Thesis for the Degree of Master of Engineering

A Study on Energy Efficient Data Transmission Method for the Underwater Wireless Sensor Networks

by

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A dissertation

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A Study on Energy Efficient Data Transmission Method for the Underwater Wireless Sensor Networks

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Abstract

Recently, there has been a growing interest in monitoring the marine environment for scientific exploration, commercial exploitation and coastline protection. Especially since our country is a peninsula, the study of ocean is more important.

The ideal method for this type of extensive monitoring is a networked underwater wireless sensor distributed system, referred to as an Underwater Wireless Sensor Networks (UWSNs). The UWSNs consist of a variable number of sensors and vehicles that are deployed to perform collaborative monitoring tasks over a given area.

Underwater sensor nodes will find applications in oceanographic data collection, pollution monitoring, offshore exploration, disaster prevention, assisted navigation and tactical surveillance applications. Moreover, unmanned or autonomous underwater vehicles, equipped with sensors, will enable the exploration of natural undersea resources and gathering of scientific data in collaborative monitoring

missions. Underwater acoustic networking is the enabling technology for these applications.

Many researchers are currently engaged in developing networking solutions for terrestrial wireless and sensor networks and ad hoc networks. Since UWSNs have more challenge than terrestrial WSNs, adopting efficient routing and data aggregation schemes is very important. However, due to the different nature of the underwater environment and applications, there are several drawbacks with respect to the suitability of the existing solutions for terrestrial WSNs.

Especially because UWSNs are respectively sparse than terrestrial WSNs and have a long transmission range, data transmission scheme is also important as much routing and data aggregation schemes.

In this thesis, we investigate how the network's energy consumption is influenced by the transceiver parameters and review the state of precious routing and data aggregation researches in terrestrial WSNs to apply those to UWSNs. Then, we adopt a hexagon tessellation approach to deploy the underwater sensor nodes, calculate ideal cell sizes for UWSNs and suggest an enhanced hybrid transmission method that considers the load balancing once the data transmission is occurred. The suggested enhanced hybrid transmission method improves the data transmission performance by applying the threshold region that is decided as the distance between a node and Base Station (BS) and by allocating different frequencies. We simulate the proposed enhanced hybrid transmission method in the environment of UWSNs. The simulation results show that the proposed method has better efficiency than the existing multi-hop forwarding methods.

Ⅰ. Introduction

The largely unexplored vastness of the ocean, covering about two-thirds of the surface of Earth, has fascinated humans for long time. Its currents, chemical composition, and ecosystems are all highly variable as a function of space and time.

Recently, there has been a growing interest in monitoring the marine environment for scientific exploration, commercial exploitation and coastline protection. Especially since our country is a peninsula, the study of ocean is more important.

The ideal method for this type of extensive monitoring is a networked underwater wireless sensor distributed system, referred to as an Underwater Wireless Sensor Networks (UWSNs) [1].

A distributed and scalable UWSNs provides a promising solution for efficiently exploring and observing the ocean which operates under the following constraints:

Unmanned underwater exploration: Underwater condition is not suitable for human exploration. High water pressure, unpredictable underwater activities, and vast size of water area are major reasons for un-manned exploration.

Localized and precise knowledge acquisition: Localized exploration is more precise and useful than remote exploration because underwater environmental conditions are typically localized at each venue and variable in time. Using sonar or other remote sensing technology may not acquire adequate knowledge about physical events happening in the volatile underwater environment.

Tetherless underwater networking: While the current tethered technology allows constrained communication between an underwater venue and the ground infrastructure, it incurs significant cost of deployment, maintenance, and device recovery to cope with volatile undersea conditions.

Large scale underwater monitoring: Traditional underwater exploration relies on either a single high-cost underwater device or a small-scale underwater network. Neither existing technology is suitable to applications covering a large area. Enabling a scalable underwater sensor network technology is essential for exploring a huge underwater space.

By deploying distributed and scalable wireless sensor networks in 3-dimensional underwater space, each underwater sensor can monitor and detect environmental events locally. Such mission can be also accomplished with fixed position sensors.

An UWSNs consists of a variable number of sensors and vehicles that are deployed to perform collaborative monitoring tasks over a given area. And UWSNs consist of sensor nodes equipped with the small battery powered device with limited energy resources. Hence, the energy efficiency is a key design issue that needs to be enhanced in order to improve the lifetime of the network.

To realize underwater sensor network applications, UWSNs have to adopt many of the tools that have been developed for terrestrial sensor networks: wireless communication, low-power hardware, energy conserving network protocols, time synchronization and localization, and programming abstractions and so on. However, some of the techniques are fundamentally different.

Especially since UWSNs have more challenge than terrestrial WSNs, adopting efficient routing and data aggregation schemes is very important. And because UWSNs are respectively sparse than terrestrial WSNs and have a long transmission range, data transmission scheme is also important as routing and data aggregation schemes.

In this thesis, we investigate how the network's energy consumption is influenced by the transceiver parameters and review the state of precious routing and data aggregation researches in WSNs to apply those to UWSNs. Then, we adopt a hexagon tessellation approach to deploy the underwater sensor nodes, calculate ideal cell sizes for UWSNs and suggest an enhanced hybrid transmission method that considers the load balancing once the data transmission is occurred. The suggested hybrid transmission method improves the data transmission performance by applying the threshold region that is decided as the distance between a node and BS (Base Station) and by allocating different frequencies. We simulate the proposed hybrid transmission method in the environment of UWSNs. The simulation results show that the proposed method has better efficiency than the existing multi-hop forwarding methods.

The outline of the thesis is organized as follows. In Section II, we discuss the related work and analyze differences between terrestrial WSNs and UWSNs. In Section III, we propose a network model for an UWSNs and an enhanced hybrid transmission method that considers a threshold region and the frequency allocation. In Section IV, we describe the simulation results. Finally we conclude this thesis in Section V.

Ⅱ. Background

1. Underwater Wireless Sensor Networks

1.1 Underwater Wireless Sensor Network Architecture

For the past several centuries, the ocean has played an increasingly important role in transportation and military campaign. In emergent event investigations, e.g., for marine incidents (especially involved with chemical pollution and oil spill) and military demands (for example submarine attacks and submarine hunting), the state-of-the-art in communication technology has significantly surpassed the state-of-the-art of physical investigation in regard to effectiveness and efficiency.

Since underwater monitoring missions can be extremely expensive due to the high cost involved in underwater devices, it is important that the deployed network be highly reliable, so as to avoid failure of monitoring missions due to failure of single or multiple devices. For example, it is crucial to avoid designing the network topology with single points of failure that could compromise the overall functioning of the network. And the network capacity is also influenced by the network topology. Since the capacity of the underwater channel is severely limited, it is very important to organize the network topology such a way that no communication bottlenecks are introduced.

There are several different architectures for Underwater Acoustic Sensor

Networks, depending on the application [2]:

Two-dimensional UWSNs for ocean bottom monitoring. These are constituted by sensor nodes that are anchored to the bottom of the ocean. Typical applications may be environmental monitoring, or monitoring of underwater plates in tectonics.

Three-dimensional UWSNs for ocean column monitoring. These include networks of sensors whose depth can be controlled, and may be used for surveillance applications or monitoring of ocean phenomena (ocean bio-geo-chemical processes, water streams, pollution, etc).

Three-dimensional networks of Autonomous Underwater Vehicles (AUVs). These networks include fixed portions composed of anchored sensors and mobile portions constituted by autonomous vehicles.

1) Two-dimensional underwater sensor networks

A reference architecture for two-dimensional underwater networks is shown in Figure 1. A group of sensor nodes are anchored to the bottom of the ocean with deep ocean anchors. Underwater sensor nodes are interconnected to one or more underwater sinks (uw-sinks) by means of wireless acoustic links. Uw-sinks, as shown in Figure 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. 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).

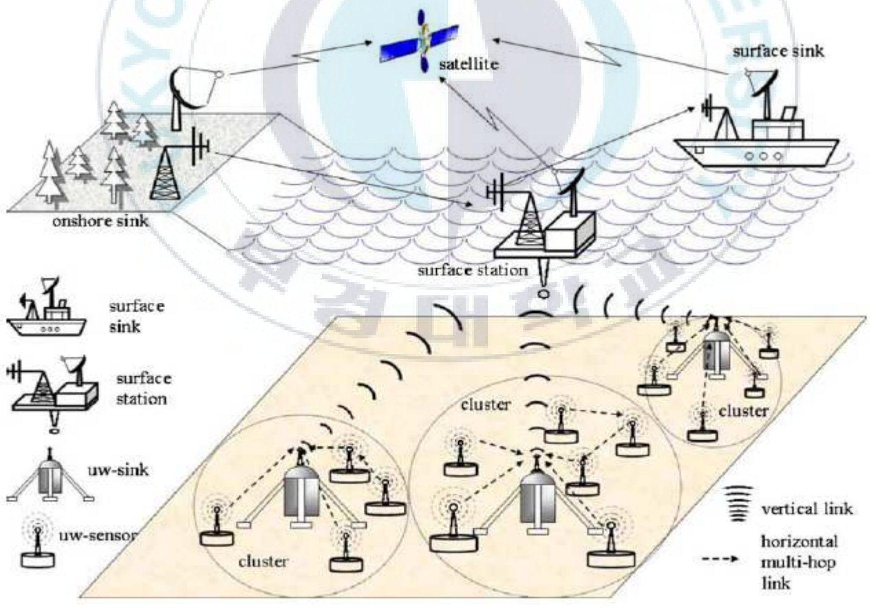

Figure 1. Two-dimensional UWSNs architecture

Sensors can be connected to uw-sinks via direct links or through multi-hop paths.

2) Three-dimensional underwater sensor networks

Three dimensional underwater networks are used to detect and observe phenomena that cannot be adequately observed by means of ocean bottom sensor nodes, i.e., to perform cooperative sampling of the 3D ocean environment. In three-dimensional underwater networks, sensor nodes float at different depths in order to observe a given phenomenon.

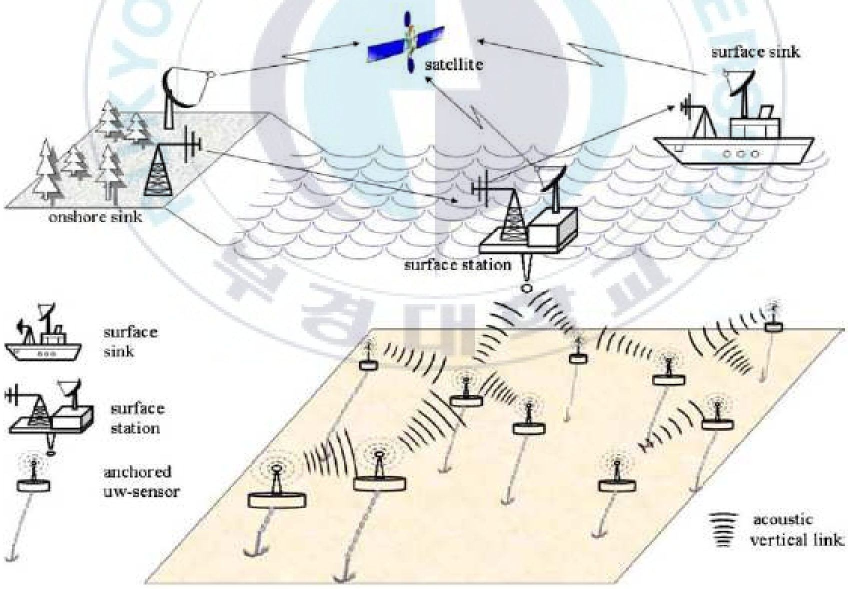

Figure 2. Three-dimensional UWSNs architecture

One possible solution would be to attach each uw-sensor node to a surface buoy, by means of wires whose length can be regulated so as to adjust the depth of each sensor node [3]. However, although this solution allows easy and quick deployment of the sensor network, multiple floating buoys may obstruct ships navigating on the surface, or they can be easily detected and deactivated by enemies in military settings. Furthermore, floating buoys are vulnerable to weather and tampering or pilfering. For these reasons, a different approach can be to anchor sensor devices to the bottom of the ocean. In this architecture, depicted in Figure 2, each sensor is anchored to the ocean bottom and equipped with a floating buoy that can be inflated by a pump. The buoy pushes the sensor towards the ocean surface. The depth of the sensor can then be regulated by adjusting the length of the wire that connects the sensor to the anchor, by means of an electronically controlled engine that resides on the sensor. A challenge to be addressed in such architecture is the effect of ocean currents on the described mechanism to regulate the depth of the sensors.

Many challenges arise with such an architecture that needs to be solved in order to enable 3D monitoring, including:

Sensing coverage: Sensors should collaboratively regulate their depth in order to achieve 3D coverage of the ocean column, according to their sensing ranges. Hence, it must be possible to obtain sampling of the desired phenomenon at all depths.

Communication coverage: Since in 3D underwater networks there may be no notion of uw-sink, sensors should be able to relay information to the surface station via multi-hop paths. Thus, network devices should coordinate their depths in such a way that the network topology is always connected, i.e., at least one path from every sensor to the surface station always exists.

3) Sensor 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 study. 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 [4]. Hence, they can be used to enhance the capabilities of underwater sensor networks in many ways. The integration and enhancement of fixed sensor networks with AUVs is an almost unexplored research area which requires new network coordination methods such as:

Adaptive sampling: This includes control strategies to command the mobile vehicles to places where their data will be most useful. This approach is also known as adaptive sampling and has been proposed in pioneering monitoring missions such as [5]. 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. They can also be used as temporary relay nodes to restore connectivity.

One of the design objectives of AUVs is to make them rely on local intelligence and 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 [6].Several types of AUVs exist as experimental platforms for underwater experiments. Some of them resemble small-scale submarines.

Others are simpler devices that do not encompass such sophisticated capabilities. For example, drifters and gliders are oceanographic instruments often used in underwater explorations. Drifter underwater vehicles drift with local current and have the ability to move vertically through the water column. They are used for taking measurements at preset depths [7].

Underwater gliders [8] are battery powered autonomous underwater vehicles that use hydraulic pumps to vary their volume by a few hundred cubic centimeters in order to generate the buoyancy changes that power their forward gliding. When they emerge on the surface, global positioning system (GPS) is used to locate the vehicle. This information can be relayed to the onshore station while operators can interact by sending control information to the gliders. Depth capabilities range from 200 m to 1500 m while operating lifetimes range from a few weeks to several months. These long durations are possible because gliders move very slowly, typically 25 cm/s (0.5 knots). In [9], a control strategy for groups of gliders to cooperatively move and reconfigure in response to a sensed distributed environment is presented. The proposed framework allows preserving the symmetry of the group of gliders. The group is constrained to maintain a uniform distribution as needed, but is free to spin and possibly wiggle with the current [10].

1.2 Applications for UWSNs

We have just described the UWSNs architectures. And there are the numerous applications for UWSNs. Tabe 1 summarizes Applications for UWSNs.

Table 1. Applications for underwater wireless sensor networks

Applications	Characteristic
Ocean sampling networks	Networks of sensors and AUVs can perform synoptic, cooperative adaptive sampling of the 3D coastal ocean environment [11]. Experiments demonstrated the advantages of bringing together sophisticated new robotic vehicles with advanced ocean models to improve the ability to observe and predict the characteristics of the oceanic environment [5].
Environmental monitoring	UWSNs can perform pollution monitoring (chemical, biological) [12]. Monitoring of ocean currents and winds, improved weather forecast, detecting climate change, under-standing and predicting the effect of human activities on marine ecosystems, biological monitoring [13].
Undersea explorations	UWSNs can help detecting underwater oilfields or reservoirs, determine routes for laying undersea cables, and assist in exploration for valuable minerals.
Disaster prevention	UWSNs that measure seismic activity from remote locations can provide tsunami warnings to coastal areas [14], or study the effects of submarine earthquakes (seaquakes).
Assisted navigation	Sensors can be used to identify hazards on the seabed, locate dangerous rocks or shoals in shallow waters, mooring positions, submerged wrecks, and to perform bathymetry profiling.
Distributed tactical surveillance	AUVs and fixed underwater sensors can collaboratively monitor areas for surveillance, reconnaissance, targeting and intrusion detection systems [3].
Mine reconnaissance	The simultaneous operation of multiple AUVs with acoustic and optical sensors can be used to perform rapid environmental assessment and detect mine-like objects.

1.3 Analysis of Underwater Communication Environment

Acoustic communications are the typical physical layer technology in underwater networks. In fact, radio waves propagate at long distances through conductive sea water only at extra low frequencies (30–300 Hz), which require large antennae and high transmission power. Moreover, transmission of optical signals requires high precision in pointing the narrow laser beams. Thus, links in underwater networks are based on acoustic wireless communications [15].

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 underwater acoustic channel limited and dramatically dependent on both range and frequency.

Hereafter we analyze the factors that influence acoustic communications in order to state the challenges posed by the underwater channel for UWSNs. The factors that influence acoustic communications in UWSNs are shown as table 2.

Table 2. The factors that influence acoustic communications in UWSNs

Factors		Characteristics
Path loss	Attenuation	This mainly provoked by absorption due to conversion of acoustic energy into heat. The attenuation increases with distance and frequency.
	Geometric spreading	This refers to the spreading of sound energy as a result of the expansion of the wavefronts. It increases with the propagation distance and is independent of frequency.
Noise	Man made noise.	This mainly caused by machinery noise (pumps, reduction gears, power plants), and shipping activity (hull fouling, animal life on hull, cavitation), especially in areas encumbered with heavy vessel traffic.
	Ambient noise	This related to hydrodynamics (movement of water including tides, current, storms, wind, and rain), and to seismic and biological phenomena [16].
Multi-path propagation		Multi-path propagation may be responsible for severe degradation of the acoustic communication signal, since it generates intersymbol interference (ISI). The extent of the spreading is a strong function of depth and the distance between transmitter and receiver.
High delay and delay variance		The propagation speed in the UWSN's channel is five orders of magnitude lower than in the radio channel. This large propagation delay (0.67 s/km) can reduce the throughput of the system considerably.
Doppler spread		The Doppler frequency spread can be significant in UWSN's channels [15], thus causing a degradation in the performance of digital communications: high data rate transmissions cause adjacent symbols to interfere at the receiver. This requires sophisticated signal processing to deal with the generated ISI. The Doppler spreading generates 1) a simple frequency translation, which is relatively easy for a receiver to compensate for. 2) a continuous spreading of frequencies that constitutes a non-shifted signal, which is more difficult to compensate for.

2. Analysis of Routing and Data Aggregation Techniques in Wireless Sensor Networks

To realize applications of UWSNs, we can borrow the routing and data aggregation schemes that that have been developed for terrestrial sensor networks. But because of different environment, there exist challenges for adoption of scheme for UWSNs.

Due to recent technological advances, the manufacturing of small and low-cost sensors has become technically and economically feasible. These sensors measure ambient conditions on the environment surrounding them and then transform these measurements into signals that can be processed to reveal some characteristics about phenomena located in the area around these sensors. A large number of these sensors can be networked in many applications that require unattended operations, hence producing a WSN.

Typically, WSNs contain hundreds or thousands of these sensor nodes, and these sensors have the ability to communicate either among each other or directly to an external base station. One of the main design goals of WSNs is to carry out data communication while trying to prolong the lifetime of the network and prevent connectivity degradation by employing aggressive energy management techniques. Especially, the underlying network structure can play a significant role in the operation of the routing protocol in WSNs.

The routing techniques are classified into three categories based on the underlying network structure [17]: flat, location-based, and hierarchical routing.

In addition to the routing protocol, data aggregation also plays one of critical factors because the data on the field can be the same information. So data aggregation can reduce the redundant data transfer to save the limited node energies. Figure 3 presents the routing and data aggregation techniques in WSNs.

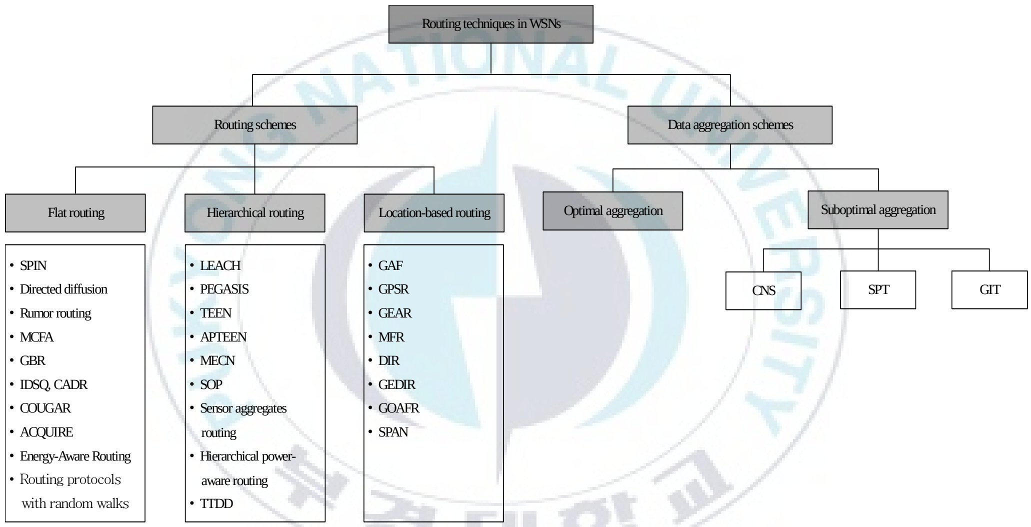

Figure 3. Routing techniques in WSNs

2.1 Routing Schemes

1) Flat Routing

Flat routing is that all nodes in the fields exchange the information with each other in the equal position. Due to the large number of such nodes, it is not feasible to assign a global identifier to each node. This consideration has led to data-centric routing, where the BS sends queries to certain regions and waits for data from the sensors located in the selected regions. Since data is being requested through queries, attribute-based naming is necessary to specify the properties of data. Early works on data centric routing (e.g., SPIN and directed diffusion [18]) were shown to save energy through data negotiation and elimination of redundant data. These two protocols motivated the design of many other protocols that follow a similar concept. As shown in Figure 3, there are several flat routing methods in WSNs.

2) Hierarchical Routing

Flat Routing method is efficient in the small-scale networks because of its simple routing construction procedure. But the large the scale of network is, the much the quantity of routing information is. And there are long delays in sending the routing information from the remote sensor node and in transferring data from the remote source nodes. Therefore it needs a routing method in which all nodes can waste the equivalent battery in order to guarantee the long lifetime.

Hierarchical routing method was proposed to resolve such a problem, in which all nodes are partitioned into logical groups and each logical group has the head node that control the data traffic in the corresponding group. The creation of clusters and assigning special tasks to CHs can greatly contribute to overall system scalability, lifetime, and energy efficiency.

Hierarchical routing is an efficient way to lower energy consumption within a cluster, performing data aggregation and fusion in order to decrease the number of transmitted messages to the BS. Hierarchical routing is mainly two-layer routing where one layer is used to select cluster heads and the other for routing. However, most techniques in this category are not about routing, but rather “who and when to send or process/ aggregate” the information, channel allocation, and so on, which can be orthogonal to the multi-hop routing function. As shown in Figure 3, there are several hierarchical routing methods in WSNs.

Table 3 summarizes the comparisons of flat and hierarchical routing methods according to the specific parameters.

Table 3. Comparisons of flat and hierarchical routing methods

	Hierarchical Routing method	**Flat Routing method**
Scheduling	Reservation-based scheduling	Contention-based scheduling
Collision	Collisions avoided	Collision overhead present
Duty cycle	Reduced duty cycle due to periodic sleeping	Variable duty cycle by controlling sleep time of nodes
Aggregation point	Data aggregation by cluster head	Node on multi-hop path aggregates incoming data from neighbors
Complexity	Simple but non-optimal routing	Routing can be made optimal but with and added complexity
Synchronization	Requires global and local synchronization	Links formed on the fly without synchronization
Overhead	Overhead of cluster formation throughout the network	Routes formed only in regions that have data for transmission
Latency	Lower latency as multiple hops network formed by cluster heads always available	Latency in waking up intermediate nodes and setting up the multipath
Energy dissipation	Energy dissipation is uniform	Energy dissipation depends on traffic patterns
Fairness	Guarantee	Not guarantee

3) Location-Based Routing

In this kind of routing, sensor nodes are addressed by means of their locations. The distance between neighboring nodes can be estimated on the basis of incoming signal strengths. Relative coordinates of neighboring nodes can be obtained by exchanging such information between neighbors [19-21].

Alternatively, the location of nodes may be available directly by communicating with a satellite using GPS if nodes are equipped with a small low-power GPS receiver [22]. To save energy, some location-based schemes demand that nodes should go to sleep if there is no activity. More energy savings can be obtained by having as many sleeping nodes in the network as possible. The problem of designing sleep period schedules for each node in a localized manner was addressed in [22, 23]. As shown in Figure 3, there are several location-based routing methods in WSNs.

2.2 Data Aggregation Schemes

1) Data aggregation in sensor networks

Data aggregation is one of the power saving strategies in the ubiquitous sensor network, combining the data that comes from many sensor nodes into a set of meaningful information.

Before starting the data aggregation techniques, we should investigate the routing models [24] that are assumed to consist of a single data sink attempting to gather information from a number of data sources. Figure 4 is a simple illustration of the difference between simple models of routing schemes that use data aggregation (which we term Data-Centric (DC)), and schemes that do not (which we term Address-Centric (AC)). They differ in the manner that the data is sent from a source to a sink. In the AC routing, each source independently sends data along the shortest path to the sink based on the route that the queries took ("end-to-end routing"), whereas in the DC routing the sources send data to the sink, but routing nodes on the way look at the content of the data and perform some form of aggregation and consolidation functions on the data originating at multiple sources.

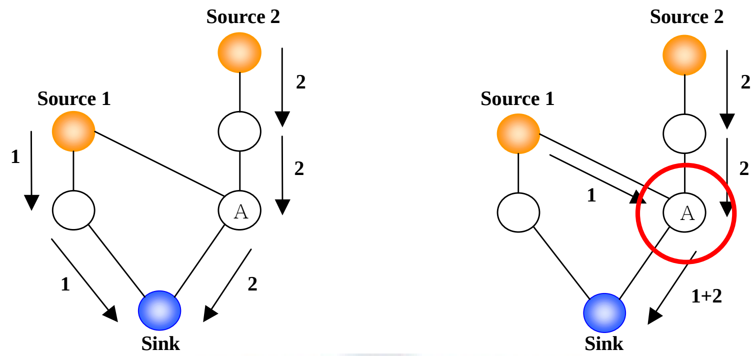

Figure 4. Illustration of AC routing Vs. DC routing

In ad hoc networks, a routing model follows the AC routing, so each source sends its information separately to the sink like the Figure 4(a). In sensor networks, a routing model follows the DC routing, so the data from the two sources are aggregated at node A, and the combined data is sent from node A to the sink like the Figure 4(b). Therefore in sensor networks, the data aggregation technique is a critical factor different from ad hoc networks to save the power consumptions of the nodes in order to extend the sensor network lifetime.

In sensor networks, the data aggregation tree can be thought of as the reverse of a multicast tree. So, optimal data aggregation is a minimum Steiner tree on the network graph. Instead of an optimal data aggregation, sub-optimal data aggregations are proposed to generate data aggregation trees that are aimed to diminish the transmission power. The table 3 summarizes the properties and disadvantages of sub-optimal data aggregation methods.

The prevenient data aggregation methods [24] are efficient to the model where a single point in the unit square is defined as the location of an “event”, and all nodes within a distance S (called the sensing range) of this event that are not sinks are considered to be data sources (which we term Event-Radius Model). In the model where some nodes that are not sinks are randomly selected to be sources, e.g. a temperature measurement and environment pollution detection (which we term Random-Source Model), it needs appropriate strategies for an efficient data aggregation.

Table 4. Comparisons of the data aggregation methods

Data aggregation method		Properties	Disadvantages
Optimal	Minimum Steiner Tree	The optimal number of transmissions required per datum for the DC protocol is equal to the number of edges in the minimum Steiner tree in the network.	The NP-completeness of the minimum Steiner problem on graphs.
Sub-optimal	CNS (Center at Nearest Source	The source that is nearest the sink acts as the aggregation point. All other sources send their data directly to this source that then sends the aggregated information on to the sink.	The more great the gaps between the aggregation point and sources, the more the batteries consumptions.
	SPT (Shortest Paths Tree)	Each source sends its information to the sink along the shortest path between the two. Where these paths overlap for different sources, they are combined to form the aggregation tree.	The shorter the overlapped paths when the shortest route is established from each source to the sink, the more the batteries consumptions.
	GIT (Greedy Incremen t-al Tree)	At the first step the tree consists of only the shortest path between the sink and the nearest source. At each step after that the next source closest to the current tree is connected to the tree.	It takes some time for the identical data to arrive to the aggregation point and to aggregate the identical data from other source nodes.

2) Data aggregation in ad hoc networks

Most of the ad hoc networks are based on point-to-point communications, so the data aggregation in ad hoc networks is not considered a critical issue except the multi-path routing. In some routing protocols such as DSR [25], AODV [26], LMR [27], TORA [28], and so on, multi-paths can be established from the sources to the destination. In that case the data aggregation can be performed through the overlapped paths en route. But it depends on each routing technique, which is implemented in ad hoc networks. Amongst the multi-path routing techniques, TORA builds a directed acyclic graph rooted at the destination in ad hoc networks. So using DAG all data in the field can be assembled at the destination node.

3. Issued Problems

As remarked above many researchers are currently engaged in developing networking solutions for terrestrial wireless ad hoc and sensor networks. Since UWSNs have more challenge than terrestrial WSNs, adopting efficient routing and data aggregation schemes is very important. However, due to the different nature of the underwater environment and applications, there are several drawbacks with respect to the suitability of the existing solutions for WSNs. Main differences between terrestrial and underwater sensor networks are shown in table 5 [2].

Table 5. Differences between terrestrial and underwater WSNs

	Differences
Cost	While terrestrial sensor nodes are expected to become increasingly inexpensive, underwater sensors are expensive devices. This is especially due to the more complex underwater transceivers and to the hardware protection needed in the extreme underwater environment.
Deployment	While terrestrial sensor networks are densely deployed, in underwater, the deployment is deemed to be more sparse, due to the cost involved and to the challenges associated to the deployment itself.
Power	The power needed for acoustic underwater communications is higher than in terrestrial radio communications due to higher distances and to more complex signal processing at the receivers to compensate for the impairments of the channel.
Memory	While terrestrial sensor nodes have very limited storage capacity, uw-sensors may need to be able to do some data caching as the underwater channel may be intermittent.
Spatial correlation	While the readings from terrestrial sensors are often correlated, this is more unlikely to happen in underwater networks due to the higher distance among sensors.

Among differences between terrestrial and underwater WSNs, because UWSNs are respectively sparse than terrestrial WSNs and have a long transmission range, data transmission scheme is also important as much routing and data aggregation schemes.

The harsh characteristics of the underwater acoustic communication channel, such as limited bandwidth capacity and variable delays, require very efficient and reliable new data communication method.

Ⅲ. Proposed Network Model and Concept of Efficient Hybrid Transmission Method

1. Underwater Acoustics Transmission Model

Underwater acoustic communication has been used for a long time in military applications. Compared to radio waves, sound has superior propagation characteristics in water, making it the preferred technology for underwater communications. The main motivation for underwater acoustic networks is their relative ease of deployment since they eliminate the need for cables and they do not interfere with shipping activity. These networks are useful for effectively monitoring the underwater medium for military, commercial or environmental applications. Environmental applications include monitoring of physical indicators.

To realize underwater sensor network applications, UWSNs have to adopt many of the tools that have been developed for terrestrial sensor networks: wireless communication, low-power hardware, energy conserving network protocols, time synchronization and localization, and programming abstractions and so on. However, some of the techniques are fundamentally different. For example especially radio is not generally suitable for underwater usage because of extremely limited propagation. So, the acoustic communication is used for the majority of underwater wireless networks. Moreover, due to the fact that the energy consumption required by sensing and computation is several orders of magnitude lower than the communication energy consumption [29], we just focus on the acoustic communication energy consumption.

1.1 Passive Sonar Equation

The passive sonar equation [30] characterizes the signal to noise ratio (*SNR*) of an emitted underwater signal at the receiver:

$$SNR = SL - TL - NL + DI \qquad (1)$$

where *SL* is the source level, *TL* is the transmission loss, *NL* is the noise level, and *DI* is the directivity index. All the quantities in equation (1) are in dB re μPa, where the reference value of 1 μPa amounts to 0.67×10^{-22} Watts/cm^2 [2]. In the rest of the thesis, we use the shorthand notation of dB to signify dB re μPa.

Factors contributing to the noise level *NL* in shallow water networks include waves, shipping traffic, wind level, biological noise, seaquakes and volcanic activity, and the impact of each of these factors on *NL* depends on the particular setting. For instance, shipping activity may dominate noise Figures in bays or ports, while water currents are the primary noise source in rivers.

Since using omni-directional hydrophones in our model, the directivity index *DI* for network is 0. And considering a target *SNR* of 15 dB [30] at the receiver, an average value for the ambient noise level *NL* is 70 dB as a representative shallow water case. Through the above results, equation (2) can be expressed in the source level *SL* intensity as a function of *TL* only:

$$SL = TL + 85 \tag{2}$$

in dB.

1.2 Transmission Loss

The transmitted signal pattern has been modelled in various ways, ranging from a cylindrical pattern to a spherical one. Acoustic signals in shallow waters propagate within a cylinder bounded by the water surface and the sea floor, so cylindrical spreading applies for shallow waters. Urick [30] provides the following equation to approximate the transmission loss for cylindrically spread signals:

$$TL = 10\ log\ d + \alpha d \times 10^{-3} \tag{3}$$

where *d* is the distance between source and receiver in meters, *α* is the frequency dependent medium absorption coefficient, and *TL* is in dB.

Equation (3) indicates that the transmitted acoustic signal loses energy as it travels through the underwater medium, mainly due to distance dependent attenuation and frequency dependent medium absorption. Equation (4) expresses the average medium absorption at temperatures between 4°C and

20°C:

$$\alpha = \begin{cases} 0.0601 \times f^{0.8552} & 1 \le f \le 6 \\ 9.7888 \times f^{1.7885} \times 10^{-3} & 7 \le f \le 20 \\ 0.0601 \times f - 3.7933 & 20 \le f \le 35 \\ 0.0601 \times f - 11.2 & 35 \le f \le 50 \end{cases} \quad (4)$$

where f is in Khz, and α is in dB/Km [31].

Through equation (4), we can calculate medium absorption for any frequency range of interest. We use this value for determining the transmission loss at various internode distances through Equation 3 which enables us to compute the source level in Equation 2 and subsequently to compute the power needed at the transmitter.

1.3 Transmission Energy

We have shown how the source level *SL* is related to inter-node distance and frequency through equations (2), (3) and (4). *SL* is also related to the transmitted signal intensity at 1 m from the source according to the following expression:

$$SL = 10 \; log \; \frac{I}{1 \mu Pa} \quad (5)$$

where I is in μPa. Solving for I yields:

$$I = 10^{SL/10} \times 0.67 \times 10^{-18} \tag{6}$$

in Watts/m^2, where the constant converts μPa into Watts/m^2

Finally, the transmitter energy, *e*, needed to achieve an intensity I at a distance of 1 m from the source in the direction of the receiver is expressed as:

$$e = 2\pi \times 1\text{m} \times H \times I \tag{7}$$

in Watts, where *H* is the water depth in m [30].

Conclusively, we have presented a method to obtain the required transmitter power for signal transmissions at a given distance d and frequency *f*. First, we calculate the transmission loss *TL* in terms of *f* and d and we subsequently compute the source level *SL*, which yields the source intensity *I*. Finally, we can obtain the corresponding transmit power needed to achieve a source intensity of *I*.

2. Suggested Network Model for UWSNs

2.1 Hexagon Tessellation Model

Figure 1 shows a network topology with several clusters. Every cluster has an uw-sink that is assumed as a BS in this thesis. Here, we apply a hexagon tessellation scheme to cover the surface of the cluster as shown in Figure 5.

The BS is located in the center of the cluster, and each cell has several sensor nodes. Cells next to each other are adjacent cells. We defined the set of cells that are adjacent to the center cell as the center annulus A_1 and use A_i (i>1) to represent the set of cells surrounding A_{i-1} from the opposite side of the BS.

In each cell, a node is randomly chosen as the cluster head. Only the cluster head in each cell will receive and forward a packet from the outside annulus. Other nodes in the cell can sleep most of the time and wake up only to sense the phenomenon or transmit their own packets. To balance the energy consumption within each cell, the cluster head can be re-elected periodically [32].

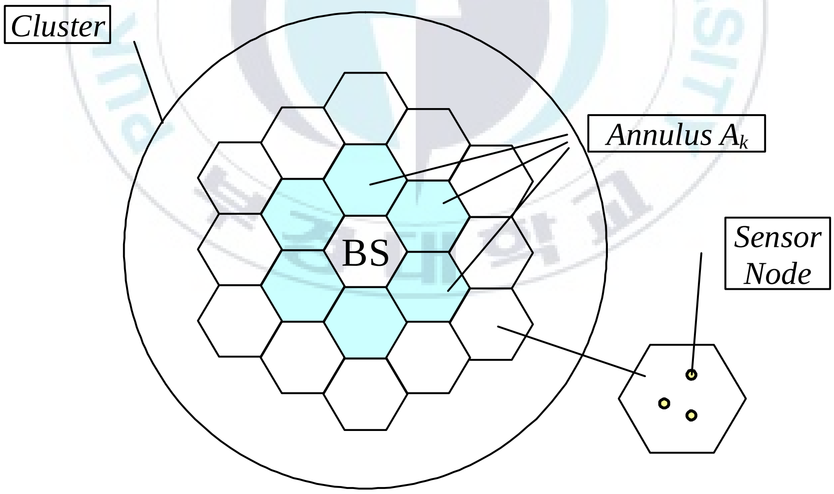

Figure 5. Hexagon tessellation model for each cluster given in Figure 1

We observe that annuluses hold the following properties:

- The number of cells in annulus, A_k, is $6k$, k = 1, 2….
- The total number of annuluses, q, needed to fully cover the disk of

radius of *R*, satisfies:

$$\begin{cases} \dfrac{(3q+1)l}{2} = R; & \text{if } q \text{ is odd} \\ \dfrac{l\sqrt{(3q+1)^2+3}}{2} = R & \text{if } q \text{ is even} \end{cases} \quad (8)$$

In this model, the communication between a sensor and its BS can be established through either multiple small hops forwarded by intermediary sensors or a one-hop direct connection. For each sensor, we define two transmission ranges as in next Subsection.

1) Uniform Forwarding Range

For sensor networks using a multi-hop forwarding method, a uniform forwarding range is used by nodes. As shown in Figure 6, in order to guarantee that any two nodes in adjacent cells can always reach each other, we choose the forwarding range to be:

$$r_f \geq \sqrt{13}l \quad (9)$$

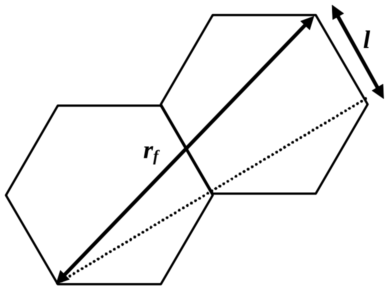

Figure 6. Range of multi-hop forwarding

2) Direct Transmission Range

In addition to forwarding packets via multiple intermediate hops, each node can also directly transmit to the BS. Due to the symmetry property of the cluster, every node in annulus A_k uses the same direct transmission range r_k given by:

$$r_k \geq l\sqrt{3(k+1)^2+1}, \qquad k=1,2\cdots. \tag{10}$$

As shown in Figure 7, we observe that the direct transmission range for each node depends on the distance between the corresponding node and its BS.

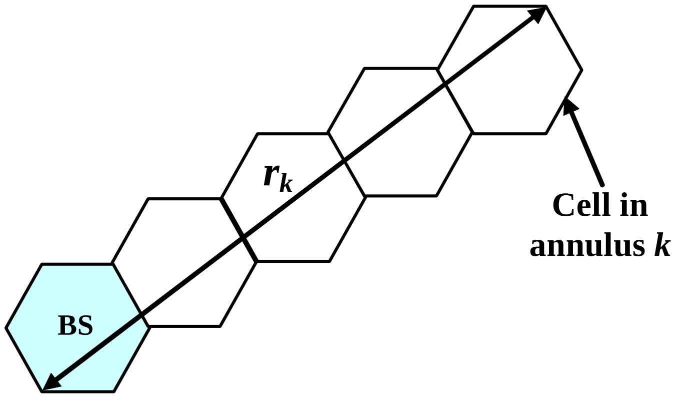

Figure 7. Range of direct transmission

3) Calculation of Ideal Cell Size

One of the most important considerations in designing a sensor network is the limited battery resources in each sensor node, largely due to the difficulty in and the cost of recharging sensor batteries once the network is deployed. In proposed network model, the inter-node distance *d* has a significant impact on energy consumption. Since d is dependant on the cell size, the optimal decision on the ideal cell size is crucial for the longevity of the entire UWSN.

In hexagon model, the number of nodes in annulus A_k can be given by:

$$n_k = 6k \times \frac{3\sqrt{3}}{2} nl^2 / (\pi R^2) = \frac{9\sqrt{3}knl^2}{\pi R^2} \qquad (11)$$

Then we can write the total energy consumption of all of the nodes which transmit packets from outer annuluses as well as its own packets in A_k:

$$E_k = \frac{e_t(r_f)\sum_{i=k}^{q} 9\sqrt{3}inl^2 + e_r \sum_{i=k+1}^{q} 9\sqrt{3}inl^2}{\pi R^2} \quad (12)$$

The average energy consumption per node in A_k is given by:

$$e_k = \frac{E_k}{n_k} = \frac{e_t(r_f)\frac{q+k}{2}(q-k+1)+e_r\frac{q+k+1}{2}(q-k)}{k} \quad (13)$$

From equation (7), we can obtain the required energy, e_t, for data transmission at the uniform forwarding range: $r_f = \sqrt{13}l$ m and the frequency f = 10 *Khz*. And the receive energy, e_r, is typically around one fifth of the transmit energy in commercially available hydrophones [33].

The nodes in the center annulus A_1 are the most heavily loaded by forwarding almost all the packets in the network to the BS, and we have:

$$e_{\max} = e_1 = (e_t + e_r)\frac{q(q+1)}{2} - e_r \quad (14)$$

According to equation (14), we can obtain a relationship between e_{max} and the cell size l in the UWSN. Here, we may also consider the number of nodes together. And due to the imbalanced in energy consumption caused by asymmetric traffic forwarding toward the BS, the optimal cell size for total network energy consumption does not lead to the maximum network lifetime in stationary networks.

In order to fully cover the given disk area, we calculate optimal cell size, *l*, by adapting equation (8). The relationship between the number of annuluses *q* and cell size *l* is shown in Figure 8.

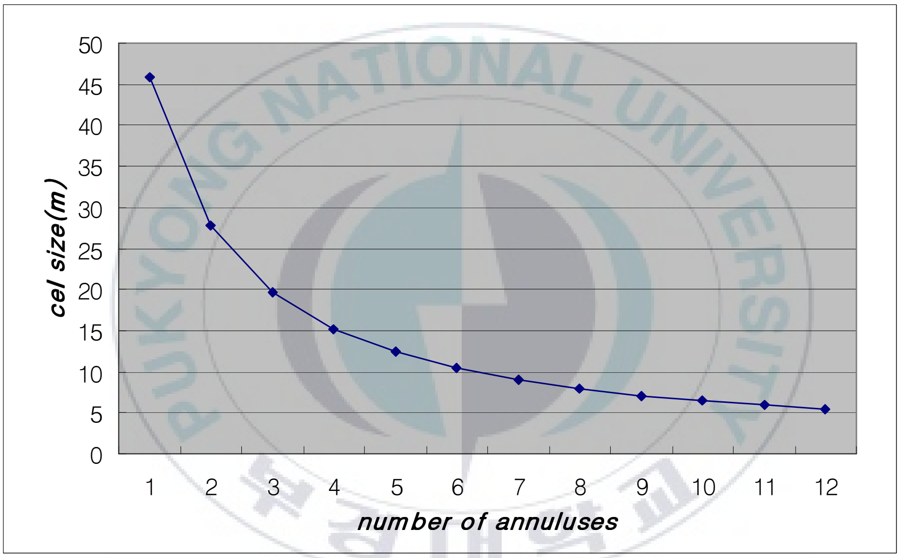

Figure 8. Relationship between annulus *q* and cell size *l* (*R* = 100 m)

2.2 Suggested Network Model for UWSNs

In order to realize environmental monitoring or monitoring of underwater plates in tectonics applications, we apply two-dimensional underwater networks architecture as shown in Figure 1. And we divide the given network area into several clusters, for each with radius *R* = 100 *m*. Then, we apply a hexagon tessellation model to clusters according to the description explained in Subsection 2.1.

When radius R is 100 m, we can calculate the number of annuluses and cell size given area. If the number of annulus q is 7 as shown in Figure 9, we obtain that the idle cell size l is 9.062 m.

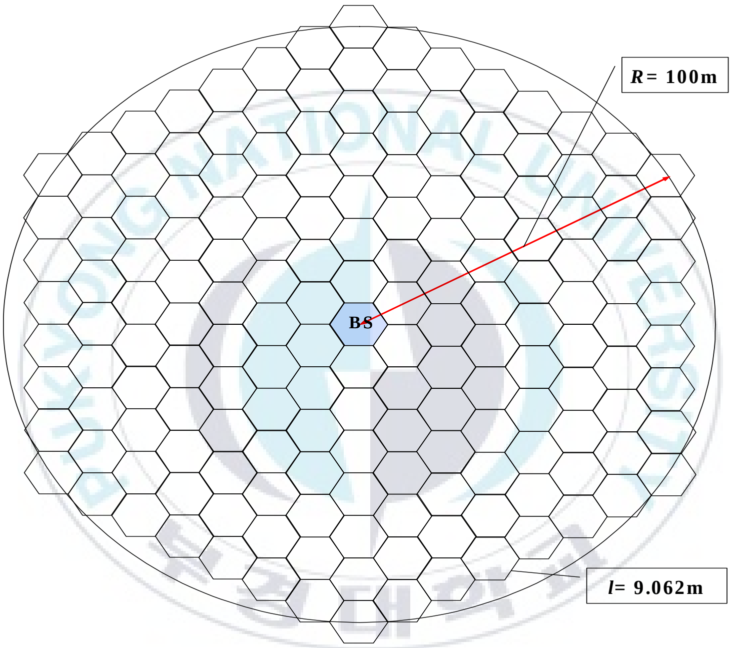

Figure 9. Network model for UWSNs

2.3 Enhanced Energy Efficient Hybrid Transmission Method

With the cellular network structure defined, we are now ready to discuss an efficient computational structure. For simplicity, we assume that only one node is active in every cell during each round in our model.

To achieve the balanced energy consumption in the given network, we propose a hybrid transmission method based on both the location dependent direct transmission and the uniform multi-hop forwarding. As shown in Figure 7, the proposed hybrid transmission method can be summarized as follows.

- For nodes in annulus A_k, where $m < k \le q$, use the multi-hop forwarding scheme;
- For nodes in Annulus A_k, where $1 \le k \le m$, transmit the data directly to the BS;

The value *m* is the threshold for choosing the forwarding scheme.

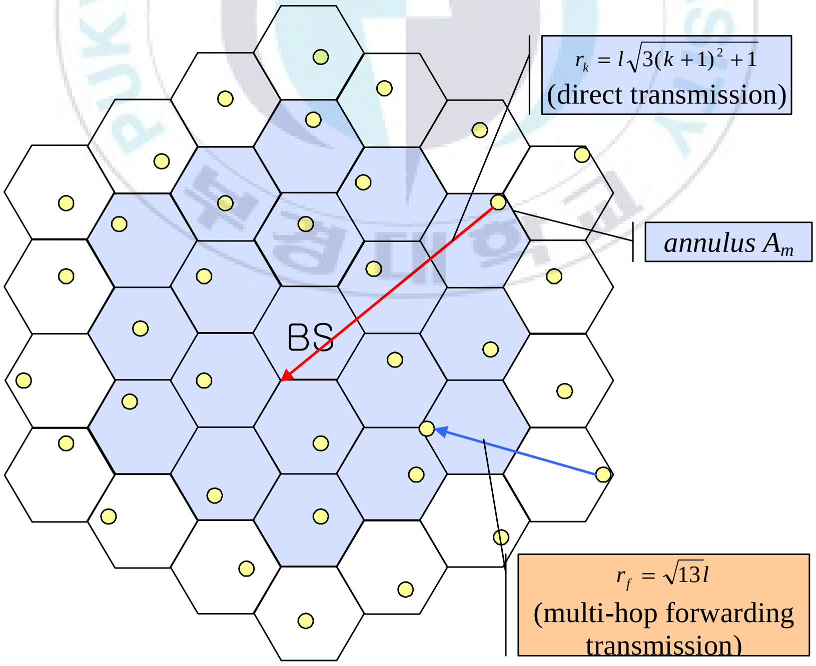

Figure 10. Hybrid transmission method

In the case of the existing uniform forwarding method, the total traffic is concentrated on the nodes in the annulus A_1. But with the proposed hybrid transmission method, the total energy consumption is shared among the nodes in annulus A_m. There being more nodes in A_m than A_1, $e_{\max}$, is reduced proportionately while the lifetime is increased.

Note that in the uniform transmission method, applying equations (9) and (10), the total energy consumption of the annulus A_k is:

$$E_k = e_t(r_k)N_k^d + e_t(r_f)N_k^f + e_r N_{k+1}^f \tag{15}$$

where N_k^f represents the number of packets forwarded to A_{k-1}. Since all nodes are using the uniform forwarding scheme, the total traffic is concentrated on the nodes in the annulus A_1.

From equations (11) and (15), we obtain the average energy consumption per node in A_k:

$$e_k = \frac{E_k}{n_k}, \qquad k = 1,\ 2 \cdots . \tag{16}$$

In the proposed method, the nodes in the threshold annulus A_m directly transmit all the data to the BS. Therefore the total energy consumption at annulus A_k can be written as:

$$
\begin{cases}
k = q: & E_k = \sum [e_t(r_k) N_k^f] \\
m < k < q-1: & E_k = e_t(r_f) N_k^f + \sum_{i=1}^{q-k} [e_t(r_f) N_{k+i}^f] \\
 & \qquad + \sum_{i=1}^{q-k} [e_r(r_f) N_{k+i}^f] \\
k = m: & E_k = e_t(r_k) N_k^d + \sum_{i=1}^{q-m} [e_t(r_k) N_{k+i}^d] \\
 & \qquad + \sum_{i=1}^{q-m} [e_r(r_f) N_{k+i}^f] \\
\text{otherwise}: & E_k = \sum [e_t(r_k) N_k^d]
\end{cases}
\tag{17}
$$

where N_k^f represents the number of packets forwarded to A_{k-1}, and N_k^d the number of packets directly transmitted to the BS. Since the nodes in annuluses outside of A_m use the uniform forwarding scheme, the maximum energy consumption per node occurs in annulus A_1. With the hybrid transmission method, the total energy consumption is shared by the nodes in annulus A_m. The nodes in annuluses inside of A_m transmit only their data with increased power consumption to reach a greater distance to BS. Since the higher m, the more cells exist in A_m, the transmission load will be shared by more cells. In this way, e_{max}, can be reduced and the lifetime is prolonged.

Moreover, we can further enhance the hybrid transmission method by allocating the frequency adaptively. According to equations (3) and (4), the transmission loss is greater at higher frequencies, which implies that the nodes using high frequencies need to transmit acoustic signals at a higher energy in the underwater environment. Therefore, it is desirable to assign lower frequency bands to nodes in low annuluses and increasingly higher frequency bands to the outer annuluses according to the rule implied in discussed in Subsection 1. This assignment allows the nodes with a higher forwarding load to use the lower frequencies and thus save the energy.

Ⅳ. Simulation and Performance Evaluation

We evaluate the performance of the proposed method via simulations. The network and transmission models Section Ⅲ are used as the simulation model for our simulation. We assume every cell has equivalent probability of data detection. Since every cell covers equivalent size of area, each cell has the same number of data packets.

We compare the proposed enhanced hybrid transmission method (f allocation) to the multi-hop forwarding method and with the threshold m = 4. In these tests, the threshold annulus A_m is allocated the lowest frequency, and others are allocated 50 kHz of frequency.

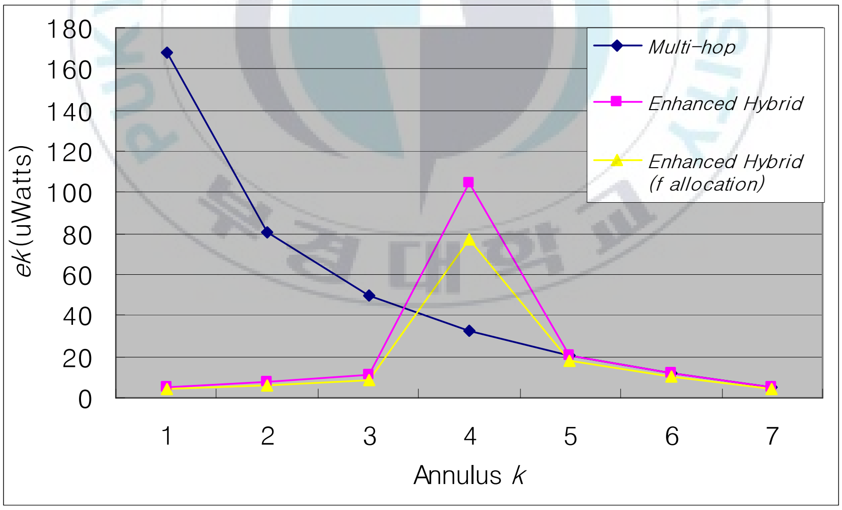

Figure 11. Per node energy consumption over a range of annuluses (R = 100 m, l = 9.062 m, H = 100 m)

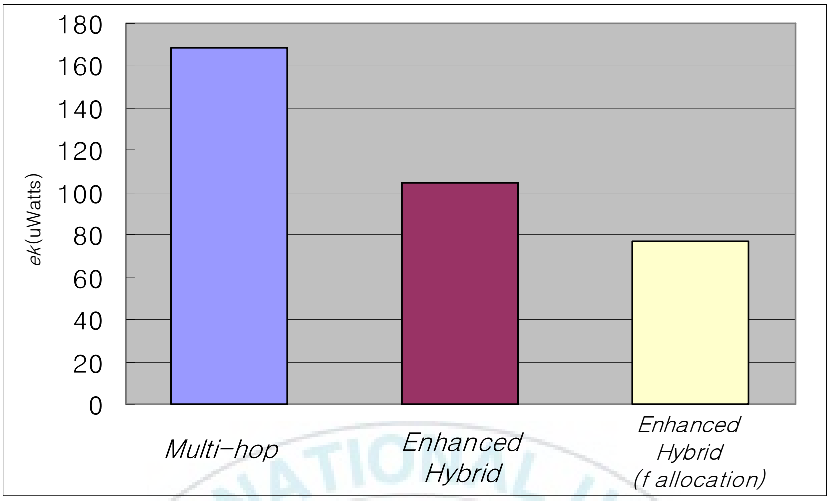

Figure 12. Comparison of the the maximum energy consumption cell(R = 100 m, l = 9.062 m, H = 100 m)

Figure 11 and 12 shows that the enhanced hybrid transmission method records lower energy consumption than the multi-hop transmission method. The enhanced hybrid transmission method reduced approximately 37.65 % of the energy consumption for e_{max}. And there was a further reduction of 54.41 % with the introduction of a clever frequency allocation.

Ⅴ. Conclusion

In this thesis, we investigate how the network's energy consumption is influenced by the transceiver parameters and review the state of precious routing and data aggregation researches in WSNs to apply those to UWSNs. Then, we propose an energy efficient transmission strategy for Underwater Wireless Sensor Networks. By using the hybrid transmission method, the total network traffic load can be shared by a greater number of nodes in the annulus A_m, thus alleviating the substantial overload at the innermost annulus of multi-hop forwarding method. Moreover, the network traffic load can be reduced further by allocating different frequencies to different annuluses.

According to the simulation results, the enhanced hybrid transmission method could reduces the energy consumption of the central annulus leading to an increased lifetime of the entire UWSNs through cleverer load balancing. This result means that the proposed hybrid transmission method is more energy efficient than the multi-hop forwarding method and the existing hybrid transmission method. Consequently, we can conclude that the proposed hybrid transmission method outperforms other methods from an energy-efficient data transmission point of view, and our method is more suitable for UWSN applications.

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수중센서네트워크를 위한 에너지 효율적인 데이터 전송 기법 연구

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요 약

최근 과학적, 상업적 탐구와 해안선 보호를 위한 수중 환경의 관찰에 대한 관심이 증대되고 있다. 특히 우리나라의 경우는 삼면이 바다로 이루어져 있기 때문에 해양에 대한 연구는 더욱 중요하다.

광범위한 해양 관찰을 위한 이상적인 기법으로 수중 무선 센서 네트워크라고 불리는 수중 무선 센서들로 이루어진 분산 시스템이 있다. 주어진 영역에 대한 협동적인 관찰 임무를 수행하는 다양한 수의 센서들과 센서들을 장착한 무인 또는 자동 수중 장치들은 수중 자원 탐사와 과학적 자료 수집을 가능하게 한다. 수중 센서 노드들은 해양 데이터 수집, 오염 관찰, 근해 탐사, 재해 예방, 항해, 전략적 감시 등의 어플리케이션들에 사용될 수 있다. 수중 음파 네트워크는 이러한 어플리케이션들을 가능하게 하는 기술이다.

현재 많은 연구자들이 지상 센서 네트워크에 대한 네트워크 기법들에 대하여 연구하고 있다. 수중센서네트워크는 지상 센서네트워크에 비해 더 많은 제약 조건들을 가지고 있기 때문에, 효율적인 라우팅과 데이터 통합 기법이 더욱 중요하다. 그럼에도 불구하고 수중환경과 어플리케이션들의 차이점들로 인해 지상 센서네트워크를 위해 개발된 기법들을 수중 센서네트워크에 직접 적용하는 것은 적합하지 않은 점이 존재한다.

특히 수중센서네트워크가 지상센서네트워크에 비해 공간적으로 덜 조밀하고 더 긴 전송 거리를 가지고 있기 때문에 데이터 전송 기법은 라우팅이나 데이터 통합기법만큼 중요성을 가진다.

본 논문에서, 우리는 전송 파라미터들에 의해 네트워크의 에너지 소모가 얼마나 영향을 받는지 조사하고, 이전의 수중센서네트워크에 적용하기 위해 기존의 지상 센서네트워크에서 연구되었던 라우팅 및 데이터 통합 기법들에 대한 살펴보았다. 그리고 우리는 수중 센서 노드들을 배치하기 위하여 육각형 모자이크 접근방식을 적용하여, 수중 센서네트워크를 위한 이상적인 셀 크기를 계산하고 데이터 전송이 일어날 때 로드밸런싱을 수행하는 하이브리드 데이터 전송 기법을 제안하였다. 제안된 하이브리드 데이터 전송 기법은 하나의 노드와 BS 사이의 거리에 의해 결정되는 임계 영역을 적용하는 방식으로 데이터 전송 성능을 향상시킨다.

그리고 우리는 시뮬레이션을 수중 센서네트워크 환경에서 수행하였다. 시뮬레이션 결과에 따르면, 중앙 고리에 집중되던 에너지 소모가 임계 영역 안에 존재하는 고리들에 분산된 것을 알 수 있다. 이러한 결과는 시뮬레이션 결과는 제안된 기법이 기존의 멀티홉 포워딩 기법보다 효율적이라는 것을 나타낸다. 결과적으로 우리는 제안된 하이브리드 데이터 전송 기법이 효율적인 데이터전송 관점에서 수중센서네트워크 어플리케이션들에 더욱 적합하다고 결론지을 수 있다.

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