Joint Clustering and Routing Protocol for 3-D Underwater Acoustic Sensor Network

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***Abstract*—When the network nodes are randomly deployed in three-dimensional Underwater Acoustic Sensor Network architecture, the working of initialization phase of a network is very crucial. One of the most important protocol in the initialization phase is a clustering protocol, which also aids in the route formation. In this paper, a joint clustering and routing protocol has been proposed for three-dimensional Underwater Acoustic Sensor Network. This proposed protocol uses a non-probabilistic approach which selects the Cluster-Head node based on the weighted cost of residual energy and network connectivity. Route is then formed to the Base-Station node using chain of Cluster-Head nodes of the network. Description of this protocol along with its implementation on UnetSim and results of implementation have been discussed in this paper.**

***Keywords*—Underwater Acoustic Sensor Network (UASN), Clustering, Routing.**

I. Introduction

From the scientific and commercial point of view, a continuous, real-time, effective and synoptic sampling of ocean has gained huge importance. From the necessity of various possible applications such as ocean environmental monitoring, undersea exploration, seismic monitoring, assisted navigation, tactical surveillance and so on, a new technology of Underwater Acoustic Sensor Network (UASN) has been developed [1–3].

In this paper, a problem of deployment of three-dimensional UASN has been considered. 3D UASN can be utilized for the ocean column monitoring. It is assumed that the groups of nodes are randomly deployed at various levels (depths) below sea-surface in the ocean column. An algorithm is developed for the initialization phase of the network, where-in the Cluster-Heads are chosen from among the groups of nodes at each level, and also the routing path is established from network nodes to the Base-Station via chain of Cluster-Head nodes. Successful initialization of the network in the harsh underwater environment and in-accessible domain is a major research challenge for the network designer. Clustering is one of the most desirable techniques in an initialization phase of sensor networks. Clustering helps in improving energy efficiency and prolonging the network lifetime. It can additionally help in developing an effective data aggregation policy, achieving low latency, balancing traffic load and in improving system capacity by enabling bandwidth reuse [4]. Clustering can also help exploit the advantages of topology by forming multi-hop geographical routing towards Base-Station of the network.

Here, a distributed, non-probabilistic, cost-based, joint clustering and routing algorithm has been developed for selection of Cluster-Head node from among the group of nodes deployed at various levels in the ocean column. Nodes are assumed to be programmed with the proposed algorithm at the time of deployment. Once the nodes are deployed, an algorithm is run to elect the Cluster-Head node based on the cost of energy values and neighbor connectivity. When a Cluster-Head is elected at each individual level, these Cluster-Heads discover the Cluster-Heads of adjacent clusters to form a geographical routing towards Base-Station. This algorithm has been simulated using UnetSim software tool, an open-source simulation tool for UASN. Details of the proposed algorithm, its implementation and results have been provided in this paper.

The organization of the paper is as follows: In Section II, related work on clustering protocols has been detailed from literacture review. The proposed network architecture along with assumptions has been provided in Section III. Description of proposed clustering and routing algorithm has been elaborated in Section IV. Details of implementation of proposed algorithm on UnetSim simulation tool have been provided in Section V. Results of these implementations have also been discussed in this section. Conclusions have been provided in Section VI.

II. Literature Survey

Use of clusters and multi-hop communication for transmitting data to the Base-Station leverages the advantages of small transmit distances for most nodes, requiring only a few nodes to transmit data over long distances to the Base-Station. Since, the energy dissipation during a data transmission is proportional to distance between the transmitter and the receiver, short distance transmissions are comparatively energy efficient. Further, in order to equalize the energy distribution (or dissipation) across all nodes, it is essential to rotate the Cluster-Head based on the residual energy of node. Several clustering protocols have been proposed by the authors such as DUCS [5], MCCP [6], S-LEACH and C-LEACH [7].

In [5], author has proposed a distributed clustering scheme for shallow water scenario. In this protocol, nodes compute their residual energy and calculate the probability to become Cluster-Head. Based on the probability value and threshold, node elects itself as Cluster-Head. This node then uses CDMA for advertisement of this election. CDMA has been used to avoid collisions. Nodes which receive the advertisement select a lower-cost Cluster-Head and sends a join-request message. CDMA technique is also used to provide TDMA MAC scheduling to cluster-member nodes. Nodes in a cluster send their data to the Cluster-Head via single hop using TDMA schedule. The Cluster-Head performs data aggregation, and forwards the data to the sink using a multi-hop route (via Cluster-Heads) using CDMA codes. Randomized rotation of Cluster-Head is implemented for even distribution of energy among all nodes.

In [6], a node clustering problem has been formulated into a cluster-centric cost-based optimization problem with an objective to improve the energy efficiency and prolong the lifetime of the network. Authors have defined a metric termed as cluster cost for each potential cluster in UASN. This cluster cost takes the following parameters into consideration : i) total energy consumption of cluster nodes, ii) residual energy of Cluster-Head and cluster nodes, and iii) relative distance of Cluster-Head and sink. The proposed protocol, termed as Minimum Cost Clustering Protocol (MCCP), selects a set of non-overlapping clusters from all potential clusters and attempts to minimize the overall cost.

In [7], authors have proposed two novel cluster formulation protocols for the Low Energy Adaptive Clustering Hierarchy Protocol (LEACH) focusing on energy conservation. It states that the standard LEACH protocol designed for terrestrial network perform poorly in underwater networks owing to the unique characteristics of underwater acoustic channel. Compared with the standard LEACH protocol, the proposed S- LEACH (Slotted-LEACH) protocol can avoid the collision of the advertisement packets completely by dividing the broadcast time in slots. Another improved protocol termed as C-LEACH (Controlled-LEACH) has also been proposed in this paper. In C-LEACH, control node is added at the center of the network topology, which is used to avoid the collisions between advertisement messages and also for broadcasting the advertisement messages on behalf of Cluster-Heads.

In general, the clustering protocols can be classified as a) Probabilistic or b) Non-probabilistic protocols. Non-probabilistic clustering algorithms use deterministic criteria for Cluster-Head election and cluster formation. These criteria include nodes proximity (connectivity, degree, and so on.) and information received from other closely located nodes. The cluster formation procedure here is mainly based on the communication of nodes with their neighbours (one or multi-hop neighbours) and generally requires more intensive exchange of messages and probably graph traversing in some extent, thus leading sometimes to worse time complexity than probabilistic/random clustering algorithms. On the contrary, these algorithms are usually more reliable toward the direction of extracting robust and well-balanced clusters. In addition to node proximity, some algorithms also use a combination of metrics such as the available energy, transmission power, mobility, and so on, (forming corresponding combined weights) to achieve more generalized goals than single-criterion protocols. In this paper, a non-probabilistic, joint clustering and routing protocol has been proposed for 3D UASN considering the requirement of robustness and reliability. This protocol requires a simple algorithm and lesser number of message exchanges for electing a cluster-head node. For increase in number of nodes in the network, the number of message exchanges does not increase substantially.

In the next section, network architecture of 3D UASN which is used for implementation of proposed clustering algorithm has been detailed.

III. Proposed network architecture and assumptions

In this work, a generic three-dimensional UASN architecture has been designed for monitoring of ocean column over a long time. This network consists of multiple levels of clusters, deployed at varying depths from sea-surface. Each cluster further consists of number of nodes in horizontal plane. Maximum distance of nodes is R_u meters from center of column. Multiple such clusters have been arranged vertically below each other in the column. Vertical distance between two successive clusters has been denoted by d_u meters. Total depth of cylindrical column has been denoted by D_u meters and radius of column has been denoted by R_u meters. At sea-surface, a Base-Station node is deployed.

A generic three-dimensional architecture has been shown in Figure 1. Various levels have been indicated as Level 1, Level 2, Level 3 and so on from top to bottom of the network. The nodes have been address configured as LXX, wherein L denotes the level number and XX denotes the two-digit number of a node. For example, nodes at level 2 have addresses as 200, 201, 202 and so on. Similarly, nodes at level 3 have address numbers as 300, 301, 301 and so on. Node at level 1 has been configured with address 100 and it acts as a Base-Station node. Total number of levels in the network has been denoted by L_T.

In the design of this three-dimensional architecture, following assumptions have been made:

1) It has been assumed that $\mathrm{D}_u >> \mathrm{R}_u$. This network has been deployed to observe the ocean parameters along the depth of ocean.

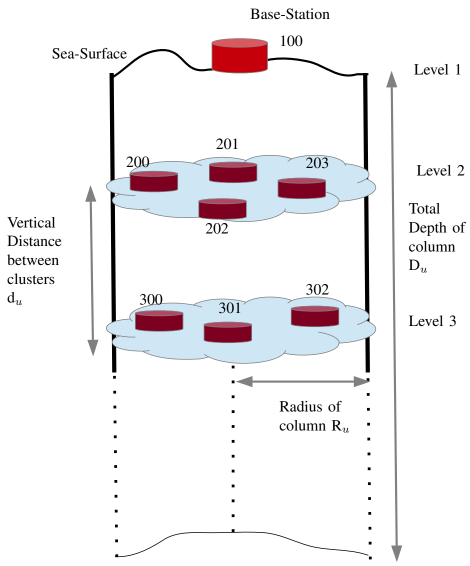

Fig. 1: A generic three-dimensional architecture of UASN.

2) It has been assumed that suitable mechanical/electrical arrangement is available to keep the sensor nodes floating at suitable depths.
3) It has been assumed that, $D_u > d_u > R_u$. It suggests that the vertical distance between clusters is larger than the radius of cluster. With this setting, an effective power level management strategy can be used for parallel intra-cluster communication.
4) All nodes have been assumed to have multiple power level for communication. A node is able to communicate till distance R_u with lower power level setting and can communicate till distance d_u with higher power level setting. Power level of a node can be dynamically changed during run-time.
5) All sensor nodes have been assumed to have bidirectional acoustic link available for underwater communication. In this architecture, N_o number of nodes have been considered at every level of deployment (other than level 1).

In the following section, detail description of the proposed protocol has been provided.

IV. Description of Proposed Joint Clustering and Routing Protocol

The proposed joint clustering and routing algorithm is divided into three phases as follows:

1) Neighbor discovery and Classification of nodes
2) Temporary Cluster-Head (TCH) and Final Cluster-Head (FCH) selection
3) Route formation

A. Phase 1 -Neighbor discovery and Classification of nodes

It is assumed that the nodes are deployed in the cluster formation without finer control on their positions. Nodes are aware of the cluster-size and hence the maximum number of nodes to be discovered as their neighbors. First phase of the protocol is the neighbor discovery phase, wherein nodes transmit broadcast messages at lower power levels for broadcasting their own information to other nodes. With this power level, node can communicate till R_u distance and will not interfere in the parallel ongoing communication in the adjacent cluster. In this way, the Phase 1 can be operated parallely in multiple cluster. Nodes include their Node ID in the broadcast message. Other nodes upon hearing this message form a tabular entry of their neighbor nodes. These broadcast messages are transmitted at random intervals by each node. Since the scenario is contention-based, nodes attempt number of broadcasts for the possibility of successful transmission of messages.

Considering that the number of re-attempts are fixed, and the random interval policy is based on binary exponential back-off, a neighbor discovery phase should end in "ND-time" as shown in Figure 2. Sufficient guard-time interval (GT) can be appended for the separation of subsequent phases. This guard-time also provides time allowance in the situation where clocks of the nodes are not tightly synchronized.

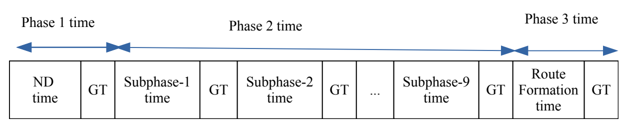

Fig. 2: Phase timing values in proposed protocol

After completing the neighbor discovery phase, nodes have tabular entries of neighbor node IDs. Each node then calculates its network connectivity based on the number of entries in its table. Based on node's own available energy and network connectivity, each node classifies itself into one of the nine categories for becoming eligible as Cluster-Head of the cluster. This categorization is based on hybrid criteria of energy and connectivity. Table I shows various categories. If the node has energy more than 90% of the initial energy and is connected with more than 90% of the neighbor nodes, then it is self-categorized as category 1 node. If its connectivity is with more than 75% nodes but less than 90%, then it is category 2 node and so on. Accordingly, each node categorizes itself into one of the category. In case, the nodes energy is less than 50% of the initial energy and/or its connectivity is less than 50% of the node density, then the node does not become eligible for Cluster-Head, and denotes itself as cluster-member node. This node can join the elected Cluster-Head node of its cluster.

B. Phase 2 -Temporary Cluster-Head (TCH) and Final Cluster-Head (FCH) selection

A Temporary Cluster-Head (TCH) selection is essentially for the eligible Cluster-Head nodes to contend for

TABLE I: Classification of nodes

Category	Energy	Connectivity
Category 1	High (>90%)	High (>90%)
Category 2		Medium (90% to 75%)
Category 3		Low (75% to 50%)
Category 4	Medium (90% to 75%)	High (>90%)
Category 5		Medium (90% to 75%)
Category 6		Low (75% to 50%)
Category 7	Low (75% to 50%)	High (>90%)
Category 8		Medium (90% to 75%)
Category 9		Low (75% to 50%)

becoming the Cluster-Head. Here, the network timing is partitioned into nine sub-phases for the nodes of nine categories for contention. Subphase-1 is for the nodes of category 1 nodes, subphase-2 is for category 2 nodes and so on. In each subphase, nodes of the respective category contend to become a Temporary Cluster-Head first. After becoming TCH node, the node forms a cluster by establishing connection with its cluster-member nodes. Once these links are established, a TCH node is termed as Final Cluster-Head (FCH) node. If the FCH node selection is accomplished in any one of the categories, then the remaining categories and their corresponding timings are inactive.

For illustration, operation of subphase is described as follows:

Any node categorized as node of respective category can broadcast information at random interval within the duration specified for that category or subphase. Phase 2 timing along with subphase timing has been illustrated in Figure 2. After every subphase time, a guard time interval (GT) has been appended. In broadcast, a node includes its node ID, energy and connectivity. Other nodes, after listening to the message, compare their respective parameters or values as per the Algorithm 1. The terminologies used in Algorithm 1 are as follow:

- NCV - Node Connectivity Value
- RCV - Received Connectivity Value
- NEV - Node Energy Value
- REV - Recived Energy Value
- NID - Node ID
- RID - Received ID

As outcome of this algorithm, the receiver node either has "poor parameters" or "better parameters" than the earlier broadcasted node. Hence a receiver node either classifies itself as cluster-member node (and gives-up the eligibility of becoming Cluster-Head node) or sends its own broadcast message (after random interval) so as to supersede the earlier broadcast message. Since, this scenario is contention-based, each contending node makes the broadcast announcement twice in order to avoid failure due to collisions or noisy channel conditions. But, a node does not make broadcast (remains silent) after hearing the announcement of another node having "better parameters" or "better candidacy of Cluster-Head" than its own parameters at any instance of time. It indicates that if a node listens to a broadcast having "better parameters" than its own, before making its own announcement, or after making one or both announcement, it classifies itself as a cluster-member node and withdraws the eligibility of becoming Cluster-Head node.

Algorithm 1: Phase 2 Algorithm

```
1  if NCV <RCV then
2  |  go to 15 ;
3  else if NCV >RCV then
4  |  go to 16 ;
5  else if NCV == RCV then
6  |  if NEV <REV then
7  |  |  go to 15 ;
8  |  else if NEV >REV then
9  |  |  go to 16 ;
10 |  else if NEV == REV then
11 |  |  if NID >RID then
12 |  |  |  go to 15 ;
13 |  |  else
14 |  |  |  go to 16 ;
15 Label itself as cluster member node
16 Broadcast its own TCH message (after random
   interval)to supersede the earlier node
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If a contending TCH node has made two announcement and have not heard any other supersede broadcast message, then it can assume that it has better candidacy of becoming Cluster-Head of the cluster, and performs the procedure for becoming Final Cluster-Head. For that, it makes another broadcast termed as FCH broadcast stating its Node ID, energy value and IDs of all of its neighbor (based on neighbor table). It then awaits acknowledgements from the neighbor nodes. Neighbor nodes after hearing this broadcast, transmits the acknowledgement to the node in the order received in the message. If the announcing node receives reply or acknowledgement messages from more than a certain threshold number of neighbour nodes, then it is selected as Final Cluster-Head of the cluster. (This threshold can be determined from the channel conditions or desired accuracy of results.) The subphases after this current subphase are taken as null and void. But, if the announcing TCH node does not receive sufficient number of acknowledgements, then the selection fails and network enters into next subphase. All nodes of previous category or subphase along with current category contend to become FCH node of the cluster. Nodes of previous category still have a dutiful right to become the Cluster-Head node in this manner.

It should be noted that operation of Phase 2 also happens parallely among all the cluster, because of utilization of lower power level of transmission.

C. Phase 3 - Route formation

Once the Phase 2 is over, it can be suitably assumed that the Cluster-Head nodes have been selected at each level or cluster. Phase 3 starts with Base-Station broadcasting a message for route discovery. Base-Station node first broadcasts a message to find out whether a Cluster-Head node has been elected in the level below it. Cluster-Head node of the cluster (geographically below it) responds to this query message of Base-Station. These message transmissions are done at higher power level so as to cover a vertical distance of d_u meters. Further, the Cluster-Head node of the recent cluster broadcasts a message to find out the election results of the cluster below it. Cluster-Head node of a cluster from lower level responds to this query message. Such message exchanges continue till the bottom-most level of the network. When a Cluster-Head node does not receive a response for its query message, it assumes that it is the last cluster and route discovery ends at this stage. In the underwater environment, owing to the unpredictable channel conditions, number of retries might be required and this can be decided based on the channel model or practical channel performance. Timing of phase 3 along with a guard time interval (GT) has been presented in Figure 2.

In this manner the proposed protocol runs after the deployment of network nodes in the ocean, and achieves the cluster formation as well as route formation. Setting-up the network in the initialization phase is more critical and failure-prone. Hence, such issue has been handled in detail in this proposal using non-probabilistic approach for more robustness. The proposed joint clustering and routing protocol has been implemented on UnetSim, an open-source simulation tool for underwater acoustic sensor network [8]. Details of implementation and results have been discussed in the following section.

V. Implementation of protocol and Results

The proposed protocol has been implemented on UnetSim simulator [8]. The parameters of channel and network architecture have been tabulated in Table II.

Simulation has been run multiple times with randomized positions of the nodes at multiple levels. Number of broadcasts of phase 1 and retries of phase 3 has been set as 3 and 2 respectively from the performance parameters of the channel. Average timing values of various phases have been provided in column 2 of Table III. Column 3 shows the average number of message exchanges in each phase in the (complete) network. First entry in the column 3 indicates that total 30 messages have been broadcasted by 10 nodes (3 messages per node) per cluster. Since there are 3 clusters (for $L_T = 4$), total 30 messages have been broadcasted by the nodes. Total time of the phase 1 is 50 seconds considering random interval between broadcasts and the guard time interval. Similarly, TCH election of phase-2 requires average 5 message transmission per cluster, per subphase. Time period of 40 seconds has been provided for each subphase, considering random intervals of messages and guard time. There would be only 1 FCH message per cluster (and per subphase) in the network. This FCH message will receive acknowledgements from $N_o - 1$ number of nodes. Time period for the FCH-ACK communication is 10 seconds per subphase. In phase 3, route formation is done starting from the Base-Station node to the lowest Cluster-Head of the network. hence, total 9 messages are transmitted in the network (assuming 2 retries by the lower-most Cluster-Head node). Time period is 36 seconds for phase 3. Sizes of different messages have been provided in column 4.

TABLE II: Simulation parameters for UnetSim

Parameter	Value
Channel Type	Basic Acoustic Channel
Noise Level (NL)	40 dB
Frequency of communication	25 kHz
Data rate	2400 bps
L_T	4
N_o	10
Lower power level (Acoustic)	128 dB
Higher power level (Acoustic)	135 dB
d_u	500 m
R_u	10 m

Since the lower power levels have been used for the intra-cluster communication, message exchanges in one cluster does not interfere in the ongoing communication of adjacent clusters. Various clusters deployed one-below-other can perform phase 1 and phase 2 parallely. This leads to optimization in terms of timing. Also, utilization of lower power level reduces energy consumption and interference levels in the network. In phase 3, for the inter-cluster communication, a higher power level is utilized. In this case, the communication happens sequentially, first from Base-Station node to Cluster-Head node of level 1, then from Cluster-Head node of level 1 to Cluster-Head node of level 2 and so on.

In the simulation on UnetSim, the protocol operation has been observed for various phases. Under ideal channel condition and Noise Level of 40 dB, the neighbour table formation is complete usually after 3 broadcasts by every node. Classification of nodes into various subcategories is the internal processing of each node. With this categorization as the input to phase 2, operation of phase 2 leads to election of FCH with robustness and reliability. The feature of two broadcasts by an eligible TCH node and a provision of supersede message adds to the robustness of the protocol. Route to the Base-station

TABLE III: Details of various phases

Phase		Time (s)	No. of messages (transmitted)	Size of each message (Bytes)
1		50	30 ×3	2
2	TCH	40 (per subphase)	Avg. 5 ×3	4
	FCH	10 (per subphase)	1 ×3	12
	ACK		9 × 3	3
3		36	9	3

Note - Phase 1 and 2 operates parallely among multiple levels.

node is formed by connecting the Cluster-head nodes of all clusters.

The implementation has been tested with various factors such as 1) Scalability, 2) Data rate variations and 3) Multiple noise levels.

1) Scalability - In order to showcase the scalability of the protocol, the network has been simulated with 15, 20 and 25 nodes in each cluster. Results of the simulation for varying number of nodes have been tabulated in Table IV. Column 2 presents the total number of messages transmitted by the nodes in the network for election of Cluster-Head nodes and the route formation. Column 3 presents the total time taken for the joint clustering and routing protocol to complete. It can be observed that the number of message exchanges or time taken by the protocol does not increase substantially for the increase in number of nodes in the network.

TABLE IV: Results for varying number of nodes

No. of nodes	Total no. of messages transmitted in the network	Total time taken (s)
10	144	136
15	196	166
20	270	206
25	336	246

2) Data rate variations - The simulation has been tested with the changes in data rate from 2400 bps to 1800 bps and 1200 bps. In this case too, the timing values of various phases has to incorporate the changes proportionately. It does not affect the operation of protocol.
3) Multiple Noise Levels - One of the main characteristics of underwater acoustic channel is the highly unpredictable channel performance. In order to approximate the practical situation, the noise level have been increased from 40 dB to 65 dB in the portions of 5 dB. It has been observed that at 60 dB, the vertical links between Cluster-Heads are not formed correctly. The failure of establishing vertical links renders the network unusable.
   The increase in noise level beyond certain threshold affects the formation of neighbour table as well. The neighbour table of every node does not have the entries of all of its neighbours. This leads to the election of possible sub-ordinate node.

The proposed joint clustering and routing protocol has been tested for the parameters specified above. One of the requirement in adhering to phase timings is the time-synchronization between network nodes. Utilization of guard time gives the allowance of clock-mismatches between the nodes. The effect of timing inaccuracies has to be evaluated in detail, and will be studied in future by implementing time-synchronization protocol.

VI. Conclusion

In this paper, a joint clustering and routing protocol has been proposed for the three-dimensional Underwater Acoustic Sensor Network. This protocol has been implemented on UnetSim simulation platform. The details of implementation and results of implementation have been provided. It has been showcased that this cost-based, non-probabilistic protocol ensures reliability and robustness in Cluster-Head election as well as route formation in the network.

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