IEEE Access
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

Received January 18, 2021, accepted January 31, 2021, date of publication February 9, 2021, date of current version February 19, 2021.

Digital Object Identifier 10.1109/ACCESS.2021.3058160

Joint Algorithm for Multi-Hop Localization and Time Synchronization in Underwater Sensors Networks Using Single Anchor

REHAN SHAMS[1], **PABLO OTERO**[2], **(Member, IEEE), MUHAMMAD AAMIR**[1], **AND FOZIA HANIF KHAN**[3]
[1]Department of Telecommunication Engineering, Sir Syed University of Engineering and Technology, Karachi 75300, Pakistan
[2]Department of Telecommunication Engineering, University of Malaga, 29016 Málaga, Spain
[3]Department of Mathematics, University of Karachi, Karachi 75270, Pakistan

Corresponding author: Rehan Shams (r.shams@hotmail.com)

ABSTRACT In this study, an effort to synchronize and localize the underwater sensors simultaneously in a multi-hop environment is considered. Underwater Sensor Networks (UWSNs) has limited range and connectivity due to propagation delay and limited bandwidth. By using a multi-hop environment, we can extend the range and enhancing the network connectivity for providing more accurate localization and synchronization technique. We have established a connection between sensors point to point directed links and then analytically construct the model for the synchronization as a function of range, delay, and timestamps. Secondly, we have formulated the unconstrained optimization problem for localization by using a gradient technique. The proposed research scheme first synchronizes and then localizes the unknown nodes with known depth by using the single anchor node in a multi-hop scenario. According to the literature survey, this joint effort has never been addressed before; both localization and time synchronization for multi-hop scenarios are addressed separately. The proposed algorithm will also calculate the propagation delay that will be generated during message propagation for both localization and time synchronization. The numerical results are compared with some well-known techniques in terms of the number of nodes, localization error, synchronization error, total processing time up to four hops. Experimental results show that the proposed model outperforms in terms of localization and synchronization accuracy, but since this work has never been done before therefore, we compare our results with the techniques that had separately address this problem having some constraints.

INDEX TERMS UWSNs, multi-hop, joint localization and time synchronization, propagation delay, clock skew, offset.

I. INTRODUCTION

Many applications are associated with the underwater environment such as surveillance, ocean monitoring, and disaster mitigation, which like to measure the level of the sea due to the melting process of the ice sheet. All this can be possible due to randomly placed underwater sensors that collect some important hydrologic data for example pressure, temperature, and salinity [1]. Underwater sensor nodes are mostly in moving positions because of the sea flow and other creatures after their deployment. Mostly these nodes can't search for isolated nodes which results in poor localization. It is very important in many applications that the location of sensors is known otherwise the collected information is meaningless and since the localization is depending upon synchronization then it is very useful to perform both within the same scenario. Like localization, synchronization is a fundamental problem in distributed sensor networks especially since the timestamp is an important factor while sensing the data. The multi-hop scenario is also essential for traditional wireless sensor networking systems (WSNs) such as, [2] has given the localization system in a multi-hop for monitoring the environmental system. In [3] UAVs approach has been used to analyze the data topology in a multi-hop scenario. Indoor localization in hospitals by using an angle of arrival (AOA) has been performed by [4]. A time synchronization algorithm based on dynamic routing and forwarding certification (DRFC-TSP) is given by [5] also, energy-aware MAC protocol in a WSN

The associate editor coordinating the review of this manuscript and approving it for publication was Fang Yang.

is given by [6]. But maintaining the energy in a multi-hop environment is always been a major challenge for researchers in both WSNs and UWSNs. This study tries to address this issue for underwater sensors but, in a multi-hop environment. Many algorithms jointly addressed the localization and time synchronization but, within a single hop scenario. Limited literature is available for multi-hop localization and time synchronization. The reason behind not dealing with this issue is that it is very difficult to maintain the energy level during these joint efforts in multi-hop underwater sensors Networks. The proposed technique will utilize the energy which is less than the energy that mostly consumes by these separately performed procedures. Another issue is to maintain the computational complexity during this process, which ultimately affects energy consumption. Here we are making the effort to achieve both localization and time synchronization in a multi-hop situation, which can able to maintain the computational complexity together with the energy consumption. For the proposed localization and time synchronization with low computational complexity in a multi-hop situation, we are using a single anchor or reference node which localized and synchronized simultaneously. For the localization process, we use the technique of angle of elevation of beacon message which helps in calculating the coordinates of unknown nodes by using a single anchor. The remainder of this paper is as follows; section 2 describes related literature but as said earlier that joint work has not been considered before therefore this section separately discusses the previously developed techniques. Section 3 gives the network architecture and assumptions for the implementation of the proposed algorithm, section 4 provides the complete model of synchronization with an explanation, along with the calculation of propagation delay, section 5 presents the localization procedure with the steps of the complete process and range computation, Section 6 discusses the results and simulations related to the proposed technique along with the comparison from previously developed techniques, section 7 gives the conclusion and future work in the end, we have the references.

A. MAIN CONTRIBUTIONS

The main contribution can be summarized as follows,

- We develop a novel approach called joint localization and time synchronization in multi-hop wireless sensor networks by using a single anchor. The algorithm starts with the calculation of the skew and offset for the time synchronization first by using a message exchange between the sensor nodes and the anchor node by using a single anchor. The proposed model provides an efficient underwater data transmission environment, that reduces time, energy consumption for the number of exchanged messages.
- In most of the time synchronization algorithms, the calculation of delay is neglected which results in poor accuracy. The proposed model also calculates the propagation delay which is generated due to temperature pressure and salinity.
- The proposed algorithm, not just calculating the skew and offset but also calculates the location of unknown sensor nodes hop by hop with the help of the same messages change procedure that is used for the calculation of the time synchronization process. The localization of multi-hop UWSNs is formulated by using an angle of an incident from anchor to sensor node. The reason behind using the single anchor is to reduce the computational complexity that would be generated in the calculation process.
- Finally, we verified our proposed localization algorithm with extensive simulation results for different system parameters such as the number of nodes, ranging error, communication cost, localize right ratio, and Complete processing time by making the comparison of performance with other well-known network localization schemes such as MDS-MAP, MSL, and DRL. Furthermore, the proposed scheme for estimating the skew and offset is also compared with other previously developed algorithms such as V-sync, E-Tri sync, MU-sync, and Mul-sync for different parameters such as skew error, offset error with their corresponding elapsed time after synchronization. In the proposed network architecture of multi-hop, we have shown our performance up to three hops that consist of a single static anchor node with several other moving ordinary sensor nodes.

II. RELATED WORK

On the basis of the literature survey [7]–[10] we can say that this joint effort was not done by any researcher for localization and time synchronization in multi-hop underwater sensors. All have proposed different methods either for localization or time synchronization so far. So here we are discussing those kinds of literature that had separately done these two processes in a multi-hop environment for UWSNs. First, we discuss the localization then time synchronization for the different scenarios.

A. LOCALIZATION IN UNDERWATER ACOUSTIC WIRELESS SENSOR NETWORKS

Currently, the Underwater communication System is based on ''Acoustic communication'', ''Electromagnetic Waves Communication'', and ''Optical Communication''. Among them, Acoustic Communication Systems are the most used for underwater communication technologies and are mostly highlighted by many researchers due to their long-range connectivity. Over the past many years, the problem of localization and time synchronization for underwater acoustic sensor networks (UWASNs) has been tackled separately [11], among them some gave poor accuracy [12] as they did not consider the variation of sound speed. Although some latest research has also been conducted by many researchers to localize the underwater acoustic sensors. Novel localization was given by [13] which tries to meet this challenge with the help of the Kalman filter to align different time instants and perform range bending compensation for localization as a mobile node receives timestamps from different anchors.

This technique is based on Snell's law that compensates for the variation of sound speed by using ray racing theory. The recognition algorithm of the D2D device was proposed by [14] to enhance the trust management of network communication by obtaining the location information of unknown nodes of the network with the help of a few anchor nodes. Another node localization algorithm was given by [15] that saves the energy and cost consumption by using range free algorithm. This algorithm works on is the application of compressive sensing theory to UASNs different from the traditional range-free algorithm. Proposed by [16] a Virtual node localization algorithm for UWANs which works on two parts. This algorithm effectively improves localization by dividing the algorithm into a virtual node assisted static (VAS) localization algorithm and a virtual node assisted dynamic (VAD) localization algorithm. An improved AUV-based UASNs time difference localization algorithm was given by [17] in which the regular signal is sent by AUV, to obtain the localization. This algorithm gives less computational complexity with high accuracy. Another UASNs mobile node localization was suggested by [18] that first divides the underwater monitoring area into cubic modules and calculates the location of unknown nodes by QR decomposition algorithm by using the energy relationship mobile nodes and unknown nodes. This algorithm also studied the mobile path of nodes.

A lot of studies have been done on TS algorithms for underwater acoustic networks such as D-sync, MU-sync, E 2DTS [19]–[21]. These protocols synchronize the clock skew and offset by simply exchanging the beacon messages between the anchors and ordinary sensor nodes.

Recently a new protocol [22] called TSMA that works on the combination of control frames of TS and MACP makes an effective data transmission system underwater for reducing time delay and energy consumption during the messages exchange procedure.

Another recent TS algorithm has been proposed for UASNs [23] which solve the problem of long transmission delay but did address the multi-hop environment, however, this algorithm ignored the node movement problems. G-MAC algorithm [24] which is based on OFDMA- MAC protocol that implements the data transmission among the AUGs by using multiple access control process (MACP) called multiple access data transmission (MADT), which reduces the throughput and the transmission delay. DE-Sync proposed by [25] is a Doppler-enhanced TS algorithm for mobile UWSNs that provides accuracy and energy efficiency by directly substituting the Doppler scale factor into linear regression for the calculation of clock skew and offset. DE-Sync is much better as compare to existing TS algorithms in terms of accuracy and energy efficiency.

B. UNDERWATER LOCALIZATION IN OPTICAL WIRELESS SENSORS NETWORK

Optical communication technologies contain low energy consumption but a high data rate with the disadvantage of low transmission range. Different researchers have given their localization techniques for Optimal Sensors Networks such as [26] proposed a new technique for the localization for energy harvesting hybrid acoustic-optical underwater wireless sensor networks (AO-UWSNs). The purpose of using AO-UWSNs is, that on long-range transmission it employs acoustic communication for low data rate and at short rang transmission it employs optical communication for a higher rate. Another approach for the localization in underwater optical wireless sensor Networks is given by [27] in which the localization is based on received signal strength (RSS) for energy harvesting underwater optical wireless sensor networks (EH-UOWSNs). This technique improves the accuracy of localization by using a modified iterative majorization formulation that includes the anchor's location directly in the process of estimation. Another localization technique is addressed by [28] in which the connectivity analysis is investigated by driving analytical expression to show the probability of network connectivity is directly depending upon transmission range, transmission signals, and the number of nodes in the network. In [29] a technique of UOWSN localization is addressed which is the combination of time of arrival (ToA) and RSS methods for optical code-division multiple access networks. An approach given in [30] called energy harvesting is a promising potential solution that collects energy from ambient sources in the aquatic environment to be stored in an energy buffer.

Getting accuracy in OWSNs is not an easy task because OWSNs contain scattering, absorption, and turbulence impairments of seawater which create limited range attainability (10-100 m). Major problems of OWSNs are noise sources which include sunlight, background, thermal, and dark current noises Long range transmission

Therefore, to implement the joint effort of localization and time synchronization for multi-hop scenarios, an underwater acoustic sensor network is a much better beneficial environment as compare to OWSNs.

C. JOINT LOCALIZATION AND TIME SYNCHRONIZATION (JLTS)

From the above discussion, we can easily say that the individual effort of localization and time synchronization can produce a good result but, researchers have also proved that the combined effort of localization and time synchronization could produce better results. Previously by handling these two problems separately, results are not good and because of getting poor efficiency of handling this problem independently, joint efforts have started to get good results due to the dependency of these two processes of localization and time synchronization. Most of the accurate localization techniques in UWSNs are based on the measurement of time of arrival and their clock synchronization between the nodes, in contrast to this process of time synchronization takes advantage of the location information which can be further use in calculating the propagation delay. The message exchange between anchor and sensors has got both the information of location and clock information, on the basis of this information can be calculated simultaneously with the help of a single sort of messages, which ultimately reduces the energy. Many researchers have done this combined work with the help of a one-way message to save the overall energy of the system [31]. Although a two-way message exchange can also provide good results [32] as compare to those efforts which have been previously done for either localization or time synchronization. As considered JSL was the first effort which is made by the researcher for the joint procedure of localization and synchronization with the consideration of the stratification effect. This joint technique was given by [33] which only compensated the stratification effect in the underwater medium along with this assumption that sound waves travel in a straight line The joint effort has given by [34] in which the stratification effect is calculated along with the sound effect by the help of an iterative method, but this paper did not calculate the continuous deflection of sound wave angle it only measures the initial angle of deflection of sound waves.

All the above-mentioned algorithms provide better accuracy somehow but none of them tires to extend their techniques in a multi-hop environment. JSL has tried to implement his joint technique of localization and time synchronization on a multi-hop scenario but failed to give low energy consumption.

D. LOCALIZATION IN UWSNs FOR MULTI-HOP

In [35] there is a method called DV-Hop which calculates the distance between the nodes in communication hop. With the help of the average hop size provided by the anchor node, in this method, sensor calculated the distance between itself and anchor by simply multiplying its own hop number and average hop size. It is a very simple method that is immune to distance measurement errors and provides low accuracy. Another approach that is similar to DV-hop is called DV-distance [36]. The difference between these two is that the forwarded distance between the nodes is in meters instead of in a hop. In [37] multi-hop fitting approach for node localization has been done. Euclidian method [38] estimates the Euclidian distance from anchor to sensor nodes and due to this, it is more accurate. But this method produces better results if there are many sensors in the network. The law of cosine has also been used for the distance estimation in multi-hop [39] by the help angles of incoming signals from its neighboring nodes. But this method is sensitive to measurement errors and can be applied in 2-D space. With the help of an intermediate node as a router and sensor node, a distance-based scheme measures the shortest distance between them using a greedy algorithm. As far as the accuracy is concerned this method gives slightly better accuracy as compare to DV distance and can be used in both 2D and 3D space. In [40] localization for multi-hop has also been proposed for large scale underwater sensor networks. As defined earlier when underwater nodes search for the isolated node mostly localization is not accurate. There are two main methods for this type of scenario [41], [42], the first one is called AUV-aided localization however this method fails to give real localization. The second method is a multi-hop localization algorithm, which uses intermediate nodes between beacons and unknown nodes as routers for the transmission of coordinates from beacons. This method can be improved to get good results. The method proposed by [43] for localization in optical wireless sensor networks within a multi-hop environment. This method first established the connection between sensors by point to point directed link, then by analytically calculating the probability of network connection to calculate the localization as an unconstrained optimization problem.

E. MULTI-HOP TIME SYNCHRONIZATION TECHNIQUES

A multi-hop time synchronization algorithm is given by [44] called MUSAN which considers the overhearing criteria which receive synchronization packets from parent and neighbor node for reducing the error of synchronization. Another method called Mul Sync [45] for multi-hop UWSNs with few numbers of beacon nodes, it estimates skew and offset by using the linear regression thrice on different time stamp which gathers through a different neighboring node. Based on OPNET [46] provides and implementation of multi-hop time synchronization called MUSAN. This scheme modifies the pipeline stage propdel-stage and power stage and Bkgnoise-stageto makes it more applicable in the underwater channel. In past, most of the algorithms proposed for the synchronization of UWSNs were based on the assumption that propagation latency is negligible such as TPSN [47], LTS [48], where authors did not consider the clock drift during synchronization. MU-Sync [49] assumes that the propagation delay difference is little between two-way message exchange. Mobi-Sync [50], E2DTS [51], D-Sync [52] and TSMU [53] exploit special hardware's or deployment conditions. In [54] THSL has been introduced that works for high latency communication. In [55] tri-message technique is used by keeping the resource constraints as the primary focus. Extension of tri-message discussed by [56] for the multi-hop scenario and attain good accuracy with the consideration of overhearing as a tool that is not feasible and recommended according to [57]. Therefore, here we present a very simple joint protocol without a stringent requirement of overhearing.

III. NETWORK ARCHITECTURE

For the proposed joint algorithm, the network is composed of two types of sensors. Anchor nodes (AN) or Beacon nodes, are usually distributed on the sea surface area of interest, serving as fixed anchors attached to a GPS receiver and has acoustic and radio frequency transceivers and the other are sensor nodes (SN) or we can call them ordinary nodes mainly get the information from the neighboring sensing nodes, with the use of proper data fusion process and pass this fused information to the sink node in a multi-hop way and use two-way message exchange procedure is required to realize the time information among the UWSNs. The anchor node is the gateway and can able to communicate with the network.

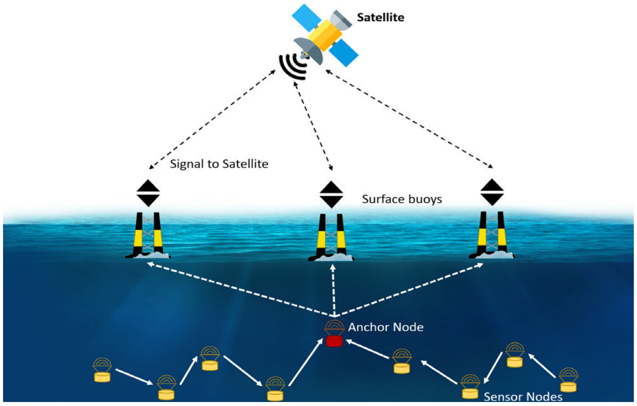

FIGURE 1. Network architecture for multi-hop.

All nodes are attached with multimodal directional piezoelectric underwater transducers that design to meets the acoustic requirements in terms of mechanical and thermal performances. References [58]–[60] which can able to measure the angle of elevation on nodes [39]. Also, sensor nodes are randomly deployed and equipped with depth sensors, they are different from those static nodes, or are not static like ground-based sensor networks nodes. Instead, they move with water current due to different activities and circumstances of the underwater environment, usually 2-3m/sec. they are dynamic nodes and their movements may be random. Network architecture is represented in Figure 1.

A. ASSUMPTIONS

All sensors are distributed over a 3 D space and anchor nodes are buoys on the surface of the ocean and all anchors already aware of their positions and time without error. All sensor nodes are identical in terms of their transmission, sensing range, and their transmission and sensing region and they can able to perform the calculation. In underwater three-dimensional sensor networks architecture, the ocean bottom is utilized to anchored sensor nodes. The depth of these nodes is controlled using wires which are attached to these anchors. Initially, sensors do not have any information about their locations and time. Each timestamp is inserted at the MAC-layer. Except for propagation delay, all uncertainties will be considered as time jitters which follow a normal distribution with zero expectation.

IV. SYNCHRONIZATION IN MULTI-HOP UWSNs

‘‘In this section, the scenario to realize of multi-hop localization and time synchronization for the relay nodes is explained. Here, the series multi-hop synchronization and localization procedure has adopted to achieve the multi-hop both time synchronization and localization of relay nodes, and this strategy can be seen in Figure 2’’. From figure 2 it is clear that the ordinary sensor node sends the first beacon message at time *T(1,1)* to the sensor node which is within the communication range of the sensor node and this massage is received by the sensor node at Time *T(2, 1),* after this, ordinary sensor node sends back the acknowledgment message to the node sensor node at time *T(3, 1)* which is received at *T(4,1).* Also, node j receives the beacon message from the node ordinary node at time *T(5, 1)* and sends back an acknowledgment message to the ordinary node at time *T(6, 1)* which is received by node *j* at time *T(7,1).* Furthermore, node j will get the beacon message from the anchor node *j-1* at time *T(8, 1)* which was actually sent by node j, and as a reply, node anchor node give the acknowledgment message at time *T(9, 1)* which is received by j at time *T(10, 1).* In this way, N number of messages can send to each node. ‘‘Finally, node *j* estimates and adjusts its own clock offset and skew, and start act as reference node to synchronize the next ordinary node and next nodes repeat the above process so that each node in the network can be synchronized to the reference clock. This process can easily be extended for the entire chain process for any number of sensor nodes through *N* times of synchronization exchange of information’’.

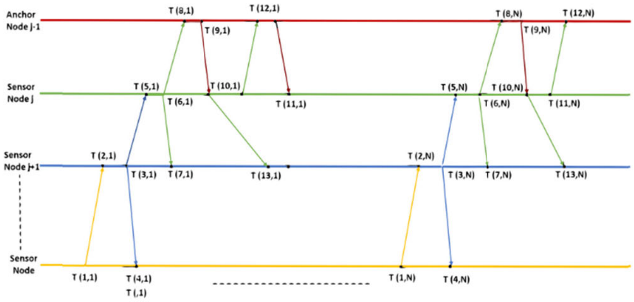

FIGURE 2. Multi-hop scenario in UWSNs.

The delay is divided into two components, first is δ which is the non-deterministic delay like jitter and noise whereas $d_{x,i}$ is the deterministic delay which is not constant and will be calculated.

Therefore, the generalized model for the first hop j for sending *N* massages can be written as,

$$T^{j}_{s(k,i)} = T^{j-1}_{r(k-1,i)} + \delta_j + d^{j}_{x,i} + \alpha_j \left(T^{j-1}_{r(k-1,i)} - T^{j-1}_{r(k-1,1)} + \delta_j + d^{j}_{x,i} \right) + \beta_j \quad (1)$$

$$T^{j}_{s(k,i)} = (1+\alpha_j) \left(T^{j-1}_{r(k-1,i)} + \delta_j + d^{j}_{x,i} \right) + \beta_j \quad (2)$$

where the term $\alpha_j \left(T^{j-1}_{r(k-1,i)} + \delta_j + d^{j}_{x,i} \right)$ is due to the effect of clock skew in equation (1), similarly the time stamp at node j in the ith downlink massage $T_{(11,i)}$ is given by,

$T^{j-1}_{r(k,i)}$ = is the sending time of i^{th} message round from the reference node *j – 1*

$T^{j}_{s(k,i)}$ = is the time when j sensor node receiving the i^{th} message round

$$T^{j}_{s(k+1,i)} = T^{j-1}_{r(k+2,i)} - \delta_j - d^{j}_{y,i} + \alpha_j \left(T^{j-1}_{r(k+2,i)} - T^{j-1}_{r(k+2,1)} - \delta_j - d^{j}_{y,i} \right) + \beta_j \quad (3)$$

$$T^{j}_{s(k+1,i)} = (1+\alpha_j) \left(T^{j-1}_{r(k+2,i)} - \delta_j - d^{j-1}_{y,i} \right) + \beta_j \quad (4)$$

In equation (3) $T^{j}_{s(k+1,i)}$ is the time of jth sensor node receiving ith acknowledgment message round from j-1 anchor node, and $d^j_{y,i}$ is again the deterministic delay while receiving the message but in the opposite direction which is not constant and will be calculated later,

we can write (2) for $T^j_{(k,1)} and T^j_{(k,N)}$ in the form of (5) and (6) respectively as,

$$T^j_{s(k,1)} = (1+\alpha_j)\left(T^{j-1}_{r(k-1,1)} + \delta_j + d^j_{x,1}\right) + \beta_j \tag{5}$$

$$T^j_{s(k,N)} = (1+\alpha_j)\left(T^{j-1}_{r(k-1,N)} + \delta_j + d^j_{x,N}\right) + \beta_j \tag{6}$$

similarly (4) can be write in the form of (7) and (8) as,

$$T^{j+1}_{s(k+1,1)} = (1+\alpha_j)\left(T^j_{r(k+2,1)} - \delta_j - d^j_{y,1}\right) + \beta_j \tag{7}$$

$$T^{j+1}_{s(k+1,N)} = (1+\alpha_j)\left(T^j_{r(k+2,N)} - \delta_j - d^j_{y,N}\right) + \beta_j \tag{8}$$

By subtracting (5) from (6) we get (9),

$$\begin{aligned} T^j_{s(k,N)} - T^j_{s(k,1)} &= T^{j-1}_{r(k-1,N)} - T^{j-1}_{r(k-1,1)} + d^j_{x,N} - d^j_{x,1} + \alpha_j \\ &\quad \times \left(T^{j-1}_{r(k-1,N)} - T^{j-1}_{r(k-1,1)} + d^j_{x,N} - d^j_{x,1}\right) \end{aligned} \tag{9}$$

again, by subtracting (7) from (8) we get (10),

$$\begin{aligned} T^{j+1}_{s(k+1,N)} - T^{j+1}_{s(k+1,1)} &= T^j_{r(k+2,N)} - T^j_{r(k+2,1)} - (d^j_{y,N} - d^j_{y,1}) \\ &\quad + \alpha_j\left[T^j_{r(k+2,N)} - T^j_{r(k+2,1)} - \left(d^j_{y,N} - d^j_{y,1}\right)\right] \end{aligned} \tag{10}$$

we define the difference in the stamps as,

$$t^j_k = \sum_{i=1}^{N} t_{s(k,i)} = T^j_{s(k,N)} - T^j_{s(k,1)}$$

$$t^j_{k+1} = \sum_{i=1}^{N} t_{s(k+1,i)} = T^{j+1}_{s(k+1,N)} - T^{j+1}_{s(k+1,1)}$$

$$t^{j-1}_{k-1} = \sum_{i=1}^{N} t_{r(k-1,i)} = T^{j-1}_{r(k-1,N)} - T^{j-1}_{r(k-1,1)}$$

$$t^j_{k+2} = \sum_{i=1}^{N} t^j_{r(k+2)} = T^j_{r(k+2,N)} - T^j_{r(k+2,1)}$$

By using the above notations, we can write (9), (10) in the form of,

$$t^j_k = t^{j-1}_{k-1} + W + \alpha\left(t^{j-1}_{k-1} + W\right) \tag{11}$$

$$t^j_{k+1} = t^j_{k+2} - Q + \alpha\left(t^j_{k+2} - Q\right) \tag{12}$$

where,

$$W = d^j_{x,N} - d^j_{x,1} \tag{13}$$

$$Q = d^j_{y,N} - d^j_{y,1} \tag{14}$$

From the above equations (11-14) the joint density functions can be written by using (15),

$$f_{W,Q}(w,q) = \left(\frac{1}{4\pi\sigma^2}\right)^2 e^{-\frac{1}{4\sigma^2}(w^2+q^2)} \tag{15}$$

The maximum likelihood function will be given by equation (16),

$$L(\hat{\alpha},\sigma^2) = \left(\frac{1}{4\pi\sigma^2}\right)^2 e^{-\frac{1}{4\sigma^2}\left[t^2_{10}(\hat{\alpha}^2-\varpi^2)^2 + t^2_{12}(\hat{\alpha}^2-\chi^2)^2\right]} \tag{16}$$

where $\varpi \triangleq \frac{t^j_{k-1}}{t^j_k}$, $\chi \triangleq \frac{t^j_{k+2}}{t^j_{k+1}}$, $and\,\hat{\beta} \triangleq \frac{1}{1+\alpha}$

By differentiating the log-likelihood function with respect to $\hat{\alpha}$ we get equation (17),

$$\begin{aligned} \frac{\partial lnL(\hat{\alpha},\sigma^2)}{\partial\hat{\alpha}} &= \left(\frac{1}{2\sigma^2}\right)\left[(t^j_k)^2\left(\hat{\alpha}^2 - \varpi^2\right)\right. \\ &\quad \left. + (t^j_{k+2})^2\left(\hat{\alpha}^2 - \varpi^2\right)\right] \end{aligned} \tag{17}$$

based on above calculation, the clock skew can be found by equation (18) as,

$$\hat{\alpha}_j = \frac{(t^j_k)^2 + (t^j_{k+2})^2}{t^{j-1}_{k-1}t^j_k + t^j_{k+1}t^j_{k+2}} + 1 \tag{18}$$

for the i number of massages we can write (2) and (4) as,

$$U_{(i)} = \delta_j + d^j_{x,i} + \alpha_j\left(T^{j-1}_{r(k-1,i)} + \delta_j + d^j_{x,i}\right) + \beta_j \tag{19}$$

$$V_{(i)} = -\delta_j - d^j_{y,i} + \alpha_j\left(T^j_{r(k+2,i)} - \delta_j - d^j_{y,i}\right) + \beta_j \tag{20}$$

where, $U_{(i)} = T^j_{s(k,i)} - T^{j-1}_{s(k-1,i)}$, $V_{(i)} = T^j_{s(k+2,i)} - T^{j+1}_{s(k+1,i)}$ in equation (19-20) and $\hat{\alpha}_j$ will be estimated by using (18). The sets of delay observations $(U_{(i)}, V_{(i)})$ can be recomputed as,

$$U'_{(i)} = U_{(i)} - \alpha_j T^{j-1}_{r(k-1,i)}, = \delta'_j + d'_{x,i} + \beta_j \tag{21}$$

$$V'_{(i)} = V_{(i)} - \alpha_j T^j_{r(k+2,i)}, = -\delta'_j - d'_{y,i} + \beta_j \tag{22}$$

where $d'_{y,i} = (1+\alpha_j)\, d^j_{y,i}$, $d'_{x,i} = (1+\alpha_j)\, d^j_{x,i}$ and $\delta' = (1+\alpha_j)\,\delta_j$ in equation (21-22).

Therefore, the clock offset can be calculated by,

$$\hat{\beta}_j = \frac{\bar{U}'_{(i)} + \bar{V}'_{(i)}}{2} \tag{23}$$

A. CALCULATION OF DELAY IN TIME SYNCHRONIZATION

In the proposed scenario due to the mobility of nodes, there is the instability of propagation delay. Here the nodes move with the fixed relative velocity V. To improve the efficiency of the proposed joint technique and to avoid error accumulation point to point calculation of the propagation delay is applied with the relationship between time information and different time stamp between anchors to sensor nodes and d^j_i is the corresponding propagation delay within a hop j as given by the figure 3. According to [44] the relation for propagation delay can be written by using equation (24) as,

$$d^j_i = \frac{L^j_i}{v_s} \tag{24}$$

$$\Delta d^j_i = \frac{\Delta L^j_i}{v_s} = \frac{L_i - L_{i-1}}{v_s} \tag{25}$$

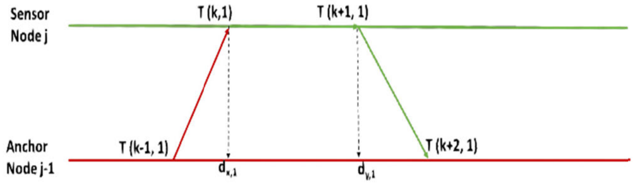

FIGURE 3. Depiction of synchronization delay.

We can expand the equation (25) as,

$$d^j_{y,1} - d^j_{x,1} = \frac{V\left[d^j_{y,1} + \left(T^j_{r(k+1,1)} - d^j_{y,1}\right) - \left(T^{j-1}_{r(k-1,1)} + d^j_{x,1}\right)\right]}{v_s} \tag{26}$$

$$d^j_{y,1} - d^j_{x,1} = \frac{V[\left(T^j_{r(k+1,1)} - T^{j-1}_{r(k-1,1)}\right) - d^j_{x,1}]}{v_s} \tag{27}$$

$$d^j_{y,1} - d^j_{x,1} = \frac{V}{v_s}[\left(T^j_{r(k+1,1)} - T^{j-1}_{r(k-1,1)}\right) - d^j_{x,1}] \tag{28}$$

similarly

$$d^j_{y,2} - d^j_{x,2} = \frac{V}{v_s}\left[\left(T^j_{r(k+1,2)} - T^{j-1}_{r(k-1,2)}\right) - d^j_{x,1}\right] \tag{29}$$

where L_j is the propagation distance from any node *j-1* to *j* at time $T_{k+1,1}$ and j receives the packets at time $T_{k-1,1}$ where v_s is the acoustic propagation velocity underwater in equation (26-29). Here we use $K = \frac{V}{v_s}$, so the above equations can be simplified by considering the equation (28)

$$\begin{aligned} d^j_{y,1} - d^j_{x,1} &= K[\left(T^j_{r(k+1,1)} - T^{j-1}_{r(k-1,1)}\right) - d^j_{x,1}] \\ d^j_{y,1} &= K\left[\left(T^j_{r(k+1,1)} - T^{j-1}_{r(k-1,1)}\right) - d^j_{x,1}\right] + d^j_{x,1} \\ d^j_{y,1} &= K\left(T^j_{r(k+1,1)} - T^{j-1}_{r(k-1,1)}\right) - Kd^j_{x,1} + d^j_{x,1} \\ d^j_{y,1} &= K\left(T^j_{r(k+1,1)} - T^{j-1}_{r(k-1,1)}\right) + d^j_{x,1}(1-k)(30) \end{aligned}$$

The delay for 2^{nd} set of massages can be calculated according to [44].

$$d^j_{x,2} = \frac{K}{1-K}\left(T^j_{s(k+1,2)} - T^{j-1}_{s(k-1,1)}\right) + d^j_{x,1} \tag{31}$$

$$d^j_{y,2} = K\left(T^j_{r(k+1,2)} - T^{j-1}_{r(k-1,1)}\right) + d^j_{x,2}(1-K) \tag{32}$$

Equation (30-32) can estimate the delay at different points by assuming that $0 < K < 0.01$ which is reasonable as the maximum velocity of sensors is 3 m/s in an underwater scenario. The next section will give the localization in multi-hop environment which works simultaneously with the process of time synchronization whenever an anchor node sends a beacon message to sensor nodes. The next section will first compute the range between and anchor and sensor node and then compute the coordinates by using an angle of arrival (AOA).

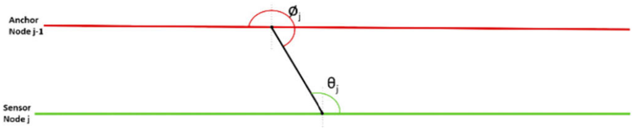

FIGURE 4. Showing the angle of arrival.

V. LOCALIZATION IN MULTI-HOP SCENARIO

It can be seen from figure 4 that each node has a local coordinate system (LCS). When communicating with its neighboring node each node measures the signals bearing i.e. AOA with respect to the local coordinate system. As defined earlier all nodes are equipped with multimodal directional piezoelectric underwater traducers that help in the calculation of the angle of elevation [39]. From figure 4, we can say that reference node 0 is located at (x_1, y_1) and the arbitrary mobile node 1 is needed to be localized by determining its coordinates (x_2, y_2) with known node 0 and the corresponding angle of arrival (AOA) which is measured by node 0 called Ø. Since the depth of sensor node is known therefore for the convenience of description, all coordinates in this study are expressed in a two-dimensional cartesian coordinate system, and (AOA) is considered to be positive if it is counterclockwise and negative otherwise.

When sensor node 1 receives a beacon message from anchor node 0 then during communication, sensor node 1 can extract the following information, whose details are as follows,

"ID1: Identifier of the neighboring sensor node from the incoming message.
2. AoA: anchor's angle of arrival $Ø_j$.
3. ToA: anchor node's time of arrival.
4. Coordinate1: Coordinates of the neighboring anchor node, in LCS due to ToA and measured AoA. Both AOA and location send back to the neighboring anchor in the communication trial. This scenario is given in figure 3.
5. Coordinate2: the coordinates of the sensor node in the LCS of the neighboring anchor node, similar to Coordinate1, this is estimated from the ToA and AoA measurements.
6. ID2: Anchor's ID.

A. RANGE COMPUTATION

The first step of the proposed localization is to estimate the distance between a sensor node (SN) and anchor node (AN) called $D_{j,j+1}$ which can be directly obtained through the TOA approach [61] that is based on the assumption that both AN and SN are time-synchronized and performs the localization by using a single anchor. Since the proposed technique performs synchronization initially, therefore distance estimation will be more accurate. Let T_{arr} is the time of arrival and T_{tra} is the time of transmission and S_{sound} denotes the sound wave speed. The speed of sound waves in seawater depends upon many factors such as water quality, temperature, pressure, and salinity. In actuality, the sound wave speed is taken to be

1500 m/s. The distance is calculated through the following equation (33),

$$D_{j,j+1} = (T_{arr} - T_{tra}) \times S_{sound} \tag{33}$$

B. COORDINATE COMPUTATION

As defined earlier φ^j is the AOA from anchor to sensor which can be estimated through the local coordinate system.

The inclination from anchor to sensor can be obtained from the following relation,

$$\theta^j = \varphi^j - 180 \tag{34}$$

where θ^j is the projected angle between the line from D to C within the first hop in (34) as shown in figure 4. By using θ^j the slope of the line joining the P to A is given by (35),

$$Slope = tan\theta^j = \frac{y_1 - y_2}{x_1 - x_2} \tag{35}$$

As the distance between anchor to the sensor is already known from (33), so we can use the relation,

$$D_{j,j+1} = \sqrt{(x_1 - x_2)^2 + (y_1 - y_2)^2} \tag{36}$$

By solving the above two equations (35-36) we can have the coordinates of the sensor node by following (37-38),

$$x_2 = x_1 - D_{j,j+1}cos\theta^j \tag{37}$$

$$y_2 = y_1 - D_{j,j+1}sin\theta^j \tag{38}$$

The above procedure will be repeating for the next sensor node. A newly localized and synchronized node will now act as a reference node which is further localized and synchronized is nearest sensor nodes by using the above joint technique. These nearest sensor nodes will locate and synchronized themselves by receiving the different rounds of messages from their reference nodes and in this way the above procedure goes on for next-hop as well.

C. STEPS OF LOCALIZATION ALGORITHM

Consider that the network consists of one anchor node different ordinary nodes which are randomly deployed in 3-D space with known depth.

Step 1: Initially anchor node broadcasts a "hello" message to the network. Nodes that receive this message send back and an acknowledgment message that includes sender ID and sending time and other information as described earlier.

Step 2: After the completion of step 1, each nearest node calculates its distance from the anchor-based on TOA as described in section V (A).

Step 3: Because of the distance obtained in step 2 anchor node chooses the nearest node to be the second reference node sends all the distance information to that node.

Step 4: By using the information related to the angle of arrival the slop of line from anchor to sensor will be calculated by using the equation (35).

Step 5: Finally, the coordinates of the sensor node can be computed by using the calculation given in section V(B).

D. PSEUDOCODE OF ALGORITHM

```
Begin
Input: i. Number of messages form sensor nodes
       ii. Number of messages from anchor nodes
       iii. Timestamps of messages
       iv. Initial delay
       v. Anchor node coordinates $(x_1, y_1)$
       vi. Angle of arrival $\O_j$
       vii. Transmission time $T_{trans}$
       viii. Arrival time $T_{arr}$
Output: i. Calculate skew $\hat{\alpha}_j$
        ii. Calculate $\hat{\beta}_j$
        iii. Calculate the coordinate of ordinary
       sensor node $(x_2, y_2)$
REPEAT
    for anchor node do
        Calculates the range by using (33)
        Reply to those sensors which have MIN D.
        Save the N timestamps of minimum delay
      form nearest sensor node
    endfor
    for selected nearest sensor do
        Set Acoustic propagation velocity $v_s$
        Set fixed relative velocity V
        Calculate $d_{y,N}$ by using (30)
    endfor
      for selected nearest sensor node do
        Set time stamps
        Calculate W, Q by using (13) and (14).
        Calculate skew $\hat{\alpha}_j$ and offset $\hat{\beta}_j$ by using
      (18) and (23) respectively.
    endfor
    for selected nearest sensor node do
        Set sound wave speed
        Calculate range by (33)
        Compute $\theta_j$ by using (35)
        Calculate coordinates of sensor node
      $(x_2, y_2)$ by using (37) and (38)
    endfor
    After localization the ordinary sensor node will act
    as a reference node.
UNTIL all ordinary sensor become anchor node
(reference
  END node)
```

VI. PERFORMANCE ANALYSIS OF THE PROPOSED ALGORITHM

This section provides the lower bound with the help of a covariance vector which can be estimated by using an unbiased estimator. We have used the maximum likelihood estimator in the provided technique, and to evaluate the performance of the proposed method, we analyze the Cramer Rao Lower Bound (CRLB) for the proposed ToA based localization and time synchronization algorithm as follows, Supposed we have $r = [r_1^T, r_2^T, r_3^T \ldots .r_n^T]$ is the measurement of time of receiving vector $r_n = [r_{n,0}, r_{n,1}, r_{n,2} \ldots .r_{n,N}]$.

Also, $t = [t_1^T, t_2^T, t_3^T \ldots .t_n^T]$ is the time of transmission vector and $t_n = [t_{n,0}, t_{n,1}, t_{n,2} \ldots .t_{n,N}]$ with zero mean Gaussian distribution $\chi(\Theta)$ along with the variance σ^2. According to the suggested methodology, the joint probability density function of the observation can be written as,

$$\chi_{r,t}\left(r, t/\Theta\right) = \left(\frac{1}{4\pi\sigma^2}\right)^2 \exp\left[-\frac{1}{4}\chi\left(\Theta\right)^T C^{-1}\chi\left(\Theta\right)\right]$$

The covariance vector matrix C will be $\sigma^2 I_{N(k+1)}$ for N(K+1) number of equations. The natural algorithm of $\chi_{r,t}\left(r, t/\Theta\right)$ is,

$$\mathcal{L}\left(\Theta\right) = -\frac{1}{2}[4\pi\sigma^2 + \chi\left(\Theta\right)^T C^{-1}\chi\left(\Theta\right)]$$

The estimation of CRLB is done by using an inverse of Fisherman Information Matrix (FIM) F as follows,

$$[\mathcal{F}]_{m,n} = \left[\frac{\partial L}{\partial \Theta_m}, \frac{\partial L}{\partial \Theta_n}\right]$$

where Θ_m, Θ_n are the m^{th}, n^{th} elements of Θ respectively, for m, n $\leq$5 we can write as,

$$[\mathcal{F}]_{m,n} = \frac{1}{\sigma^2}\frac{\partial\chi\left(\Theta\right)^T}{\partial\Theta_m}.\frac{\partial\chi\left(\Theta\right)}{\partial\Theta_n}$$

For m $\leq$ 5, n = 6 we have,

$$[\mathcal{F}]_{m,6} = \frac{1}{\sigma^2}\frac{\partial\chi^T\left(\Theta\right)}{\partial\Theta_m}E[\frac{\partial\chi^T\left(\Theta\right)}{\partial\alpha}]$$

The last case is n = m = 6 we can write,

$$[\mathcal{F}]_{m,6} = N^2(K+1)^2 + \frac{1}{\sigma^2}E\left\{\frac{\partial\chi^T\left(\Theta\right)}{\partial\alpha}\right\}E\frac{\partial\chi\left(\Theta\right)}{\partial\alpha}$$

We define R_0 as,

$$R_0 \triangleq [\frac{\partial\chi}{\partial x}, \frac{\partial\chi}{\partial y}, \frac{\partial\chi}{\partial\beta}, E\frac{\partial\chi}{\partial\alpha}]$$

And Fisherman information matrix will be,

$$\mathcal{F} = \frac{1}{\sigma^2}(R_0^T R_0 + \begin{bmatrix} 0_{5\times5} & 0_{5\times1} \\ 0_{5\times1} & N^2\left(K+1\right)^2\sigma^2 \end{bmatrix})$$

Given that the estimation results are very close to the actual values, which shows that $\text{cov}\{\Theta\} \approx \mathcal{F}^{-1} \approx R_0^T R_0$ and estimation error of the proposed algorithm is very closed to CRLB.

VII. SIMULATION ANALYSIS

To simulate the underwater environment and acoustic communication all the simulations have been done on MATLAB to evaluate the performance of our proposed joint technique. The simulation environment is 600m×600m×500m, and the propagation speed of the acoustic signals is taken to be 1500m/s. The simulation is based on one single anchor along with different ordinary nodes. The skew of the ordinary nodes is randomly set up to 50 pp where the offset is initially set between (0.0-0.08) s. The random backoff is between (0.0 – 0.1) s. If the synchronization messages fail, it will not be retransmitted, the clock jitter is $15\mu s$, the maximum speed of the sensors is 3 m/s and the waiting time is 5s where the maximum retransmit count is 3 s. For the simulation, we will compare our results with the previously developed localization and time synchronization procedures which were implemented in a multi-hop environment. For performing the simulation, all the values of the above-mentioned parameters are according to the real-world environment. Based on that, we can say that the proposed framework performs equally well in a real laboratory bed environment. Our simulation will show that the performance of our algorithm is better than previously developed multi-hop procedures. Also, we will show that the joint effort of localization and time synchronization in multi-hop is better than the separate procedures of localization and synchronization in multi-hop scenarios.

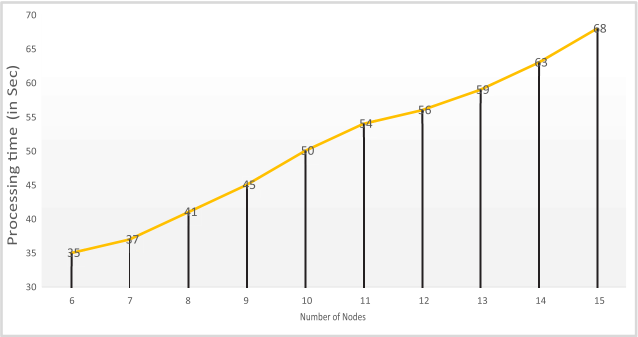

FIGURE 5. Showing the localization right ratio for number of nodes.

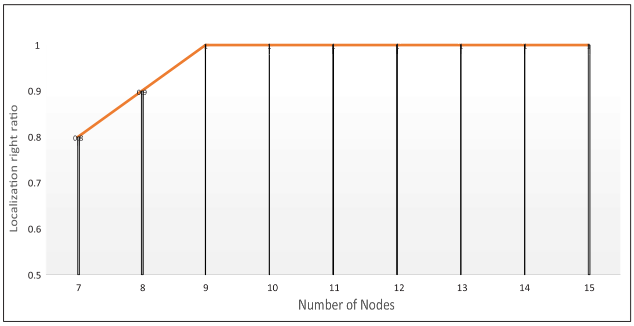

FIGURE 6. Showing processing time to complete the procedure.

First of all, we have done our simulation evaluation on different measurement scales such as (i) localize right ratio: which can be defined as the nodes which successful to get localized versus the total nodes number; (ii) Complete processing time to evaluate the whole network performance. Figure 5 is showing the right localize ratio which is stable and showing good results. Similarly, figure 6 is showing the processing time taken by the whole procedure as the number of nodes is increased and according to figure 6 we can see that our joint technique takes very little time in completing the whole process of localization and time synchronization. Although we were not able to compare these results with other previously developed techniques because these results are not available in the literature for multi-hop.

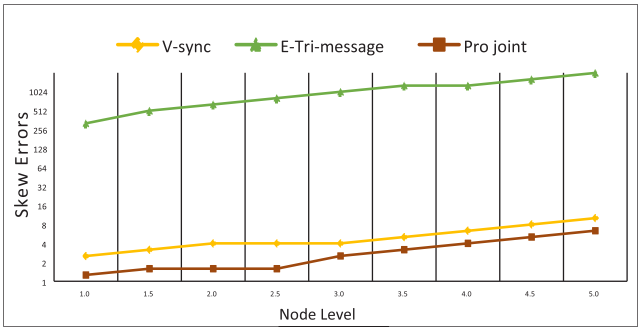

FIGURE 7. Relationship between skew error and the node level.

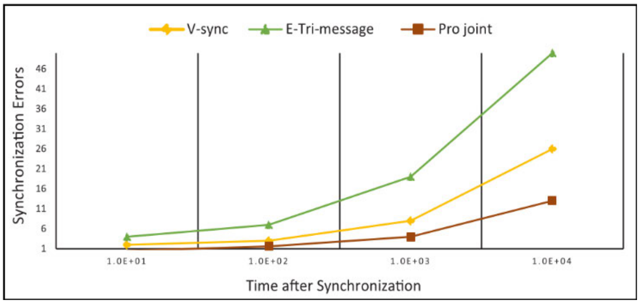

FIGURE 8. Effect of time after sync on synchronization error.

A. COMPARISON OF RESULTS FOR MULTI-HOP TIME SYNCHRONIZATION

In terms of node level effect, we have compared our algorithm with [44] for V-Sync and E-Tri message techniques, these techniques had performed the multi-hope time synchronization for underwater sensor networks.

From figure 7 we can see that the skew error of our proposed algorithm is much better than V-sync and E- Tri message procedure, because E-tri message does not calculate the point to point propagation delay they used the assumption that packet propagation delay is always constant that is why error will be ultimately increased. On the other hand, the error in V-sync is less than the E-tri message but not less than the proposed algorithm. Due to the above simulation, we can say that error of skew is directly affected by the node level.

We also compare the synchronization error with the time elapsed after synchronization. It can be seen from figure 8 that the proposed joint technique possesses very low synchronization error as compare to V-sync and E-Tri message techniques.

Furthermore, we compare our simulation results with other multi-hop synchronization methods like MU-sync and Mul-sync [44]. MU-sync works hop by hop for the synchronization which means the reference node first synchronized the ordinary node within one hop range which later works as a reference node for the synchronization of other ordinary nodes for the next hop after being synchronized and this procedure goes on.

Figure 9 shows the error on simulation time 10^5s after a single iteration of synchronization. According to figure 9, we can see that the average synchronization error for Mul-sync is lower than the MU-sync in the first hop after 10^5s. But the error for the second, third, and fourth hop in the case of Mul-sync is much higher than the MU-sync. Our simulation results for the proposed joint algorithm show very good performance as compared to the other two procedures.

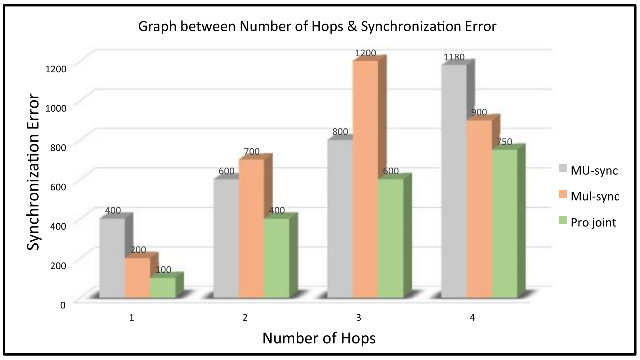

FIGURE 9. Relationship between synchronization error and the number of hops.

B. RESULTS ANALYSIS FOR THE LOCALIZATION IN MULTI-HOP

1) EFFECT OF COMMUNICATION COST

For the localization in multi-hop, we compare our simulation with the algorithms presented in [62]. First, we compare the communication cost for localization with other algorithms that performed the multi-hop localization for UWSNs. It is important to note that the proposed localization technique is based on a single anchor while the other technique like MDS-MAP, DRL, and MSL, is performing the localization with three or four anchors. Single anchor localization consumes less computational cost and it estimates the sensor co-ordinates with the help of launching angle and anchor node co-ordinates with better accuracy [61]. The data size which is measured in bits during transmission for the localization procedure must be limited. Since UWSNs possess low memory and maintain the communication cost is very important while transmitting the data during localization.

Mostly in UWSNs the data transmission is done by using the frame which consists of the two-parts first part is the header of the frame and the second part is the frame body that consists of data that needs to be transmitted.

Sending the hello message during localization calculates the node distance between them. Similarly, range information packets contain all the distance related information of nodes in the network. The communication cost can be computed by using the formula given by (39),

$$Communication\ Cost = (3M - 2)log_2M + 39M - 20\ (bits) \tag{39}$$

where M is the packet length in bytes,

Figure 10 shows the comparison of the communication cost of the proposed joint technique along with the previously developed techniques and from figure 10, it is clear that by the increase of a number of nodes communication cost increases but our proposed joint algorithm performs very

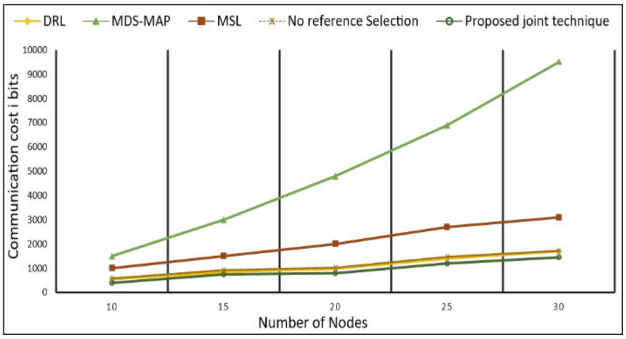

FIGURE 10. Showing the relation between communication cost and number of nodes.

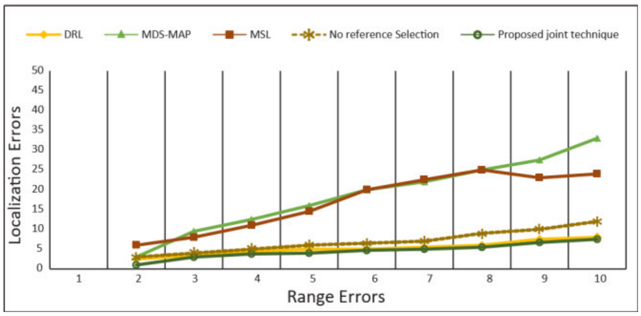

FIGURE 11. Comparison of different algorithm between range error and localization error.

well and shows relatively low increment when the number of node increase. The low consumption of communication cost affects energy consumption, so we can say that our proposed technique can also manage to consume less energy as compared to these compared techniques.

2) EFFECT OF RANGE ERROR

We perform another test to analyze the impact of RMSE (Root mean square error) of different localization techniques on range error. Here, we examine the performance of the proposed technique in the presence of ranging error. Assuming that the ranging errors are Gaussian distributed with zero mean and variance σ^2. Here we suppose that range error with the variance of σ^2 ranging from 1m to 5 m. It can be seen from figure 11 that algorithms like MDS-MAP and MSL showing high localization error as compared to other algorithms. Among all previously developed techniques, DRL shows low localization error but our proposed joint technique showing lower error as compared to the DRL. Also, the proposed algorithm improves the ranging accuracy which directly affects the localization performance.

3) RELATIONSHIP BETWEEN LOCALIZATION ERROR AND NUMBER OF NODES

We have made another comparison to analyze the relationship between the localization error in meters and the number of nodes by fixing the variance σ^2 to be 5 m and increase the number of sensor nodes from 20-180. It is clear from figure 12 that DRL and no optimal reference and proposed joint techniques are less sensitive by the node number which is also mentioned in [62]. Because after the process of localization and time synchronization the ordinary sensor node act as reference nodes which gradually improves the localization error. Whereas, MSL and MDS-MAP improve with the number of nodes because the increase of nodes' number will improve the communication connectivity.

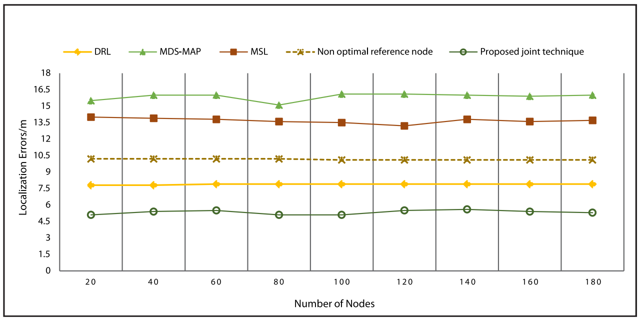

FIGURE 12. Effect of number of nodes on localization error.

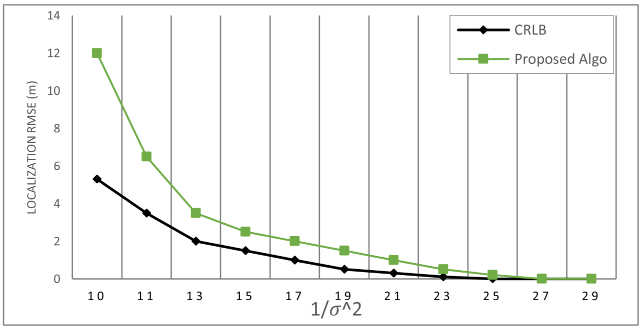

FIGURE 13. RMSE of location estimates vs. $\frac{1}{\sigma^2}$.

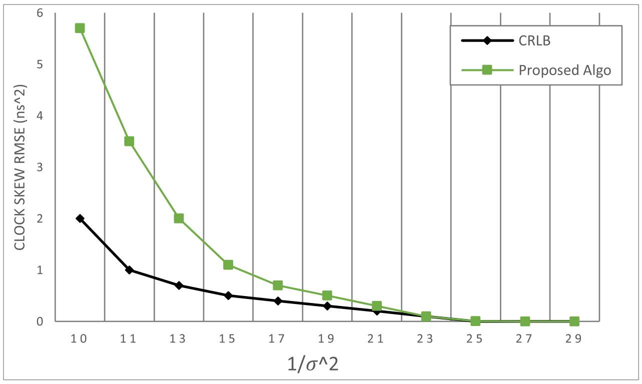

FIGURE 14. RMSE of clock skew estimates vs. $\frac{1}{\sigma^2}$.

4) PERFORMANCE OF THE PROPOSED ALGORITHM WITH CRLB

We have compared the performance of the proposed algorithm with CRLB. We have taken the root mean square error of localization as a function of $\frac{1}{\sigma^2}$ for the proposed method and CRLB. According to figure 13, it is clear that the proposed technique proves to be more accurate in terms of location because its performance falls on the CRLB which is obvious. Similarly, the performance of the proposed algorithm in comparing CRLB with estimation error of the clock parameter as a function of variance is sufficiently accurate according to figure 14 for clock skew and figure 15 for

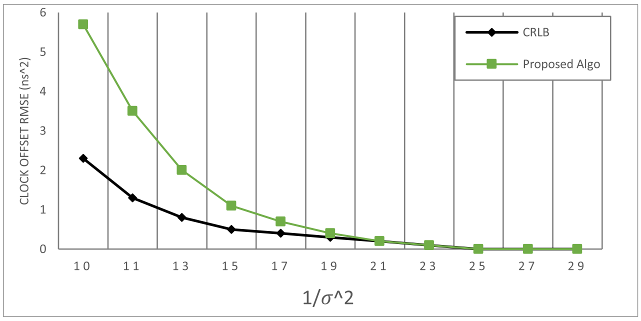

FIGURE 15. RMSE of clock offset estimates vs. $\frac{1}{\sigma^2}$.

clock offset respectively. As both RMSE of clock parameters touches CRLB which shows the accuracy of the proposed technique. So, we conclude that the proposed estimator achieves more accurate synchronization and location.

The above-mentioned results clearly show the superior performance of our proposed joint technique with respect to the literature, as it has the advantages of low processing time, low localizing error, and low synchronization error. Therefore, we can say that this joint technique outperforms as compare to separate efforts that have been done in the past.

VIII. CONCLUSION AND FUTURE WORK

This study has attempted to jointly perform multi-hop localization and time synchronization in UWSNs with the help of a single anchor node. This is the main novelty of this work. We have performed this joint effort up to four hops with good accuracy. The proposed methodology had first performed synchronization than localization and it can be seen from the results that the proposed methodology performs well and consumes less energy as compared to other techniques. Our simulations have been done by considering the different previously developed algorithms such as MDS-MAP, MSL, DRL, and no reference node. For the synchronization procedure, we have compared V-sync and E-Tri message techniques with the proposed joint technique. Through experimental analysis, it has been demonstrated that the use of the proposed framework significantly enhanced the localization and synchronization as compared to the previously developed separate procedures. For the proposed model in the multi-hop scenario, we have used a single anchor procedure to perform this joint technique which gives low computational complexity. By using more than one anchor node the computational cost would be high which directly affects the energy consumption. This technique will gradually produce accuracy in single-hop environment with the increase of the number of reference nodes and give energy efficiency by using one-way message exchange between reference and sensor nodes.

To conclude our effort, the proposed work is a new gateway for the researcher to make the effort in the joint process of localization and time synchronization in the multi-hop scenarios of underwater acoustic sensor networks. In the future, we are planning to perform this procedure by integrating secure communication protocols.

ACKNOWLEDGMENT

The authors would like to thank the anonymous reviewers for their comments that truly helped to make this article fruitful.

REFERENCES

[1] M. Huang, K. Zhang, Z. Zeng, T. Wang, and Y. Liu, "An AUV-assisted data gathering scheme based on clustering and matrix completion for smart ocean," *IEEE Internet Things*, vol. 7, no. 10, pp. 9904–9918, Oct. 2020.

[2] M. R. Brust, M. İ. Akbaş, and D. Turgut, "Multi-hop localization system for environmental monitoring in wireless sensor and actor networks," *Concurrency Comput., Pract. Exper.*, vol. 25, no. 5, pp. 701–717, Apr. 2013.

[3] H. Teng, K. Ota, A. Liu, T. Wang, and S. Zhang, "Vehicles joint UAVs to acquire and analyze data for topology discovery in large-scale IoT systems," *Peer Peer Netw. Appl.*, vol. 13, no. 5, pp. 1–24, 2020.

[4] Y. Hou, X. Yang, and Q. H. Abbasi, "Efficient AoA-based wireless indoor localization for hospital outpatients using mobile devices," *Sensors*, vol. 18, no. 11, pp. 1–17, 2018.

[5] D. Zhang, Y. Yuan, and Y. Bi, "A design of a time synchronization protocol based on dynamic route and forwarding certification," *Sensors*, vol. 20, no. 18, p. 5061, 2020.

[6] S. Liu, G. Huang, J. Gui, T. Wang, and X. Li, "Energy-aware MAC protocol for data differentiated services in sensor-cloud computing," *J. Cloud Comput.*, vol. 9, no. 1, pp. 1–31, Dec. 2020.

[7] K. F. Haque, K. H. Kabir, and A. Abdelgawad, "Advancement of routing protocols and applications of underwater wireless sensor network (UWSN)—A survey," *J. Sensors Actuator Netw.*, vol. 9, no. 2, pp. 1–31, 2020.

[8] K. M. Awan, P. A. Shah, K. Iqbal, S. Gillani, W. Ahmad, and Y. Nam, "Underwater wireless sensor networks: A review of recent issues and challenges," *Wireless Commun. Mobile Comput.*, vol. 2019, pp. 1–21, 2019.

[9] J. Luo, L. Fan, S. Wu, and X. Yan, "Research on localization algorithms based on acoustic communication for underwater sensor networks," *Sensors*, vol. 18, pp. 1–25, Jan. 2018.

[10] C. B. Anil and V. S. M. Joshi, "A survey on various time synchronization techniques underwater sensor networks," *Int. J. Comput. Eng. Technol.*, vol. 15, no. 12, pp. 116–122, 2014.

[11] C. Xiuzhen, S. Haining, L. Qilian, and H. D. Du, "Silent positioning in underwater acoustic sensor networks," *IEEE Trans. Veh. Technol.*, vol. 57, no. 3, pp. 1756–1766, May 2008.

[12] P. Carroll, S. Zhou, H. Zhou, X. Xu, J. H. Cui, and P. Willett, "Underwater localization and tracking of physical systems," *J. Elect. Comput. Eng.*, vol. 31, pp. 1–11, May 2012.

[13] S. Jiang, J. Fan, X. Xia, X. Li, and R. Zhang, "An effective Kalman filter-based method for groundwater pollution source identification and plume morphology characterization," *Water*, vol. 10, p. 1063, Aug. 2018.

[14] Z. Zhang, X. Guo, and Y. Lin, "Trust management method of D2D communication based on RF fingerprint identification," *IEEE Access*, vol. 6, pp. 66082–66087, 2018.

[15] S. Wang, Y. Lin, H. Tao, P. K. Sharma, and J. Wang, "Underwater acoustic sensor networks node localization based on compressive sensing in water hydrology," *Sensors*, vol. 19, no. 20, pp. 1–14, 2019.

[16] C. Liu, X. Wang, H. Luo, Y. Liu, and Z. Guo, "VA: Virtual node assisted localization algorithm for underwater acoustic sensor networks," *IEEE Access*, vol. 7, pp. 86717–86729, 2019.

[17] K. Yu, K. Hao, C. Li, X. Du, B. Wang, and Y. Liu, "An improved TDoA localization algorithm based on AUV for underwater acoustic sensor networks," in *Proc. Artif. Intell. Commun. Netw. (AICON)*, Harbin, China, May 2019, pp. 419–434.

[18] Y. Lin, H. Tao, Y. Tu, and T. Liu, "A node self-localization algorithm with a mobile anchor node in underwater acoustic sensor networks," *IEEE Access*, vol. 7, pp. 43773–43780, 2019.

[19] C. G. Priya and P. Shobana, "Time synchronization in mobile underwater sensor network," *Adv. Natural Appl. Sci.*, vol. 8, no. 19, pp. 58–64, Nov. 2014.

[20] Z. Li, Z. Guo, F. Hong, and L. Hong, "E2DTS: An energy efficiency distributed time synchronization algorithm for underwater acoustic mobile sensor networks," *Ad Hoc Netw.*, vol. 11, no. 4, pp. 1372–1380, Jun. 2013.

[21] F. Lu, D. Mirza, and C. Schurgers, "D-sync: Doppler-based time synchronization for mobile underwater sensor networks," in *Proc. WuWNet*, Woods Hole, MA, USA, 2010, Art. no. 3.

[22] Z. Jin, M. Ding, Y. Luo, and S. Li, "Integrated time synchronization and multiple access protocol for underwater acoustic sensor networks," *IEEE Access*, vol. 7, pp. 101844–101854, 2019.

[23] F. Zhou, "Q. Wang, G. Han, G. Qiao, Z. Sun, and A. Niaz, "APE-Sync: An adaptive power efficient time synchronization for mobile underwater sensor networks," *IEEE Access*, vol. 7, pp. 52379–52389, 2019.

[24] Y. Su, R. Fan, Z. Jin, and X. Fu, "Design of an OFDMA-based MAC protocol for an underwater glider network with motion prediction," *IEEE Access*, vol. 6, pp. 62655–62663, 2018.

[25] F. Zhou, Q. Wang, D. Nie, and G. Qiao, "DE-sync: A Doppler-enhanced time synchronization for mobile underwater sensor networks," *Sensor*, vol. 18, no. 6, pp. 1710–1724, Jun. 2018.

[26] N. Saeed, A. Celik, T. Y. Al-Naffouri, and M.-S. Alouini, "Localization of energy harvesting empowered underwater optical wireless sensor networks," *IEEE Trans. Wireless Commun.*, vol. 18, no. 5, pp. 2652–2663, May 2019.

[27] N. Saeed, A. Celik, T. Y. Al-Naffouri, and M.-S. Alouini, "Underwater optical sensor networks localization with limited connectivity," in *Proc. IEEE Int. Conf. Acoust., Speech Signal Process. (ICASSP)*, Apr. 2018, pp. 3804–3808.

[28] N. Saeed, A. Celik, T. Y. Al-Naffouri, and M. S. Alouini, "Energy harvesting hybrid acoustic-optical underwater wireless sensor networks localization," *Sensors*, vol. 18, no. 1, p. 51, 2017.

[29] F. Akhoundi, A. Minoofar, and J. A. Salehi, "Underwater positioning system based on cellular underwater wireless optical CDMA networks," in *Proc. 26th Wireless Opt. Commun. Conf. (WOCC)*, Apr. 2017, pp. 1–3.

[30] N. Saeed, A. Celik, T. Y. Al-Naffouri, and M.-S. Alouini, "Energy harvesting hybrid acoustic-optical underwater wireless sensor networks localization," *Sensors*, vol. 18, no. 1, pp. 1–25, Jan. 2018.

[31] B. Zhang, H. Wang, L. Zheng, J. Wu, and Z. Zhuang, "Joint synchronization and localization for underwater sensor networks considering stratification effect," *IEEE Access*, vol. 5, pp. 26932–26943, 2017.

[32] Z. Gong, C. Li, and F. Jiang, "AUV-aided joint localization and time synchronization for underwater acoustic sensor networks," *IEEE Signal Process. Lett.*, vol. 25, no. 4, pp. 477–481, Apr. 2018.

[33] J. Liu, Z. Wang, J.-H. Cui, S. Zhou, and B. Yang, "A joint time synchronization and localization design for mobile underwater sensor networks," *IEEE Trans. Mobile Comput.*, vol. 15, no. 3, pp. 530–543, Mar. 2016.

[34] E. Mortazavi, R. Javidan, M. J. Dehghani, and V. Kavoosi, "A robust method for underwater wireless sensor joint localization and synchronization," *Ocean Eng.*, vol. 137, pp. 276–286, Jun. 2017.

[35] N. D. H. Will and J. Schiller, "Distance-based distributed multihop localization in mobile wireless sensor networks," in *Proc. 8th GI/ITG KuVS Fachgesprch Drahtlose Sensornetze (FGSN)*, 2009, p. 34.

[36] Z. Zhu, W. Guan, L. Liu, S. Li, S. Kong, and Y. Yan, "A multi-hop localization algorithm in underwater wireless sensor networks," in *Proc. 6th Int. Conf. Wireless Commun. Signal Process. (WCSP)*, Oct. 2014, pp. 1–6.

[37] L. Liu, J. Wu, and Z. Zhu, "Multihops fitting approach for node localization in underwater wireless sensor networks," *Int. J. Distrib. Sensor Netw.*, vol. 11, no. 7, Jul. 2015, Art. no. 682182.

[38] D. Niculescu and B. Nath, "Ad hoc positioning system (APS)," in *Proc. IEEE Global Telecommun. Conf. (GLOBECOM)*, vol. 5, Nov. 2001, pp. 2926–2931.

[39] H. Huang and Y. R. Zheng, "Node localization with AoA assistance in multi-hop underwater sensor networks," *Ad Hoc Netw.*, vol. 78, pp. 32–41, Sep. 2018.

[40] Z. Zhou, J. H. Cui, and S. Zhou, "Efficient localization for large-scale underwater sensor networks," Ad Hoc. Netw. vol. 8, no. 3, pp. 267-279, 2010, doi: 10.1016/j.adhoc.2009.08.005.

[41] M. Erol, L. F. M. Vieira, and M. Gerla, "AUV-aided localization for underwater sensor networks," in *Proc. Int. Conf. Wireless Algorithms, Syst. Appl. (WASA)*, Chicago, IL, USA, Aug. 2007, pp. 44–54.

[42] L. Liu, Q. Liu, and J. Wu, "An AUVs-aided localization scheme for underwater wireless sensor networks," *J. Comput. Inf. Syst.*, vol. 9, no. 19, pp. 7711–7718, 2013.

[43] N. Saeed, A. Celik, T. Y. Al-Naffouri, and M.-S. Alouini, "Performance analysis of connectivity and localization in multi-hop underwater optical wireless sensor networks," *IEEE Trans. Mobile Comput.*, vol. 18, no. 11, pp. 1233–1536, Nov. 2018.

[44] S. L. Sun, "V-sync: A velocity-based time synchronization for multi-hop underwater mobile sensor networks," *Fuzzy Syst. Data Mining II*, vol. 293, pp. 420–428, Nov. 2016.

[45] F. Hong, B. Yang, Y. Zhang, M. Xu, Y. Feng, and Z. Guo, "Time synchronization for underwater sensor networks based on multi-source beacon fusion," in *Proc. 20th IEEE Int. Conf. Parallel Distrib. Syst. (ICPADS)*, Dec. 2014, pp. 218–224.

[46] C. Sun, F. Yang, L. Ding, L. Qian, and C. Zhi, "Modeling and simulation of multi-hop time synchronization for underwater acoustic networks based on OPNET," in *Advances on Digital Television and Wireless Multimedia Communications*. Berlin, Germany: Springer, 2012, pp. 347–354.

[47] S. Ganeriwal, R. Kumar, and M. B. Srivastava, "Timing-sync protocol for sensor networks," in *Proc. 1st Int. Conf. Embedded Netw. Sensor Syst. (SenSys)*, 2003, pp. 138–149.

[48] J. van Greunen and J. Rabaey, "Lightweight time synchronization for sensor networks," in *Proc. 2nd ACM Int. Conf. Wireless sensor Netw. Appl. (WSNA)*, 2003, pp. 11–19.

[49] N. Chirdchoo, W. Soh, and K. Chu, "MU-Sync: A time synchronization protocol for underwater mobile networks," in *Proc. WUWNet*, 2008, pp. 35–42.

[50] J. Liu, Z. Zhou, Z. Peng, J. H. Cui, M. Zuba, and L. Fiondella, "Mobi-sync: Efficient time synchronization for mobile underwater sensor networks," *IEEE Trans. Parallel Distrib. Syst.*, vol. 24, no. 2, pp. 406–416, Feb. 2013.

[51] Z. Li, Z. Guo, F. Hong, and L. Hong, "E2DTS: An energy efficiency distributed time synchronization algorithm for underwater acoustic mobile sensor networks," *Ad Hoc Netw.*, vol. 11, no. 4, pp. 1372–1380, Jun. 2011.

[52] F. Lu, D. Mirza, and C. Schurgers, "D-Sync: Doppler-based time synchronization for mobile underwater sensor networks," in *Proc. WUWNet*, 2010, pp. 1–8.

[53] J. Liu, Z. Wang, Z. Peng, M. Zuba, J.-H. Cui, and S. Zhou, "TSMU: A time synchronization scheme for mobile underwater sensor networks," in *Proc. IEEE Global Telecommun. Conf. (GLOBECOM)*, Dec. 2011, pp. 1–6.

[54] A. A. Syed and J. Heidemann, "Time synchronization for high latency acoustic networks," in *Proc. IEEE 25th Int. Conf. Comput. Commun. (INFOCOM)*, Apr. 2006, pp. 1–12.

[55] C. Tian, H. Jiang, X. Liu, X. Wang, W. Liu, and Y. Wang, "Tri-message: A lightweight time synchronization protocol for high latency and resource-constrained networks," in *Proc. IEEE Int. Conf. Commun.*, Jun. 2009, pp. 1–5.

[56] C. Sun, F. Yang, L. Ding, L. Qian, and C. Zhi, "Multi-hop time synchronization for underwater acoustic networks," in *Proc. Oceans*, 2013, vol. 1, no. 7, pp. 14–19.

[57] S. C. Dhongdi, K. R. Anupama, R. H. Sant, and L. J. Gudino, "Implementation of multi-hop time synchronization on miniature test-bed setup of underwater acoustic sensor network," in *Proc. IEEE Digit. Library, Nat. Conf. Commun.*, 2014, pp. 1–6.

[58] H. Li, Z. D. Deng, Y. Yuan, and T. J. Carlson, "Design parameters of a miniaturized piezoelectric underwater acoustic transmitter," *Sensors*, vol. 12, no. 7, pp. 9098–9109, Jul. 2012.

[59] S. E. Freeman, L. Emokpae, M. Nicholas, and G. F. Edelmann, "A highly directional transducer for multipath mitigation in high-frequency underwater acoustic communications," *J. Acoust. Soc. Amer.*, vol. 138, no. 2, pp. 1–5, 2015.

[60] M. Shevtsova, A. Nasedkin, S. Shevtsov, I. Zhilyaev, and S. Chang, "Conference: 23rd international congress on sound & vibration at: Athens," in *Proc. Greece*, 2016, pp. 1–8.

[61] A. P. Das and S. M. Thampi, "Single anchor node based localization in mobile underwater wireless sensor networks," in *Proc. Int. Conf. Algorithms Archit. Parallel Process.*, in Lecture Notes in Computer Science, vol. 9532, G. Wang, Ed. Cham, Switzerland: Springer, 2015, pp. 757–770.

[62] J. Gao, X. Shen, R. Zhao, H. Mei, and H. Wang, "A double rate localization algorithm with one anchor for multi-hop underwater acoustic networks," *Sensors*, vol. 17, no. 984, pp. 1–18, 2017.

REHAN SHAMS received the M.S. degree from the University of Plymouth, U.K. He is currently pursuing the Ph.D. degree with the Department of Electronics Engineering, Sir Syed University of Engineering and Technology, Karachi, Pakistan. This research work is the contribution for his Ph.D. thesis. He is also a Ph.D. scholar working as an Assistant Professor with the Department of Telecommunication Engineering, Sir Syed University of Engineering and Technology. His fields of interests are underwater sensor networks, cryptography, network security, and wireless sensors networks.

PABLO OTERO (Member, IEEE) received the M.Sc. degree in telecommunications engineering from the Polytechnic University of Madrid, Spain, in 1983, and the Ph.D. degree from the Swiss Federal Institute of Technology (EPFL), Lausanne, Switzerland, in 1998. From 1983 to 1993, he was with Spanish companies, i.e., Standard Eléctrica, E. N. Bazán, and Telefónica, where he was involved in communications and naval radar systems engineering. In 1993, he joined the University of Seville, Spain, where he was a Lecturer for two years. In 1996, he joined the Laboratory of Electromagnetism and Acoustics, EPFL, where he was a Research Associate, working under a Spanish Government Grant. In 1998, he joined the University of Malaga, Spain, where he is currently an Associate Professor and the Director of the Institute of Oceanic Engineering Research. His research interests include communications and wireless systems in oceanic engineering. He received the Best Doctoral Thesis Award from the Spanish National Association of Telecommunication Engineers in 1999.

MUHAMMAD AAMIR received the B.S. degree in electronics engineering, in 1998, the M.S. degree in electronic engineering (with a specialization in telecommunication), in 2002, and the Ph.D. degree in electronic engineering from the Mehran University of Engineering and Technology. During his Ph.D. studies, he has accomplished his research work at the University of Malaga under the Erasmus Mundus Scholarship. He is currently associated with Sir Syed University of Engineering and Technology as the Chairman of the Department of Telecommunication Engineering. He has authored and coauthored more than 50 research papers and book chapters published in various journals, books, and conferences of international repute. He is a Life Member of the Pakistan Engineering Council and a professional member of the IEEE for the last 12 Years. He was also awarded with a grant by the Ministry of Education Spain to teach at the University of Malaga, which he availed in May. He is also a member of NCRC in the Higher Education Commission (HEC) for revision of Electronic Engineering Curriculum and Telecommunication Engineering Curriculum at the National Level. He is also an HEC approved supervisor for Ph.D. candidates. He is a member of the Steering Committee of the CENTRAL project, which is supported by the EU. He is a Guest Editor for the special issue of Springer's Journal "*Wireless Personal Communication*," which was published in May 2015.

FOZIA HANIF KHAN received the Ph.D. degree in the field of operations research from the University of Karachi, Karachi, Pakistan, in 2012. She held a postdoctoral position with the University of Malaga, Spain, in September 2019. She is currently working as an Assistant Professor with the Department of Mathematics, University of Karachi. Her fields of interests are cryptography, graph theory, optimization network security, wireless sensors networks, and underwater sensor networks.

• • •