

Implementation of Multi-hop Bidirectional Communication Link with Time-Synchronization on Miniature Test-bed of Underwater Acoustic Sensor Network

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Abstract

In Wireless Sensor Networks (WSNs), multi-hop communication links are preferable over single hop communication for energy efficiency. In Underwater Acoustic Sensor Network (UASN) it provides additional importance in terms of better utilization of the scarce acoustic bandwidth.

For the convergence of various protocols in WSN and UASN such as Localization, Medium access control and Routing, nodes in the network are required to maintain time-synchronization. In this paper, we discuss the implementation details of multi-hop bidirectional communication link with time-synchronization on miniature test-bed of UASN. Successful implementation of this bidirectional link gives confidence and flexibility in developing higher layer protocols on the test-bed and expanding the network topology.

Keywords: Underwater Acoustic Sensor Network (UASN), Wireless Sensor Network (WSN), Time Synchronization, Multi-hop Communication.

1. Introduction

Though acoustic telemetry and underwater acoustics has been in existence for several decades, most of the major discoveries in oceanography have occurred only within the last 50 years. The ocean covers 71% of Earth's surface, and so far we have only studied a very small percentage of the ocean floor and the global ocean. Many new discoveries await us as we use new instruments and deep submergence vehicles to explore "inner space" in the 21st century. [1]

Ocean studies are important not just because the ocean holds various natural treasure, but also because of various factors such as,

- Ocean is the dominant physical feature on our planet; it is no surprise that the ocean plays an important role in shaping our weather and climate.
- From tiny microbes to blue whales, the diversity of life in the ocean is astounding. It supports unimagined ecosystems and exotic communities of life.
- Ocean is a powerful force on our planet, helping to shape the physical features of Earth.
- Ocean and humans are inextricably interconnected. From providing us with food, energy and mineral resources, and recreation opportunities to holding archaeological clues to the past, the ocean affects every aspect of human life. In turn, our actions, from use of resources to pollution or conservation, directly affect the ocean.[2]

Oceanographers, marine biologists, scientists wish to explore more of the inner space of the ocean by establishing observatories with the help of modern technology including wireless sensor nodes, underwater instruments and autonomous underwater vehicles. Collecting and analyzing real time data continuously from these devices will help researchers to have a better understanding of the ocean properties, life-processes and events. Ocean bed (rocks and sediments) is really the archive of information that allows us to unravel Earth's geological processes and history. At the same time, analyzing the ocean processes data will help us to predict the future climate changes and its impact on human life.

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 UASN is formed cooperatively by several sensor nodes that use bidirectional acoustic links

1.1 Underwater Acoustic Communication

Underwater acoustic communication channel possesses the following characteristics, [3-7]

- 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)

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sometime occurs, due to the extreme characteristics of the channel.

- IV. The channel impulse response is spatially as well as temporarily varied.
- V. The 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. [8-11]

1.2 Underwater Acoustic Sensor Network

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 this modern technology of WSN.

One such application is that of long term, ocean-column monitoring. The 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, the data to be collected might be limited since capacity of on-board storage devices may be limited. [12]

To overcome these issues, sensor nodes having wireless communication capability can be used to set up an underwater network. Along with sensor nodes, various underwater instruments, Autonomous Underwater Vehicles (AUVs) or Unmanned Underwater Vehicles (UUVs) can also be deployed. These sensor nodes along with underwater instruments and/or vehicles form an Underwater Wireless Sensor Network (UWSN). The network is then connected to a surface station that can further be connected to a backbone network, such as the Internet, through an RF link. In totality, this configuration provides a complete real-time interactive environment. A remote observer can monitor, extract and analyze the real time data from specific area of the ocean. It is also possible to re-tune or reconfigure the network by sending control messages from base-station to an individual/ 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.

Setting up of underwater acoustic networks requires an optimized approach in resource (Bandwidth, Memory, Power etc.) allocation and utilization when compared to their terrestrial WSN counterpart. Peculiar characteristics of underwater acoustic communication such as a) Limited Bandwidth, b) Long and variable propagation delay, c) Spatially as well as temporarily varying channel impulse response, and d) Very high probability of bit error bear important implications on the design of network architectures and related protocols. The characteristics of the physical layer influences medium access as well as higher-layer protocol design [13-14]

In this paper, first we propose the real-time Three Dimensional (3-D) Underwater Acoustic Sensor Network (UASN) for ocean column monitoring. The communication architecture of this model is detailed. A miniature test-bed which logically resonates with the idea of column structure

of the proposed 3-D UASN was set up in the laboratory. We have implemented the multi-hop bidirectional communication link with the help of time synchronization message exchanges on this set-up, which is analyzed in the paper.

Paper organization is as follows - In Section 2, we establish the necessity of multi-hop communication link and time synchronization is UASN from literature review. In Section 3, communication architecture for 3-D UASN for column monitoring is proposed. In Section 4, miniature test-bed setup is discussed along with the details of components, their interconnections, multi-hop communication model, time synchronization algorithm, time frame used for transmitting data over the bidirectional communication link. Brief overview of tri-message time synchronization and its multi-hop version is provided in section 5. Results of this test-bed are analyzed in terms of PDR in section 6. Effect of implementation of time-synchronization is also illustrated in this section. In last Section, we provide the conclusions and future scope of the work.

2. Related Work

In general, WSN or UASN can be evaluated by using metrics like (i) lifetime, (ii) coverage, (iii) response time, (iv) temporal accuracy, (v) security, (vi) effective sampling rate, (vii) overall cost and (viii) ease of deployment. The design factors like (i) heterogeneity, (ii) distributed processing, (iii) low bandwidth communication, (iv) large scale coordination, (v) optimum utilization of sensors, (vi) real time computation, (vii) fault tolerance under normal and severe environmental conditions can be considered in sensor networks. [15-16]. One of the most important operational challenges is "Energy Efficiency". The design of the sensor network can be done by keeping the energy efficiency as a primary focus. Not just the network architecture but the entire protocol stack of individual node needs to be critically examined and modified for the energy optimization under the chosen area of implementation, which can substantially help in increasing the lifetime of the deployed network. In this aspect, two significant underlying points are important, a) Requirement of multi-hop links to save energy, b) Requirement of time synchronization to effectively schedule 'Sleep-period' to save energy.

2.1 Requirement of multi-hop nature of communication in UASN

Available bandwidth of acoustic communication system decreases with distance. Hence multi-hop communication is preferred when compared to single hop communication over larger distances. In an acoustic setting, dividing a long link into a number of shorter hops will not only allow power reduction, but will also allow the use of greater bandwidth [8]. A greater bandwidth yields a greater bit rate and shorter packets - as measured in seconds for a fixed number of bits per packet. While shorter bits imply less energy per bit, shorter packets imply fewer chances of collision on links with different, non-negligible delays. Both facts have beneficial implications on the network performance and lifetime.

2.2 Requirement of time synchronization in sensor networks

The process of achieving and maintaining common time base is called as time-synchronization. Wireless Sensor

Networks (WSNs) are distributed systems where operations of individual nodes are controlled by the timing information available from local clock. WSN applications require collaborative information from multiple sensors, so the timing information associated with data at each sensor device needs to be consistent. Certain applications of sensor networks need the right chronology of the events to be detected (e.g. Target tracking), while some applications need the absolute time of the events (e.g. Disaster prevention system). In MAC protocols, low power 'Sleep mode' is used in order to save energy. As pointed out in [17-18], there is incentive in putting the nodes in sleep mode to conserve energy, since the power consumption in sleep mode is less than during the ideal listening mode. For effective scheduling of sleep-wake pattern, time synchronization in sensor network is indispensable. Many important protocols in the sensor network (e.g. TDMA-MAC protocol) cannot work without time-synchronization [19]. Achieving initial time synchronization itself is challenging, since the nodes might be turned on at different time interval. Even after synchronization in initial phase, the inaccuracies in node's clock, changes in topology, inclusion or failure of nodes requires re-synchronization to be performed at regular intervals.

Though many protocols have been suggested for terrestrial sensor networks (RBS [20], TPSN [21], FTSP [22] and LTS [23]) and they perform reasonably well, very few protocols (THSL [24], Tri-message [25]) have been suggested for the high-latency underwater acoustic networks, since achieving time-synchronization for high-latency networks is even more challenging issue.

In [25], 'Tri-message time-synchronization protocol' is suggested for high latency networks, keeping the resource constraint as primary focus. Authors Tian et. al, suggests the idea of using only three messages for achieving the time-synchronization, thus reducing the time and energy spent in the process. Protocol is designed assuming several factors such as (i) constant propagation delay over the duration of message exchange (ii) Time-stamping at lowest possible layer of protocol stack (iii) short-term skew-stable clocks. In [26], authors have developed a very simple and modular extension of this protocol for the use in multi-hop scenario. This multi-hop version of time-synchronization has been implemented on our set-up. These protocols are briefly explained in section 5.

In majority of the sensor network scenarios, the data is routed to gateway node via multi-hop communication path. For the same reason, the time synchronization information has to percolate from the reference node (mostly the gateway node) to every other node of the network; essentially via multi-hop. In such scenario, the reference node first synchronizes the nodes in its single hop region. Once these nodes of single hop region get synchronized, these nodes synchronize other nodes in their respective single hop and so on.

In the next Section, we propose the deployment of 3-D communication architecture for UASN.

3. 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 20 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 Urick's model) is shown in the Figure 1. Data communication path is shown by dotted lines connecting the cluster-head nodes at various levels.

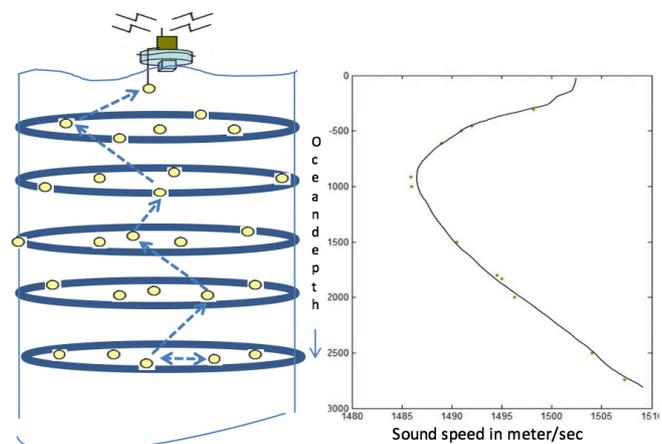


Fig. 1. Three dimensional UASN deployment along with standard velocity profile of acoustic signal along depth of ocean. (Yellow solid circles represent the nodes)

3.1 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 battery powered. Antenna consumes tremendous amount of power during transmission as well as reception. Underwater mote should implement the 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 20 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.

3.2 Calculations of communication delay and Time slots

As shown in Figure 1, the complete column has depth of 2500m and radius of 20m. It can fully cover the volume of 70650 cubic meters for the monitoring applications. For networking parameters, we can assume following features:

- (i) Data Packet size (DP) = 20 Bytes
- (ii) Control Packet size (CP) = 5 Bytes (RTS/CTS etc.)
- (iii) Average Propagation Speed of acoustic signal in water (PS) = 1500m/s.
- (iv) Frequency used by modem (Transceivers) in range of 30-40 kHz.
- (v) Bit rate (BR) = 50 bits per sec.

Data Packet Transmission Time (DPTT) = DP/BR
(1)

Control Packet Transmission Time (CPTT) = CP/BR
(2)

Propagation time (PRT) = Distance/ PS
(3)

Data Packet Delivery Time (DPDT) = DPTT+PRT
(4)

Control Packet Delivery Time (CPDT) = CPTT+PRT
(5)

Data Delivery Time with Three way Handshake (PDTHS) =
(3 × PRT) + (2 × CPTT) +DPTT
(6)

In this scenario,

- DPTT = 3.2 sec.
- PRT (for horizontal link of 20m) is 0.0133 sec.
- PRT (for vertical link of 500m) = 0.3333 sec.
- DPDT (Horizontal link) = 3.2133 sec
- DPDT (Vertical link) = 3.5333 sec

On the horizontal link, we are assuming the collision based MAC protocol, so the system of RTS/CTS (Request To Send/ Clear To Send) would be idealistic method to use. Assuming three-way handshaking method, the actual packet delivery time on horizontal link i.e. PDTHS is 5sec (approx). Over vertical link, we are using time slots for each level to transmit the data. Each level transmits data at a periodic/cyclic interval of 10 mins, with initial time staggering. For example, the bottommost level's (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 1. At each level, the cluster head node will collect the data from its cluster nodes in a minute preceding their transmission schedules.

Level	Cycles with timing (minutes)					
	Cycle 1	Cycle 2	Cycle 3	Cycle 4	Cycle 5	Cycle 6
1	18	28	38	48	58	68
2	16	26	36	46	56	66
3	14	24	34	44	54	64
4	12	22	32	42	52	62

In the next section, we describe development of miniature test-bed for testing various protocols and topologies of UASN. This novel test-bed is implemented using Simple Acoustic Modems and Telos-B motes. Currently we have implemented multi-hop bidirectional communication link along with effective time-synchronization protocol. Using this as basic building block, we can develop and expand the topology to match with proposed 3-D architecture of section 3.

4. Test Bed Implementation

Problem Statement- Our main objective in the test-bed implementation is to build an autonomous Underwater Acoustic Sensor Network and demonstrate the possibility of setting up successful multi-hop bi-directional underwater communication in presence of time-synchronization protocol. Successful implementation of these basic features gives confidence and flexibility in implementing higher layer protocols.

Components used in the test-bed are (i) Simple Acoustic Modem (SAM) from Desert Star System (ii) TelosB motes.

4.1 Simple Acoustic Modem (SAM)

SAM can transmit and receive digital data between underwater stations up to a typical range of 250 meters, with up to 1000 meters possible under ideal (deep-water) conditions. The SAM modem is designed for reliable exchange of data in a variety of underwater environments, from shallow areas or harbors all the way to deep oceanic waters.

4.1.1 SAM Features

- Acoustic data exchange in shallow, confined and deep waters alike.
- Works in high multi-path and noisy environments.
- Small size and low cost
- Low standby power consumption and energy efficient data transmission.
- Instant operation (no configuration) for use with “dump devices”.
- Configuration through serial commands for use with “smart devices”.

4.1.2 Typical Configuration of SAM

- Serial data port: 4800 baud, 8 data bits, no parity, one stop bit (Xon/Xoff software handshaking)
- Serial data port levels: RS-232
- Acoustic data transmit or receive speed: Speed 5 (13 bit/sec, single channel)
- Receiver Sensitivity: ‘High’ (detection threshold 16 units)

4.2 Telos Rev -B:

Telos-B is an ultra low power wireless module for use in sensor networks, monitoring applications, and rapid application prototyping. In our scenario, we are not using the default CC2420 radio, but the processed data (assuming it to be the data available from the underwater sensor module) is sent to the acoustic modem via 10 pin expansion connector i.e. UART0 port. By default, the TinyOS network protocol stack for serial communication on the TelosB is routed through the UART1 port which does not allow external access. Moreover, the UART1 port is multiplexed on the same bus with the USB port, rendering a modem link through this port unfeasible. Therefore, we modified the TinyOS serial communication protocol stack for connection with acoustic modem. The serial protocol stack is ported to function through the UART0 port. This enabled external access to the serial port.

Figure 2 shows the test-bed setup installed in the laboratory. In this test-bed, the Simple Acoustic Modems (SAMs) are immersed in the water tank. These modems are powered by using 15V, 2A adaptors. SAM features a 5-pin connector through which it communicates with the host and receives power. We have connected the TelosB mote with the acoustic modem by serial communication. (i.e. connecting UART0 port of the TelosB with the RS-232 cable connected with modem’s utility connector). The modem transmits or receives data at 4800 baud, 8 data bits, no parity, one stop bit. These acoustic modems are set to use RS-232 level by default. The acoustic modem simply transmits the data passed to it from TelosB. The modem can be configured for various transmit/receive data rate. We have used the data rate of 8 bits per second in this test-bed. Each packet to be transmitted is 22 bytes. Since the modems are very close in the set-up, the actual propagation delay can be neglected. The overall packet delivery time is equal to packet transmission time, which turns out to be about 22 seconds at 8bps. In the test-bed shown, the modem on the right-most corner (termed as Node) transmits the data to the node in the middle (termed as Cluster Head, CH). This data is further transmitted to the node on the left-most side (termed as Gateway, GW). Further, since this data received by GW is available with Telos-B mote, the data can be relayed to the ground based Base Station (BS) by using radio link. The Telos-B mote connected with the GW is made

capable of having communication from serial port with acoustic modem, as well as radio communication with the BS using its CC 2420 antenna set-up. A software bridge was programmed using Tiny-OS for this mote to support the different packet formats. The communication link is depicted in pictorial format in Figure 3. Here, Node to cluster-head (CH) link is termed as Hop 1 where as link between CH to Gateway (GW) is termed as Hop 2. Our aim in this network set-up was to have guaranteed delivery of data as the grade of service. For achieving this we have made following provisions,

- Securing Time Synchronization
- Allowing multiple re-transmissions for time synchronization

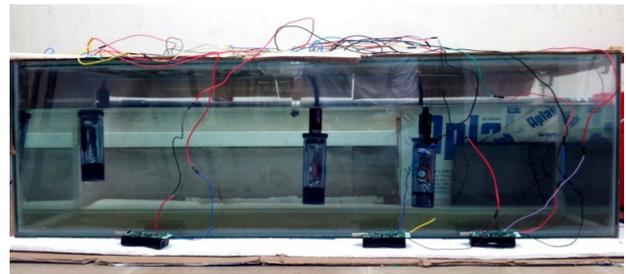


Fig. 2. Miniature test-bed set-up for the UASN.

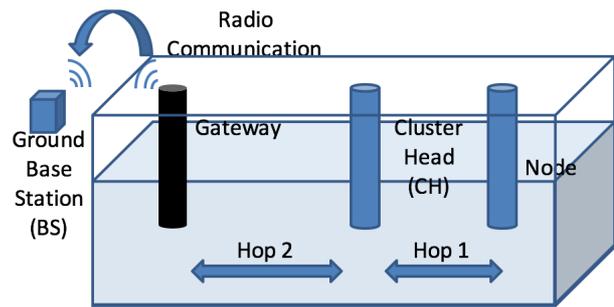


Fig. 3. Communication architecture of miniature test-bed for the UASN.

$$\beta = (B_3 - B_1) / (A_3 - A_1) \tag{7}$$

$$\alpha = (B_1 + B_2) / 2 - (A_1 + A_2) \beta / 2 \tag{8}$$

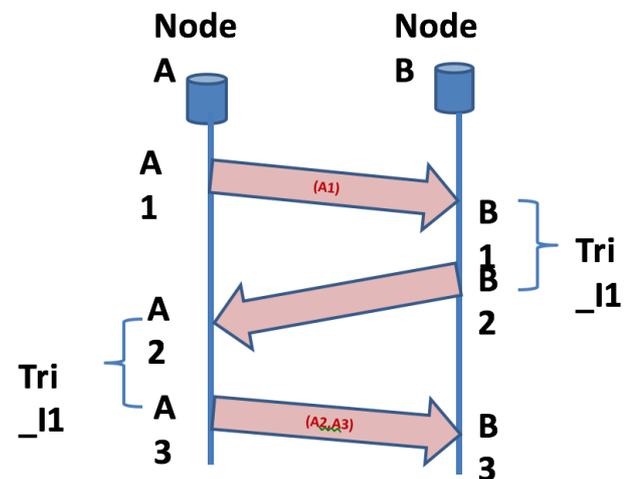


Fig.. 4. Tri-message time synchronization protocol

5. TIME SYNCHRONIZATION PROTOCOL

In this section brief overview of Tri-message and Multi-hop version of Tri-message is provided, along with details of its implementation on set-up. We also discuss the feature of retransmission for reliability of control message exchanges in the network.

5.1 Tri-message time synchronization [25]

In this section we provide the brief overview of Tri-message time-synchronization proposed by Tian et.al in [25].

For the operation, two-node situation is considered; one anchor Node A, and other Node B, to be synchronized with Node A. As shown in Figure 4, Node A sends the message at time A1, and includes the timestamp A1 in this message. Node B receives this message at time B1. It records timestamp A1 and B1. Later Node B sends the message back to Node A, at time instant B2 (and records the time stamp B2). Time interval or gap of duration Tri_{I1} is used to allow the processing time. Node A receives this message at time instant A2. Node A then sends the third message at time A3, including time-stamps A2 and A3. (Again the duration Tri_{I2} is used by Node A). Node B receives the third message at time instant B3 and thus have all the 6 time-stamps available with it. Following equations are then used to calculate clock skew (β) and offset (α).

5.2 Extension of Tri-message protocol for multi-hop scenario [26]

Authors Dhongdi et.al, have extended and implemented the multi-hop version of time-synchronization protocol [26]. The extension of Tri-message protocol is done in modular fashion. Here, authors assumed that one anchor node (Node A) is available, which is synchronizing another node (Node B) in its single hop region. This Node B then can synchronize another node i.e. Node C in its own single hop distance as shown in Figure 5. Global time scaling can be readily available since the equations can be resolved in linear fashion. Considering that A(t), B(t) and C(t) are clocks of nodes A, B, and C respectively, following equations demonstrate the global timing base:

$$\beta_1 = (B_3 - B_1) / (A_3 - A_1) \tag{9}$$

$$\alpha_1 = (B_1 + B_2)/2 - (A_1 + A_2) \beta_1/2 \tag{10}$$

$$B(t) = \beta_1 A(t) + \alpha_1 \tag{11}$$

$$\beta_2 = (C_3 - C_1) / (B_6 - B_4) \tag{12}$$

$$\alpha_2 = (C_1 + C_2)/2 - (B_4 + B_5) \beta_2/2 \tag{13}$$

$$C(t) = \beta_2 B(t) + \alpha_2 \tag{14}$$

Putting B(t) from (11) into (14), we get

$$C(t) = \beta_1 \beta_2 A(t) + \beta_2 \alpha_1 + \alpha_2 \tag{15}$$

Based on this version, our set-up disseminates the time synchronization information from GW to Node in multihop. That is, time information is sent in control packets from GW to CH and then from CH to Node.

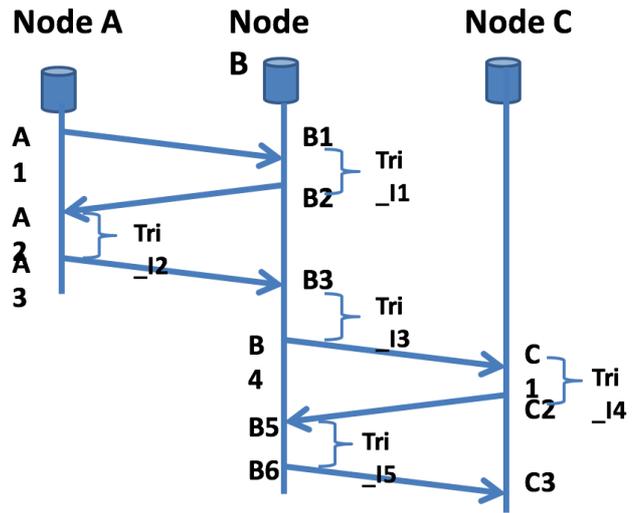


Fig. 5. Extension of Tri-message protocol for multi-hop

5.3 Retransmissions

Control information is very crucial for the network to function properly. For this reason, the concept of multiple retransmission methodology is considered for time synchronization messages here. If the acknowledgement for the packet carrying time synchronization is not received within stipulated time, the packet is assumed to have lost and is re-transmitted by the sender. The network works in the cyclic manner, where each cycle contains mainly two parts, wake period and sleep/idle period. The wake period can be further assumed to contain two parts, a) Time synchronization period and b) Data transmission period. Time synchronization information is sent in hops from GW to Node (GW → CH → Node). If the time synchronization packet is not received by receiver or the acknowledgement has not received by the sender in stipulated time period, then the time synchronization packet is sent again. Maximum number of retries was set as seven. After the time synchronization period is over, the data is transmitted in opposite direction in data transmission period (Node → CH → GW). Data transmission does not have the retransmission mechanism in our set-up currently. After data transmission period, network goes in sleep/idle mode. By this method, though the time synchronization period is flexible, overall cycle duration remains constant by effectively reducing the sleep period. We have set cycle timing as 30 minutes. The best case scenario involves no retransmissions at all; wake period calculated for this case is 12 minutes (40% duty cycle). Observed wake periods on our test bed ranged from 14 minutes (46.67% duty cycle) to 24 minutes (80% duty cycle). Illustration of the best case scenario is given in Figure 6. As shown in Figure 6, the time synchronization period is of 10 minutes, data transmission period is of 2 minutes and the sleep period is of 18 minutes respectively.

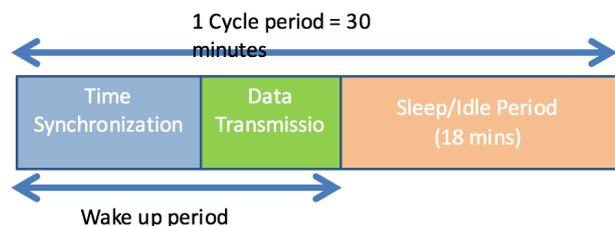


Fig. 6. Illustration of cycle period

6. Results

6.1 Multi-hop communication without Time Synchronization

The TelosB motes connected with the acoustic modems are programmed to run the whole test-bed in the autonomous manner. The data is sent from the TelosB mote to the acoustic modem using serial interface in the requisite intervals. This data is transmitted immediately by the acoustic modem. In the multi-hop fashion, this data is relayed from Node to Cluster Head, and then from Cluster Head to Gateway. Finally, Gateway sends the data to the Ground based base-station using RF link. Base-station is connected to PC on USB port, providing the data for analysis.

The test-bed set-up is run in an autonomous fashion for different time durations. The data collected by the PC is analyzed for the success of communication link, in terms of packet delivery ratio (PDR). Table 2 tabulates the results of over ten different runs. As the results show, an average PDR of 78% is observed at the first hop and a PDR of 73.1% is obtained at the second hop.

6.2 Multi hop communication with Time Synchronization

The TelosB motes connected with the acoustic modems are programmed to run the whole test-bed in the autonomous manner. Initially, the GW starts sending the time synchronization message using Tri-message time synchronization protocol. This control information is sent from GW to CH and then from CH to Node. Once the (final) Node is synchronized, the whole network is assumed to be time-synchronized.

After this, the Node starts sending the data towards the GW in the multihop fashion (Node → CH → GW). Finally, the data is available on the PC through the radio link set-up between underwater GW and the BS. The data collected by the PC is analyzed for the successful packet delivery in the data transmission period. We can mention the protocol efficiency by considering the ratio of total number of data packets (in terms of bits) delivered in the data transmission period to the total number of time synchronization packet (in terms of bits) transmitted in the time synchronization period. In best case scenario, there were only 8 time synchronization packets transmitted and 3 data packets were transmitted, so the protocol efficiency is around 3/8 i.e. 37.5%. In worst case observed on the set-up, 13 time synchronization packets were transmitted (i.e. 5 retransmissions were observed), while the number of data packets remain the same, so the efficiency is around 3/13 i.e. 23.07 %. The results of various runs on this test-bed are tabulated in Table 3. In second column of the table, PDR is calculated for the data transmission period. On average of ten runs, PDR of data transmission period is observed as 90.00 %. In third column, the PDR of complete wake period is provided. Wake period consists of time synchronization period (with possible retransmissions) and data transmission period (without retransmission) is mentioned. On average of ten runs, PDR over the wake period was observed as 75.26. PDR of the data transmission period is considerably high, because of the success of time synchronization on the network as compared to the PDR of 75% without presence of this protocol as pointed out earlier.

Table 2. % Packet delivery ratio (PDR) of multi-hop communication model.

Test Run	No. of packets Tx. by Node	No. of Packets Rx. by CH	No. of packets Tx. by CH	No. of packets Rx. by GW	Hop 1 (% PDR)	Hop 2 (% PDR)
1	47	41	47	21	87.23	44.68
2	46	39	46	41	84.78	89.13
3	50	20	50	38	40.00	76.00
4	17	14	16	11	82.35	68.75
5	37	35	37	30	94.59	81.08
6	34	26	33	19	76.47	57.57
7	16	16	16	15	100.00	93.75
8	15	12	15	10	80.00	66.67
9	14	12	14	12	85.71	85.71
10	55	27	53	36	49.09	67.92
Avg					78.02	73.13

Table 3:- Performance evaluation of the test-bed setup

Sr. No.	PDR (%) of data transmission period	PDR (%) of complete wake period
1	100	68.75
2	100	73.33
3	100	91.67
4	100	73.33
5	100	84.61
6	66.67	83.33
7	66.67	58.82
8	100	78.57
9	100	68.75
10	66.67	71.43
Average	90.00	75.26

6. Conclusion

We have shown the successful deployment of multi-hop Underwater Acoustic Sensor Network on the miniature test bed set-up. This setup has the provision for bidirectional communication link. Data from sensors can be delivered from bottom node to the base station via multi-hop links and the important control and network management information can be transmitted from base station to the node in the opposite direction. Here, the implementation of time synchronization protocol was successfully accomplished as example of network management protocol. It also proved helpful in increasing reliability of data packet transmission in the network.

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