DEVELOPMENT OF TDMA BASED MAC PROTOCOL FOR 3D MOBILE UNDERWATER ACOUSTIC SENSOR NETWORK

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This paper presents a simple network architecture and protocol stack for the three-dimensional Underwater Acoustic Sensor Network. The network consists of combination of static and mobile nodes deployed at different depths in the ocean. A clustering protocol is designed and developed to select a cluster-head node from among the cluster/group of nodes located in a common geographical area. Data is relayed from cluster-members to cluster-head using TDMA based MAC protocol. Mobile data mule collects the data from cluster-head nodes located at various depths. This network is simulated using UnetSim simulator developed by National University of Singapore. Detailed results and analysis have been provided in the paper. This 3D mobile UASN can be used for real-time monitoring of ocean environment, or for marine habitat monitoring.

1. Introduction

Oceanographers and marine scientists wish to explore more of the inner space of the ocean by establishing observatories using modern technologies. Collecting and analysing real time data continuously using new technologies will help researchers to have a better understanding of the ocean properties, life-processes and events. At the same time, analysing the data of ocean processes will help us to predict the future climate changes and its impact on human life.

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 [1-5]. UASN can be considered as a conglomeration of underwater acoustic wireless communication and Wireless Sensor Network (WSN) [6,7]. WSN deployed underwater is termed as UWSN (Underwater Wireless Sensor Network), and if the acoustic signal is used to form wireless communication links between sensor nodes, then it is termed as UASN (Underwater Acoustic Sensor Network).

UASN is a type of network that can be adapted to the application of interest. In UASN, depending on the requirement and constraints of application, a suitable architecture and protocol stack can be developed. The network architectures can be classified as i) two-dimensional or three-dimensional, ii) cluster-based hierarchical or flat, iii) structured or random, iv) static or mobile and so on. A proper choice of network architecture makes a huge impact on coverage, scalability, longevity as well as on protocol stack development.

For applications involving three-dimensional coverage, several types of devices such as Autonomous Underwater Vehicles (AUVs), Autonomous Surface Vehicles (ASVs), moored and drifting systems can be used in combination. A detailed review of various applications of three-dimensional underwater networks is available in [8]. Authors have provided review of static, semi-mobile and mobile deployments. It is also stated that underwater deployment are sparse and of longer range compared to terrestrial sensor networks. However, large scale, dense networks handling complex tasks and applications might be reality in near future. In [9], authors have stated that mobile platforms are required to make an ocean observatory system more rapid, refined, and sophisticated. Authors also provide a study of usage of marine vehicles as the nodes of mobile sensor networks for coverage sampling of a regional ocean area and ocean feature tracking.

In this paper, a simple network architecture and protocol stack has been designed for the three-dimensional UASN. This network consists of combination of static and mobile nodes deployed at different depths in the ocean. Base-Station node (or a sink node) is stationed at the sea-surface. Group of nodes deployed at various depths in the ocean selects a cluster-head node. Data is relayed by each node of the group to the cluster-head node using a set time schedule. Network consists of one data mule, which periodically dives down to collect data from each cluster-head node, and climbs up to the sea-surface to finally relay the (collected data) to the Base-Station. Data-mule is an AUV equipped with sensors on board which can also collect the data of the region of its trajectory. For this specific network architecture, a data collecting strategy using TDMA based MAC has been developed. This network is simulated using UnetSim simulator developed by National University of Singapore. Detailed results and analysis are provided in the paper.

This paper is organized as follows: Section 2 provides the network architecture for 3D mobile UASN. Section 3 provides the description of proposed protocols on the given architecture. Section 4 provides details of implementation on UnetSim along with results of implementation. Section 5 presents conclusion and future scope of the work.

2. Network Architecture for 3D UASN

In this work, we assume that the monitoring area is a cylindrical column in the ocean. Total depth of this column is denoted by D_u meters and radius of column is denoted by R_u meters. Various levels are indicated as Level 1, Level 2, Level 3 and so on from top to bottom in the column. Total number of levels in the network is denoted by L_T .Vertical distance between two successive levels is denoted by d_u meters. At each level, multiple static and mobile sensor nodes are deployed in a small cuboid area. At sea-surface, an energy efficient node is deployed with the help of underwater buoy. This node is stationary and acts as an underwater Base-Station for the network. In addition, the network contains an AUV which dives in and climbs up the column at regular periodic intervals collecting data from all levels of the column along the path, thus acting as data mule for the network.

The nodes are 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, 302 and so on. Node at level 1 has been configured with address 100 and it acts as a Base-Station (BS) node. Data mule has an address of 101.

In the design of this 3D mobile UASN architecture, following assumptions are used:

1) All nodes are homogeneous and have the same communication capacity, sensing range, and data-processing capability. These nodes move between the boundaries of their respective cuboid area based on passive (static nodes) or active (mobile nodes) mobility features.

2) The column dimensions have, $D_u >> R_u$. This network has been deployed to observe the ocean parameters along the depth of ocean. It is known that, the variations of ocean parameters along the horizontal plane are insignificant as compared to variations along the depth. Hence, a column of smaller radius has been considered as compared to depth. Further, $D_u > d_u > R_u$. It suggests that the vertical distance between levels is larger than the radius of column.

3) The power level setting of the node is suitable to communicate to the distance of $2 \times R_u$. With this power level, it can communicate with any node in the cuboid area of its own level, but cannot communicate with a node in another (or adjacent) levels.

4) Nodes use relevant time synchronization and positioning algorithm to know their real-time and location status.

This proposed network architecture is depicted in Figure 1 below:

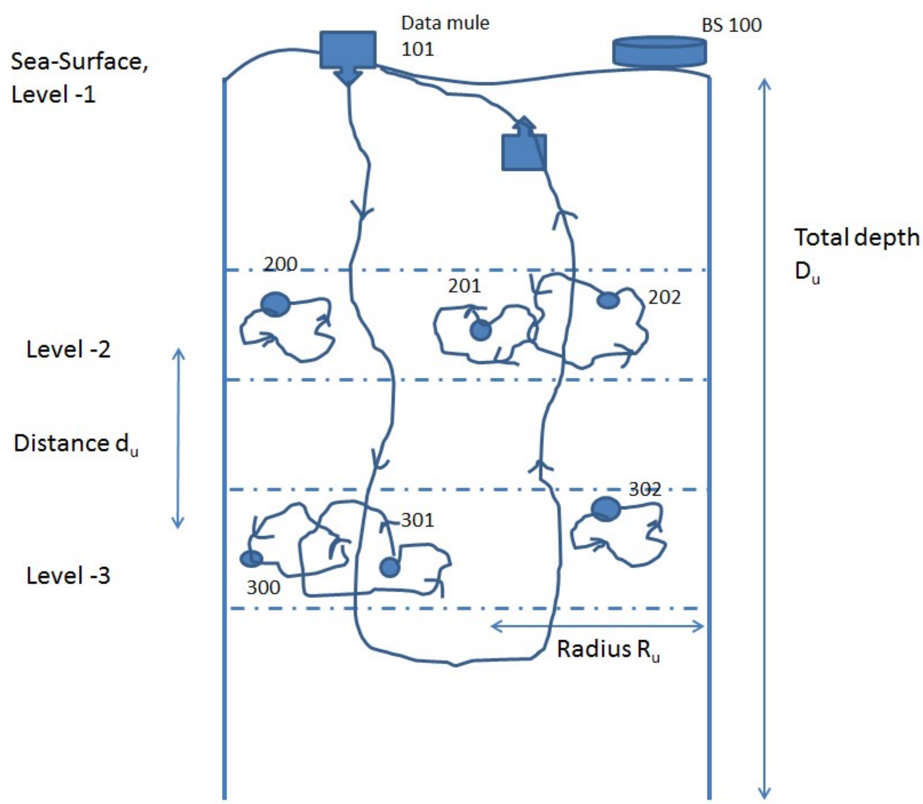

Figure 1. Proposed Network architecture for 3D mobile UASN

For this 3D mobile network architecture, protocol stack consisting of clustering protocol, TDMA based MAC protocol, and data collection algorithm is designed and simulated. Details of these protocols are provided in the next section.

3. Protocol Description

Initially, nodes of the network are deployed as per the architecture specified in Section 2, without finer control on their positioning. Nodes are programmed with their node address and networking algorithms. Network does contain static as well as mobile nodes. Passive mobility of the nodes is assumed to be bounded by the boundaries of the cuboid area. If the node deviates beyond the region, it might be untraceable and hence assumed to be dead or lost. Mobile nodes move according to defined trajectory, within the boundaries of the cuboid region.

After this initial deployment, nodes at each level start the process of selecting a cluster-head. For this selection, a probabilistic value has been provided (programmed) with each node. At each level, nodes broadcast the probability value using a power level (P_L). (With this power level P_L of transmission, a node can reach to all other nodes at its level of deployment.) All nodes then have the probability values of its neighbours. Based on the values of probability (which is also taken as weight here), each node selects a node with highest probability value as a cluster-head node. This way each node in a particular cluster refers to one of the nodes as the cluster-head.

After the selection of cluster-head node at each level of deployment, data collection process starts. For this data collection in a cluster, a simple TDMA based MAC protocol is designed. TDMA based MAC protocol design is chosen here, since these protocols can exploit advantages in terms of simplicity, fairness and energy efficiency. Collisions, idle listening and over-hearing can be avoided in these protocols.

In the proposed TDMA MAC protocol, data collection starts with the cluster-head node broadcasting a message to all nodes requesting them to send the data of the corresponding cycle. The nodes then transmit their data to the cluster-head at a specified delay from the time when they receive cluster-head's message. The specified delay is given by the following equation:

$$D = t_{PDT} * (1 + rem(A\%10)) \tag{1}$$

here**, D** is the delay in ms, **A** is the address of the node, rem(I % J) refers to the remainder of **I** when divided by **J**. The multiplying factor of t_{PDT} (milliseconds) is the packet delivery time.

Packet delivery time t_{PDT} can be calculated as follows:

Consider S = size of packet to be transmitted (in bits), B = bit rate in bps, c =Average propagation Speed of acoustic signal in water i.e. 1500 m/s, and R is the distance of communication. Then,

Packet transmission time = $t_{PTT} = S / B$ (2)

Propagation time = $t_{PT} = R / c$ (3)

And Packet delivery time = $t_{PDT} = t_{PTT} + t_{PT}$ (4)

This TDMA MAC schedule is executed at all the clusters to collect the data from the cluster-member nodes. The interference among the adjacent cluster is avoided by using proper power level of transmission by each node.

After the data collection at each cluster (or level), the next phase is for the data mule to collect the data from cluster-head node of each cluster. After a time period T seconds, the data mule starts moving downwards to visit the region of deployment of clusters, level by level. When it reaches to the region of clusters, it broadcasts a "Hello" message to indicate its arrival and availability in the particular cluster. The cluster-heads, on receiving "Hello" message, transmits the collected data to the data mule. After collecting data from all clusters, a data mule node climbs-up to the sea-surface to finally relay the data to the base-station node. This cycle continues in the network for the purpose of continues data collection in (quasi) real time.

4. Implementation of proposed protocols and results

UnetSim simulator has been used for the implementation of proposed protocols. UnetSim simulator is developed by Acoustic research laboratory of National University of Singapore under Unet Project. Main component of UnetSim is the agent-based network stack termed as UnetStack [10]. It has a service oriented architecture which allows information to be shared, services to be provided, and behaviors to be negotiated between different agents. In UnetStack, user can describe a code in Domain Specific Language (DSL) developed using Groovy. This same code can be run in simulation and can also be deployed on underwater modems.

The parameters of network architecture and simulation set-up are provided in the Table 1:

Table 1. Parameters of network architecture and simulation set-up

Network architecture parameters		**Simulation Parameters**	
Total Depth D_u	1500 m	Frequency of operation (f)	25 kHz
Distance d_u	500 m	Bandwidth (BW)	4096 Hz
Radius R_u	20 m	Bit Rate (B)	2400 bps
Data mule speed	1 m/s	Size of data packet (S)	128 bits
No. of levels of deployment (L_T)	3 (excluding sea-surface level)	Power level (P_L)	-35 dB
No. of nodes in each level	10	Average propagation Speed of acoustic signal in water (c)	1500 m/s

Results of one run of the simulation are summarized below:

Step 1 – Cluster-head selection – Based on the probability values in the nodes and execution of clustering protocol, following results are obtained in the test-run.
Cluster-head node of cluster 1 (At level 2 of 500 m) = node 203
Cluster-head node of cluster 2 (At level 3 of 1000 m) = node 319
Cluster-head node of cluster 3 (At level 4 of 1500 m) = node 428

Step 2 and 3 –Schedule of the data collection at each cluster by its cluster-head node is briefly provided in the Table 2. Along with this, schedule of data collection by data mule node at each cluster is also provided in the table.

Table 2. Schedule of the data collection at each cluster

Level	Event	Time
2	CH broadcast	159.000 sec
	Node 201 transmits to CH	159.405 sec
	Node 210 transmits to CH	160.694 sec
	Data mule “Hello” message	680.115 sec
	CH transmits to Data mule	680.230 sec
3	CH broadcast	205.622 sec
	Node 301 transmits to CH	206.021 sec
	Node 310 transmits to CH	207.334 sec
	Data mule “Hello” message	1180.144 sec
	CH transmits to Data mule	1180.288 sec

4	CH broadcast	234.000 sec
	Node 401 transmits to CH	234.248 sec
	Node 410 transmits to CH	235.597 sec
	Data mule "Hello" message	1680.170 sec
	CH transmits to Data mule	1680.318 sec

Step 4 : Data transmission by data mule to the Base station –
At end of the round of data mule, it reaches to the sea-surface and transmits the collected data to the base-station node at 3420 sec. Data mule repeatedly traverses in the network to collect the data and to relay it to the base-station node.

5. Conclusion and future scope of the work

In this paper, simple network architecture for three-dimensional mobile UASN is proposed. In this network, number of nodes are deployed at different depths in the water column in the ocean. These nodes are bounded by the cuboid shaped region for their movement. For this 3D mobile UASN architecture, a clustering protocol, TDMA based MAC protocol, and data collection strategy using mobile data mule is designed. Simulation of the proposed network and protocols is performed using UnetSim simulation platform for an ideal simulation environment.

For the future work, trajectories of the mobile nodes can be planned to suit the requirements of applications, or based on the constraints of energy, network lifetime, sampling rate and so on. Network can be allowed to form multiple (overlapping or non-overlapping) clusters depending on various parameters on optimization. Further, simulation parameters can be modified to evaluate the working of proposed protocol in more realistic and dynamic ocean environment. Effect of quality of communication links on the proposed protocols can be tested using practical channel models from simulation platform.

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