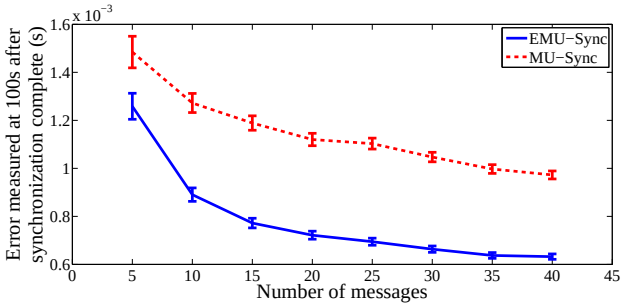


Fig. 3: Effect of changing the number of messages

### B. Results

Each data point shown in the simulation results is obtained from the average of 10,000 simulation runs. The error bar associated with each data point represents the standard deviation. Note that the term "No-Sync" indicates the performance of a node that do not apply any synchronization scheme. As a result, the performance of No-Sync is expected to be the worst among the studied schemes (e.g., EMU-Sync, MU-Sync and No-Sync). Fig. 2 shows that the synchronization error keeps increasing as time goes by for all schemes. However, the performance of EMU-Sync is better than MU-Sync while No-Sync performs the worst as expected. This performance improvement of EMU-Sync, when compared with MU-Sync, confirms that the one-way propagation delay estimation method proposed in EMU-Sync yields higher accuracy than the one used by MU-Sync.

Fig. 3 indicates that for the same number of control

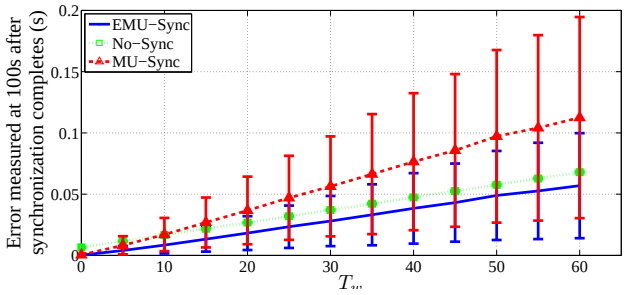


Fig. 4: Effect of $T_w$.

TABLE I: Table of frequency of re-synchronization with vary process time and error tolerance

| Protocols | $T_w$ | $e$ | $\hat{a}_n$ | $a - \hat{a}_n$ | $b - \hat{b}_n$ | $\kappa$ |
|---|---|---|---|---|---|---|
| MU-Sync | 0 | 0.01 | 56.9 ppm | 6.9 ppm | 169 ppm | 607 |
| | | 0.05 | | | | 120 |
| | 5 | 0.01 | 98 ppm | 48 ppm | 5713 ppm | 9720 |
| | | 0.05 | | | | 941 |
| EMU-Sync | 0 | 0.01 | 54.1 ppm | 4.1 ppm | 40 ppm | 356 |
| | | 0.05 | | | | 71 |
| | 5 | 0.01 | 84 ppm | 34 ppm | 2498 ppm | 3910 |
| | | 0.05 | | | | 617 |

messages used during the linear regression process, to obtain both the estimated skew and offset, EMU-Sync can achieve significant lower error than MU-Sync. This implies that in order to achieve the same performance, EMU-Sync requires lesser number of control message exchanges, making it a higher energy-efficient protocol.

Next, we examine the effect of waiting duration $T_w$ on the performance of each scheme. From the results shown in Fig. 4, it is obvious that a large value of $T_w$ leads to high synchronization error for both MU-Sync and EMU-Sync. Surprisingly, the performance of MU-Sync is so sensitive to $T_w$ that its performance is worse than No-Sync when $T_w$ is greater than 10 s. For the case of EMU-Sync, although its performance degrades with increasing $T_w$, it is still more robust than MU-Sync since it maintains significant better performance than both No-Sync and MU-Sync. The main reason causing MU-Sync to perform badly when $T_w$ increases is due to the assumption of $d_i^{\mathrm{C}\to\mathrm{n}} = d_i^{\mathrm{n}\to\mathrm{C}}$ that leads to large error, especially in mobile network. To elaborate further, assuming the case that two nodes are moving at the same speed but with the opposite direction, the longer the neighboring node waits before responding to the cluster head, the larger the value $\left|d_i^{\mathrm{C}\to\mathrm{n}} - d_i^{\mathrm{n}\to\mathrm{C}}\right|$ as well as higher synchronization error. Although EMU-Sync also uses the half of a round trip time in calculating $d_i^{\mathrm{C}\to\mathrm{n}}$ and $d^{\mathrm{n}\to\mathrm{C}}$, averaging of the estimated skew and offset from the perspective of both cluster head and neighboring node before obtaining the final estimate skew and offset helps to minimize the error.

To understand the performance gain achieving from EMU-Sync over MU-Sync, we attempt to calculate the energy efficiency ($\rho$) for both protocols using:

$$\rho = \frac{\vartheta}{\kappa\varrho\gamma}, \tag{11}$$

where $\varrho$ and $\gamma$ are the number of message used in performing a linear regression and the REF packet size (in bytes), respectively. $\kappa$ denotes the number of re-synchronization required within a certain duration, denoted as $\vartheta$. TABLE I shows an example of how to obtain $\kappa$. Specifically, we run simulations to obtain the estimated skew ($a_n$) and offset ($b_n$) for $T_w$ = 0 and 5 s and $e$ = 0.01 and 0.05 s. Moreover, $\vartheta, \varrho, \gamma$ are set to 10 days, 25 and 32 bytes, respectively. These values are then used to calculate $\kappa$ according to

$$\kappa = \frac{\vartheta}{\frac{\hat{a}e+(b-\hat{b})}{a-\hat{a}}}. \tag{12}$$

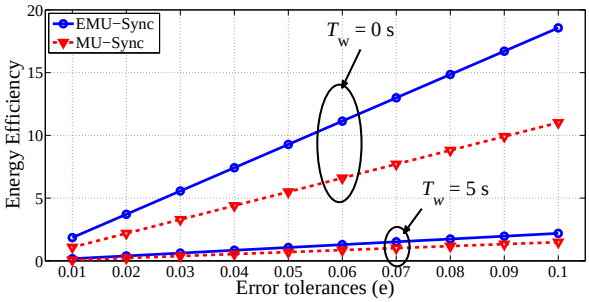


Fig. 5: Energy efficiency with varying error tolerance

$\kappa$ is then used in (11) to obtain $\rho$ which are shown in Fig.5. It is obvious that EMU-sync has a better energy efficiency than MU-Sync for all range of error tolerances, although the significance decreases with increasing $T_w$ (generally, $T_w$ <1 s).

## VI. Conclusion

In this paper, we present EMU-Sync, a time synchronization protocol developed for mobile underwater network. The protocol is an enhancement of MU-Sync. By estimating the skew and offset of the node using an average between the estimated skew and offset of the node based on the perspective of both a cluster head and a neighboring node, EMU-Sync is able to show significant gain in both accuracy and energy efficiency over MU-Sync. Despite this performance gain, EMU-Sync is able to maintain the attractive characteristics of being a simple and low complexity protocol of MU-Sync. Extensive simulation results also confirm that EMU-Sync is highly robust to the variation of the duration the node takes before responding to the REF packet to which MU-Sync is highly sensitive.

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