Real-Time Underwater Communication Technique for Energy Efficient Ocean Monitoring

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***Abstract*—The need for underwater communications exists in the areas of pollution monitoring, ocean sampling networks, tactical surveillance applications, exploration of natural undersea resources, mine reconnaissance and predicting wave tides. Deployment of underwater sensor networks for real-time investigation is the major challenge. There is a need to deploy underwater networks that will enable real-time monitoring of selected ocean areas, remote configuration and interaction with onshore human operators. This can be obtained by connecting underwater instruments by means of wireless links based on acoustic communication is the most versatile physical link for continuous wireless sensor networks in underwater scenarios. In this paper large-scale underwater Sensor Networks (UWSN) and Underwater Ad-hoc Networks (UANETs) using Solar-Powered Autonomous Underwater Vehicles (SAUV) to explore the oceanic environment is proposed. Kong Wobbler base station with acoustic communication devices is considered, which locates the pre-deployed underwater sensor modules through acoustic communication. The sensor modules are installed with various acoustic sensors and video capturing devices to study the underwater resources as well as for surveillance needs for predicting the environmental conditions highlighting potential applications of seismic monitoring that provides a better disaster warning mechanism. The simulation results are encouraging as this approach is extremely helpful in surveillance; intruders are tracked and real-time data streaming is processed.**

Keywords - Underwater Ad-hoc Networks (UANET's); Underwater Sensor Networks (UWSN); Solar-Powered Autonomous Underwater Vehicles (SAUV); Acoustic Communication; Underwater Acoustic Sensor Networks (UW-ASN); Geographic Adaptive Fidelity (GAF) Protocol; Kong Wobbler.

I. INTRODUCTION

Sensor networks have the promise of revolutionizing many areas of science, industry, and government with their ability to bring computation and sensing into the physical world. The ability to have small devices distributed near the objects being sensed brings new opportunities to observe. Monitoring the underwater environment is vital in predicting wave tides, pollution monitoring, oceanic data collection, tactical surveillance applications, disaster prevention and exploring natural resources. While sensor networks are beginning to be fielded in applications today on the ground, underwater operations remain quite limited by comparison. The largely unexplored vastness of the ocean, covering about 79% surface of the earth, has fascinated human race for a very long time. The traditional approach for ocean-bottom or ocean-column monitoring is to deploy underwater sensors that record data during the monitoring mission and recover the instruments finds disadvantages:

- Real-time monitoring is critical especially in surveillance or in environmental monitoring applications such as seismic monitoring wherein the recorded data cannot be accessed until the instruments are recovered, which may happen several months after the beginning of the monitoring program.
- No interaction is possible between onshore control systems and the monitoring instruments which impedes adaptive tuning of the instruments nor it is possible to reconfigure the system.
- In case of failures, it is not possible to detect them before the instruments are recovered which leads to the complete failure of a monitoring mission.
- The amount of information that can be recorded during the monitoring mission by every sensor is limited by the capacity of the on-board storage devices in the instrument [1].

The paper is organized as follows. Section II illustrates the Kong Wobbler's design, which carries the base station for information relay. Section III and Section IV explain the internal architecture of the underwater sensors and SAUV. Section V presents the characteristics of the suggested acoustic communication channel for the underwater scenario; to assess the aqueous environment; its role and function in the need for large-scale, long term and distributed information collection networks for periodic oceanic monitoring. The large scale aquatic applications demand us to build UWSN and UANETs to explore the inhibited oceans. Energy efficient routing protocols are the most important criteria for the design of underwater sensor networks, since the sensor nodes will be powered by batteries with limited power capacity. Power failure of a sensor node not only affects the node itself but also its ability to forward data packets to the other nodes. Hence Section VI is dedicated to Energy Efficient, Geographical Adaptive Fidelity (GAF) protocol [3]. A general layout is presented in the Section VII. Sections VIII and IX, explain the Implementation of the work and numerical results obtained by Simulation in the Network Simulator (NS2) [2], respectively. Conclusions are summarized in Section X.

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II. KONG WOBBLER

A wireless access point with Kong Wobbler structure is made to float on the surface of sea around the area of investigation to which the structure of the base station is fixed on the top. The weight of the base station is less than the Wobbler base structure, maintaining a ratio of 1:4 to prevent the whole structure from toppling. Kong Wobbler is made up of non toxic Food and Drug Administration (FDA) approved polypropylene chosen for its overall strength, impact absorption, sound deadening and non toxicity on the surface of sea made up of high strength polymer and is Bisphenol A (BPA) and phthalate free. Kong Wobbler is filled with compressed CO_2 that allows the structure to float and uses play grade sand for its weight. The sand remains in a compartment that has been permanently sealed using ultrasonic technology. The Kong Wobbler is made to float on the surface of sea and anchored to the sea bed through cables to keep in position such that due to its unique structure it floats vertically. They are hand-launched over the side of a ship or air dropped in the area of investigation. The column of fluid has greater pressure at the bottom of the column of ocean than at the top. This difference in pressure results in a net force that tends to accelerate the Kong Wobbler structure upwards. The magnitude of that force is equal to the difference in the pressure between the top and the bottom of the column, and is also equivalent to the weight of the fluid that would otherwise occupy the column. For this reason, if the density of the structure is greater than that of the fluid in which it is submerged, tends to sink. The buoyancy of the Kong Wobbler exceeds its weight and tends to rise. Density is maintained lesser than the liquid and shaped appropriately so that force can keep the whole structure afloat. The floating Kong Wobbler tends to restore itself to an equilibrium position after a small displacement. It has vertical stability, in case it is pushed down slightly, which will create a greater buoyancy force and unbalanced by the weight force, will push the object back up. Rotational stability is of great importance as given a small angular displacement, the structure returns to its original position [3].

Kong Wobbler is of less density than the seawater and will float upward until it reaches the surface of the seawater at which position, only part of it is submerged. Wobbler is made out of such material, displaces a lot of water on the surface of ocean as the force of the water trying to get into the space keeps the wobbler afloat.

Submerged fraction depends on the density of the Kong Wobbler, as compared to the seawater. Hence:

$$\rho_s V_s = \rho_o V_o (Archimede's principle) \tag{1}$$

where ρ_s the density of the seawater, V_s the volume submerged, ρ_o the density of the Kong Wobbler, V_o the volume of the whole structure,
The Submerged volume is maintained around 0.5 times the total volume of the whole structure, as the density of the whole Kong Wobbler lies in between the density of polypropylene and compressed CO_2.

ρ_s = 1027kg/m3, Density of seawater at the surface.
ρ_o= 946kg/m3, Density of polypropylene.
ρ_{co_2}= 1.52 kg/m3, Density of compressed CO_2
As the Wobbler is displaced vertically, a parcel of fluid in contact is also displaced. The buoyancy force F acting on the Kong Wobbler is the difference between the weight of the displaced parcel of fluid with density ρ', (gV ρ') and the weight of the surrounding water with density ρ_2, (gV ρ_2), where V is the volume of the parcel.

$$F = gV(\rho_2 - \rho') \tag{2}$$

The acceleration of the displaced parcel is:

$$a = \frac{F}{m} = g\frac{(\rho_2 - \rho')}{\rho'} \tag{3}$$

but

$$\rho_2 = \rho + \left(\frac{d\rho}{dz}\right)_{water} \delta z \tag{4}$$

$$\rho' = \rho + \left(\frac{d\rho}{dz}\right)_{parcel} \delta z \tag{5}$$

Using (4) and (5) in (3), ignoring terms proportional to δz^2,

$$E = \frac{-1}{d\rho}\left[\left(\frac{d\rho}{dz}_{water}\right) - \left(\frac{d\rho}{dz}_{parcel}\right)\right] \tag{6}$$

where $E = \frac{-a}{(gdz)}$ is the stability of the water column. This can be written in terms of the measured temperature and salinity t(z), S(z) in the water column [3].

$$E = \alpha\left(\frac{dt}{dz} - g\rho\Gamma\right) - \beta\frac{dS}{dz} \tag{7}$$

where

$$\alpha = \frac{-1}{\rho}\left(\frac{\partial\rho}{\partial t}\right) |_{S,p}$$

$$\beta = \frac{-1}{\rho}\left(\frac{\partial\rho}{\partial S}\right) |_{t,p}$$

$$\Gamma = \left(\frac{\partial t}{\partial p}\right) |_{adiabatic}$$

with α, the thermal expansion coefficient, β the saline contraction coefficient, and Γ is the adiabatic lapse rate, the change of temperature with pressure as the water parcel moves without exchanging heat with it's surroundings. p is pressure, t is temperature in celsius, ρ is density, and S is salinity. Few kilometers from the surface of the ocean, stability is large such that the first term in (6) is much larger than the second. The first term is proportional to the rate of change of density of the water column; the second term is proportional to the compressibility of sea water, which is very small. Hence, neglecting the second term, stability equation reduces to:

$$E \approx \frac{-1}{\rho}\frac{d\rho}{dz} \tag{8}$$

The approximation used to derive (8) is valid for

$$E > 50 * 10^{-}8/m$$

Below, about a kilometer in the ocean, the change in density with depth is so small that we must consider the small change in density of the parcel due to changes in pressure as it is moved vertically, and (7) must be used [4]. Stability is defined such that

$$E > 0, Stable$$

$$E = 0, Neutralstability$$

$$E < 0, Unstable$$

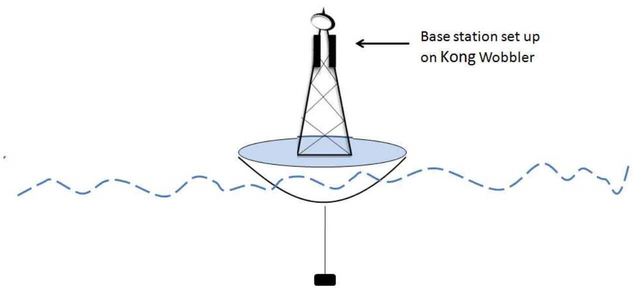

Fig. 1. Kong Wobbler structure

III. SENSORS

Sensor nodes collect data through their sensors. One possible approach to node deployment and communicate with other nodes through short-range acoustic couplers. They have batteries, but for long-term operation they spend most of their life asleep. All nodes are integrated with temperature, vibration, pressure, viscosity, turbidity, seismic, proximity, chemical & gas, fluid flow, speed, water level, altitude and visibility sensors to measure the different parameters in the marine environment which are small, robust, inexpensive, low power consuming yet efficient. Real-time readings are taken from all the sensors to check readings crossing the threshold values to take necessary actions. The typical internal architecture of an underwater sensor is shown in Fig. 2. It consists of a main controller/CPU (Central Processing Unit), which is interfaced with an oceanographic instrument or sensor through a sensor interface circuitry. The controller receives data from the sensor and it can store it in the onboard memory, process it, and send it to other network devices by controlling the acoustic modem. The electronics are usually mounted on a frame which is protected by a PVC housing. Sensor components are protected

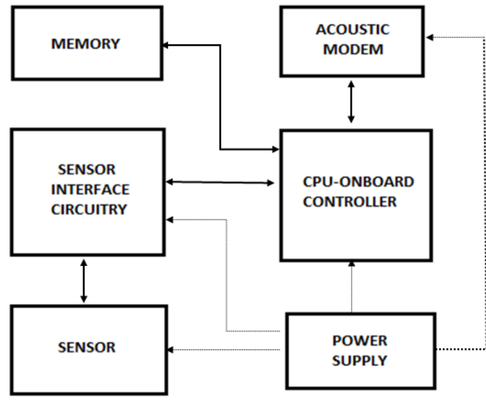

Fig. 2. Sensor node Architecture

by bottom-mounted instrument frames that are designed to permit azimuthally omnidirectional acoustic communications, and protect sensors and modems from potential impact of trawling gear, especially in areas subjected to fishing activities. The protecting frame is designed so as to deflect trawling gear on impact, by housing all components beneath a low-profile pyramidal frame. Underwater sensors include sensors to measure the quality of water and to study its characteristics such as temperature, density, salinity (interferometric and refractometric sensors), acidity, chemicals, conductivity, pH (magnetoelastic sensors), oxygen (Clark-type electrode), hydrogen, dissolved methane gas (METS), and turbidity. Disposable sensors exist that detect ricin, the highly poisonous protein found in castor beans and thought to be a potential terrorism agent. DNA microarrays can be used to monitor both abundance and activity level variations among natural microbial populations. Other existing underwater sensors include hydrothermal sulfide, silicate, voltammetric sensors for spectrophotometry, gold-amalgam electrode sensors for sediment measurements of metal ions (ion-selective analysis), amperometric microsensors for H_2S measurements for studies of anoxygenic photosynthesis, sulfide oxidation, and sulfate reduction of sediments. In addition, force/torque sensors for underwater applications requiring simultaneous measurements of several forces and moments have also been developed, as well as quantum sensors to measure light radiation and sensors for measurements of harmful algal blooms [5].

IV. SOLAR-POWERED AUTONOMOUS UNDERWATER VEHICLES (SAUV)

The SAUV [6] is a solar powered AUV designed for long endurance missions that require monitoring, surveillance/station keeping, with real-time bi-directional communications to shore.

- The SAUV is a solar-powered autonomous vehicle which is equipped with rechargeable lithium ion batteries to allow maximum mission endurance even under conditions where minimal solar radiation is available.

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- Operate autonomously at sea for extended periods of time from weeks to months. Typical missions require operation at night and solar energy charging of batteries during daytime.
- In case of failure of Kong Wobbler, SAUVs Communicate with a remote operator on daily basis via the Satellite phone or the RF radio or the acoustic telemetry.
- Operate at speed up to about 3 knots when needed and cruise at speed of about 1 knot.
- Battery system is to provide a total capacity of around 1.5 kwh.
- Capability to acquire GPS updates on the ocean surface and compute SAUV position at all times using GPS.
- Capability to maintain fixed depth and fixed altitude and to smoothly vary depth or altitude profile.
- Capability to log and upload all sensor data correlated in time and SAUV geodetic position.
- Provide sufficient volume, power, interfaces and software hooks for future payload sensors.
- Allow user to program missions easily using a Laptop PC and provide for graphical display of mission [6].

Fig. 3. SAUV

V. Acoustic Communication

Wireless underwater communication is challenging task with the growing need for underwater surveillance and develop persistent long-term ocean observation has led to many underwater wireless technologies. Present underwater communication involves transmission of data in the form of optical waves, electromagnetic or sound waves. Optical waves involved in underwater communication are generally limited to very short ranges because of the strong backscatter from the suspended particles in the ocean, severe absorption by water at optical frequencies and high level of ambient light in the upper part of the water column. Even the clearest water has 1000 times the attenuation of clear air and turbid water has more than 100 times the attenuation of densest fog. Electromagnetic waves in radio frequencies, does not work underwater due to high conducting nature of the medium, especially sea water. Average conductivity of sea water is 4 mhos/meter, therefore the attenuation for 2.4GHz is around 1695dB/meter which is not feasible. Underwater acoustic communications is an important alternative to Radio-Frequency (RF) communications. It is the most versatile and widely used technique in underwater wireless communication which has low attenuation of sound in water used as the primary carrier for underwater wireless communication systems that holds well in thermally stable and deep water settings [3]. It is seen that in simple acoustic propagation models that multi-hop routing saves energy in underwater networks with respect to single hop communications, especially with distances of the order of some kilometers.

The challenges posed by the underwater channels for underwater sensor networking are :

1) Path loss
   - Attenuation: Is mainly provoked by absorption due to conversion of acoustic energy into heat, which increases with distance and frequency. It is also caused by scattering and reverberation (on rough ocean surface and bottom), refraction, and dispersion (due to the displacement of the reection point caused by wind on the surface). Water depth plays a key role in determining the attenuation.
   - Geometric Spreading: This refers to the spreading of sound energy as a result of the expansion of the wave fronts. It increases with the propagation distance and is independent of frequency. There are two common kinds of geometric spreading: spherical (omni-directional point source), and cylindrical (horizontal radiation only).
2) Noise
   - Man made noise. This is mainly caused by machinery noise (pumps, reduction gears, power plants, etc.), and shipping activity (hull fouling, animal life on hull, cavitation).
   - Ambient Noise. Is related to hydrodynamics (movement of water including tides, currents, storms, wind, rain, etc.), seismic and biological phenomena.
3) Multi-path
   - Multi-path propagation may be responsible for severe degradation of the acoustic communication signal, since it generates ISI (Inter-Symbol Interference).
   - The multi-path geometry depends on the link conguration. Vertical channels are characterized by little time dispersion, whereas horizontal channels may have extremely long multi-path spreads, whose value depend on the water depth.
4) High delay and delay variance:
   - The propagation speed in the UW-A channel is order of five, magnitude lower than the radio channel. This large propagation delay (0.67 s=km) can reduce the throughput of the system considerably.

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- The very high delay variance is even more harmful for efficient protocol design, as it prevents from accurately estimating the Round Trip Time (RTT), key measure for many common communication protocols.

5) Doppler spread
   - The Doppler frequency spread can be signicant in UWA channels causing a degradation in the performance of digital communications: transmissions at a high data rate cause many adjacent symbols to interfere at the receiver, requiring sophisticated signal processing to deal with the generated ISI (Inter-Symbol Interference) [5].

Perhaps the most distinguishing property of acoustic channels is the fact that path loss depends on the signal frequency. This dependence is a consequence of absorption, i.e., transfer of acoustic energy into heat. In addition to the absorption loss, signal experiences a spreading loss which increases with distance. The ambient noise, which is always present, may be modeled as Gaussian, but it is not white. Its power spectral density decays at approximately 18 dB/decade. The acoustic bandwidth depends on the transmission distance. The bandwidth is severely limited at longer distances: at 100 km, only about a kHz is available. At shorter distances, the bandwidth increases, but it will ultimately be limited by that of the transducer. The fact that bandwidth is limited implies the need for bandwidth efficient modulation methods if more than a bps/Hz is to be achieved over these channels. Another important observation to be made is that the acoustic bandwidth is centered at low frequencies [5].

The fact that the acoustic bandwidth depends on the distance has important implications on the design of underwater networks. Specifically, it makes a strong case for multi-hopping, since dividing the total distance between a source and destination into multiple hops enables transmission at a higher bit rate over each (shorter) hop. The same fact helps to offset the delay penalty involved in relaying. Since multi-hopping also ensures lower total power consumption, its benefits are doubled from the viewpoint of energy-per-bit consumption on an acoustic channel [5].

By dividing the available bandwidth into a number of narrower bands, Orthogonal Frequency Division Multiplexing (OFDM) [7] systems can perform equalization in frequency domain and eliminate the need for complex time-domain equalizers. OFDM modulation and de-modulation can easily be accomplished using Fast Fourier Transforms (FFT) [7]. When the delay spread is long, the prefix length can significantly affect the bandwidth efficiency. Maximum likelihood sequence detection (MLSD) on individual sub-carriers using a low complexity PSP can combat ISI when the symbol period is smaller than the delay spread. Other channel shortening techniques such as sPRE may also be used in future OFDM systems to reduce the prefix length and improve bandwidth efficiency. Careful consideration of the physical layer parameters can help to design data packets so as to take maximal advantage of limited resources.

Low carrier frequencies typically 15 kHz is ideal for underwater acoustic data communication. Acoustic waves experience $1/R^2$ attenuation due to spherical spreading and also absorptive losses [5] are significant in underwater scenario. Hence, the practical range selected for our carrier frequency is 11-19 khz.

A. Ad hoc Networks

A wireless ad hoc network is a system of self-directed nodes which form a decentralized communications network. Wireless communication allows for a dynamic network topology where new nodes can be rapidly deployed and likewise rapidly removed. The nodes act as both host and router, performing tasks and forwarding information to each other. The mobile nodes can form dynamic networks where they are linked with their nearest neighboring node and when they move too far from their neighboring nodes might lose connection but come into contact with other nodes to begin interacting and changing the network topology. Efficient routing protocols is needed to communicate new data over multi-hop paths consisting of possibly several links to cope with noise and interference as well as sharing limited bandwidth. A class of Ad hoc networks, UANET are used in underwater explorations.

1) UWSN and UANETs: UANET and UWSNs are essential to explore large uninhibited oceans. In the characteristics of these new networks, the propagation delay, floating node mobility, and limited acoustic link capacity are hugely different from ground based mobile ad-hoc networks (MANET) and Wireless Sensor Networks (WSN). UANET and UWSN rely on low-frequency acoustic communications because RF radio does not propagate well due to underwater energy absorption. Unlike wireless links amongst land-based ad hoc nodes, each underwater acoustic link features large-latency and low bandwidth. Most ground sensor nodes in a WSN are typically stationary and large portion of UWSN sensor nodes, except some fixed nodes mounted on the sea floor are with low or medium mobility (3-5 knots) due to environmental water current. The large-scale aquatic applications demand to build UANET and UWSN to explore the large uninhabited oceans. The difference between UANET and UWSN is due to controlled mobility and associated implementation cost. In a UANET, mobile nodes can be implemented by SAUV and Autonomous Underwater Vehicles (AUV) or Remotely Operated Vehicles (ROV), which are high cost robots that can move under the water by following pre-programmed or autonomous motion patterns. On the other hand, UWSN only incurs a fraction of implementation cost of UANET at the same network scale. All sensor nodes in a UWSN are of low-cost [8].

The advantages of the new UANET and UWSN paradigm are:

- Localized and coordinated sensing and attacking is far more precise than the existing remote telemetry technology.
- Scalability of UWSN ensures that a large area can be covered for time-critical applications.
- Casualty ratio is expected to be zero if unmanned UANET and UWSN platforms are used.
- Implementing reusable underwater nodes reduces the deployment and maintenance cost. Each underwater sensor unit can be bundled with an electronically controlled air bladder device. Once the network mission is accomplished, the command center issues commands to trigger all air-bladder devices and all sensor units float to surface to be recollected for next mission [1].

VI. GAF Protocol

When ad hoc networks are deployed using battery powered sensor nodes, the effect of limited battery power on the lifetime and performance becomes critical. In underwater applications, it is vital to let every underwater node know its current position and the synchronized time with respect to other coordinating nodes. GAF protocol uses Global Positioning System (GPS) to get the node location.As Global Positioning System (GPS) is unavailable under the water surface as the high-frequency radio waves used by Global Positioning System (GPS) is quickly absorbed by water, hence cannot propagate deeply under the water surface. Therefore, underwater networks rely on Doppler Instrumentation or distributed GPS-free localization and time synchronization schemes to let the sensor nodes know their positions and the network clock value. In other words, before the network can use geo-routing schemes, it needs a multi-hop packet delivery service, which must be GPS-free. Geographic adaptive fidelity protocol is an energy effective position based routing protocol. Position based protocols are also referred to as geographic routing protocols as the sensor nodes are addressed by means of their locations instead of the information that they carry. Location information is needed in order to calculate the distance between two particular nodes so that energy consumption can be estimated. In GAF protocol, each node uses location information to associate itself with a virtual grid so that the entire area is divided into several square grids, and the node with the highest residual energy within each grid becomes the master of the grid. Only a single node from a cell of a given virtual grid is chosen to be active at any given time. The nodes will select one sensor node to stay awake for a certain period of time which is responsible for monitoring and reporting data to the sink on behalf of the other nodes in the zone is known as the master node. Other nodes in the same grid can be regarded as redundant with respect to forwarding packets, and thus they can be safely put to sleep without sacrificing the routing fidelity [3].

A. GAF Architectures

- Virtual Square Grids: In GAF, the entire network area is divided into virtual square grids. All the nodes in the network divide themselves in virtual square grids and all those nodes which are under a same grid known as equivalent nodes with respect to forwarding packets. The nodes under a same grid coordinate among themselves to decide the sleep time interval and sequence of sleep. Load balancing is performed and a single node will not get drained with a rigorous work.

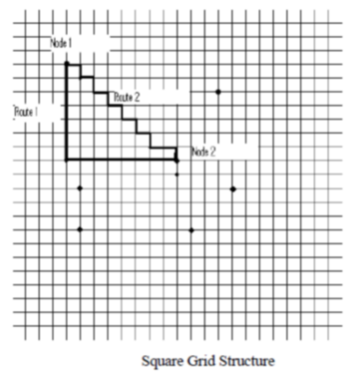

Fig. 4. GAF square grid structure

  GAF algorithm can communicate directly to its adjacent horizontal and vertical grid cells. But the diagonal cell cannot be covered directly by virtual grid method due to range limitations. For the diagonal cell, packets should be transferred through vertical and horizontal cell which cause the longer path else if a node tries to transmit directly then the packet drop rate increases due to low radio range. In the figure illustrating the virtual square grid, the Node 1 is sending packets to Node 2. It can take any route vertically and horizontally (see Fig. 4).
- Virtual Hexagon Grid: The hexagon GAF grid architecture uses the hexagonal grid structure. In this, the square grid in GAF is replaced with a hexagon mesh. Cell O now has six neighbors covering destinations from all directions. The hexagon architecture is named as GAF-HEX (HGAF). A Hexagon cell in GAF-HEX is defined as, for two adjacent cell O and B, all nodes in cell O can communicate with all nodes in cell B and vice versa. For a cell O, all of its six adjacent cells are at the next hop, they have the same maximum distance to cell O (see Fig. 5).
  This is the scoring feature of hexagon mesh. In the square grid architecture, there are eight neighboring cells (four diagonal, two vertical and two horizontal cells) but only four (vertical and horizontal two each) are at the next hop distance while the hexagon cell covers all six possible next hop cells with a single maximum distance due to its symmetry property. Therefore all of the next hop cells

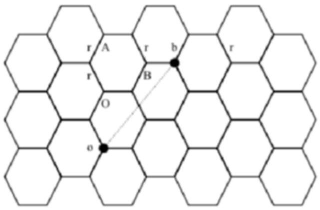

Fig. 5. GAF hexagon structure

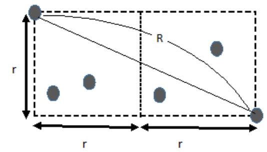

Fig. 6. GAF virtual grid

for cell O are equally reachable.

GAF, the basis of HGAF, is an adaptive fidelity algorithm in which nodes working as cluster heads are selected in a distributed manner. GAF assumes that a large number of sensor nodes are placed in the observation area. The fewest nodes in the observation area are selected to transmit messages, while the other nodes sleep. This way, GAF reduces the number of nodes needed to form a network and saves node battery power. GAF divides the observation area into square/hex areas and groups nodes according to their position. In each group, one active node is selected to work as the cluster head for routing packets between groups. Other nodes sleep to save their battery power. The selection of the active node in each group is done in a distributed manner by referring to the remaining battery power of each node [9].

Assume that the observation area is divided into squares with r units on a side. We call each square a cell. Each node decides which cell it belongs to according to its position. One active node is selected in each cell. Thus, if we can enlarge the cell size, we can reduce the number of active nodes in the network and save even more battery power. However, in enlarging the cell size, the communication between active nodes in two adjacent cells must be guaranteed because active nodes work as cluster heads. Therefore, the distance between the two farthest nodes in any adjacent cell has to be smaller than the radio communication range. The maximum cell area SGAF is constrained by the maximum radio communication range of sensor nodes R. The length of each cell r has to satisfy the following condition:

$$r^2 + (2r)^2 \leq R^2$$

Thus, $r \leq \frac{R}{\sqrt{5}}$
The maximum cell area is thus

$$S_{GAF} = (max r^2) = \frac{R^2}{5}$$

In GAF, the nodes are in one of three states: sleeping, discovery, or active. Nodes start out in the discovery state. One node in each group is selected as an active node, by referring to the residual battery power of nodes in the group. The active node in each group is changed dynamically as time passes. When a node is in the discovery state, it turns on its radio and broadcasts a discovery message to find other nodes within the same group. Each discovery message includes a node ID, group ID, estimated node active time, and the node state. Half of the estimated node active time is denoted by Ta. When a node enters the discovery state, it sets a timer which expires Td seconds later. When the timer goes off, the node broadcasts a discovery message and becomes active. Then, it sets a timeout value Ta that specifies the length of time in which it can stay active. After Ta, the node returns to the discovery state. While in the active state, the node periodically broadcasts its discovery message at intervals of Td. A node in discovery or active states can change to the sleeping state when it receives a discovery message.

- When a discovery node receives a discovery message, it goes into the sleeping state.
- When an active node receives a discovery message, the node compares its own expected lifetime with the one in the discovery message. If the former is longer than the latter, the node goes into the sleeping state.

A sleeping node wakes up after Ts seconds and goes back into the discovery state. Ts is calculated from the estimated node operation time of the current active node, which is written in the received discovery messages [9].

VII. System Architecture

The general architecture of underwater sensor network is reviewed before describing the specific applications. The rough capabilities of a sensor node are estimated on its interaction with the environment, other underwater nodes and applications. At the lowest layer is the large number of sensor nodes to be deployed on the sea floor which has computing power, and storage capacity. They collect information through their sensors and communicate with other nodes through short-range acoustic communication. In large networks, there exists a type of nodes, called

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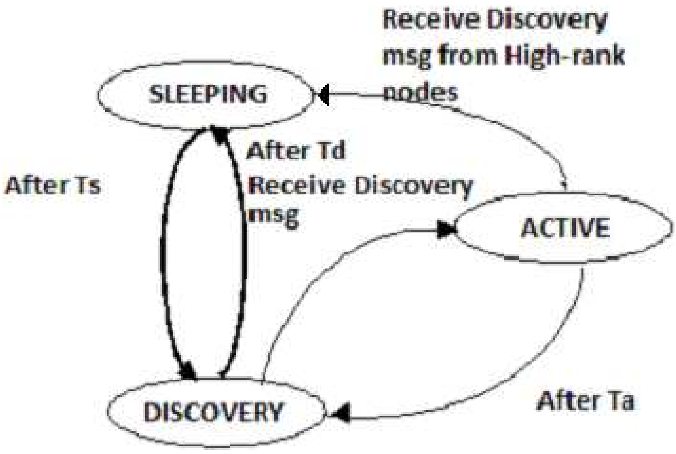

Fig. 7. GAF transition states

supernodes, having access to higher speed networks and can relay data to the base station very effectively with rich network connectivity creating multiple data collection points. Battery power and the ability to carefully monitor energy consumption are essential for the sensor node. All components of the system operate at as low a duty cycle as possible which is enabled by examining each layer of system software to minimize energy consumption and in addition nodes entirely shut off for very long periods of time, up to hours or days during not in use. In a harsh, underwater environment, some nodes will be lost over long deployments due to fishing trawlers and underwater life affecting cables or node which needs redundancy in communication and sensing as loss of a node will not have wider effects. In addition, multiple failures can be recovered, either with mobile nodes or with human deployment of replacements [11].

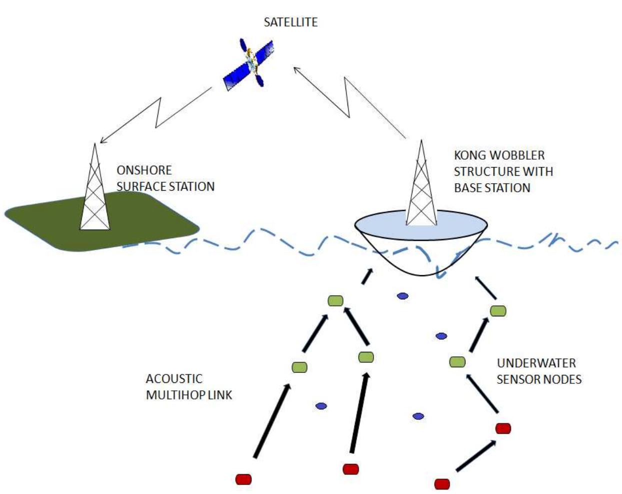

Fig. 8. Logical diagram of System Architecture.

VIII. Implementation

Initially, the UWSNs and UANETs are deployed in the ocean. Sensor nodes with limited battery power are deployed to record the environmental changes underwater. The recorded data is transferred to the surface of the earth through the nearest access point, the base station fixed to the specially designed Kong Wobbler floating on the surface of the water by the multi-hop network of sensor nodes which results in energy savings and increased network capacity. The base stations monitor the entire sensor nodes within the network and receive as well as stores the recorded sensor data within its area of range. These data are further relayed to an onshore surface station via satellite transceiver. Acoustic communication proves to be efficient in data transfer underwater from the sensor nodes to the base station. During the process, the base station monitors the battery power level of all the nodes. Upon receiving the request from the nodes to recharge its batteries, the base station then guides the submarines towards the requested nodes which is continued with all the sensor modules deployed underwater. The sub-marines would in turn charge themselves at the base stations, which are installed with the solar panels. The power required by the base station for the reception of the data from the sensor modules and transmission is supplied by the solar panels. Once the surface station has finished collecting data from each sensor module, the processing and analysis of data is performed to get the real-time study of the underwater scenario. As the nodes have limited battery power, it is essential to implement an energy efficient routing protocol that conserves power during transmission and reception of data. Power failure of a node not only affects the node itself but also its ability to forward packets on behalf of other nodes and thus the overall network lifetime. GAF is an energy efficient routing protocol as the transmitting power is altered according to the distance of the neighboring nodes. The flow chart explains the process undertaken in the investigation of underwater environment.

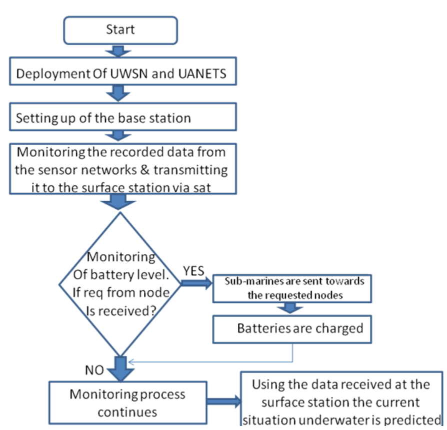

Fig. 9. Flow Chart of the system

The investigation of the underwater resources is thus collected at real-time. Compilation of all the recorded sensor data is done in the surface station which acts as the command center and thus predicting the current scenario of the environment underwater.

IX. Simulation and Results

Continuous network development and higher functionality requirements have created the need for tools that could monitor network transmissions and analyze them. Network Simulator (NS) for communication networks works under UNIX and Windows system platforms and is mainly used for network research. The simulation is performed using NS2 (version 2.34) running on LINUX platform (Ubuntu 11.04). The graphical representation of this simulation is shown with Network Animator(NAM-1.14). 20 nodes are considered for each Kong Wobbler base station on the surface of ocean bed. The Kong Wobbler carrying base station act as the center that monitors the entire sensor node within the network and receives as well as stores the recorded sensor data. UANETs along with Kong Wobbler structure is hand dropped by the side of the ship. Kong Wobbler structure starts to float on the surface of the ocean and the UANETs start moving randomly. The black fixed nodes are anchored to the ocean bed at specific co-ordinates (see Fig. 6). Some of the nodes in UANET are mobile which are implemented by SAUV and AUV or ROV, which are high cost robots that move under the water by following pre-programmed or autonomous motion patterns. And remaining nodes in UWSN are stationary, mounted on the sea floor are with low or medium mobility (3-5 knots) due to environmental water current. The trace file and NAM file results provided by the NS2 gives enormous amount of information. It specifies position of the node, number of nodes within the network of access point and also visualizes in detail about the packet transmission among the nodes and the Kong Wobbler carrying base station is simulated. The red nodes represent nodes in UANET on the ocean bed which are moving around collecting data. The black nodes are fixed nodes anchored to oceanic bed. The blue node indicate the Kong Wobbler structure with base station which covers the area under investigation.

Nodes discovering their themselves (Discovery State), (see Fig. 10)

UANETs continue their random motion gathering data. Both stationary UWSNs and mobile UANETs collect information and relay it to base station which is carried by Kong Wobbler structure (see Fig. 11). The acknowledgements are sent after receiving the information.

NS simulation can produce a visualization file (NAM) and an ascii file trace corresponding to the events generated in the network. When tracing into an output ascii file, the trace is organised into 12 fields as- Event/Time/From Node/To Node/Pkt Type/Pkt Size/Flags/Fid/Source addr/Destination addr/Sequence no/Pkt ID. The Traces are studied and information is extracted from them to make Performance analysis. Trace graph architecture enables implementing new system

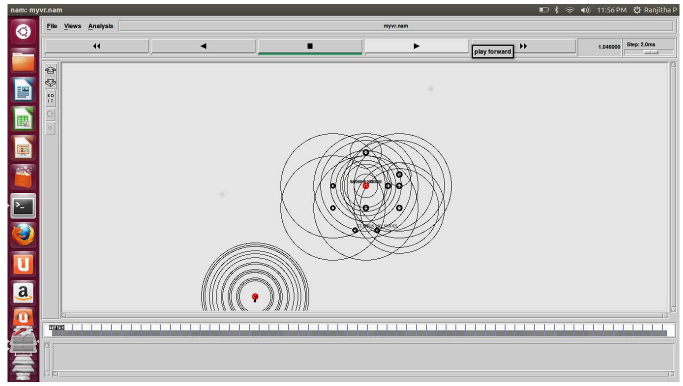

Fig. 10. Simulation in NS2

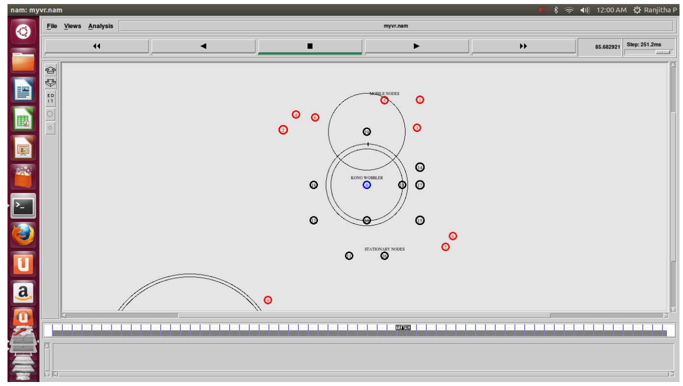

Fig. 11. Simulation in NS2

functions very easy. For example adding a new graph can take only 10 minutes. The system could be expanded to read other trace file formats like real network traces, e.g., a trace format converter could be created for conversion to Trace graph format. Nodes movements with packets flows 2D/3D visualization could be added. More parameters from trace files could be used for new graphs implementation; see snapshot of our Trace file in Fig. 12.

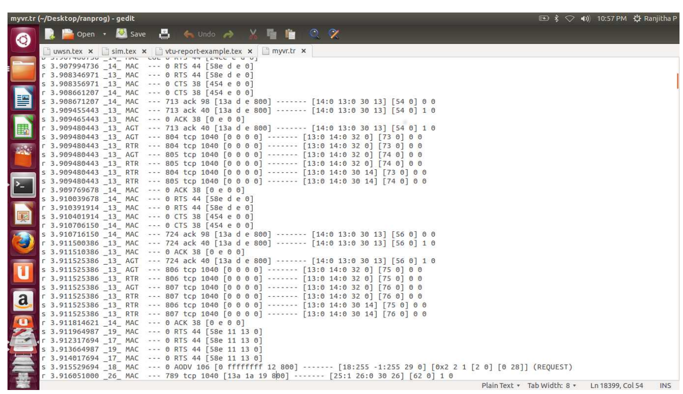

Fig. 12. Trace file

The investigation is carried out in two phases considering: Packet Delivery Fraction (PDF): It is the ratio of the data packets delivered to the destination to the total number of packets generated by the Constant Bit Rate (CBR) source

1) First phase is with variation of the speed of the nodes with PDF for AODV-GAF and DSDV-GAF is as shown in Fig. 13.

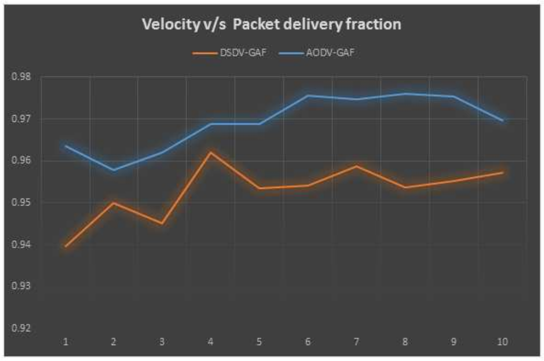

Fig. 13. Velocity v/s PDF

2) Second phase is the variation of simulation time with PDF AODV-GAF and DSDV-GAF is as shown in Fig. 14.

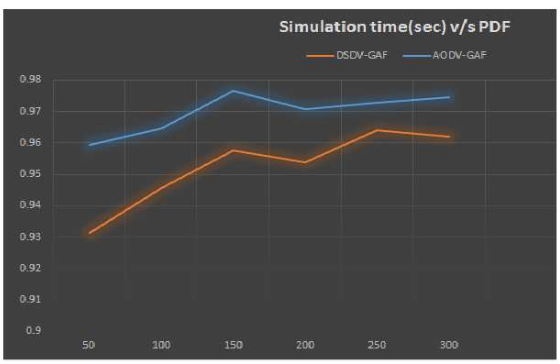

Fig. 14. Simulation Time v/s PDF

Inferring from the graphs, GAF implemented on AODV protocol is more suitable for underwater environment than DSDV-GAF.

X. Conclusion

This paper has summarized our ongoing research in underwater sensor networks, including applications and research challenges. It is explained that traditional approach to deploy underwater sensors that record data during the monitoring mission, then recovering the instruments is not a feasible and the need of large-scale long-term and distributed information collection networks for periodic oceanic monitoring is essential. GAF (Graphical Adaptive Fidelity) protocol was adopted as it proves to be an energy efficient routing protocol. It is also explained that acoustic communication is the most versatile technique in underwater wireless communication. The applications of UANET using SAUV and UWSN and their reliability in implementing a localized, precise, and large-scale networking efficiently than any existing small-scale Underwater Acoustic Network (UAN) is described. The main objective of the paper was to develop advanced communication techniques for efficient real-time investigation of large uninhibited oceans. Development of underwater communication and networking for enhanced oceanic monitoring is also essential for pollution monitoring, tactical surveillance, exploration of natural undersea resources, predicting wave tides and various applications.

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