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APE-Sync: An Adaptive Power Efficient Time Synchronization for Mobile Underwater Sensor Networks

FENG ZHOU[1,2,3], QI WANG[1,2,3], GUANGJIE HAN[1,4], (Senior Member, IEEE), GANG QIAO[1,2,3], ZONGXIN SUN[1,2,3], AND AHMED NIAZ[1,2,3]

[1]Acoustic Science and Technology Laboratory, Harbin Engineering University, Harbin 150001, China
[2]Key Laboratory of Marine Information Acquisition and Security, Ministry of Industry and Information Technology, Harbin Engineering University, Harbin 150001, China
[3]College of Underwater Acoustic Engineering, Harbin Engineering University, Harbin 150001, China
[4]Key Laboratory for Ubiquitous Network and Service Software of Liaoning Province, School of Software, Dalian University of Technology, Dalian 116024, China

Corresponding author: Guangjie Han (hanguangjie@gmail.com)

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ABSTRACT Time synchronization is a cooperative work's foundation among underwater sensor networks' nodes; it takes a crucial role in the application and the study of underwater sensor networks. Several time synchronization protocols have been presented for terrestrial radio networks, but they cannot be instantly utilized to real-time underwater sensor networks due to the slow propagation speed of the underwater acoustic signals, the mobility among sensor nodes, and the energy limitation in the underwater wireless sensor networks. In this paper, we propose an adaptive power-efficient time synchronization for mobile underwater sensor networks, called APE-Sync. The proposed scheme takes into account the time-varying clock skew and combines the Doppler-Enhanced synchronization protocol (DE-Sync) and the Kalman filter tracking the clock skew to achieve time synchronization. The proposed scheme also helps in reducing the energy consumption of the nodes by guaranteeing accurate time synchronization. The simulation results are presented, which show that APE-Sync outperforms existent time synchronization schemes in both power efficiency and precision.

INDEX TERMS Networks, synchronization, Kalman filter, mobility, sensor.

I. INTRODUCTION

Underwater sensor networks (UWSN) have played an important role in environmental monitoring, disaster prevention, mine exploration, and other fields. The research and application of underwater sensor networks have attracted considerable attention [1]–[5]. Nevertheless, due to underwater acoustic channels' characteristics, the research and application of UWSN has suffered from a lot of challenges [6], [7] and complications as it is way different than the conventional terrestrial radio networks. Similarly, underwater sensor networks' time synchronization, as one of the supporting technologies, is also very different and challenging from the existing synchronization protocol of terrestrial radio networks.

In real-time synchronous application, sensor nodes are usually equipped with a clock that helps them to be synchronized. As time passes, these clock drift and loose synchronization due to the difference of the crystal oscillator's angular frequency and the different boot time of the distributed systems. Based on the time synchronization sensitivity, the synchronizations of these applications are classified into three classes [8], namely the synchronization of order of events, time interval synchronization and absolute time synchronization. The order of events occurring is only required by some applications [9]–[11], whereas other functionalities

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depend on the time interval of each of the events [12]–[14]. There are also a number of applications that require an absolute time at which each affair happens, and these applications' implementation is subject to an exactly synchronized time among nodes. For instance, the time-sensitive information with time stamp from multiple nodes is then aggregated to a cluster head node, and accurate timing is required by other applications such as node tracking and position. Besides, not only would the application layer depend on time synchronization; other layers, like the medium access control (MAC) layer, likewise possess respectable functionalities benefiting from time synchronization.

Various publications have proposed numerous time synchronization protocols for terrestrial wireless sensor networks, such as the fine-grained network time synchronization using reference broadcasts (RBS) [15], the timing-sync protocol for sensor networks (TPSN) [16], the flooding time synchronization protocol (FSTP) [17] and others [18]–[21]. These protocols, however, cannot be instantly applied to underwater sensor networks for the obvious reason that they suppose that the propagation delay is negligible among nodes which is not true in case of underwater acoustic communication. Besides, as the sensor nodes are mobile, the propagation delay is variable among nodes in water, and needs to be taken into account while designing a scheme. In general, the terrestrial synchronization algorithms allow nodes to exchange frequent re-synchronization messages as they are not highly dependent on power constraints and available bandwidth. On the other hand, underwater acoustic communication systems possess a limited bandwidth of some hundred kilohertz, which even falls down to a few kilohertz when the targeted communication scope reaches tens of kilometers [6]. Time synchronization that is required for frequent re-synchronization thus is not practical in UWSN because of this bandwidth limitation. In addition, nodes are also restricted by power limitations in most applications and to conserve energy frequent re-synchronization should be avoided.

Several time synchronization protocols for underwater sensor networks are proposed to work out the challenges including the dynamic and long propagation delay [22], [23], such as the time synchronization proposed for high latency networks (TSHL) [24], the time synchronization protocol proposed for mobile underwater networks (MU-Sync) [25], the efficient time synchronization proposed for underwater mobile sensor networks (Mobi-Sync) [26], the Doppler-based time synchronization proposed for underwater mobile sensor networks (D-Sync) [27], the Doppler-assisted time synchronization Scheme proposed for underwater mobile sensor networks (DA-Sync) [28], and the Doppler-Enhanced time synchronization proposed for underwater mobile sensor networks (DE-Sync) [29]. However, all of these protocols overlook the time-varying property of the clock skew. Figure 1 borrowed from [30], [31] shows that clock error curve is linear during the short time interval, but the clock error curve is nonlinear during the long time interval.

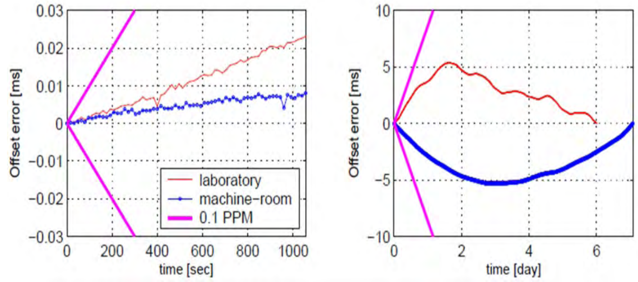

FIGURE 1. Illustration of clock drift.

At present, there is lack of an efficient synchronization protocol for underwater sensor networks that accounts time-varying skew issues. In this paper, we propose a new time synchronization approach based on Kalman filter tracking time-varying skew, called APE-Sync. Our new scheme aims to overcome the time-varying skew issue for time synchronization in a resource-constrained underwater wireless sensor networks.

APE-Sync consists of two stages, DE-Sync and Kalman filter. In the first stage, DE-Sync is adopted to estimate clock skew and clock offset to complete the initial time synchronization. DE-Sync can achieve the high accurate estimation of clock skew and clock offset by restraining the long and dynamic propagation delay. The estimated skew as the initial value of skew periodically tracked by Kalman filter, can then be substituted in the second stage. Different from the existing time synchronization protocols, the main improvement of APE-Sync is to take into account the scenario of time-varying skew. When assuming a constant clock skew, the network nodes only need a single time synchronization. However, as shown in Figure 1, the time-varying skew will lead to time synchronization launched by network nodes periodically. In this scenario, usually more than ten message exchanges are required for each time synchronization between the unsynchronized node and the beacon node to ensure time synchronization, which results in high energy overhead. In the proposed scheme, the nodes only require multiple message exchanges performing DE-Sync in the first stage of APE-Sync. Each subsequent synchronization only requires a single message interaction, which greatly reduces the energy consumption of nodes. For mobile underwater sensor networks, the comparison of simulation results shows that the performance of APE-Sync protocol is better than that of existing time synchronization approaches, in both energy efficiency and accuracy. APE-Sync that has high power efficiency is suitable for time synchronization in energy-constrained underwater sensor networks.

The rest of this paper is organized as follows. The previous works of the existing time synchronization protocols for underwater sensor networks are reviewed in Section 2. Then, in Section 3, a description of APE-Sync is provided. In Section 4, we show the simulation results which compare the new proposed scheme and other two time-synchronization protocols. Finally, our conclusions are given in Section 5.

II. RELATED WORK

The two main factors to be considered in the design of time synchronization protocol for underwater sensor network are: the relative mobility among nodes and the long propagation delay during communication among nodes. A lot of work has been done in this direction and a few time-synchronization protocols have been proposed such as TSHL, MU-Sync, Mobi-Sync, D-Sync, DA-Sync and DE-Sync. All these protocols have their advantages and disadvantages which are explained in the later of this section. One of the main disadvantages for these time synchronization protocols is high energy consumption in a resource-constrained underwater sensor networks among nodes.

TSHL was the first time synchronization protocol that was designed for high latency networks. TSHL assumes a constant propagation delay among sensor nodes and, therefore considers a static network only. Nodes, however, have small mobility due to the sea drift (around 0.83–1.67 m/s) [32], and even faster in case of self-propelled vehicles, such as autonomous underwater vehicles (AUVs). Therefore, TSHL protocol is not suitable for practical applications where nodes are mobile.

MU-Sync takes into account the time variation of the propagation delay due to the relative mobility of nodes using a two-phase operation: the synchronization phase and the offset, and skew acquisition phase. MU-Sync supposes that the one-way propagation delay is calculable as half of the round trip time. However, when the nodes move rapidly, the one-way propagation delay will significantly deteriorate the performance of MU-Sync, especially when the unsynchronized nodes have a long response time to the cluster head.

Mobi-Sync presents spatial correlation of velocities of the nodes to estimate the time-varying propagation delay. In the protocol, all nodes are categorized into three classes: super nodes, ordinary nodes and surface nodes. Mobi-Sync, however, is only applicable to certain special scenarios, because it assumes that the exact correlation among neighboring nodes is known, which in practice is quite difficult especially with a long distance of self-propelled vehicles or between nodes.

D-Sync makes use of the Doppler shift that is caused by nodes' relative motion in underwater environments. D-Sync does not consider the skew's effect during Doppler scaling factor estimation, hence reduces the Doppler shift estimation's accuracy and affects time synchronization's accuracy. As the initial skew rises, time synchronization's accuracy deteriorates.

DA-Sync also utilizes the Doppler effects that are caused by the relative movement among nodes during the time synchronization's process. At the same time, the effect of the skew is considered during the process of estimating the Doppler scales factor from the physical layer. Moreover, calibration process and the Kalman filter are exploited during the time synchronization process. However, due to the sound speed in water as a function of salinity, temperature and depth, the estimated sound velocity is directly applied into the computation during the time synchronization process, which causes extra errors. Besides, there are three parameters to be adjusted, initial skew, weight and the time period, which affect efficiency and the accuracy of synchronization.

DE-Sync possesses two principal distinguishing attributes. On one hand, DE-Sync considers the clock's effect to be skew during Doppler scale factor estimation, and compensates for the estimation error that is introduced by the clock skew. On the other hand, the Doppler scale factor, in place of the relative moving velocity between nodes, is taken in the exchange information, which cuts down division computations' quantity. It is widely known that the acoustic velocity is related to salinity, temperature and depth in water. DE-Sync does not instantly involve the computation of acoustic speed, which enhances the precision of time synchronization, and cuts down the error of estimating the clock offset and skew over the process of linear regression. Time synchronization based on Doppler scale estimation is dealt with by DE-Sync. Doppler scale estimation is typically a crucial research subject for underwater acoustic communication, and there are two common ways for Doppler scale estimation [33]. One of them is to send insensitive Doppler signals for Doppler scale estimation [34]–[37]. The other method is to send a sensitive Doppler waveform for Doppler scale estimation [38]–[41]. Both of these two methods are not ideal for real time processing of the estimation algorithm and have limited applications. A combined Doppler scale estimation scheme involving two steps to enhance the accuracy of the Doppler scale factor that is acquired in real time is adopted by DE-Sync [42]–[44]. Two identical short orthogonal frequency-division multiplexing (OFDM) symbols preceded by a cyclic prefix (CP) and one linear frequency modulation (LFM) are utilized as a preamble for initial Doppler scale estimation in the first step. The fine Doppler scale estimations are achieved based on the CP of each CP-OFDM block in the second step. However, DE-Sync has one of the same disadvantages as existing synchronization protocols that require more than ten message exchanges during each synchronization process among nodes, which leads to high energy cost.

III. PROTOCOL DESCRIPTION

A. OVERVIEW OF THE APE-SYNC

Figure 2 shows the block diagram of APE-Sync that splits time synchronization into two stages. In the first stage, after collecting data that includes time stamps of nodes and the estimation of Doppler scale factor, the initial time synchronization is achieved by performing DE-Sync to estimate the clock skew and offset. In the second stage, after collecting data that includes time stamps of nodes and propagation delay, the estimation of clock skew as initial input obtained in the first stage is substituted into Kalman filter which tracks the time-varying skew periodically. The two models introduced in this paper are clock model and clock skew model.

Each node is equipped with a clock timer that uses a crystal oscillator. The crystal oscillator operates at a certain angular frequency, and determines the clock rate [8]. Generally, the clock in each node possesses an inherent drift in

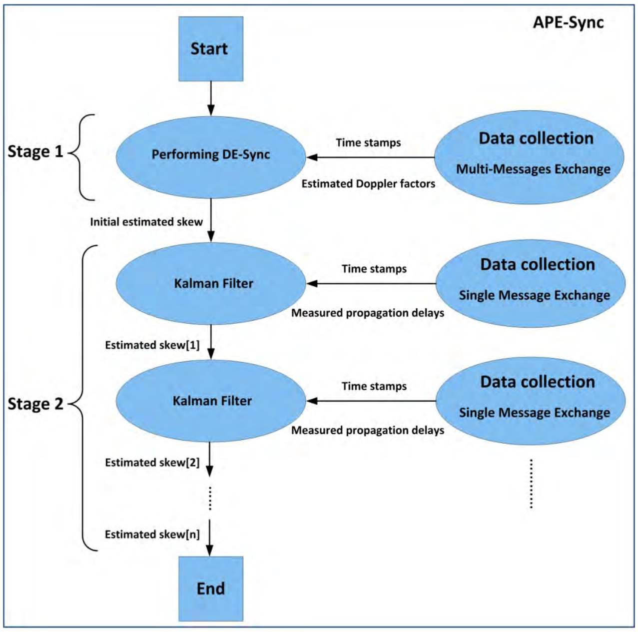

FIGURE 2. Block diagram of APE-Sync.

angular frequency owning to the manufacturing procedure. APE-Sync also follows the common time model used by numerous synchronization protocols to estimate the skew and offset. The local time of any node is shown by (1), which is relevant to the reference time.

$$T = \alpha t + \beta \tag{1}$$

where t denotes the reference time, i.e., beacon time, and T represents the local time of nodes at time t. β and α are the relative clock offset and the skew, respectively. Furthermore, β is influenced by the starting time of the system and α is relevant to the angular frequency of the crystal oscillator.

Based on the existing results [31], the time-varying clock skew can be modeled as a random variable with zero mean. The adjacent discrete values of the clock skew follow the auto-regressive model (AR) model, as shown in (2).

$$\alpha[n] - 1 = p(\alpha[n-1] - 1) + \eta[n] \tag{2}$$

where p is less than but close to 1 as a positive number, $\eta[n]$ is the model noise. Its mean is zero and variance $\sigma_\eta^2 =$ (1 - p^2)σ_α^2, and σ_α^2 is the variance of $\alpha[n]$. Based on equation 2, p can be regarded as the skew between n-1 and n moment. In this paper, p is called clock auto-skew, and the skew between different clocks can also be regarded as clock cross-skew. According to [24]–[31], the difference between p and 1 should be less than the clock cross-skew. In the simulation of this paper, the difference between p and 1 was set as 200ppm. Table 1 lists all the parameters being used.

B. OVERVIEW OF THE DE-SYNC

The synchronization procedure of DE-Sync is divided into three stages: data collection, linear regression and calibration. Firstly, the unsynchronized node N_B initiates synchronization

TABLE 1. Parameter description.

Parameters	Description
N_A	the beacon node
N_B	the unsynchronized node
α	the clock skew
β	the clock offset
a_{AB}	measured Doppler scaling factor from N_A to N_B
a_{BA}	measured Doppler scaling factor from N_B to N_A
T_1	sending time-stamp from unsynchronized node
T_2	receiving time-stamp from beacon
T_3	sending time-stamp from beacon
T_4	receiving time-stamp from unsynchronized node
$T_{backoff}$	T_3-T_2, that is response time
τ_1	propagation delay from N_B to N_A
τ_2	propagation delay from N_A to N_B
$\hat{\alpha}$	initial estimation of clock skew
$\hat{\beta}$	estimation of clock offset

process. The unsynchronized node N_B sends a synchronization request to beacon N_A when it moves to the coverage area of the underwater sensor networks. Meantime, node N_B records T_1(the sending time-stamp) obtained from the MAC layer. Upon receiving the time synchronization request, beacon N_A marks the receiving time-stamp T_2 (the local time of N_A) and records the Doppler scaling factor a_{AB}, obtained from the physical layer of N_A. $T_{backoff}$ is a random time that is backed off by beacon N_A to avoid message collisions before beacon N_A transmits a response message back to the node N_B at T_3, and the response message also contains T_2, T_3 and a_{BA}. As explained, when receiving the time synchronization response message, the Doppler scale factor a_{AB} and the receiving time are recorded by node N_B. After several rounds of message exchanges, a set of time-stamps consisting of T_1, T_2, T_3 and T_4 will be collected by node N_B, and a_{BA} and a_{AB} as the measured Doppler scale factor . It is shown in Figure 3 that the message exchange process between node N_A and node N_B. In order to estimate the clock skew and offset, the first linear regression with LS (least square estimation) is performed by the unsynchronized node in the linear regression phase. The calibration process is performed by the unsynchronized node by updating the initial skew, and the unsynchronized node re-performs the synchronization process to obtain the final clock skew and offset in the calibration phase. The algorithm is as follows, and specific derivation process is shown in [29].

$$\begin{aligned} \hat{\Lambda} &= \left[\hat{\alpha}, \hat{\beta}\right]^T = \left(H^T H\right)^{-1} H^T Y \\ Y[i] &= 2T_1^i + T_4^i\left(2 - \left(a_{\mathrm{AB}}^i + a_{\mathrm{BA}}^i\right)\right) \\ H[i,1] &= 2T_3^i + T_2^i\left(2 - \left(a_{\mathrm{AB}}^i + a_{\mathrm{BA}}^i\right)\right) \\ H[i,2] &= \left(4 - \left(a_{\mathrm{AB}}^i + a_{\mathrm{BA}}^i\right)\right) \end{aligned} \tag{3}$$

C. KALMAN FILTER

In the second stage of APE-Sync, Kalman filter is adopted to track clock skew, for which the network nodes need one

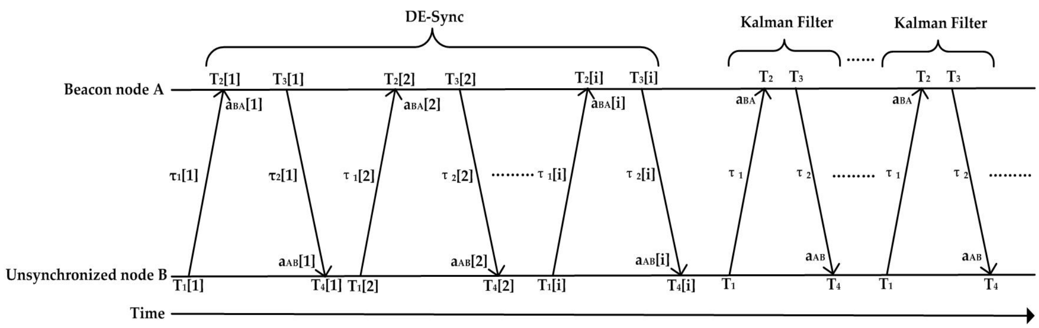

FIGURE 3. APE-Sync message exchange Scheme.

time synchronization. The synchronization process using for Kalman filter only requires a single message interaction. The message interaction process is similar to that of the first stage, namely DE-Sync, and the only difference between two stages is that nodes working in the first stage require more message exchanges than those working in the second stage. After single message exchange, a set of time-stamps consisting of T_1, T_2, T_3 and T_4 will be collected by unsynchronized node N_B, and a_{BA} and a_{AB} as the measured Doppler scale factor. Based on the collected data, node N_B calculates the propagation delay, and performs Kalman filter to achieve the tracked value of skew. Figure 3 shows the message exchange process between node N_A and node N_B.

As given by (1), the following equation of the node's local time can hence be derived:

$$T_1[n] = \alpha[n](T_2[n] - \tau_1[n]) + \beta \tag{4}$$

Based on the derivation in [29], the propagation delay can be formulated as:

$$\tau_1[n] = \frac{T_4[n](1-\theta[n]) - T_1[n] + \theta[n]\beta}{2\alpha[n]} + \frac{T_2[n](1+\theta[n])}{2} - \frac{T_3[n]}{2} \tag{5}$$

$\theta[n] = 0.5 \times (a_{AB}[n] + a_{BA}[n]) + \varepsilon$, where $\theta[n]$ denotes the average of Doppler scaling factor, and ε is measurement noise.

Based on (2), the state equation of Kalman filter can be expressed as:

$$X[n] = FX[n-1] + u[n] \tag{6}$$

where $X[n] = \left[\alpha[n]\ 1-P\right]^T$, $F = \begin{bmatrix} P & 1 \\ 0 & 1 \end{bmatrix}$, $u[n] = \left[\eta[n]\ 0\right]^T$

Based on (4), the measurement equation of Kalman filter can be expressed as:

$$Z[n] = KX[n] + v[n] \tag{7}$$

where $Z[n] = T_1[n] - \beta$, $K = \left[(T_2[n] - \tau_1[n])\ 0\right]$, $v[n]$ denotes measurement noise.

Combining (6) and (7), and based on Kalman filter, a set of equations of the tracking clock skew in APE-Sync can be expressed as:

$$X[n|n-1] = FX[n-1|n-1] \tag{8}$$

$$P_a[n|n-1] = FP_a[n-1|n-1]F^T + C_u \tag{9}$$

$$G[n] = P_a[n|n-1]K^T\left(KP_a[n|n-1]K^T\right)^{-1} \tag{10}$$

$$X[n|n] = X[n|n-1] + G[n](Z[n] - KX[n|n-1]) \tag{11}$$

$$P_a[n|n] = (I - G[n]K)P_a[n|n-1] \tag{12}$$

The initial value of $X[n|n]$ and $P_a[n|n]$ can be expressed as:

$$X[0|0] = \left[\hat{\alpha}\ 1-P\right]^T, \quad P_a[0|0] = \begin{bmatrix} \sigma_v^2 & 0 \\ 0 & \sigma_\alpha^2 \end{bmatrix} \tag{13}$$

where $\hat{\alpha}$ denotes the estimation of clock skew obtained in the first stage of APE-Sync, which is used as initial value of tracking skew. σ_v^2 and σ_α^2 are the variances of $v[n]$ and $\alpha[n]$, respectively.

IV. PERFORMANCE EVALUATION

A. SIMULATION SETUP

MU-Sync was the first time synchronization approach designed for mobile underwater sensor networks, and DA-Sync was the first time synchronization protocol that adopted Kalman filter to track the mobile nodes. So we therefore compare the performance of APE-Sync with MU-Sync and DA-Sync. We obtain the simulation results by changing the various parameters for a pair of nodes. We set the sensor nodes to move randomly within an area of 1000 meters by 1000 meters in the simulations. Figure 3 shows the simulation signal exchange scheme. Unless otherwise specified, the parameters summarized in Table 2 are used for our simulations. Without loss of generality, the average of each data point is obtained by the 1000 runs.

Notice that all simulation consequences show the synchronization error two hours after a node is synchronized.

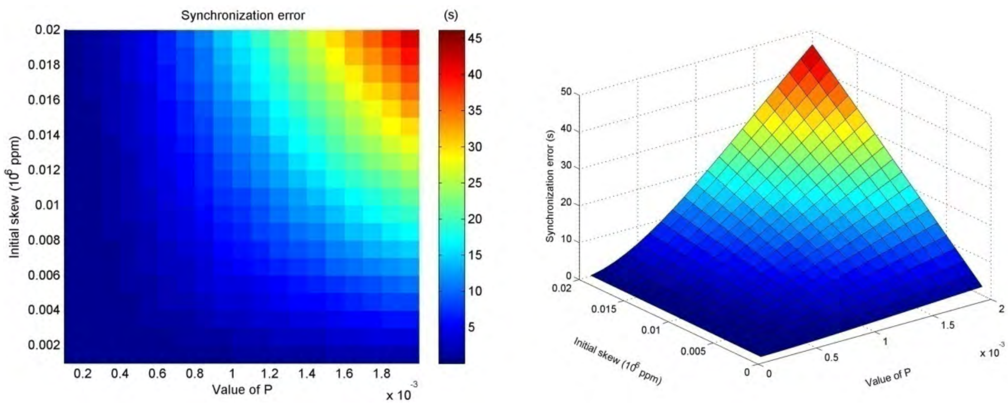

FIGURE 4. Performance with clock skew and P Value.

TABLE 2. Simulation parameters.

Parameters	Value
maximum distance (d_m)	1000 m
maximum speed (v_m)	4 m/s
maximum acceleration (A_m)	0.2 m/s^2
maximum skew (α_m)	200 ppm
maximum clock offset (β_m)	100 ppm
response time (T_r)	0.5 s
interval between request messages (M_{int})	2 s
number of messages (N_m)	24
granularity of clock (T_g)	0.1 µs
clock jitter (T_{jit})	10 µs
clock auto-skew (p)	0.9998

B. SIMULATION RESULTS AND ANALYSIS

1) EFFECT OF CLOCK SKEW AND P VALUE

Figure 4 shows the regularity of synchronization error for APE-Sync with clock skew and p value. In order to analyze the regularity of synchronization error, the p value is varied between 0.9998 and 0.998, which is equivalent to the variety of clock auto-skew between 200ppm and 2000ppm [45]. Moreover, the initial skew can be selected with the range from 0.002 to 0.02 (10^6ppm). The clock skew and p value affect the performance of Kalman filter performed in APE-Sync. From Figure 4, we can find that synchronization error is in a small range and almost no fluctuation when the clock skew or p value is a small value. However, the synchronization error becomes significantly larger with increased clock skew and p value, and the difference between the maximum and minimum synchronization error is approximately 10 times, thus starting the performance to deteriorate. However, p value that is regarded as clock auto-skew should be less than the clock skew that rarely can be out of 100ppm in practice, so the synchronization error is always a small value. Figure 4 shows the simulation results that meets the expectation.

2) INITIAL SKEW

Figure 5 shows the standard deviation and the mean of synchronization error for MU-Sync, DA-Sync and APE-Sync when the initial skew among nodes is varied between 0.01 and 0.1 (10^6ppm). APE-Sync consists of two stages, DE-Sync and Kalman filter. The performance of DE-Sync is not affected by the initial value of the clock skew [29], that can achieve the high accurate estimation of clock skew. The estimated skew as the initial value of skew tracked by Kalman filter can be substituted into the second stage. Therefore, the synchronization performance of APE-Sync is not affected by the initial skew in theory. From Figure 5, synchronization error for MU-Sync and DA-Sync deteriorate with the increase of initial skew. This is because that MU-Sync does not take into account the effect of dynamic propagation delay between nodes, and in DA-Sync, the estimation of sound velocity and the relative moving speed among nodes are directly applied to the calculation in the process of synchronization, resulting in extra errors. Simulation results are as shown in Figure 5, and APE-Sync has consistent performance across different initial skew.

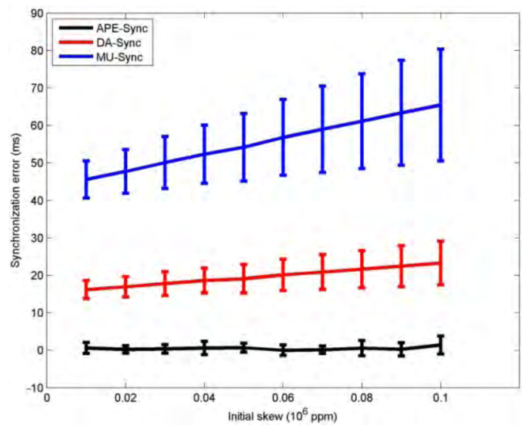

FIGURE 5. Performance with initial skew.

3) RESPONSE TIME

Figure 6 shows the standard deviation and the mean of synchronization error for MU-Sync, DA-Sync and APE-Sync when the response time of a node is varied from 1 sec

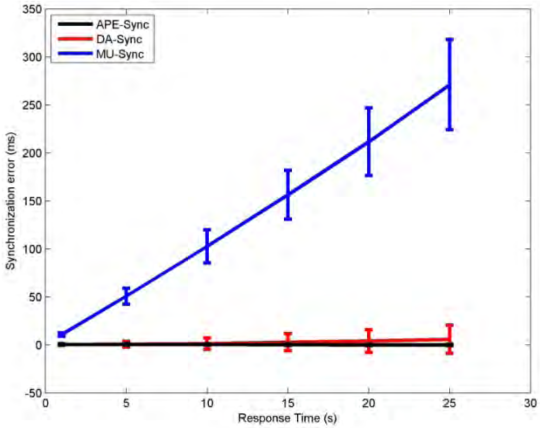

FIGURE 6. Performance with response time.

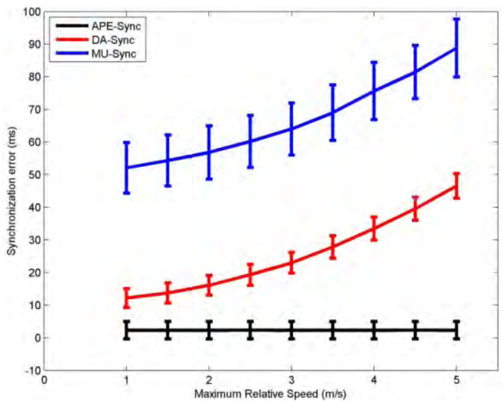

FIGURE 7. Performance with relative speed.

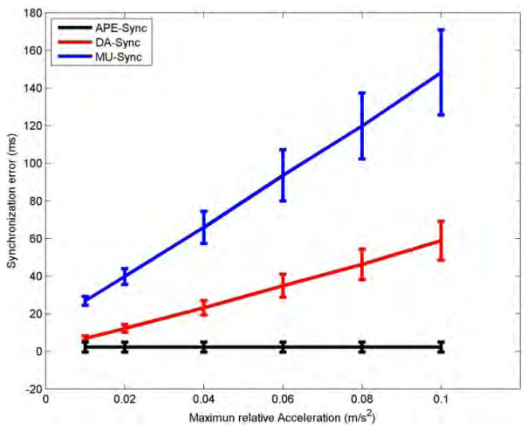

FIGURE 8. Performance with relative acceleration.

to 25 sec. Meanwhile, we set the relative moving speed among nodes to be nonzero, and with the increase of the response time, the difference of the round trip time also increases. MU-Sync supposes that the one-way propagation delay is calculable as half of the round trip time, which will significantly increase the synchronization error. DA-Sync takes the dynamic propagation delay into account

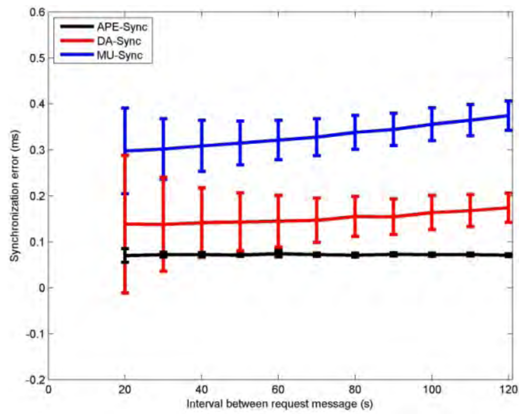

FIGURE 9. Effect of message interval.

and results with a better performance. After the first stage of APE-Sync, nodes only require a single message exchange when performing Kalman filter in the second stage, thus not affecting the performance by response time. Simulation results show that APE-Sync has the best performance in three protocols.

4) EXTENT OF MOBILITY

Figure 7 shows the standard deviation and the mean of the synchronization error for MU-Sync, DA-Sync and APE-Sync when the maximum relative speed of a node is varied from 1 m/s to 5 m/s. In MU-Sync, the time synchronization is achieved by performing linear regression twice via multiple message exchanges. But MU-Sync supposes that the one-way propagation delay is calculable as half of the round trip time, which will increase the synchronization error when the relative moving speed among nodes increases. DA-Sync considers the effect of the moving speed among nodes during synchronization process. However, as the velocity of sound in water is related to salinity, temperature and depth, the estimation of sound velocity is directly applied to the calculation in the synchronization process, resulting in extra errors. In DA-Sync, the synchronization error will increase when the relative moving speed among nodes increases. APE-Sync only needs to track the time-varying skew by performing Kalman filter, which does not involve the computation of the moving speed and acoustic velocity directly. Therefore, in APE-Sync, the synchronization error does not change when the moving speed among nodes increases. From Figure 7, simulation results show that APE-Sync has a better performance than MU-Sync and DA-Sync.

The standard deviation and the mean of the synchronization error for MU-Sync, DA-Sync and APE-Sync when the maximum relative acceleration of a node is varied from 0.01 m/s^2 to 0.1 m/s^2 are illustrated in Figure 8. Due to the fact that the maximum relative speed will increase when maximum relative acceleration increases, As explained earlier about the relative speed, the synchronization error of MU-Sync and DA-Sync will increase with increase in relative acceleration, while the synchronization error of APE-Sync will not change when relative acceleration among nodes

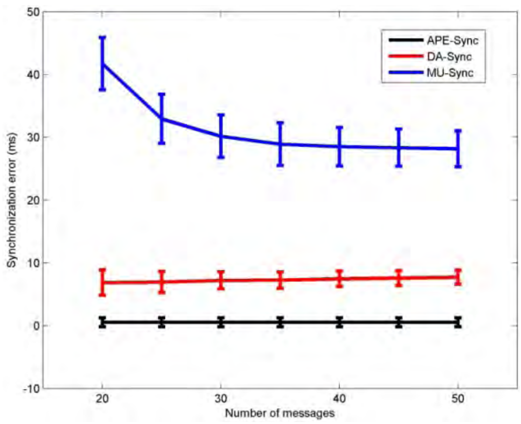

FIGURE 10. Performance vs number of messages.

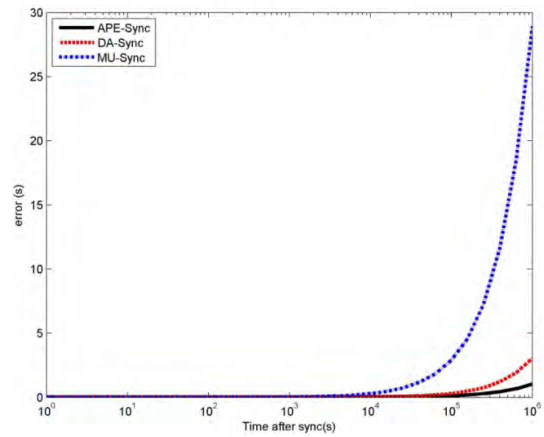

FIGURE 11. Clock error vs time after sync.

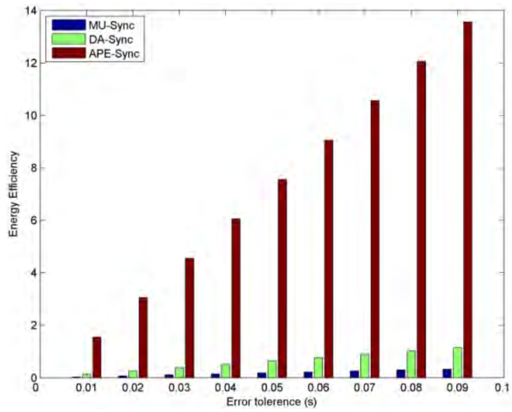

FIGURE 12. Energy efficiency vs error tolerance.

increases. Figure 8 shows the simulation results, that are consistent with expectations as APE-Sync outperforms MU-Sync and DA-Sync.

5) INTERNAL BETWEEN REQUEST MESSAGES

The standard deviation and the mean of the synchronization error for MU-Sync, DA-Sync and APE-Sync when the time interval between request messages of a node is varied from 20 sec to 120 sec are illustrated in Figure 9. The dynamic range of linear regression of MU-Sync and DA-Sync is increased by increasing the interval between request messages. It allows enough time to elapse before the next message exchange is initiated. The synchronization error decreases with the increased interval. Meantime, the acceleration of the node is set to nonzero in the simulation process, so the mean of synchronization error for MU-Sync and DA-Sync increases slightly with the increased interval. In APE-Sync, nodes only require a single message exchange, so the performance is not affected by the increased interval. Figure 9 shows the simulation results that again are consistent with expectations as APE-Sync outperforms MU-Sync and DA-Sync.

6) NUMBER OF REQUEST MESSAGES

Figure 10 shows the standard deviation and mean of the synchronization error for MU-Sync, DA-Sync and APE-Sync when the number of messages of a node is varied from 5 to 45. The dynamic range of linear regression adopted in MU-Sync and DA-Sync will be increased by increasing the number of request messages, so the synchronization error of MU-Sync and DA-Sync decreases when increasing the number of messages. In APE-Sync, nodes only require a single message exchange, so the performance is not affected by the number of request messages. Simulation results shown in Figure 10 are consistent with expectations that APE-Sync outperforms MU-Sync and DA-Sync.

7) ERROR AFTER SYNCHRONIZATION

Figure 11 demonstrates how synchronization errors grow after time synchronization completes with the three different protocols, namely, DA-Sync, MU-Sync and APE-Sync. It can be clearly seen that APE-Sync works a great deal better than DA-Sync and MU-Sync, that achieves more precise skew, which influences the degree of synchronization error. It is assumed that the propagation delay of each round of message exchanges is constant in MU-Sync, so larger amount of errors are caused. In DA-Sync, the error is till high as the estimated sound speed is directly applied to the calculation in the synchronization process. Besides, there are three parameters to be adjusted, initial skew, weight and the time period, which affect efficiency and the accuracy of synchronization. APE-Sync is the best among all schemes, for it corrects the shortcomings of the other schemes, as described before.

8) COMPARISON OF ENERGY EFFICIENCY

The energy efficiency of the three synchronization approaches is compared in Figure 12. Computational cost and message-exchange overhead directly affect the energy efficiency. Nevertheless, compared with the consumption of energy that is used to send and receive acoustic signals in underwater sensor networks, the energy cost can actually be negligible in calculation. So, in this paper, computational cost is ignored. (14) is used as an evaluation formula of energy efficiency [46].

$$\rho = \frac{\vartheta}{\kappa \mu \gamma} \tag{14}$$

In this equation, υ is set to 10^6 sec, which represents a period of time after synchronization completes. γ and μ are the packet size and the number of messages used in performing a linear regression, respectively. γ and μ are set to 40 Bytes and 24 messages, respectively. However, in APE-Sync, nodes only require a single message exchange by using Kalman filter, hence, γ and μ are set to 40 Bytes and two messages, respectively. κ denotes the number of re-synchronization required within a certain duration of υ, which keeps synchronization error below a certain clock error tolerance e. It is expressed as follows.

$$\kappa = \frac{\vartheta}{\left(\frac{\hat{\alpha}e+\left(\hat{\beta}-\beta\right)}{\alpha-\hat{\alpha}}\right)} \tag{15}$$

Observing (14) and (15), the accuracy of the estimated skew and the number of messages determines energy efficiency. In other words, the scheme that has higher accuracy time synchronization and less number of messages will have higher energy efficiency. It is shown in Figure 12 that APE-Sync has better energy efficiency with respect to MU-Sync and D-Sync.

V. CONCLUSIONS

This paper proposes APE-Sync, an innovative time synchronization protocol designed for underwater mobile sensor networks, which periodically adopts Kalman filter to track the time-varying skew. Compared to the existing schemes, APE-Sync has better synchronization precision, and only requires one message exchange during the second stage of synchronization process as opposed to an average of ten message exchanges in the existing protocols. This helps to greatly reduce the energy of consumption of nodes. The simulation results confirm that APE-Sync is a high precision time synchronization scheme with a lower message overhead, which is great for time synchronization in energy-constrained mobile underwater sensor networks.

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FENG ZHOU received the B.S. and M.S. degrees in communication and information system from Jilin University, China, n 2002 and 2005, respectively, and the Ph.D. degree from the College of Underwater Acoustic, Harbin Engineering University (HEU). He was with HEU for the past 14 years, where he is currently an Associate Professor with the College of Underwater Acoustic. Throughout his career, he has worked primarily on underwater acoustic communications. His current research interests include underwater acoustic spread spectrum communications, underwater acoustic multi-carrier communications, localization in underwater networks, and underwater acoustic modem development. He received the National Natural Science Foundation Award to design efficient communication solutions for underwater applications, in 2013 and 2015.

QI WANG received the B.S. degree in electronic information engineering from Jilin University, China, in 2002, and the M.S. degree in underwater acoustic engineering from Harbin Engineering University, Harbin, China, in 2006, where he is currently pursuing the Ph.D. degree in communication and information engineering. From 2006 to 2008, he was a Research Assistant with the Institute of Measurement and Control, Dalian, China. From 2008 to 2016, he was a Communications Software Engineer with Huawei Technology, Co., Ltd., Shanghai, China. His research interests include time synchronization, medium access control protocol, and routing protocol for mobile underwater sensor networks.

GUANGJIE HAN (S'03–M'05–SM'18) received the Ph.D. degree from Northeastern University, Shenyang, China, in 2004. From 2004 to 2005, he was a Product Manager of ZTE Company. From 2005 to 2006, he was a Key Account Manager of Huawei Company. In 2008, he finished his work as a Postdoctoral Researcher with the Department of Computer Science, Chonnam National University, Gwangju, South Korea. From 2010 to 2011, he was a Visiting Research Scholar with Osaka University, Suita, Japan. In 2017, he was a Visiting Professor with the City University of Hong Kong, China. He is currently a Professor with the Department of Information and Communication System, Hohai University, Changzhou, China, and a Distinguished Professor with the Dalian University of Technology, Dalian, China. He is the author of over 330 papers published in related international conference proceedings and journals, including the IEEE COMST, IEEE TII, IEEE TMC, IEEE TVT, IEEE TIE, IEEE TPDS, IEEE TETC, IEEE IoT Journal, IEEE TETCI, IEEE TCC, IEEE Systems Journal, IEEE Sensors Journal, IEEE Wireless Communications, *IEEE Communications*, and *IEEE Network*. He holds 125 patents. His H-index is 32 and i10-index is 90 in Google Citation (Google Scholar). Total citation of his papers by other people is more than 4408 times. His current research interests include the Internet of Things, the industrial Internet, mobile computing, artificial intelligence, and security.

GANG QIAO received the B.S., M.S., and Ph.D. degrees from the College of Underwater Acoustic Engineering, Harbin Engineering University (HEU), China, in 1996, 1999, and 2004, respectively. In 1999, he was with the College of Underwater Acoustic Engineering, HEU, where he is currently a Professor and the Associate Dean of the College of Underwater Acoustic Engineering. He has already published more than 80 papers. He holds seven national invention patents. His current research interests include underwater communication and networks, detection and positioning of underwater targets, and the sonar designed for small carriers. He is a member of the Acoustical Society of China and the Youth Federation of Hei Longjiang Province and the Vice Chairman of the Robotics Society of Hei Longjiang Province. He received the National Award for the Outstanding Scientific and Technological Workers and the Science & Technology Award for Young Talents in Hei Longjiang Province.

ZONGXIN SUN received the M.S. degree in underwater acoustic engineering and the Ph.D. degree in signal and information processing from Harbin Engineering University (HEU), Harbin, China, in 2006 and 2015, respectively. From 2008 to 2016, he was an Assistant Professor with the College of Underwater Engineering, HEU, where he has been an Associate Professor, since 2016. His research interests include the areas of underwater acoustic communication systems, communication sonar, and underwater telephone.

AHMED NIAZ received the B.S. degree in telecommunication engineering from NUCES-FAST University, Lahore, Pakistan, in 2010, the M.S. degree in computer engineering from CASE University, Islamabad, Pakistan, in 2012, and the Ph.D. degree in electrical engineering from the Missouri University of Science and Technology, Rolla, MO, USA, in 2017. He is currently an Associate Professor with Harbin Engineering University, Harbin, China. His research interests include wireless communication, underwater wireless sensor networks, and embedded systems.