Simulation and Testbed Implementation of TDMA MAC on Underwater Acoustic Sensor Network

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Abstract—Three Dimensional (3-D) Underwater Acoustic Sensor Network (UASN) can be used to detect and observe ocean environment using co-operative and distributed sampling. We are proposing a multi-level clustering topology for ocean column monitoring application. A simple Cluster-Based TDMA MAC (CB-TDMA) protocol is simulated on this network using SUNSET platform developed by SENSES lab, Sapienza University, Rome. Analysis is provided in terms of packet delivery ratio, network delay and energy consumption. This CB-TDMA MAC along with multi-hop tri-message time synchronization is also implemented on a hardware test-bed in our laboratory. Brief description of this implementation is also provided in this paper.

Keywords—Underwater Acoustic Sensor Network, TDMA MAC, Packet Delivery ratio, Energy Analysis, Test-bed

I. INTRODUCTION

Many important features of Wireless Sensor Network such as distributed processing, real time computing and communication, large scale coordination and self-organization has motivated researchers to use this networking paradigm for underwater applications. Various tasks such as (i) oceanographic data collection, (ii) pollution monitoring, (iii) offshore exploration, (iv) disaster prevention, (v) assisted navigation and (vi) tactical surveillance applications can be performed more efficiently using WSN. One such application is that of long term, ocean-column monitoring. Traditional approach used for ocean-bottom or ocean-column monitoring is to deploy oceanographic sensors, record the data, and recover the instruments. This approach creates long lags in receiving the recorded information. In addition, if a failure occurs before recovery, all the data is lost. Adaptive tuning or reconfiguration of the system is not possible in ad hoc fashion. Also, amount of data to be collected might be limited because of limited storage capacity of onboard devices [1]. To overcome these issues, sensor nodes having two-way communication capability can be deployed underwater (along with possible use of other Underwater Instruments, Autonomous Underwater Vehicles (AUVs) or Unmanned Underwater Vehicles (UUVs)). The sensor nodes along with underwater instruments and/or vehicles form the Underwater Wireless Sensor Network (UWSN). This network is then connected to a surface station which can further be connected to a backbone, such as the Internet, through an RF link. In this manner, UWSN provides a complete real-time interactive environment. A remote observer can monitor, extract and analyze real time data from specific area of the ocean. It is also possible to re-tune or reconfigure this network by sending control messages from base-station to an individual or to the group of sensor nodes of network. Since data is transferred to the control station when it is available, data loss is prevented until a complete failure occurs. This paper is organized as follows, in section II, a brief literature of UASN, Underwater acoustic communication, Data link layer developments and SUNSET framework is provided. In section III, proposed deployment of three dimensional communication architecture is described. In section IV, simulation results of Cluster-Based TDMA (CB-TDMA) MAC along with PDR, Delay and Energy analysis is given, whereas in section V, hardware testbed implementation of this MAC is briefly presented. In section VI, we present the conclusions.

II. LITERATURE SURVEY

Underwater communication has been used around for over a century, mainly for the purpose of oceanographic explorations. The preferred carrier for underwater communication is acoustic wave. Acoustic waves suffer lesser attenuation, interference or scattering when compared to RF or Optics waves. Understanding intricacies of underwater acoustic communication is fundamental to developing an underwater acoustic network. Basically, an Underwater Acoustic Sensor Network (UASN) is formed cooperatively by several sensor nodes that use bidirectional acoustic links.

UASN can be classified based on the depth of deployment (Shallow or Deep water network) along with further criteria such as mobility (Static or Mobile Networks), architecture (2-Dimensional or 3-Dimensional), duration (Short term or Long term network), distance (Large or Small network), number of nodes per cubic meter (Scarce or Dense) and topology (Random or Structured). Ocean depth less than 100 meters is referred as shallow water and the network deployed in shallow water is termed as shallow water network. This type of network would be generally 2-Dimensional. On other hand, network deployed in deep water, termed as deep water UASN is usually a 3-Dimensional network. Certain deployments of UASN use AUVs/UUVs as part of the network. In this case, or in case of availability of mobile sensor node, the network becomes a mobile network. Otherwise, it is considered as a static network. Though sensor nodes drift because of underwater current in static networks too, such mobility is termed as passive mobility as compared to the active mobility of AUV/UUVs. UASNs can have a random topology (wherein all the sensor nodes are
randomly deployed), or have structured topology (wherein the nodes are deployed in certain pre-determined fashion). Other classification of the UASN network such as Short term/Long term, Large/Small, Dense/Scarcce do not have very widely accepted definitions, and can be taken in relative manner. Network designer has to choose an appropriate type of network based on the requirement of applications and availability of resources at hand.

A. Underwater Acoustic Communication

Underwater acoustic communication channel possesses the following characteristics [2]–[6],

i. The absorption loss increases with frequency as well as with distance, eventually imposing a limit on the available bandwidth within the practical constraints of finite transmission power.

ii. Propagation delay in underwater environment is very large and variable.

iii. Probability of bit error is much higher and temporary loss of connectivity (shadow zone) sometime occurs, due to extreme characteristics of the channel.

iv. Channel impulse response is spatially as well as temporally varied.

v. Channel is severely impaired, especially due to multi-path propagation and fading.

The factors of underwater acoustic communication that influences the underwater networking are described in detail in the literature [7]–[10].

B. Data Link Layer development for UASN

Media Access Control (MAC) protocol of the data link layer is essential for controlling and managing the shared communication medium among all the nodes in the network. MAC protocol used in wireless sensor network provides self-organizing capabilities to the network by providing necessary infrastructure for hop-by-hop wireless communication [11]. Important attributes of MAC layer are energy efficiency, scalability, network throughput, fairness, latency, and bandwidth utilization. An efficient MAC protocol can ensure energy saving (by possibly providing sleep-wake patterns, collision avoidance mechanism etc.), high network throughput and low channel access delay.

Protocols for UASN can be classified into two main categories

i. Contention free protocols (FDMA, TDMA, CDMA based protocols)

ii. Contention-based protocols. Contention based protocols can be further categorized into protocols based on random access method and those based on collision avoidance methods.

Among contention free (or schedule based) protocols, FDMA based MAC protocols are not suitable for UASN since the available bandwidth in UASN is very limited. FDMA needs to further divide the band into narrower sub-bands for allocation to individual node. The narrow bandwidth channel of sub-bands would be more vulnerable to fading and multipath phenomenon.

Researchers have developed many TDMA centric MAC protocols such as (STUMP [12], I-TDMA [13], C-MAC [14], DSSS-TDMA [15], TDMA [16]). TDMA based MAC protocols can exploit advantages in terms of simplicity, fairness and energy efficiency. Collisions, idle listening and over-hearing can be avoided in these protocols. Hidden node problem is easily solved without using extra message overhead because neighboring nodes transmit at different time slots. There are also certain disadvantages associated with TDMA based MAC protocols such as poor channel utilization, scalability on dynamic basis and requirement of time synchronization.

Most researchers prefer the CDMA based approach for designing MAC protocols such as [17], [18]. Large bandwidth channels of CDMA are quite robust to frequency selective fading caused by multi-paths in underwater networks. CDMA provides better performance with the possibility of coherently combining the multipath arrivals by employing Rake filters at the receiver. According to [1], CDMA and spread-spectrum signaling appear to be a promising multiple access technique for shallow-water acoustic networks. On the other hand, CDMA system capacity is restricted by the presence of multiple access interference (MAI) in the system. CDMA also suffers from the issue of Near-Far effect.

C. SUNSET (UWSN group, SENSES Lab, Sapienza University)

SUNSET [19] is the Sapienza University Networking framework for underwater Simulation, Emulation and real-life Testing. It is a new solution, developed by the UWSN Group, to seamlessly simulate, emulate and test in real-life novel communication protocols. SUNSET allows the user to develop the code with the help of NS-2 and NS-2 MIRACLE. It is a powerful toolkit for implementation and testing of novel protocol solutions for underwater sensor networks. SUNSET enables testing and enhancement of underwater solutions using a controlled simulation environment. The simulation code can be then transparently ported to various hardware and underwater platforms for protocol emulation and actual in field testing. SUNSET was the first open source framework for seamless simulation, emulation and actual at sea testing of novel underwater systems. The new SUNSET version 2.0 has been recently released to the community in October 2013 [20].

When running simulations SUNSET can use different underwater acoustic channel models, such as empirical formulae and Bellhop ray tracing. On the other hand, in emulation mode, SUNSET is interfaced with real external hardware: Acoustic modems for underwater communication; sensing platforms for data collection; the navigation system of AUVs (Autonomous Underwater Vehicles) and ASVs (Autonomous Surface Vehicles) to control the vehicle; etc. The designed architecture is flexible and open so as to allow the integration of any external device provided the APIs are available to control the operation.

III. PROPOSED DEPLOYMENT OF THREE DIMENSIONAL COMMUNICATION ARCHITECTURE

Three-dimensional underwater networks are used to detect and observe phenomena that cannot be adequately observed by means of sensor nodes at the bottom of the ocean, i.e., to perform cooperative sampling of the 3D ocean environment. In
this architecture, sensors float at different depths to observe a given phenomenon. We propose this 3-D architecture assuming suitable mechanical/electrical arrangement would be available to keep the sensor motes and modems floating at suitable heights. This architecture aims to cover the ocean column of cylindrical shape. The depth of the column is around 2500 meters and the radius of around 10 meters. This column is further divided into 5 levels of 500 meters each [Figure 1].

At each level, several nodes will be placed. One of these nodes will be appointed as cluster-head node, by the initial cluster-head selection algorithm. All the nodes will have sensing, processing and communication capabilities. The power level of the transmission/reception of the antenna of cluster-head node would be set at maximum level, while that of the cluster nodes would be at minimum level. All the nodes will sense the required parameter at regular intervals and then send the data to the cluster-head node. Cluster-head node will relay data in the upward direction, in its assigned time period after it has appended its own data with the data from its cluster-nodes at its depth as well as the data received from its bottom level cluster-head node. In this fashion, finally data will be collected by the node residing at the sea surface of the column, which also acts as underwater-gateway station. Further this data will be relayed via radio towards the gateway/control station/base station at the shore. This 3-D UASN deployment along with velocity profile of the acoustic signal for the ocean (according to Uricks model) is shown in the Figure 1. Data communication path is shown by dotted lines connecting the cluster-head nodes at various levels.

Fig. 1. Three dimensional UASN deployment along with standard velocity profile of acoustic signal along depth of ocean. (Yellow solid circles represent the nodes)

A. Communication range and sensing area

Parameter of sensing is application dependant. The sensor has to be embedded with the modem set-up, i.e. ideally the underwater mote should have sensing, processing, and communication capability. Motes should be powered from battery source available on board. Since antenna consumes tremendous amount of power during transmission as well as reception, underwater mote should implement mechanism of sleep-wake pattern along with different power levels for the communication. This is essential in the column monitoring deployment since the interference in horizontal and vertical communication can be avoided with such mechanism. We are assuming that the vertical distance of 500 meters can be reached with the maximum power level of the acoustic modem and the horizontal distance of 10 meters can be reached with the minimum power level transmission. Cluster-head node will communicate with the other cluster-head nodes in the level above and below it, at the maximum power level which may drain the node out of energy sooner. For this reason, there should be an algorithm to determine the residual power with each node in the network, and a cluster-head re-selection process is necessary. When the current cluster head node energy is below the threshold value, a new cluster head should be re-elected, which can be any node among its cluster-nodes that has the maximum power available at that time instance.

It also dictates the need of adaptiveness in power levels of the nodes as well as in routing criteria. These changes in the network topology can be driven by the gateway, which essentially means a top-down communication at regular intervals. A provision can be made for the communication flow from gateway to the bottom-most node, which can be used to send any form of network control information like time-synchronization, status of the network i.e. addition-removal of any node, re-routing, or immediate query of any specific location by the base station.

B. Calculations of communication delay and Time slots

As shown in Figure 1, the complete column has depth of 2500m and radius of 10m. For networking parameters, we have assumed following parameters:

i Data Packet size (DP) = 100 Bytes

ii Control Packet size (CP) = 5 Bytes (Time synchronization information)

iii Average Propagation Speed of acoustic signal in water (PS) = 1500m/s.

iv Bit rate (BR) = 100 bits per sec.

Parameters such as Data Packet Transmission Time (DPTT), Control Packet Transmission Time (CPTT), Propagation Time (PRT), Data Packet Delivery Time (DPDT) and Control Packet Delivery Time (CPDT) are defined using following equations.

\[ DPTT = \frac{DP}{BR} \]  
\[ CPTT = \frac{CP}{BR} \]  
\[ PRT = \frac{Distance}{PS} \]  
\[ DPDT = DPTT + PRT \]  
\[ CPDT = CPTT + PRT \]

In this scenario,

DPTT = 8 sec.

CPTT = 0.4 sec

PRT (for horizontal link of 10m) is 0.0066 sec.
PRT (for vertical link of 500m) = 0.3333 sec.

DPDT (Horizontal link) = 8.0066 sec

DPDT (Vertical link) = 8.3333 sec

\[ i \] 
\[ ii \] 
\[ iii \] 
\[ iv \]
cycle). Time slot value is made equal to DPDT (vertical link), i.e. 8.3333 sec.

Over the vertical link, we are using time slots for each level to transmit data. Each level transmits data at a periodic/cyclic interval of 10 mins, with initial time staggering. For example, the bottommost levels (i.e. level 5) cluster-head node will send data to the cluster-head node of the level above it (i.e. level 4) at intervals 10 min, 20 mins, 30 mins and so on in the further cycles. This cluster-head node of the level 4 will send data to the cluster-head node of level 3 at intervals 12 mins, 22 mins, 32 mins and so on. Level 4 cluster-head node will augment its data to the data of level 5 which it has received earlier and will send it to the level above it. These time slots and staggering are shown in the Table I. At each level, cluster head node will collect the data from its cluster nodes in a minute preceding their transmission schedules using simple TDMA MAC.

<table>
<thead>
<tr>
<th>Level</th>
<th>Cycle 1 time slot</th>
<th>Cycle 2 time slot</th>
<th>Cycle 3 time slot</th>
<th>Cycle 4 time slot</th>
<th>Cycle 5 time slot</th>
<th>Cycle 6 time slot</th>
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<td>38</td>
<td>48</td>
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Table I. Time Slots with Staggering Used by Cluster-Head Node of the Different Level Clusters. [Level 1 is Sea-Surface Level whereas Level 5 is Bottom-Most Level]

IV. SIMULATION SCENARIO, RESULTS AND ANALYSIS

For the simulation using SUNSET, we are using 2 different scenarios to showcase the working of horizontal layer cluster and vertical link separately.

Scenario 1 consists of 11 nodes. Node at the ocean surface acts as the sink node for the network. There are two clusters (of 5 nodes each) at the depth of 500m and 1000m from sink respectively as shown in Figure 2. Cluster 1 consists of node 2,3,4,5,6 wherein node 2 is assigned as cluster-head initially. Cluster 2 consists of node 7,8,9,10 and 11, wherein node 7 is the initial cluster head. Time frame for CB-TDMA MAC consists of 11 slots where one slot is assigned per node in one frame. Time slot value is made equal to DPDT (vertical link), i.e. 8.3333 sec.

Data transmission cycle starts from cluster 2. Initially nodes 8, 9, 10 and 11 send data to cluster head node 7 in respective time slots. Cluster head node 7 sends data on a vertical link to cluster head node 2. Nodes 3,4,5,6 also send the data to cluster head of cluster 1, i.e. node 2 in their assigned time slots. After collecting data from both clusters, node 2 sends data using vertical link to node 1. Nodes are put in sleep mode for all the time except its own allotted time slot to save energy.

Scenario 2 consists of 8 nodes. One node at the ocean surface acts as a sink for the network. All other nodes form a cluster at the depth of 500 meters below this sink as shown in Figure 3. Among the 7 nodes has been assigned as cluster-head. Cluster-head collects the data from all other cluster nodes in their respective time slots and sends the information towards sink along with its own data in its allotted time slot. Time frame for CB-TDMA MAC consists of 8 slots, one slot is assigned per node in a frame. This scenario is simulated in order to show the working of one cluster in detail. Multiple such independent clusters can be utilized in order to have ocean column monitoring application.

Table II shows the delay analysis for scenario 1. Here delay is calculated on single hop. (For example) first entry in Table II refers to the delay of all packet transmission from node 11 to node 7. Further it can be observed that delay between node 7 and 2 is significantly higher since node 7 handles more packets than other nodes in cluster 2. Similarly delay from node 2 to 1 is highest since node 2 forwards all packets of cluster 1 and 2 to node 1. In simulation of scenario 1, every node is transmitting 4 packets. With the help of Equation 4, transmission of 4 nodes requires 32.0267 sec on horizontal link. Cluster head node 7 handles 20 packets, and hence the delay of vertical link transmission is 166.67 sec. Similarly node 2 forwards 36 packets along with its own 4 packets towards node 1. Hence delay in all packet transmission is 333.33 sec. In order to reduce the delay at cluster head, it is advisable to have data aggregation technique to reduce number of data packets. It would also help in conserving energy and memory requirement of cluster head. It can be noted that all nodes which need 3 hops to reach to sink will take (3 \times single hop delay), i.e.
Table III gives the analysis of energy consumed (only in transmission) at various nodes. Energy consumed in transmission (ECT) can be calculated as follows,

\[
ECT = ETX \times DPTT \times NP
\]  

Again it can be observed that node 7 and 2 have more energy consumption as compared to other nodes in the network. Node 2 has the highest energy consumed since it has to forward all the packets of cluster 1 and 2.

Energy consumed in reception (ECR) of packets can be similarly calculated using

\[
ECR = ERX \times DPTT \times NP
\]

Using Equation 7, we can theoretically calculate the energy consumed in reception at node 7 to be 108.8 Joules, of node 5 to be 244.8 Joules and of node 1 to be 272 Joules.

After end of 4 packet delivery, i.e. 4 cycles of the network, Node 7 has consumed 588.8 Joules, Node 5 about 1204.8 Joules, Node 1 about 272 Joules and all other nodes have consumed 96 Joules. For a network to last long, it is important to rotate the cluster head based on energy threshold. Cluster head would also have to work at higher power level than other nodes since it has to transmit the data at 500 m. In this scenario we are considering the energy threshold to be 1200 Joules, Node 7 and 2 have more energy consumption as compared to other nodes in the network. Node 7 has consumed 588.8 Joules, Node 5 about 1204.8 Joules, Node 1 to be 272 Joules.

On similar lines, Table IV and V shows the delay analysis of scenario 2.

Owing to the fact, that there is no overlap between the packet transmission and ideal situation, PDR is 100 percent. For practical purposes various packet error modules can be introduced in the simulation for simulating real-time behavior of ocean environment. Here, We essentially focused on algorithmic implementation of CB-TDMA MAC.

V. HARDWARE TESTBED IMPLEMENTATION OF CB-TDMA MAC

Figure 4 shows the test-bed setup installed in the laboratory. In this test-bed, the Simple Acoustic Modems (SAMs) are immersed in the water tank of the capacity of 800 liters having dimensions as 2625mm 1375 mm and height of 320 mm. We have connected the TelosB mote with the acoustic modem by serial communication. The acoustic modem simply transmits the data passed to it from TelosB. We have 4 acoustic modems available with us. So we used two different implementation cases as shown in Figure 5. In case 1 of Figure 5, the network architecture captures the working of complete vertical link. Using implementation case 2 of Figure 5, efforts are made to illustrate the working of one complete cluster.

![Fig. 4. Laboratory testbed of UASN](image-url)
modem. If the node fails to get time synchronized, then also the node can participate in the data cycle, and hopefully works (as was observed on the set-up) without causing collisions in that cycle. This can happen, provided the clock drift from the previous wake cycle is well within the limit. Time synchronization phase, along with provision of two retransmissions has 22 minutes duration allotted. Each node requires three message/packet exchange for time synchronization and one message/packet is broadcasted at end of synchronization [21]. In best case, time synchronization for network (i.e. node 2, 5, and 7) takes 12 packets (i.e. 4.4 mins) and in worst case, 48 packets (i.e., 17.6 mins). If the synchronization happens in first attempt the corresponding transmitter node is programmed to sleep in order to save energy. After 22 minutes, the data cycle starts. Data is sent only once without retransmission attempt or acknowledgement. In data cycle, node 7 first sends the data (one packet of 22 bytes) to node 5. Node 5 appends its own data (or uses data aggregation) and sends the result to Node 2. Node 2 further sends data to Node 1 after appending or aggregating with its own data. Finally, node 1 transmits the data using radio communication to BS. Two minute period is allotted for Data cycle. After the data cycle, all the nodes sleep for duration of 30 minutes, providing duty cycle of around 50 percent. At the end of sleep period, again the same sequence of time synchronization (22 mins), data cycle (2 mins), and sleep period (30 mins) is followed.

In case 2, We have used the other set of 4 nodes to showcase the working on one complete cluster. The CB-TDMA MAC protocol along with multi-hop Tri-message time synchronization [21] is implemented successfully on both cases of this network topology, one exploring the breadth (1-2-3-4) and another exploring the depth of the network (1-2-5-7). Because of significant efforts in synchronizing nodes in the network, PDR is significantly improved (observed to be 5-7). Because of significant efforts in synchronizing nodes in the network, PDR is significantly improved (observed to be 5-7).

VI. CONCLUSION

A variant of TDMA MAC protocol, CB-TDMA MAC has been successfully simulated using SUNSET framework for the application of ocean column monitoring. Various scenarios exploiting vertical and horizontal link has been analyzed in detail in paper. Total delay and energy analysis has also been presented. CB-TDMA MAC protocol gives a PDR of around 90 percent, with multi-hop Tri-message time synchronization.

REFERENCES


