# A New Architecture for Underwater Acoustic Sensor Networks

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## Abstract

*Underwater acoustic sensor networks (UASNs), have ability to monitor and predict underwater environment and gather scientific data. Essentially UASNs consist of underwater sensor nodes, underwater automatic vehicles (AUVs) and stations that are located on surface of water, which is used as gateways to prepare radio link communication with offshore stations. Quality of service in these networks is limited with some parameters such as, bandwidth of acoustic channel, propagation delay of sound and high-level ambient noise in the water.*

*In this paper, at first, several aspects of underwater acoustic communications are investigated, after that; different architectures of UASN are discussed. In addition, we propose a new multipath scheme for UASN, which can improve end-to-end packet error rate while achieving a good balance between the overall energy efficiency and the end-to-end packet delay. Simulation results show that our method is highly energy-efficient with low end-to-end packet delays.*

**Keywords:** Acoustic Communications, Architecture of Underwater Acoustic Sensor Networks, Energy Efficiency.

## 1. Introduction

Acoustic communications are the typical physical layer technology in underwater networks. In fact, radio waves propagate through conductive sea water only at extra low frequencies (30 ‹300 Hz), which require large antennae and high transmission power. Optical waves do not suffer from such high attenuation but are affected by scattering. Thus, links in underwater networks are usually based on acoustic wireless communications. (Hadidi et al. 2011) Although there exist many recently developed network protocols for wireless sensor networks, the unique characteristics of the underwater acoustic communication channel require very efficient and reliable new data communication protocols. (Stojanovic. 2011)

Major challenges in underwater acoustic networks are:

1. Propagation delay is five orders of magnitude higher than in radio frequency terrestrial channels and variable;
2. The underwater channel is severely impaired, especially due to multipath and fading problems;
3. The available bandwidth is severely limited;
4. High bit error rates and temporary losses of connectivity (shadow zones) can be experienced;
5. Sensors may fail because of fouling and corrosion;

6. Battery power is limited and usually batteries cannot be easily recharged, also because solar energy cannot be exploited;

Underwater acoustic communications are mainly influenced by path loss, noise, multi-path, Doppler spread, and high and variable propagation delay. All these factors determine the temporal and spatial variability of the acoustic channel, and make the available bandwidth of the Under Water Acoustic (UW-A) channel limited and dramatically dependent on both range and frequency. Long-range systems that operate over several tens of kilometers may have a bandwidth of only a few kHz, while a short-range system operating over several tens of meters may have more than a hundred kHz bandwidth. In both cases these factors lead to low bit rates. (Manjula et al. 2011). Moreover, the communication range is dramatically reduced as compared to the terrestrial radio channel.

Underwater acoustic communication links can be classified according to their range as very long, long, medium, short, and very short links. (Stojanovic. 2011). Acoustic links are also roughly classified as vertical and horizontal, according to the direction of the sound ray.

Acoustic communications in underwater had been a difficult problem due to the channel characteristics of the underwater acoustic channel. For long range underwater acoustic communications the main problem encountered is the presence of multipath propagation caused by reflection and scattering of the transmitted signals at the bottom and the surface. Reflections from channel boundaries and diverse objects dominate the multipath structure. The transmitted signal can go through multiple paths in order to reach the receiver. These multiple paths can cause significant time spread in received signal. Each path has can possibly have multiple surface interactions causing additional frequency spreading due to motion of the water. Underwater propagation is very sensitive to changes in the geometrical parameters like water depth, source-receiver range or bottom slope leading to variations in the impulse response of the underwater acoustic sound channel. Normal mode approaches have been widely used in underwater acoustics and are derived from an integral representation of the wave equation. When propagation is described in terms of normal modes, changed in the environment translate into energy transfer between modes.

Multipath schemes are commonly believed to be beneficial to load balance and network robustness, but they are usually not considered energy-efficient since more nodes will be involved in a multipath scheme than in a one-path scheme. In this paper, contrary to the common intuition, we show that in underwater fading environments, for time-critical applications, if multipath schemes are properly combined with power control at the physical layer and packet combining at the destination, significant energy savings can be achieved with low end-to-end delays. The rest of this paper is structured as follows:

Section 2 reviews the related work on underwater sensor networks. Sections 3 presents the communication architectures and design challenges, respectively, of underwater acoustic sensor networks. After that, In Sections 4 we introduce a new method for underwater sensor networks architecture. Then, demonstrates the simulation results and analyzes the output using different parameters. Finally, we present our conclusions in section 5.

## *2. Related Works*

Past several years have witnessed a rapidly growing interest in UWSNs from both academia and industry. Many applications, networking protocols and devices have been introduced. However, most of them are application specific, and usually lack compatibility with each other. Moreover, due to limited resources, majority of work on UWSNs remains in the stage of computer simulation. Further, with different assumptions and platforms, it is very difficult to compare solutions for similar problems. Therefore, it is imperative to have a generic architecture to facilitate UWSN research.

The problem of sensing and communication coverage for terrestrial sensor networks has been addresses in several papers. Many previous deployment solutions and theoretical bounds assuming spatiotemporal correlation, mobile sensors, redeployment of nodes, and particular deployment grid structures may not be feasible for the underwater environment. In particular, in (Shakkottai et al. 2003), methods for determining network connectivity and coverage given a node-reliability model are discussed, and an estimate of the minimum required node-reliability for meeting a system-reliability objective is provided. An interesting result is that connectivity does not necessarily imply coverage. As the node reliability decreases, in fact, the sufficient condition for connectivity becomes weaker than the necessary condition for coverage.

Although (Shakkottai et al. 2003), provides useful theoretical bounds and insight into the deployment of wireless terrestrial sensor networks, the analysis is limited to grid structures. In (Zou et al. 2003), sensor coverage is achieved by moving sensor nodes after an initial random deployment. However, (Zou et al. 2003) requires either mobile sensor nodes or redeployment of nodes, which may not be feasible for UWASNs. In (Ian et al. 2005), sensing and communication coverage in a three dimensional environment are rigorously investigated. The diameter, minimum and maximum degree of the reach ability graph that describes the network are derived as a function of the communication range, while different degrees of coverage (1-coverage and, more in general, k-coverage) for the 3D environment are characterized as a function of the sensing range. Interestingly, it is shown that the sensing range required for 1-coverage is greater than the transmission range that guarantees network connectivity. Since in typical applications $t \geq r$, the network is guaranteed to be connected when 1-coverage is achieved. Although these results were derived for terrestrial networks, they can also be applied in the underwater environment. Thus, in this paper, we will focus on the sensing coverage when discussing deployment issues in 3D UW-ASNS, as in three-dimensional networks it implicitly implies the communication coverage.

A recent work combines short-base-line (SBL) and long-base-line (LBL) by using short-range Global Positioning System (GPS)-enabled stationary buoys for autonomous underwater vehicle (AUV) tracking applications. (Shuo et al. 2005). Although SBL and LBL can be utilized for localization of disconnected individual underwater equipment, they are not convenient for UASNs. SBL requires the operation of a ship which is costly and unsalable for UASNs, whereas the long-range signals of LBL have the possibility of interfering with the communication among UASN nodes. Among the proposed solutions, GPS-based localization schemes are not suitable for UASNs since the high-frequency GPS signals do not propagate well in water, whereas GPS-less schemes are generally not convenient since they require large amounts of messaging between sensor nodes.

In (Zou et al. 2003), the authors propose a distributed hierarchical localization scheme for stationary UASNs. The hierarchical architecture of Large Scale Localization (LSL) employs three types of nodes: surface buoys, anchor nodes, and ordinary sensor nodes. Surface buoys float on the surface and learn their coordinates through GPS. Anchor nodes and ordinary sensor nodes float underwater. Anchor nodes are assumed to be localized by the surface buoys at an earlier deployment stage, and LSL considers only the localization of ordinary sensor nodes. In the ordinary sensor localization process, anchor nodes periodically broadcast their coordinates, while ordinary nodes send short messages periodically to measure distances to their neighbors via time-of-arrival (ToA). LSL has a hierarchical structure, which means this scheme can be used in large-scale UASNs. Its main drawback is having high energy consumption and overhead due to beacon exchanges, localization messages, and the messages forwarded by unlocalized nodes.

In the authors utilize the same hierarchical architecture of (Zou et al. 2003) and propose Scalable Localization with Mobility Prediction (SLMP) for mobile UASNs. Anchor nodes and ordinary nodes estimate their locations by using their previous coordinates and their mobility patterns. In a mobile UASN, mobility patterns may become obsolete in time; therefore, anchor nodes periodically check the validity of their mobility pattern and trigger an update when necessary. An anchor node, after predicting its location, uses surface buoy coordinates and distance measurements to buoys to estimate its location.

## *3. Architecture of Underwater Acoustic Sensor Networks*

### 3.1. Static Architecture

For static architecture, the network topology would be in relative static state after sensors were deployed, the network could be anchored into two-dimensional (2D) or three-dimensional (3D) either on the sea floor or surface. The main character of this architecture is that the topology doesn't change or move after deployment. In 2D case, the topology could be grid, cluster, tree, or line-relay deployment same as terrestrial wireless sensor networks (WSNs). In 3D case, sensors could be moored to anchors on ocean floor or to surface floats with fix depth.

#### 3.1.1. Two - dimensional case

A sample of underwater (uw) network environment is as shown in the Fig. 1. The network consists of a set of underwater local area networks (UW-LAN, also known as clusters or cells). (Ian et al. 2005). Each sensor is connected to the sink within the cluster. The sensors can be connected to uw-sinks via direct paths at multiple hops. The information from the sink of each cluster is transferred to surface station through vertical links.

The station at the surface is equipped with acoustic transceivers that are capable of handling multiple parallel communications with the deployed uw-sinks. uw-sinks, as shown in Fig. 1, are network devices in charge of relaying data from the ocean bottom network to a surface station. To achieve this objective, uw-sinks are equipped with two acoustic transceivers, namely a vertical and a horizontal transceiver. The horizontal transceiver is used by the uw-sink to communicate with the sensor nodes in order to: (i) send commands and configuration data to the sensors (uw-sink to sensors); (ii) collect monitored data (sensors to uw-sink). The vertical link is used by the uw-sinks to relay data to a surface station. In deep water applications, vertical transceivers must be long range transceivers as the ocean can be as deep as 10 km. The surface station is equipped with an acoustic transceiver that is able to handle multiple parallel communications with the deployed uw-sinks. (Cheng. 2008), (Eugenio et al. 2007). It is also endowed with a long range RF and/ or satellite transmitter to communicate with the onshore sink (os-sink) and /or to a surface sink (s-sink).

### 3.1.2. Three - dimensional case

Three dimensional underwater networks are used to detect and observe phenomena that cannot be adequately observed by means of ocean bottom sensor nodes to perform cooperative sampling of the 3D ocean environment. (Wenli et al. 2008). An onshore control center sends a query to an underwater sensor node via satellites and surface stations. The required data on underwater sensor nodes go backwards to the onshore control center thru same route. (Cayirci et al. 2004). In this architecture, we have several sorts of nodes which have differentiated functions and structure. An underwater sensor node is in charge of both sensing and transmitting with relatively high energy consumption. (Ian et al. 2005). The functional simplicity of a sensor node is definitely required for energy efficiency. In order to communicate between an underwater sink node and a surface station, the capacity of transmitting-receiving should be enhanced if the distance is far away. Therefore, we need underwater relay nodes in the midst of water. (Hsin et al. 2004). All communication is bi-directional.

### 3.2. Hybird Architecture

We call this as Hybrid Architecture where an UASN consists of lots of static sensors together with some mobile sensors, no matter AUVs, ROVs or any other sea gliders. In hybrid architecture, mobile nodes play a key role for additional support in accomplishing task, perhaps for data harvesting or enhancing the network capacity. Mobile nodes could be considered as super nodes which has more energy and can move independently, and it could be a router between fixed sensors, or a manager for network reconfiguration, or even a normal sensor for data sensing.

In hybrid network architecture was discussed in (Heidemann et al. 2006), there are four kinds of nodes to obtain a tiered deployment. At the lowest layer, large numbers of sensors are deployed on the seabed for data collection. One or more control nodes with connections to Internet are deployed on ocean surface or off-shore platform. Another two types are super nodes which can interconnect with high speed network and relay data efficiently, and submersible robots. A network topology using Delay-tolerant Data Dolphins (DDD) in stationary sensor grids was described in (Eugenio et al. 2007), DDDs with high energy can help to maximize the network lifetime of UASNs. Each underwater sensor is only required to transmit its data to the nearest dolphin within one-hop distance as dolphins' approaching.

An architecture for short-term time-critical aquatic exploration applications was described in (Heidemann et al. 2006), using UASN to control ROV remotely for emergency underwater investigation .A three layers architecture was considered in (Shuo et al. 2005), different physical environments present different requirements for sensors. The fixed sea-floor sensors require high robustness for long term data collection, the surface nodes acting as sinks are fixed in special regions and with GPS for localization. The mobile nodes between upper two layers are AUVs or ROVs, which can move horizontally and vertically.

An application model for underwater monitoring applications shown in Fig. 4, it works in two ways: local base station collects sensors' data with regular time resolution, and mobile actors collect data from virtual clusters with high temporal resolution. Mobile actors dive into local monitoring area from surface ships or submarines and then scatter to different regions. As mobile actors approach, sensors would self-organize to form temporary clusters according to the number of actors. Each actor serves as cluster head and collects data from all nodes within that cluster by multi-hops. After data was collected, it would switch back to local networks (Akyildiz et al. 2006). Because the clusters are alive just for a short period, they are called virtual clusters. We proposed a new strategy which is composed of three algorithms: Area partition and scattering, sub-region optimizing and virtual cluster formation algorithm. Experiment results indicate that our strategy can reduce sensors' power consumption significantly and achieve lower end-to-end delay.

We can consider the hybrid architecture as a special mobile ad-hoc network, in which the mobile nodes are not only task operators, but also network managers. Data relayed by mobile nodes can shorten the end-to-end delay. On the other hand, it can prolong the lifetime of static network. The mobile nodes build a link between surface level and seabed level, and the ability of the mobile nodes decides the efficiency of the network. Its shortcoming is that it would be expensive and difficult for practical applications.

### 3.3. Mobile UASNs and Free Flouting Networks

In this architecture, all the nodes are not restricted geographically, nodes can move freely, and the network topology would be variable. Fig. 5 shows a normal architecture that could be divided into two layers, surface layer sensors and underwater layer. Surface layer sensors often equipped with a wireless transceiver for data communication and are usually used for pollution detecting, water quality surveillance, coastal circulation monitoring and pollutant tracking. Underwater layer consists of many mobile nodes which can stay at any depth with the help of float equipment; it can be used for ocean biogeocenose investigation, fish migration and biological monitoring. Unlike the active behavior of mobile nodes, the sensors movement is passive; the dynamic ocean characters (such as waves, tides, currents) play a key role on the nodes movement.

A mobile UASN architecture for long-term non time-critical aquatic monitoring applications was proposed in (Jun et al. 2006). Low-cost sensors are deployed to cover a special continuous monitoring region, data are collected by local sensors, be relayed by intermediate nodes, and finally reach the gateway on the surface level which equipped with both acoustic and RF transceiver. Based on this architecture, a surface-level gateway deployment method was given. All the surface gateways form virtual sinks want to find the tradeoff between the number of surface gateways and the expected delay and energy consumption. A mobility model for coastal underwater environments was presented, free-floating sensors are initially deployed in a small sub area and would be shifted by the effect of meandering sub-surface currents and vortexes in a large coastal environment. Another class of ocean monitoring networks was proposed. free-floating underwater devices operate autonomously and collaborate through an acoustic communication among them, the drogue devices drift freely with the ocean currents and equip with a buoyancy control piston(Lee et al. 2008). The important application is for short term pollutant tracking.

A majority of this kind of architecture is passive; the topology would be changed according to the integrated effect of currents, winds, tides, and waves. This brings the biggest disadvantage that the coverage and communication link could not be guaranteed, and it is difficult to achieve effective topology control. The interesting characteristic of this architecture is that it can track objects moving with water currents without any manual interference. For the scenarios that mobile UASN works together with free floating sensor network, communication connection is needed between under water layer and surface layer, this calls for some free floating sensors on the surface should be equipped with acoustic modem, also under water autonomous mobile nodes is needed for keeping active data link.

### 3.4. Sensore Networks with Autonomous Underwater Vehicles

AUVs can function without tethers, cables, or remote control, and therefore they have a multitude of applications in oceanography, environmental monitoring, and underwater resource studies. Previous experimental work has shown the feasibility of relatively inexpensive AUV submarines equipped with multiple underwater sensors that can reach any depth in the ocean. The integration of UW-ASNs with AUVs requires new network coordination algorithms such as:

#### Adaptive sampling

This includes control strategies to command the mobile vehicles to places where their data will be most useful. For example, the density of sensor nodes can be adaptively increased in a given area when a higher sampling rate is needed for a given monitored phenomenon.

#### Self-configuration

This includes control procedures to automatically detect connectivity holes due to node failures or channel impairment, and request the intervention of an AUV. Furthermore, AUVs can either be used for installation and maintenance of the sensor network infrastructure or to deploy new sensors. One of the design objectives of AUVs is to make them rely on local intelligence and be less dependent on communications from online shores. In general, control strategies are needed for autonomous coordination, obstacle avoidance, and steering strategies.

Solar energy systems allow increasing the lifetime of AUVs, i.e., it is not necessary to recover and recharge the vehicle on a daily basis. Hence, solar powered AUVs can acquire continuous information for periods of time of the order of months. Reference architecture for UW-ASNs with AUVs is shown in Fig. 6.

## *4. The Proposed Method*

### 4.1. Architecture Network Model

In an underwater sensor network, with high probability, multipath routing protocols can find multiple paths between any two nodes because of the relatively high node density. This assumption holds even stronger in the multiple-sink underwater network architecture. Different paths will experience independent fading if they are node-disjoint. This work utilizes this property to provide “multipath macro-diversity”. Specifically in this technique, the source node transmits the same packet along multiple paths to the same destination. The transmission power at each intermediate node along each path is controlled by the source nodes based on the path characteristics. Multiple copies of the packet (some of these copies may be corrupted during transmission) will arrive at the destination along different paths, and the destination then recovers the packet by combining the received copies.

We consider the following multisink underwater sensor network model: Underwater sensor nodes with acoustic modems are densely distributed in a 3-D aqueous space, and multiple gateway nodes with both acoustic and RF modems are strategically deployed at the water surface. Each underwater sensor node can monitor and detect environmental events locally, As shown in Fig. 7.When an underwater sensor node has data to report, it first transfers the data toward one or multiple surface gateway nodes (each is also referred to as a sink) through acoustic links. Then, these surface gateway nodes relay the received data to the control center through radio links. Compared to the acoustic links in water, surface radio links are much more reliable, faster, and more energy-efficient. Considering that radio signal propagation is orders of magnitude faster than acoustic signal propagation, it is safe to assume that surface gateways can send packets to the control center in negligible time and with relatively small energy consumption (acoustic communications consume much more energy than radio communications. In addition, gateway nodes are usually more powerful and have more energy supplies.). In this way, all the surface gateways (or sinks) form a virtual sink.

This multisink network architecture is helpful in traffic balance and multiple-path finding, as has been studied and analyzed in (Ibrahim et al. 20067), (Seah et al. 2006), and (Zhou et al. 2007). For our scheme, this multisink architecture can effectively help to find more paths to the (virtual) sink (since any surface gateway is counted as a sink) and can greatly reduce the packet-collision probability in the MAC layer. As shown in Fig. 8, first, the source node (any underwater sensor node in our network model can be a source node) initiates a multipath routing process to find paths from the source to the destination (in our network model, the control center can be the destination). Through this route-finding process, the source will get to know some network parameters such as path length and the number of available paths. Based on this knowledge, the source node selects some paths and calculates the optimal transmitting power for each node along the selected paths. Then, it sends the same packet along the selected paths. Intermediate nodes on these selected paths will relay the packet with specified transmitting power parameters (carried in the packet header). When the destination receives all copies of the packet (some copies may get corrupted), it performs packet combining to recover the original packet.

### 4.2. Performance Evaluation of Architecture Model

Following the multiple-sink underwater sensor network model, the simulated network settings are as follows: 512 underwater sensor nodes are randomly deployed in a three-dimensional space of 4000*4000*2000 m3; 36 surface gateways are deployed in a two-dimensional area of 4000*4000 m2 at the water surface. A node can use any surface gateway as long as it can find a path to the gateway, and the node is not required to send its packets to all gateways. Unless specified otherwise, the simulation parameters are as follows: The maximal transmission range of underwater sensor nodes is set to 600 m, and the data rate is set to be 10 kb/s. Each simulation lasts for 10000 s. Thus, each node generates about 1000 packets in each simulation. We run simulations for 100 times and take the average as our final results. For comparison, we implement two other schemes in the same underwater network settings. One scheme is one-path transmission with power control but without retransmission (referred to as one-path without retransmission for short), and the other scheme is one-path transmission with retransmission and power control (referred to as one-path with retransmission for short).

In the one-path without retransmission scheme, through a routing process, the source node first finds the most energy-efficient path and transmits its packets with power control to guarantee the end-to-end packet error rate. No retransmission is performed upon transmission failure. For the one-path with retransmission scheme, it works as follows: First, the source node finds the most energy-efficient path by its routing process, and then transmits packets with power control along this path. Retransmission is allowed upon failure (i.e., if the sender does not receive an ACK for a packet from the receiver after time tr (in our simulations, we set tr=1 s), it will retransmit the packet. We set the maximal times of retransmission nr. After retransmitting a packet for nr times, a node will simply drop this packet.

B. Results and Analysis

Fig. 9(a) shows the impact of end-to-end packet error rate (PER) on various schemes. From this figure, we can observe that with the increase of end-to-end PER, the average energy consumption per packet will decrease sharply. Compared to one-path without retransmission, our method always consumes much less energy.

Fig. 9(b) clearly shows that our scheme can achieve high energy efficiency with small end-to-end delay under certain end-to-end PER requirements.

Fig. 9(c) also shows that the end-to-end delivery ratio is almost the same for these three schemes. This is because all of them are designed to adjust the transmitting power of nodes to minimize the overall energy consumption with certain end-to-end packet error rate. As shown in Fig. 9(c), all these three schemes can achieve the desired reliability for data packet delivery well.

Multipath schemes are commonly believed to be beneficial to load balance and network robustness, but they are usually not considered energy-efficient since more nodes will be involved in a multipath scheme than in a one-path scheme. This approach, contrary to the common intuition, shows that in underwater fading environments, for time-critical applications, if multipath schemes are properly combined with power control at the physical layer and packet-combining at the destination, significant energy savings can be achieved with low end-to-end delays.

## 5. Conclusion

In this paper, an overview of the state of the art in underwater acoustic sensor network was presented and the challenges posed by the peculiarities of the underwater channel with particular reference to monitoring applications for the ocean environment were described. Then, the related works about UASNs, classified the UASNs' architectures into different groups, and analyzed the characteristics of different architectures were investigated. Next, a novel multipath transmission scheme, for time-critical applications in underwater sensor networks was proposed. This approach combines the power-control strategies with multipath routing protocols and packet recovery at the destination. Without retransmission at the intermediate nodes, pattern can achieve low end-to-end packet delay. For time-critical applications in energy constrained underwater sensor networks, it is a promising transmission scheme for a good balance between packet delay and energy efficiency.
The ultimate objective of this paper is to encourage research efforts to lay down fundamental basis for the development of new advanced communication techniques for efficient underwater communication and networking for enhanced ocean monitoring and exploration applications.

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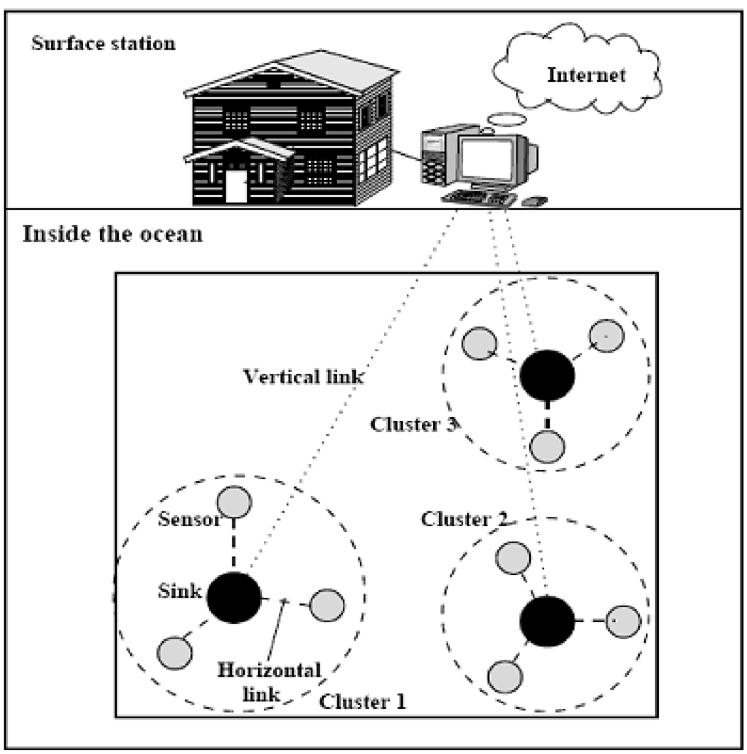



**Figure 1. Architecture for 2D underwater sensor networks**

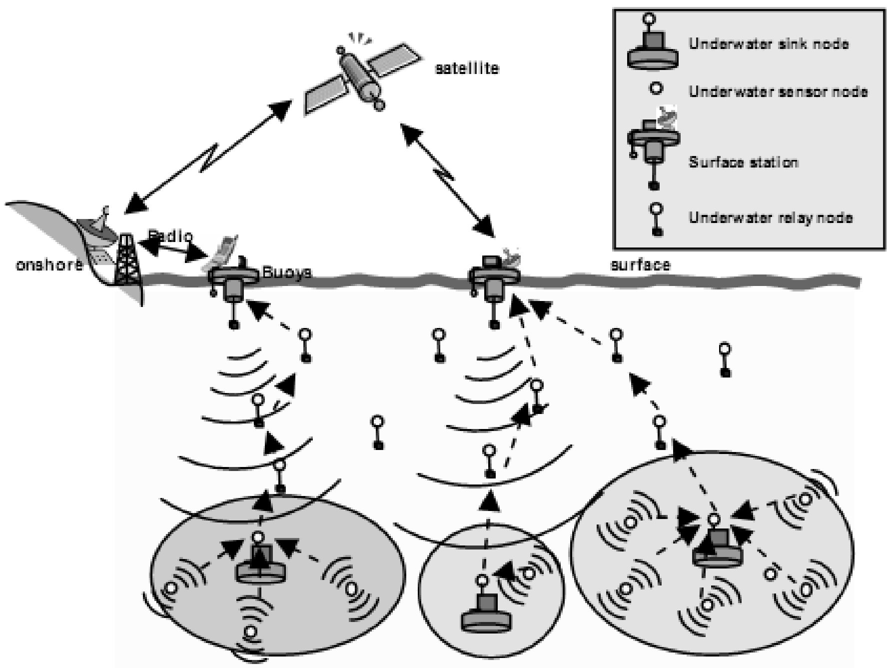



**Figure 2. Architecture for 3D underwater sensor networks**

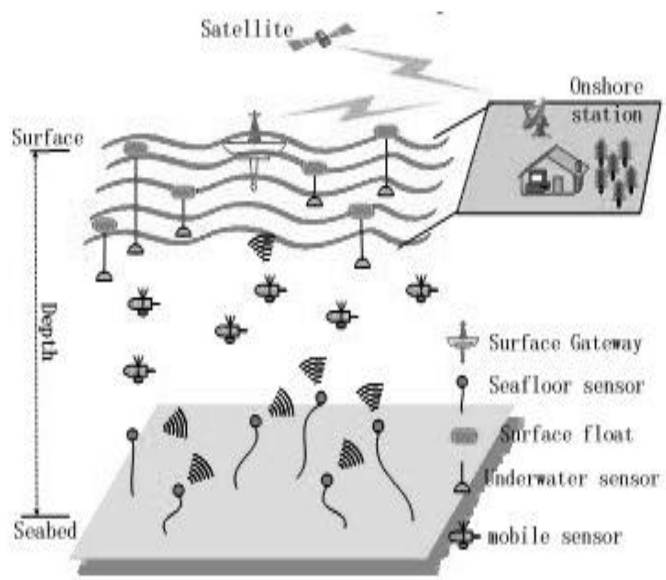



**Figure 3. Hybrid architecture: static sensor with mobile nodes**

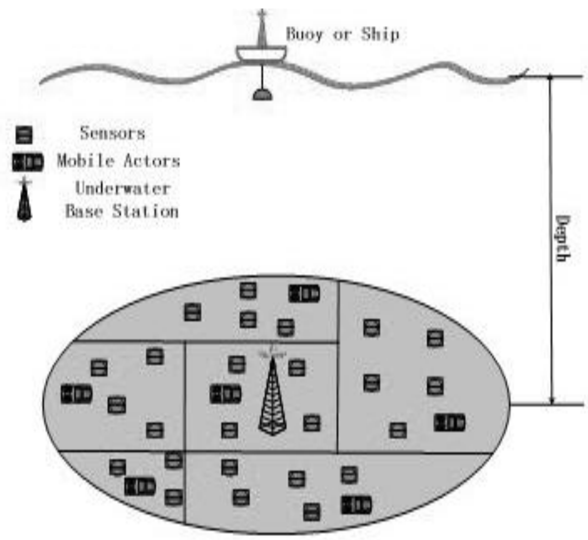



**Figure 4. UASNs' application model with multiple mobile actors**

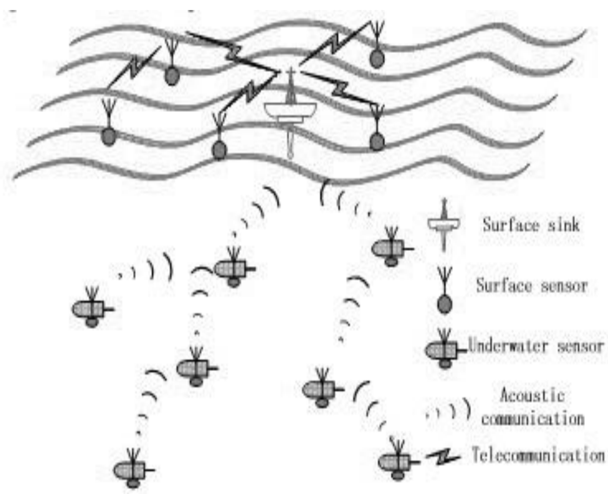



**Figure 5. Mobile UASNs with free-floating networks**

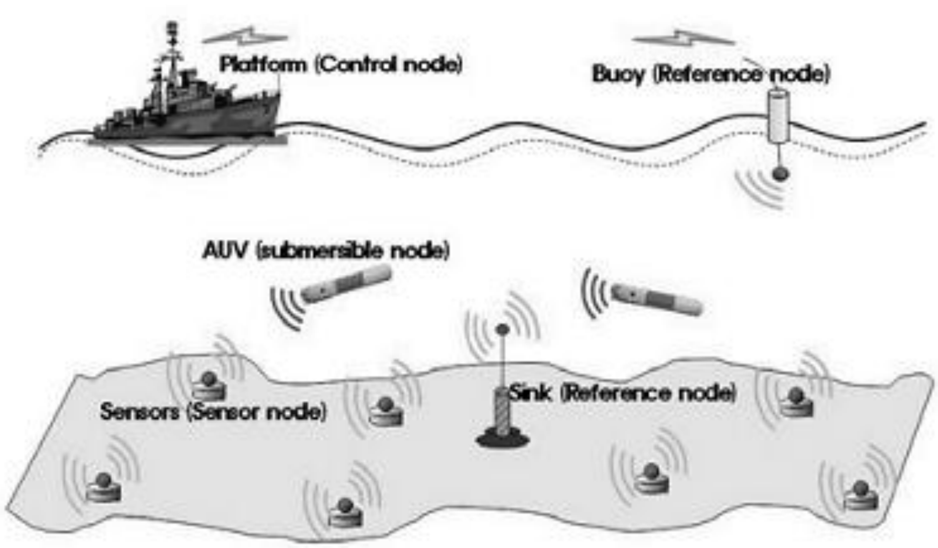



**Figure 6. Underwater Sensor Networks with AUVs**

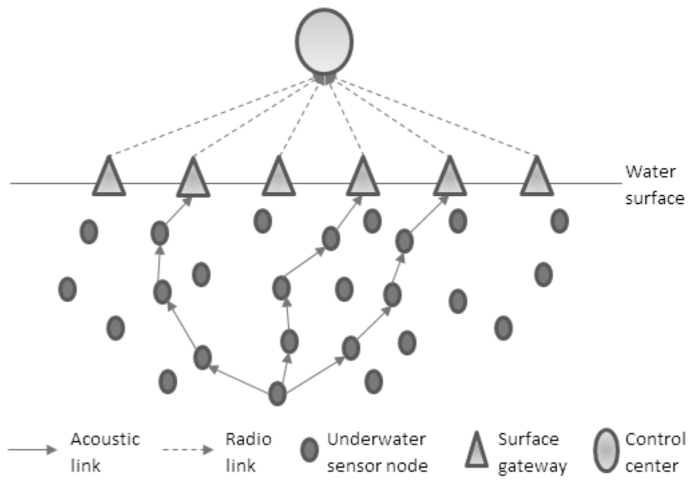



**Figure 7. Network Model**

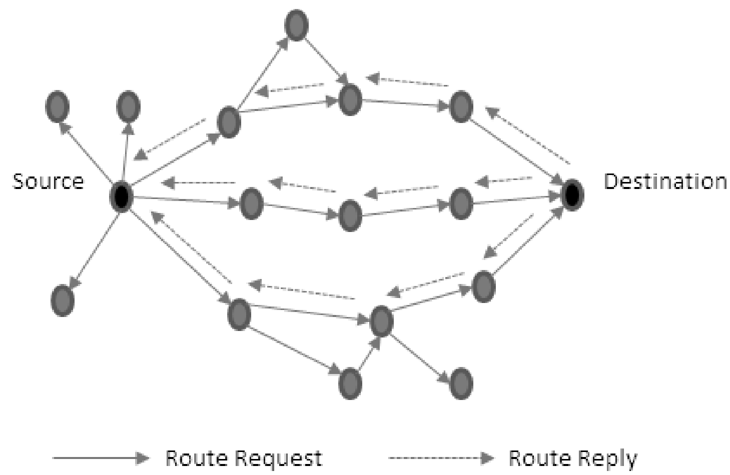
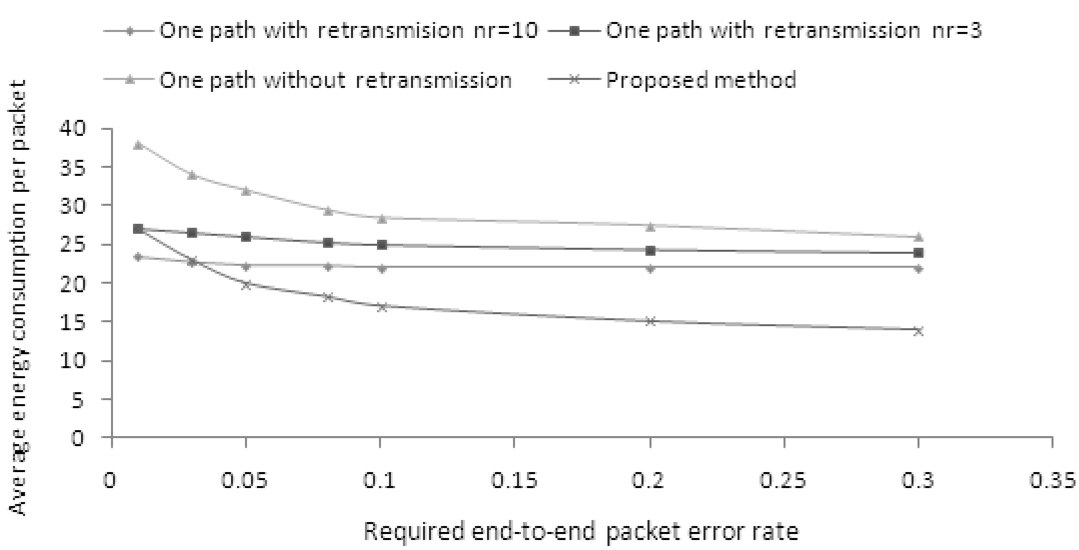
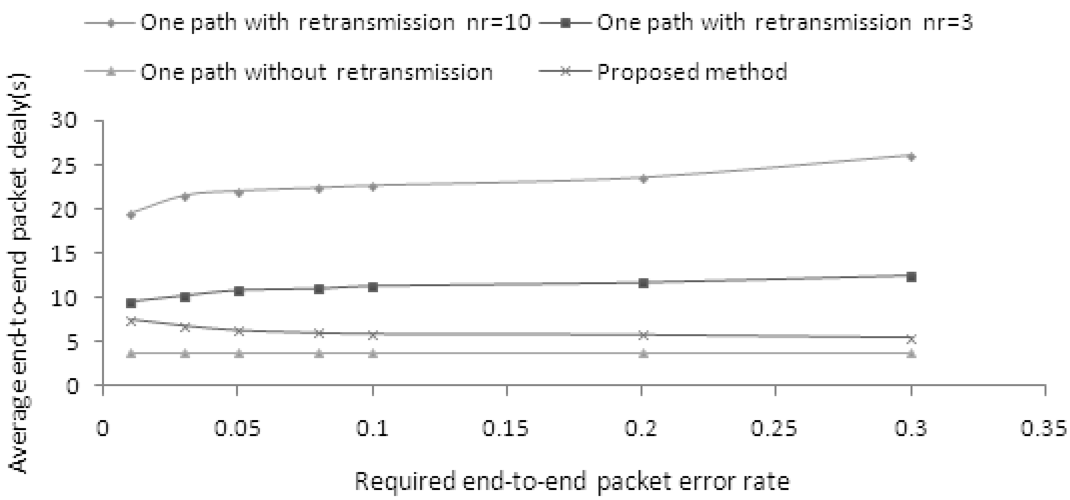


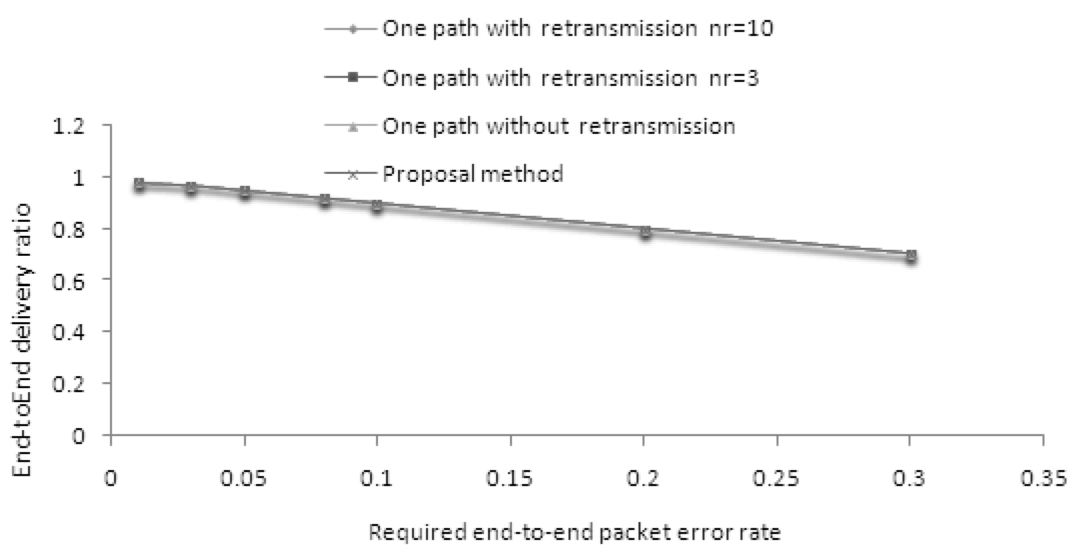

**Figure 8. Basic procedure of multipath routing**




(a) Average energy consumption per packet




(b) Average end-to-end packet delay




(c) End-to-end delivery ratio

**Figure 9. Performance with varying end-to-end PER**