Self-Organized ad hoc Mobile (SOAM) Underwater Sensor Networks

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***Abstract*— The need of underwater wireless sensor networks having mobile sensor nodes has been there for a long time in form of underwater warfare or explorations by Autonomous Unmanned Vehicles (AUVs) or Remote Unmanned Vehicles (ROVs). There are very few protocols for ad hoc mobile underwater wireless sensor networks (AMUWSN). Designing a protocol for AMUWSN is quite challenging because of continuous random movement of the sensor nodes. In addition to random movement, the challenges to design a routing protocol for AMUWSN are more demanding than terrestrial ad hoc networks due to acoustic communications which has large propagation delay in water. In this paper, we present a Self-Organized ad hoc Mobile (SOAM) routing protocol for AMUWSN. The sensor nodes may need to communicate with each other to the gateway (GW). The protocol, which we also refer to as SOAM, is a reactive, self-configuring, and self-organizing cluster-based routing protocol that uses received signal strength (RSS) for distance estimation. A beacon (BCN) packet will be sent by the gateway (GW) which will traverse through all the Cluster Heads (CHs) to form forwarding paths between the GW and the CHs. The Ordinary Sensor Nodes (OSNs) will select the CHs every time they intend to forward a packet based on the BCN they will receive from CHs. The formation of the forwarding path between the GW and the CHs and the selection CHs by OSN is explained in section IV of this paper.**

***Index Terms*—ad hoc, location free, proactive, routing protocol, self-configured, self-organized, underwater sensor networks, UWSN**

I. Introduction

The wireless underwater communication uses acoustic waves instead of electromagnetic waves because electromagnetic waves have very high absorption rate in water and cannot travel more than few meters. However, there is a significant difference between acoustic waves and electromagnetic waves in terms of propagation speed. The propagation speed of just 1500 m/s compared to electromagnetic waves which have propagation speed of 3x108 m/s. The low propagation speed of acoustic waves causes a significant delay in packet transmission between the nodes and make the protocols designed for terrestrial wireless sensor networks (TWSN) unapplicable for underwater wireless sensor networks (UWSN). The propagation speed is not the only issue for acoustic waves underwater. The variable speed of the propagation waves makes the implementation of time synchronization schemes difficult in UWSNs. The routing protocols for UWSN also have different issues than terrestrial wireless sensor networks (TWSN) because of acoustic transmission medium. The routing protocols which require timestamping based on propagation delay, like EOAR [1], are difficult to implement. There are many TWSN routing protocols which use the location of the node to select the next packet forwarding node. However, determining the location of a node in UWSN is also challenging because the nodes cannot use the facility of global navigation satellite system (GNSS) directly as they do in TWSN. Although, there are localization protocols for UWSN, but most of them are based on time synchronization. In short it is better to have UWSN routing protocols which do not need time synchronization or location information.

There are many routing protocols for UWSN where the nodes are either fixed or anchored to the bottom of the sea. These UWSNs are used to sense data in a predefined area like environmental monitoring of plume or surveillance of marine structures. However, UWSN are also needed for applications where the sensor nodes are mobiles. Ad hoc mobile underwater wireless sensor networks (AMUWSN) have applications like mobile marine surveillance and marine explorations. The mobile nodes may be the divers, Autonomous Unmanned Vehicles (AUV) or Remote Unmanned Vehicles (ROV). The randomly moving mobile nodes need to communicate with each other, either to forward each other's data or exchange the information, such as the divers need to communicate with each other. The mobile nodes may also need to send the data to some station on the sea surface or on shore data gathering station. The continuous movement of the nodes makes the communication and routing of the data packets very challenging. Any of the existing UWSN routing protocols may not work for AMUWSN,

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because they are designed for fixed topology networks. The routing protocols may be proactive and reactive. However, due to the continuous random movement of the nodes, the routing protocol must be reactive. A typical AMUWSN is shown in Fig. 1.

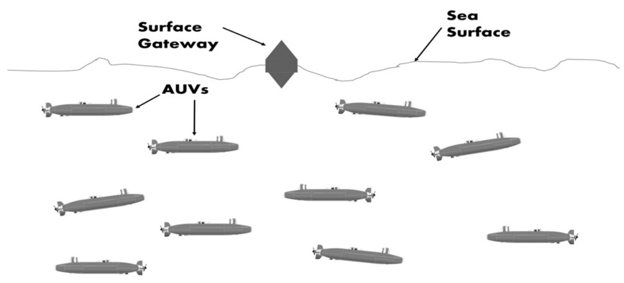

Fig. 1. Typical architecture of AMUWSN for quasi-randomly moving Autonomous Underwater Vehicles (AUV).

We can summarize our paper contribution as follows:

- We have proposed a self-organized cluster-based routing protocol for AMUWSN and compared its performance with P-AUV [2] in terms of end-to-end delay and packet delivery ratio. The comparison shows that PDR of SOAM is better than P-AUV [2].
- SOAM is a location free protocol. The clusters are formed with the help of received signal strength.
- The AUVs form the clusters to save the energy using received signal strength to select the nearest cluster head. If the RRS values are the same between the contending cluster heads, then cluster head having the minimum number of hops will be chosen. Even if the number of hops is the same then the cluster head having maximum remaining energy will be chosen.
- The cluster nodes forward the data packets to their respective cluster heads which forward the packets to the gateway.

The rest sections of the paper are organized as: In section II, the existing UWSN routing protocols are categorized and reviewed and comparison with our work is presented. In section III we have presented the mathematical equations of path loss model, received signal strength and energy consumption of nodes to transmit and receive a packet. In section IV we have described the working model of the proposed protocol. In section V we have explained the routing path formation, cluster formation and packet forwarding mechanism. In section VI we have described the simulation parameters, simulated results, and comparison with P-AUV [2]. In section VII we have presented the concluding remarks.

II. Related Work

Let's briefly review the existing routing protocols for UWSNs. The routing protocols have been categorized as cluster-based, AUV-based, opportunistic, reliability-based, self-organizing, and time-synchronization-based protocols.

The use of AUVs is nowadays expanding in variety of applications (e.g., gathering data in pollution detection [3]), performing roles as agents of data transport in UWSNs [4] or in Internet or Underwater Things (IoUT) networks [5], or acting as smart mobile nodes under control of recently developed intelligent algorithms (e.g., artificial learning [6] and cooperative behavior [7]). The Autonomous Ocean Sampling Network (AOSN) [8] is a US project to predict the physical conditions of the ocean like temperature, salinity and current. It uses AUVs to collect the samples and send to the onshore data collection center.

In order to transfer the data from fixed nodes or mobile nodes (AUVs) to their destiny (e.g., a sink or gateway node) on time [5] in a reliable manner [8], one of the main problems to address is to choose a reliable and efficient path given by the routing process. Among the recent alternatives of routing protocols for UWSNs [9] the use of AUVs to transport the data is a well-accepted idea [10].

A. Cluster-based Protocols

First, we review the cluster-based protocols. One of the cluster-based routing protocols considered, is the Distributed Underwater Clustering Scheme (DUCS) [11], which is also a self-organizing protocol. The nodes form the clusters by one of the nodes assume the role of cluster head (CH). These CHs aggregate data received from single-hop cluster nodes and send it to the sink using multihop routing via other CHs. It is assumed that within a cluster the nodes are close to each other and may send the correlated data to the CH. Therefore, a CH filters out the redundant data from the cluster nodes and sends only non-redundant data to the sink. The filtering of redundant data helps to save the energy of the CH. A node is assigned as CH on the basis of the maximum battery capacity and the current battery level. The nodes inside a cluster bind to the nearest CH which requires them to measure their distance with all the CHs. This distance is calculated by the Time of Arrival (ToA). Another function of the CH is to control the communication among the cluster nodes and with the other CHs. The cluster head assign the time slot to each cluster node based on Time Division Multiple Access (TDMA) where the time slots are assigned using Code Division Multiple Access (CDMA). CDMA is also the modulation used by the clusters to send data to the sink. Nodes in a cluster keep rotating the role of cluster head among themselves to conserve energy.

SD-UASN [12] is a software-defined protocol to make the clustering process fast. It is based on Birch algorithm which is a clustering algorithm for the unsupervised machine learning tasks. The sensors send data to the cluster heads and the AUVs collect data from the cluster heads. The gateway is equipped with Software Defined Network (SDN) technique-based controller. To improve the scalability of the network the architecture is divided into three functional layers: data layer, control layer and application layer. The results show that SD-UASN is more efficient in data collection.

DECKS [13] is a routing protocol based on the k-means clustering scheme. AUVs are used to collect the data from static sensor nodes. Once the clusters have been formed with the help of the k-means clustering algorithm, the cluster heads are selected. This selection is based on the nodes' residual energy and their location within the cluster.

WGBP [14] is a cluster-based 3D network for a fish farm composed of 6 cages. It defines three types of nodes called Regular Sensor (RS) nodes, Border Sensor (BS) nodes and Sink Sensor (SS) nodes. RS nodes sense the sedimentation of the cage, BS works as a sensor node as well as cluster head and SS collects the data from all the nodes and send to the data collection center. The farthest node in a group is selected as a BS node. RS sends data to BS which is eventually forwarded to SS.

CKP [15] is a cluster-based security protocol for a AUV based UWSN. The CHs are deployed at fixed locations for optimal network coverage. Three types of security keys are used in CKP namely: network key, group key, pair-wise key. The network key is shared by all the nodes and used to encrypt messages broadcast by the Base Station (BS). The group key is used to encrypt multicast messages from CHs. The sensor node encrypt their data with pair-wise key before sending to CH.

MLCEE [16] focuses on energy conservation by layering and clustering the network nodes. A node can be a cluster head (H) or member node (H'). Bayesian probability is applied for CH selection. The probability for a node to be a CH is calculated based on remaining energy, energy consumption rate, and link quality. Time Division Multiple Access (TDMA) is used to forward the data from H' to H.

B. AUV-based Protocols

The protocol HAMA [17] is an AUV based protocol which uses multiple AUVs to provide high availability of data collection. The nodes away from the AUV trajectory send data to the nodes close to the trajectory, which eventually forward the packet to AUVs when they pass by them. The nodes closer to the AUV path consume their energy faster than the other nodes, since they not only have to send their data, but also have to retransmit the data of the other nodes. It is also possible that the AUV goes down because of some malfunction. HAMA avoids this problem using multiple AUVs, changing trajectories and spreading the AUV failure intimation throughout the network. The nodes determine their location to use it with AUV's trajectory path to determine whether they have sufficient time to send packets to the moving AUV. However, it is not described that how the nodes will determine their location. The nodes can predict the location of the AUVs because of their predefined path.

The technique P-AUV [2] is a routing and a medium access control (MAC) protocol. The sensor nodes are deployed as AUVs by a ship or a submarine. It is assumed that the AUVs are aware of their position at the time of deployment. AUVs track and update their position and mission path using Inertial Measurement Unit (IMU) and Doppler Velocity Log (DVL). IMU is an electronic device, consisting of an accelerometer and a gyroscope, which measures axial acceleration and rate of rotation. DVL is used to estimate the velocity of an object relative to the sea bottom. DVL transmits acoustic beams in three different directions. Due to the movement of the object, the apparent shift in the frequency is used to measure the velocity of the object. Routing path depends on the self-location estimation of a node.

The objective of DGP-AUVP [18] is to minimize the energy consumption of the AUVs that are used to gather data from the nodes. The energy consumption is reduced by using the lawn mower pattern path (ELMPP) algorithm to optimize the moving path of the AUVs. The AUVs gather data from the static nodes at the bottom of the sea.

C. Opportunistic Protocols

Opportunistic Power Controlled Routing (OPCR) [19] is an opportunistic protocol for Internet of Things (IoTs). It is based on link quality, nodes density, distance, packet advancement and energy consumption. Opportunistic routing and variable transmission power control mechanism work together to reduce the energy waste. The concept of OPCR is very simple. The forwarding node reduces the transmission power where the node has high neighborhood density, if the link quality between the neighbor nodes and the forwarding nodes is good enough to deliver the data reliably. Hence, a transmitter node must have the information of the neighboring nodes. A beacon packet is used to discover the neighbor nodes. To determine which neighbor nodes can forward the packet towards the gateways, the location of the nodes need to be known. OPCR does not define any localization method itself and recommends using any localization protocol proposed for UWSNs.

UWOR [20] is an opportunistic routing protocol having the objective to maximize the goodput, which is the ratio of packets received before a preset deadline. Any packet which fails to meet its deadline is dropped. The nodes having the highest priority are selected as the forwarder nodes. The priority of the nodes is set based on their propagation and end-to-end delay.

D. Reliability-based Protocols

CELR [21] aims to have a reliable routing protocol with energy conservation. Connectivity-aware layering is implemented to avoid the void areas. The nodes have a layer-ID in addition to node ID which indicates the number of hops a node is away from the gateway. The gateway layer-ID is 0. The gateway generates a hello packet with it layer-ID 0. When a node receives a hello packet for the first time it adds 1 in the layer-ID of the sender node and adopts it as its layer-ID. The data packets are sent to the gateway from nodes having large layer-IDs to small layer-IDs.

DNCUDC [22] is an ARQ-based protocol where the gateway requests the nodes to send the packet. When the gateway sends the request, it tells the node how long it should wait to send the data. The gateway sends retransmission requests to the nodes from which the received data was not successfully decoded. This method makes the protocol unsuitable for time-critical applications. The protocol incorporates a sleep and wake mechanism for the sensor nodes. To enhance the performance Selective Relay Cooperation (SRC) and Dynamic Network Coded Cooperation (DNC) protocols are implemented. In SRC the retransmission of the data can be from the node which failed to send the data successfully or from any other node which has got a copy of that data. DNC is like SRC, but a node sends a coded packet that combines the unsuccessful data from the other nodes as well.

E. Self-organizing Protocols

Other protocol, in this case thought for radial topology, is SOFRP [23] a location free, self-organizing, cross-layered protocol. It is a proactive protocol to minimize the routing delay. Before data transmission begins, the routing path for all the nodes to send data to the gateway is formed. The routing paths formation is initiated by the gateway. The nodes find their neighbors and the network topology by using the messages only. The messages are sent at randomly selected timeslots to avoid collision. The routes are formed in such a way that the only the nodes in a straight line (called string) forward the packets. To make the protocol robust the routing path can be changed if a node goes down. The nodes forward the data packets use string identification (ID) in the header of each packet. Since the forwarding node does not need to match the source ID or change the destination ID, the packet forwarding quite fast in SOFRP.

As an example of a high data throughput and conserving energy protocol, Self-Organized Proactive Routing Protocol (SPRINT) [24] is a self-organized, proactive, cross-layered protocol. SPRINT selects the next forwarding nodes based on the distance between source and the relays, number of relays used to traverse the packet from the source node to the gateway and the number of neighbors of each relay. The distance is measured by received signal strength (RSS) to make the protocol location free.

F. Time Synchronization based Protocols

The Energy-Efficient and Obstacle-Avoiding Routing (EOAR) [1] protocol chooses the forwarding node using fuzzy logic. The decision is dependent on the propagation delay, angle between the two nodes, and residual energy. To prevent collisions, packets are routed based on their priority. The received packet's timestamp, which indicates when it was received, is used to determine the propagation delay. Due to different propagation delays and some degree of mobility, this technique requires time synchronization between the nodes, which is a difficult challenge for UWSNs.

DBR-MAC [25] is a cross-layer routing protocol based on node depth, angle information and number of hops. Time synchronization is required for the protocol to estimate the propagation delay between the nodes. The transmission and propagation times, and the fixed packet size are used by the nodes to count their neighbors' transmission and the reception schedule. This helps the nodes to schedule their own transmissions to avoid collisions. The Time of Arrival (ToA) technique is used to estimate the distance between the gateway and the nodes. The angle information is achieved with help of depth and the distance information between the gateway and the nodes. The performance of DBR-MAC highly depends on the accuracy of time estimation.

From the review of the protocols given above we can see that except P-AUV all the routing protocols are designed for the stationary nodes and AUVs are only used to collect the data from the stationary nodes. However, P-AUV also needs assertation of location which is not very accurate in UWSN. SOAM protocol is designed for continuously moving nodes like AUVs which makes it distinct from the existing protocols. In addition to that, it is location-free and no time synchronization is required between the nodes which makes it a novel protocol for underwater mobile ad hoc networks.

III. Mathematical Models

This section describes the mathematical equations of path loss of acoustic waves in water, received signal strength, and energy consumption.

A. Path Loss Model for Acoustic Waves in Water

Absorption is the one of the main reasons of propagation path loss of the acoustic waves in water. Total path loss is given as (1) [24],

$$A(l,f) = 10 * log(l^k) + \alpha(f) * l \ (dB) \quad (1)$$

where l is the transmission range in km, k is the spreading factor, f is the frequency of the acoustic wave signal in hertz and α(f) is the absorption coefficient given as (2) [24],

$$\alpha(f) = \frac{0.11f^2}{1+f^2} + \frac{44f^2}{4100f^2} + 2.75 * 10^{-4}\, f^2 + 0.0033\left(\frac{dB}{km}\right) \quad (2)$$

B. Received Signal Strength

Received Signal Strength (RSS) is measured to estimate the distance between the nodes. When the nodes are close to each other the RSS value is high and when they are far away RSS value is low. To measure the RSS (3) is used [24],

$$rss = Txpwr - TL \quad (3)$$

where rss is received signal strength, Txpwr is the power of the transmitted signal and TL is the transmission loss. TL is measured by (4) [24],

$$TL = \ \alpha d + 20log_{10}(d) \quad (4)$$

where d is the distance between the nodes

C. Model for Energy Consumption

The energy consumption is calculated by (5),

$$E_d = E_t(d) + E_r(d) \quad (5)$$

where E_d is the total energy/packet, E_t is the transmission energy for each packet and E_r is the reception energy for each packet, and d is the distance between the nodes.

E_t can be calculated by (6),

$$E_t(d) = L\big(E_{elec} + \varepsilon_{amp}\big) + P_t \frac{L}{\alpha B(d)} \quad (6)$$

and E_d can be calculated by (7),

$$E_r(d) = L(E_{elec} + E_{DA}) + P_r \frac{L}{\alpha B(d)} \quad (7)$$

where L is number of bits in a packet, E_{elec} is the electronic processing energy for each bit, ε_{amp} is the amplifier energy per bit, E_{DA} is data aggregation energy per bit P_t is the transmission power, P_r is the reception power, α is the modulation energy and B is the channel bandwidth.

IV. Overview of SOAM Protocol

Let's describe the major steps of SOAM, in brief, to understand how the protocol works. For convenience, the steps have been described in form of a flow chart as well. The movement of the AUVs has been explained in Figures 5-7.

The routing protocol presented in this work, Self-Organized ad hoc Mobile (SOAM) protocol, is intended for ad hoc mobile underwater sensor networks (AMUWSN). SOAM is a cluster-based protocol where the Gateway (GW) is stationary while the CHs and OSNs are randomly moving AUVs. Fig. 2 shows the clusters in AMUWSN topology. The triangle shows the GW, the pentagon shows the Cluster Heads (CHs), the circles show Ordinary Sensor Nodes (OSNs) and the dashed-line circles show the clusters.

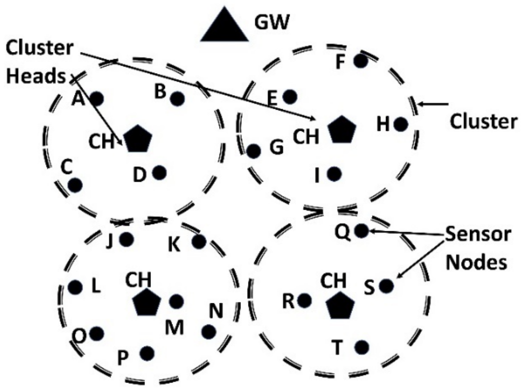

Fig. 2. Clustering of randomly moving OSNs with CHs

A CH node is assumed to have a longer transmission range and have more energy available than the OSNs. The CH will also move randomly to collect data like the OSNs and will forward the data of other OSNs within its cluster range as well. The GW will initiate the path formation by broadcasting beacon (BCN) packets periodically to find the CHs around it. The CHs that will receive the BCN packet will form a path with the GW and will be responsible to forward the data packets of their own cluster nodes and the other clusters to the GW. Therefore, they are called packet forwarder cluster heads (PFCHs). The PFCHs will announce their role of packet forwarder (PF) to their one hop away CHs by broadcasting the BCN packet. The CHs which will receive the BCN packet from the PFCH will rebroadcast the BCN. This will continue until all the CHs in the network have received the BCN packet. A CH will select the next forwarding CH when the data is to be forwarded. The selection will be based on number of hops and residual energy.

An OSN will select the nearest CH comparing the distances to the different CHs. The PFCH will broadcast the BCN packet whenever it will receive from the GW. The process of CH selection by OSNs will also occur every time the BCN packet is broadcast by the CHs. The rate of repeated broadcast of BCN packet from the gateway, PFCH and CHs, will depend on the speed of the moving nodes.

Fig. 3 shows the flowchart of routing path formation started by the GW and traverses through the CHs.

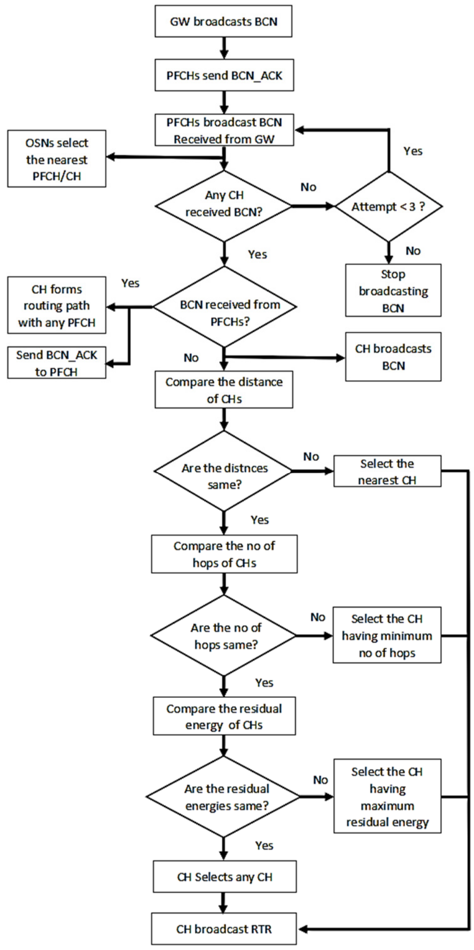

Fig. 3. Flow chart of path and cluster formation

A typical network model of the randomly moving AUVs is shown in Fig. 4. The triangle shows the sink, circles show the moving OSNs and asterisks show the moving CHs.

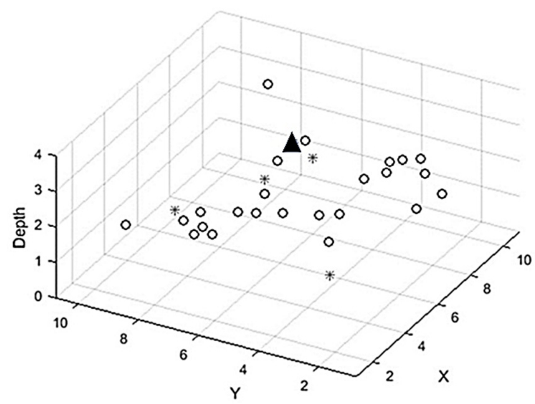

Fig. 4. 3D network of AUVs moving in random directions.

The trajectories of four randomly moving OSNs are shown in Fig. 5-Fig. 7 . The four OSNs are sown by '+', '*', 'o', and

'◊' markers. Fig. 5 shows the top view (z-axis), Fig. 6 shows side view from North (x-axis) and Fig. 7 shows side view from East (y-axis).

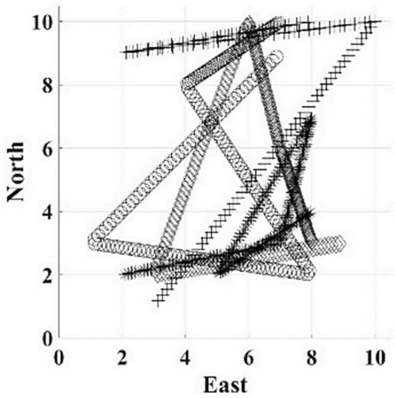

Fig. 5. Top view of moving OSNs and CHs. The lines show their moving path.

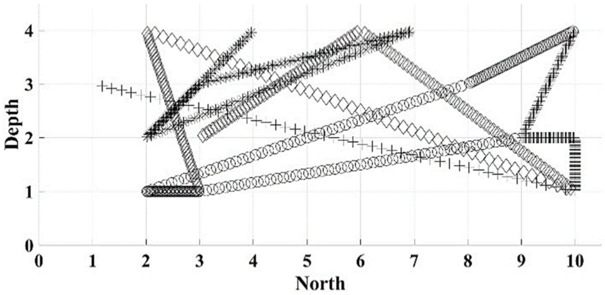

Fig. 6. North-side view of the moving OSNs and CHs.

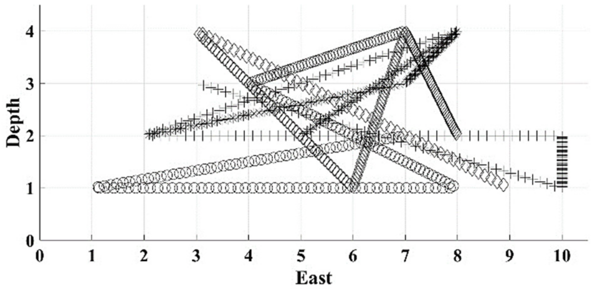

Fig. 7. East-side view of the moving OSNs and CHs.

V. SOAM Details

Now let's describe the sequence of exchange of control packets among the gateway, cluster heads and, cluster nodes to form the routing path from the sensor nodes to the gateway. The clusters' formation process and packet forwarding mechanism are also explained with help of packet header details.

The BCN will be broadcast by the GW at predefined intervals. The BCN packet will contain the gateway ID (GW_ID), packet type, number of hops, and residual energy. The BCN packet will be received by CHs and OSNs but only the CHs will send the acknowledgment (BCN_ACK) to the GW. The randomly moving CHs which received the BCN packet from the GW will be called PFCHs and they will rebroadcast the BCN packets at randomly selected time slots. The total number of time slots will be twice the number of CHs possibly present in the maximum transmission range of the GW. The length of a time slot is the sum of the maximum propagation delay and the transmission delay.

The PFCHs will set the value of the number of hops field to "1" before they rebroadcast the BCN packet. This will indicate to the other CHs that the source CH is one hop away from the gateway and it can forward their packet to the GW. The CHs which will receive the BCN from the PFCHs will select them as the next forwarding CH without carrying out any selection process because they are the only possible choice for them. If a CH will receive the BCN packet from more than one PFCH then it may select any one of them. Once the selection is done, the CHs will send BCN_ACK to the PFCHs. The PFCH will broadcast the BCN packet again if it failed to receive the BCN_ACK. A PFCH will try a maximum three times to get BCN_ACK. If a PFCH does not receive BCN_ACK after three attempts, then it will assume that there are no more clusters present in the network. To traverse the BCN packet throughout the network, the CHs will keep broadcasting the BCN packets. This process of broadcasting the BCN packets by the GW and the CHs will never stop and will be carried out at a predefined interval. The broadcasting of the BCN packet will depend on the movement of the nodes. If the nodes are moving too fast and the network topology is changing rapidly then the interval will be short. The maximum speed of the AUV will determine the frequency of BCN broadcasting. For the purposes of this work, we simulated an AUV travelling at a maximum speed of 4 m/s. If there are numerous contenders for the next forwarding CH, the CH with the highest RSS will be chosen. If the distance is equal, the CH with the fewest hops will be chosen. If there are the same number of hops, the CH with the highest leftover energy will be chosen.

In addition to finding the next forwarding CH, the formation of a cluster is another essential process. The formation of a cluster is also a continuous process due to the continuous random movement of the AUV nodes. Since both processes of finding the forwarding CH and cluster formation, are continuous and simultaneous, we need the CHs to be able to communicate with the OSNs and the other CHs simultaneously. This requires the CHs to be equipped with two modems [26] communicating at different frequencies. The BCN packets will be received by the randomly moving OSNs as well and they will estimate their distance from a CH by computing RSS of the BCN packets. The CH which will have a larger value of the RSS will be selected as the CH by an OSN. The CHs will also indicate to OSNs whether they have established a forwarding path. The OSNs will send their data packets only when they will receive Ready To Receive (RTR) packet from the CH. This will save the energy of the OSNs by refraining them from transmitting the data packets, which will be discarded by the CHs if the forwarding path has not been established. In case of collision the packet will be lost. Therefore, the OSNs will send the data to the CHs at randomly selected timeslots to avoid the collision at the CHs. However, collision may occur if two nodes the same timeslot and they are at the equal distance from the CH. There is another possible scenario of data collision where two nodes are at different distances from the CH but send their packets such that the packets arrive at the same time at CH.

Packet header format shown in Fig. 8 has seven header fields.

Bits	0	10	20	52	55	60	68	76
Field Name	S_ID	D_ID	PKT_ID	PKT_TYPE	HOPS	TX_POWER	ENERGY	DATA
Field Size	10	10	32	3	5	8	8	

Fig. 8. Packet Header Format.

Header fields S_ID and D_ID are the device IDs of sender and receiver of the packet respectively. PKT_ID is a unique packet ID constructed by the combining S_ID and a random number. S_ID is added in the PKT_ID to make sure that any two nodes do not generate the same PKT_ID. Every time a CH forwards the packet to another CH it increments the HOPS field by one. The sender node adds the power of transmission and residual energy in TX_POWER and ENERGY respectively.

Algorithm 1 shows how a BCN propagates through the CHs and form the clusters. TxR_{GW} is the transmission range of GW.

Algorithm 1: Routing Path Formation.

```
GW sends BCN
if CH is within TxR_GW
    then CH sends BCN_ACK
end if
PFCH sets HOPS = 1
repeat =1
while repeat ≤ 3 do
    PFCHs send BCN
    CHs send BCN_ACK
    if PFCH failed to receive BCN_ACK
        then repeat = repeat + 1
        else break while loop
    end if
end while
OSN estimates RSS
OSN selects CH = max [RSS]
CH sends RTR
```

VI. Simulation and Results

We evaluated the performance of the SOAM using simulation on a MATLAB simulator. The simulated network is based on autonomous randomly moving sensor nodes and CHs, and a stationary GW node on the surface of the sea. The parameters for the simulation are given in Table 1.

TABLE I
SIMULATION PARAMETERS

S. No.	Parameter	Value
1	sound speed	1500 m/s
2	data rate	35000 bps
3	OSN transmission range	1000 m
4	CH transmission range	2000 m
5	network size	10 km ×10 km
6	depth	4 km
7	packet header size	76 bits
8	data size	1024 bits
9	data packet size	1100 bits

The random movement of the AUVs is created by waypointTrajectory function of MATLAB simulator. We simulated the packets with the number of OSNs ranging from 10 to 45 and CHs from 5 to 7. The OSNs and the CHs move in random directions. We have analyzed the performance of SOAM using three parameters namely end-to-end packet delay (in seconds), throughput (in bits per second), and packet delivery ratio (PDR). The CHs forward the packets using the First In First Out (FIFO) packet forwarding mechanism. Figures 9-11 show the average end-to-end delay for the various number of nodes and cluster heads. Fig. 9 shows that the average delay increases almost linearly as the number of nodes increases. It also shows that as the number of cluster heads increases there is a slight increase in the average delay as well. Fig. 10 shows the average delay for the number of CHs from 5 to 7 for each number of OSNs. It also shows that the average delay increases slightly as the number of CHs increases while the number of OSNs remains the same. However, Fig. 11 shows that increasing the number of OSNs has a significant effect on the average delay.

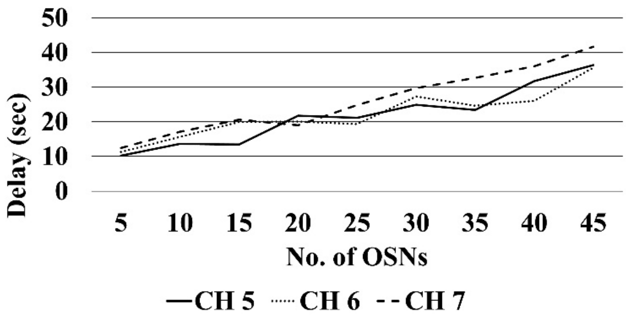

Fig. 9. Average delay of OSNs packets vs. number of CHs

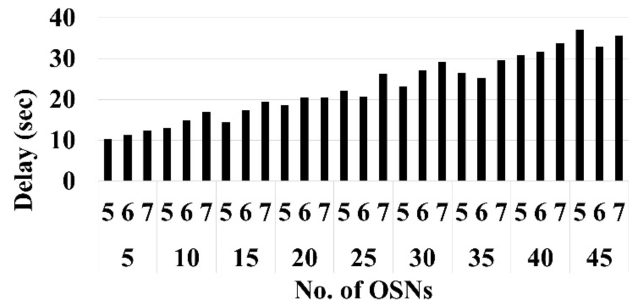

Fig. 10. Average delay vs. number of OSNs

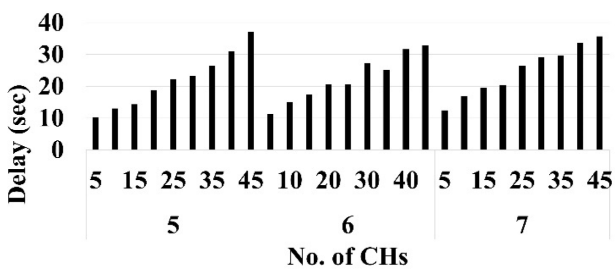

Fig. 11. Average delay vs. number of CHs

Figures 12-14 show the average throughput for the various number of nodes. There is no clear behavior to predict the throughput with the change in the number of OSNs or CHs. However, if we compare the throughput for the number of

OSNs 5 and the number of OSNs 45 in Fig. 13, we see the throughput is slightly better for 5 OSNs. This makes sense because the queue delay at cluster heads is low due to a fewer number of packets.

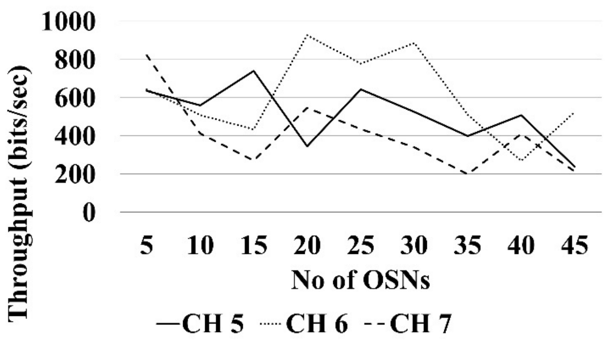

Fig. 12. Average throughput of OSN packets vs. number of CHs

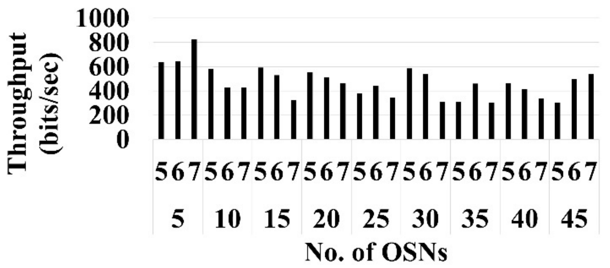

Fig. 13. Average throughput vs. number of OSNs

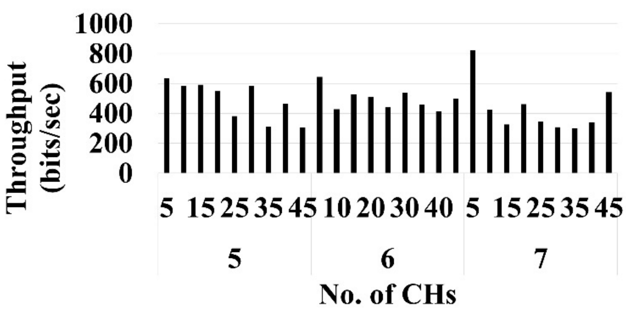

Fig. 14. Average throughput vs. number of CHs

Figures 15-17 show that average PDR also has got no clear relationship with the increase in number of OSNs. In a static network, we expect to have better PDR with increase in number of nodes. However, in the case of a fully ad hoc network, this is not the case because of the random movement of the CHs.

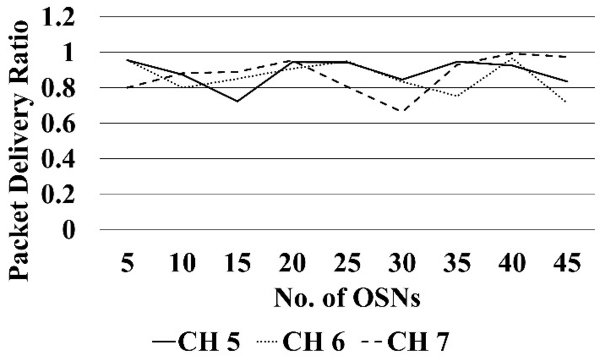

Fig. 15. Average PDR of OSN packets vs. number of CHs

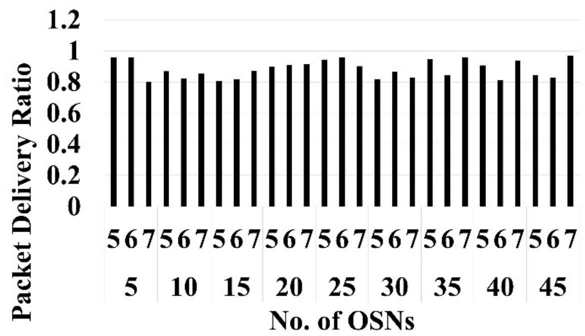

Fig. 16. Average PDR vs. number of OSNs

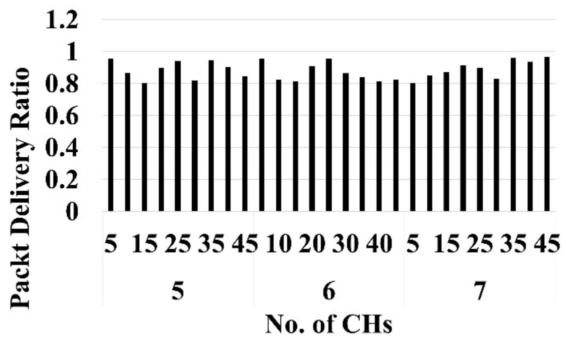

Fig. 17. Average PDR vs. number of CHs

We have compared our simulated results with P-AUV because its architecture is similar to our proposed architecture. We have compared P-AUV and SOAM in terms of end-to-end delay and packet delivery ratio. Fig. 18 shows the end-to-end delay of P-AUV for the various number of nodes. The comparison of Fig. 18 and Fig. 9 shows that end-to-end delay of P-AUV varies from 3.5 to 5 seconds (approximately) whereas end-to-end delay of SOAM varies from 10 to 40 seconds (approximately). The reason for the large delay of SOAM is that it is a cluster-based protocol and to avoid the collision the nodes select time slots randomly to send the packet.

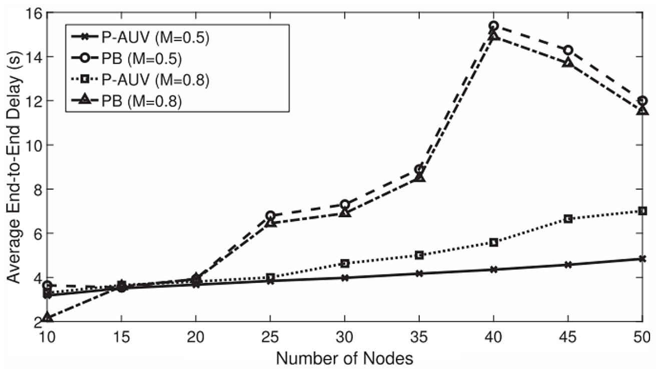

Fig. 18. Variation of end-to-end delay performance vs. number of nodes and ratio of mobile nodes [2].

Fig. 19 shows PDR of P-AUV for various number of nodes. The comparison of Fig. 19 and Fig. 15 shows that PDR of P-AUV ranges from 0.85 to 0.9 (approximately) whereas PDR of SOAM ranges from 0.7 to 0.0.98 (approximately).

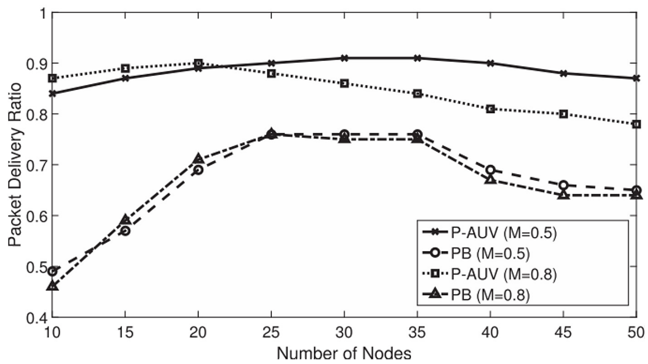

Fig. 19. Variation of PDR performance vs. number of nodes and ratio of mobile nodes [2].

The results of the comparison between SOAM and P-AUV show no clear advantage of SOAM over P-AUV. However, comparison of the routing methods shows that SOAM has some advantages over P-AUV in two ways. First is that, unlike P-AUV, there is no requirement for location assertion in SOAM. We have already mentioned in Section 2 (Related Work) that in P-AUV nodes must be aware of their location at the time of deployment and during the operation as well. In order to update its position, a node uses IMU with DVL which causes error in position estimation. [2] mentions that the expected error is 8 m/hour which is about 0.11% of traveled distance. In addition to that, due to continuous movement of the AUVs, accurate DVL transmits acoustic signals in different direction which causes unnecessary energy consumption. However, SOAM is a location free routing protocol and requires no additional sensors.

VII. Conclusion

In this paper, we have presented a reactive routing protocol for mobile underwater sensors. The movement of the sensor nodes is continuous and random. The mobile sensor nodes may be used to monitor the environment or for the marine surveillance. The protocol is designed to establish the routing path among the moving nodes to forward the data to the gateway with minimum end-to-end delay. The network is divided into clusters to minimize the number of hops. The CHs are equipped with two modems, operating at different frequencies, to communicate with the other CHs and the OSNs simultaneously. The formation forwarding path between the CHs is initiated by the GW by broadcasting a BCN packet. The BCN packet traverses through all the network to get all CHs connected. The clusters are formed by OSNs selecting the CH based on the distance. The distance between a CH and OSN is computed using RSS by an OSN. In future, the performance of the protocol can be improved by decreasing the end-to-end delay using more efficient queuing algorithm at the CHs and medium access control method between the OSNs and the CHs.

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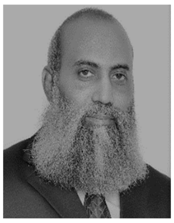

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