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Energy Consumption Analysis of DBR and VBF Protocols in Underwater Sensor Networks Using Aqua-Sim at Network Simulator 2

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Abstract — For decades, there have been significant interests in monitoring the aquatic environment for scientific exploration, commercial exploitation, coastline protection, and even disasters prevention and mitigation such as tsunami warnings. Highly precise, real-time, and temporal-spatial continuous aquatic environment monitoring system is extremely important for underwater life. To support and simulate such monitoring system, underwater sensor networks (UWSN) have emerged as a very powerful technique for many applications on underwater environment, including monitoring, measurement, surveillance, and control by using Aqua-Sim. Aqua-Sim is a simulator for UWSN developed on Network Simulator 2 platform which effectively simulates the attenuation of underwater acoustic channels and the collision behaviors in long delay acoustic networks. Currently, there are several routing protocols for UWSN which are implemented in Aqua-Sim. On this research, we did a simulation on Aqua-Sim by performing Vector-based Forwarding (VBF) protocol and Depth-based Routing (DBR) protocol performance analysis based on energy consumption parameter. Based on the result, it can be concluded that the VBF routing protocol requires more energy consumption than the DBR routing protocol.

Keywords - Underwater Sensor Networks, Aqua-Sim, Network Simulator 2, DBR, VBF, Energy Consumption

I. INTRODUCTION

More than 70% of the earth's surface is covered by oceans which means that a huge amount of resources waiting to be explored. The new technology discovered by researchers brings a new way to explore the aquatic environment that has not been explored so far. This technology provides some benefits for scientific, environmental, commercial, and military purposes including ocean sampling networks, environmental and pollution monitoring, undersea explorations, disaster prevention regarding tsunami warnings, aid navigation, offshore exploration, oil/gas spill monitoring, tactical surveillance, mine reconnaissance, and so on. However, due to the unique characteristics possessed by oceans, solutions that exist on terrestrial sensor networks cannot be applied directly to the ocean [1]. This is due to water is a conductive medium and can cause major changes in electromagnetic radiation [2].

Therefore, underwater sensor networks are needed to support underwater life sustainability. An underwater sensor network differs from any ground-based sensor network regarding cost, deployment, power, and memory. So that, it will require more attention if an underwater sensor network wants to be developed and implemented further due to the characteristic differences between underwater sensor network and terrestrial sensor network [2].

Figure 1 illustrates the system architecture on how underwater sensor networks work. It can be seen that sources which located on underwater transmit packets through sensor nodes to surface stations. After the surface stations receive the transmitted packets, they will pass the information to the central control unit. The central control unit will then receive the information from surface stations to let the people on board know the exact location of sources and possibility to know whether anything happened to the sources [1].

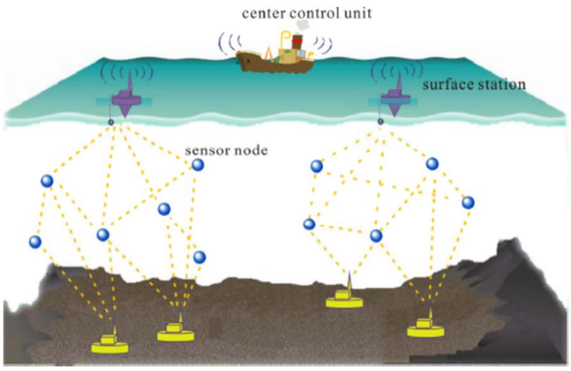

Fig.1. System Architecture of Underwater Sensor Network [4]

To facilitate research on underwater sensor networks, standard simulation platforms are needed that can be used to compare and evaluate network designs, algorithms, and protocols. Existing network simulators such as Network Simulator 2 and OPNET developed for radio networks (wireless/wired) are not possible to simulate underwater sensor networks due to there are differences in characteristics [2].

In 2009, Peng Xie et al. introduced Aqua-Sim. Aqua-Sim is a simulator for underwater sensor networks developed at Network Simulator 2 platform that can effectively simulate attenuation of the acoustic signal and the movement of packets on the underwater sensor network [3]. Currently, there are a lot of underwater sensor network routing protocols such as Depth-based Routing (DBR), Vector-based Forwarding (VBF), Hop-by-hop Vector-based Forwarding (HH-VBF), Sector-based Routing with Destination Location Prediction (SBR-DLP), Focused Beam Routing (FBR), Distributed Underwater Clustering Scheme (DUCS), Under-Water Diffusion (UWD), Multipath Routing, and so on. However, not all of the routing protocols mentioned above can be simulated in Aqua-Sim. Only several routing protocols that can be applied to Aqua-Sim such as VBF/HH-VBF, VBVA, DBR, static routing, and dynamic routing.

Based on previous research, in 2010, Giantsis and Economides surveyed routing protocols comparison for underwater sensor networks. They compared routing protocols such as DBR, VBF, HH-VBF, SBR-DLP, FBR, DUCS, UWD, and Multipath Routing with packet delivery ratio, energy consumption, and average end-to-end delay as parameters [4].

Therefore, to prove that the previous research was precise and accurate, our research focused on the small-scale comparison, comparing between DBR and VBF protocols using only one parameter which is energy consumption with only a few nodes available.

Meanwhile, the previous research focused on big scale comparison with numerous routing protocols -- including DBR and VBF protocols -- using more than one parameters with a lot of nodes available [4].

II. RESEARCH METHOD

A. Underwater Sensor Networks (UWSN)

The characteristics of underwater acoustic channels consist of unique design complexity in almost every layer of the network protocol including high propagation delay, limited bandwidth, mobility of nodes, high bit error rates and temporary losses of connectivity, sensors are prone to failures due to of fouling and corrosion, limited battery power, and diverse underwater environments [5].

There are several ways of communication under the sea caused by external challenges environment. The types of communication include the following [6].

a) Radio Frequency Communication (RF)

Radio waves do not spread well in the underwater environment due to the natural nature of seawater. As we know that high attenuation for high frequency; therefore, most commercial radio equipment cannot be used underwater when operating in the range of MHz and GHz. To avoid this, to use very low-frequency radio waves, it takes a large antenna due to much power are consumed. The attenuation of electromagnetic waves in water for the 2.4 GHz bandwidth is 1695 dB/m in seawater and 189 dB/m in fresh water.

b) Acoustic Communication

It is the most mature technology in underwater communication. The sound speed is 1.5 x 103 m/s in water while in the air it is 340 m/s. This type of communication is often used due to the capability of remote communication, but it has limitations such as large signal attenuation and low bandwidth.

c) Optical Communication

Light has a speed of 2.25 x 108 m/s in water which is very fast compared to the speed of sound waves. Also, visible light communication does not endanger marine life in any way. Higher bandwidth, faster speed, efficient power, and less noise interference are advantages of optical communication. However, the main challenge faced by optical communication is that it can only work in a very close distance.

d) Hybrid Optical Acoustic Communication

Limitations of both technologies can be calculated by combining the two — an optimal network that can be designed using the right technology at the right time. Wang et al. stated that this type of communication depends on the Signal-to-Noise Ratio (SNR) value of the signal receiver at the end which determines the technology to be used to transmit data [7]. High, medium and low SNR values use optical communication while SNR values below the threshold require acoustic communication. Also, multi-hop techniques can also be used to transfer data from the source to the destination node.

In making the design of the underwater sensor network, it requires several aspects that must be considered as follows [8].

e) Medium
Underwater sensor networks transmit data using acoustic waves and light waves. Electromagnetic waves have very high attenuation in water, especially at high frequencies and require high transmission power and large antennas. Optical or light waves can be used to reach very high data rates, but light waves are rapidly dispersed and absorbed in water. Optical waves can only be relied on for short-term long-distance communication while acoustic waves can be relied on for long-term, long-distance communication, due to acoustic waves have relatively lower absorption in water.

f) Environment
Environment refers to the implementation of the physical medium. Channel modeling is based on applications and environments such as density, depth, salinity, temperature, chemicals, sound, optics, humidity, and wind speed. These parameters vary from sea to ocean and ocean to river.

g) Mobility Node
Underwater sensor nodes are equipped with buoys on the surface. Some have special objectives so that underwater sensor nodes have moderate mobility due to water currents and other underwater activities.

h) Physical layer
Acoustic channel modeling is very important due to acoustic waves are best suited for communication on the physical layer. Parameters such as signal fading, receiving power, propagation loss, propagation delay, transmission loss, background noise, node depth, density, and mobility must be considered for efficient channel modeling.

i) MAC Protocol
The development of the MAC protocol for acoustic underwater sensor networks must include the use of modem features, a wake-up system that can reduce power consumption. Synchronization and localization are important requirements for the MAC protocol

j) Network Protocol
The proposed network protocol for ground-based sensor networks does not apply to underwater communications. The underwater sensor network has unique features and new research at almost all the necessary protocol suite levels.

k) Application Layer
Application layer protocols must support underwater network features such as reusability, performance, scalability, availability, and support for rich-semantic scripts to define experiments and process results.

As for some of the main challenges when making the design of the underwater sensor network such as battery power is limited and usually it cannot be recharged; the solar energy cannot be exploited; the available bandwidth is very limited; channel characteristics, including length and variable propagation, multipath, and fading problems; it also has a high bit error rate; and underwater sensors are susceptible to failure due to fouling, corrosion, and so on [9].

B. UWSN Simulators

Some simulators that can be used to simulate underwater sensor networks [10]. It is shown in Fig.2.

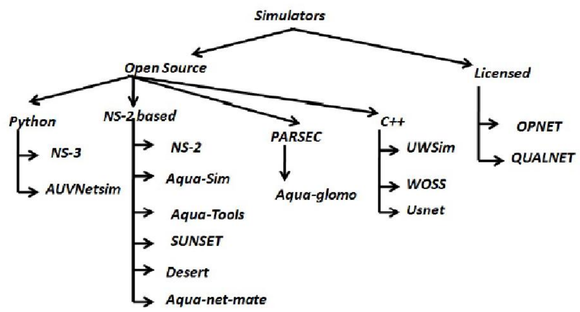

Fig.2. Some Simulators that can be Used Based on Open Source and Licensed [10]

Figure 2 explains the hierarchy of various simulators based on open source and licensed simulators. Some simulators are developed exclusively for underwater scenarios while others are used for terrestrial applications but can be further configured for underwater environments. Some simulators can only be used for software testing and validation while others can be used for real-time testing as shown in Fig.3.

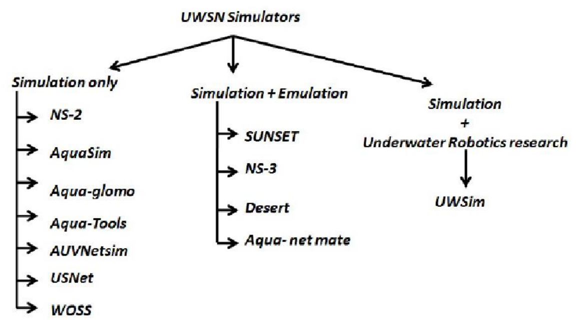

Fig.3. Some Simulators Classified Based on Utility [10]

Figure 3 shows some simulators that categorized as simulation only, simulation with emulation, and simulation with robotic submarine research. On this research, we used Aqua-Sim with NS-2 based which is open source simulator and provide simulation only.

C. Aqua-Sim

In Network Simulator 2, there is a CMU wireless package developed for terrestrial wireless networks. As discussed earlier, terrestrial network simulation packages cannot easily overcome the underwater network environment. Motivated by these needs, instead of modifying the existing wireless network simulation package, the researcher began to develop a new simulation package, named Aqua-Sim for underwater sensor networks [3]. At Network Simulator 2, Aqua-Sim is parallel to the CMU wireless simulation package. Figure 4 illustrates the relationship between Aqua-Sim, CMU wireless packages, and Network Simulator 2 basics.

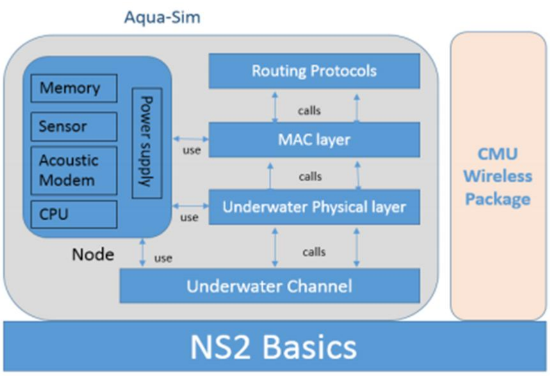

Fig.4. Aqua-Sim System Architecture [11]

Aqua-Sim is not dependent and not affected by CMU wireless simulation packages or other simulation packages on Network Simulator 2. Likewise, every change in Aqua-Sim is also limited to itself and has no impact on other packages on Network Simulator 2. In this way, Aqua-Sim can develop independently [11]. The implementation of all UWSN routing protocols follows the standard structure of the routing protocol found in Network Simulator 2. Parameters for the protocol can be adjusted via the Tcl script.

D. Vector-based Forwarding (VBF)

VBF is the first geography-based routing protocol designed for mobile underwater sensor networks [12]. The VBF protocol is designed to solve canal problems with high levels in solid networks. VBF is a location-based routing approach for underwater sensor networks [4]. VBF Network Architecture is shown in Fig.5.

VBF uses a vector-based forwarding mechanism to forward data packets from source to destination. Vectors calculated from the source to the end point and nodes within the radius calculated from the vector can only participate in the communication. VBF constraints lie in the alleged localization of sensor nodes. The selection of forwarding nodes is based on the radius that has been determined from the vector [13]. It is assumed that each node previously knows its location and each packet carries the location of all the nodes involved including the source node, the forwarding node, and the node's final destination. The forwarding path is determined by the routing vector from sender to target [14].

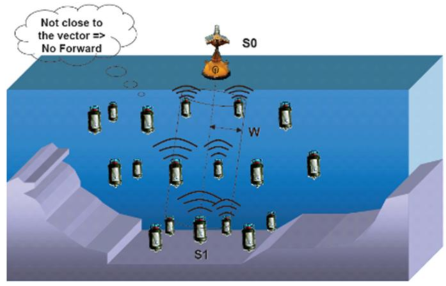

Fig.5. VBF Network Architecture [4]

VBF has many advantages and disadvantages. Advantages of using VBF such as it works depend on each of the sender's neighboring nodes which determine its candidacy to be the next relay node, it can handles node mobility efficiently, and the location of each sensor node can be obtained through a localization service [4].

Meanwhile, the disadvantages such as small data delivery ratio in sparse networks, a delivery ratio slightly decreases when nodes are mobile, sensitivity to the routing pipe's radius, multiple nodes acting as relay nodes, and high communication time in dense networks which many nodes involved in packet forwarding [4].

E. Depth-Based Routing (DBR)

DBR is a protocol that uses an approach to send data packets to the destination of the sink node on the water surface [12]. DBR Network Architecture is shown in Fig.6.

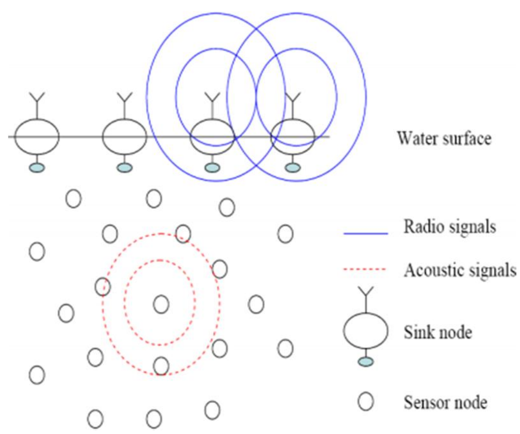

Fig.6. DBR Network Architecture [4]

DBR uses an excessive packet suppression mechanism to save energy by reducing the number of collisions between nodes and preventing other nodes from continuing the same packet [12]. In DBR, packet decisions carry forward based on the depth of the node and the depth of the previous sender. After receiving the packet, a node compares its depth to the previous sender's depth [15]. Also, the DBR protocol is a protocol that is widely used in underwater scenarios due to it only uses depth information which is easier to obtain. However, in DBR, packages can be forwarded through several paths, and sensor nodes are often used to transmit data closer to the surface so that it can cause energy waste and moderate network life [16].

There are advantages and disadvantages of using DBR as routing protocol in underwater sensor networks. The advantages such as its work based on the depth information of each sensor, it manages a dynamic network, it has good energy efficiency, it has no complete dimensional information on location, and it utilizes multiple-sink network [4].

However, it decreases the delivery ratio by increasing the depth threshold, not so good performance in sparse networks, it has a significant end-to-end delay, and it has high total energy consumption [4].

F. System Design

The system designed in this research aims to analyze energy consumption in the DBR and VBF routing protocol using simulation on Aqua-Sim. Block diagram of the system simulation is shown in Fig.7.

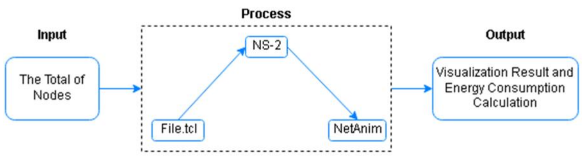

Fig.7. Block Diagram of The System Simulation

There are three main system diagrams in the simulation based on Fig.7, namely:

1. Input
   This part is the initialization of data that contains changes in the number of nodes and parameters that have been determined.
2. Process
   At this stage there are three processes carried out namely:
   - File.tcl which contains parameter data that has been input.
   - Network Simulator 2 as a process for carrying out scenarios based on DBR and VBF routing protocols. In this process, it will produce output in the form of files with extension (.nam) and calculation of energy consumption.
   - NetAnim becomes the visualization generated from the file.nam
3. Output
   Output results in the form of energy consumption of DBR and VBF routing protocols on each number of nodes that have been initialized.

G. Supporting Devices

Supporting devices which used for simulation modeling and performance analysis results are as for Table 1.

Table 1. Hardware and Software Support

Hardware	Processor Intel® Core™ i7-7500U 2.7 GHz RAM 8.00 GB
Software	Operating System Linux Ubuntu 14.04 Network Simulator 2.30 VMware® Workstation 12 Pro

H. Simulation Parameters

The parameters used in the underwater sensor network simulation areas for Table 2.

Table 2. Simulation Parameters

Num	Simulation Parameters	Total
1.	Transmitter Power	2.0 Watt
2.	Receiver Power	0.1 Watt
3.	Idle Power	0.001 Watt
4.	Initial Energy	100 Joule
5.	Minimum Speed	3 m/s
6.	Maximum Speed	5 m/s
7.	Max. Transmission Range	100 m
8.	Packet Size	20 bytes
9.	Bit Rate	10 kbps
10.	Dimension (x × y × z)	500 m × 500 m × 500 m

I. Simulation Scenarios

The simulation was done by comparing the energy consumption between the DBR and VBF protocol on the underwater sensor network with the dimension of 500 m × 500 m × 500 m with the condition of the nodes number and the location of each node different on its coordinate as described in Table 3.

Table 3. Node Coordinate on Simulation Scenarios

Node(s)	Coordinate (m)		
	X	Y	Z
0	500	0	0
1	440	0	0
2	450	50	0
3	500	70	0
4	470	20	30
5	380	90	10
6	350	100	20
7	340	10	30
8	500	30	40
9	400	40	50
10	375	60	60
11	300	80	70

Node(s)	Coordinate (m)		
	X	Y	Z
12	290	20	80
13	500	30	90
14	400	70	0

After the simulation has done, the result of energy consumption will be obtained. Energy consumption is the amount of energy needed by nodes to transmit and receive packages [17]. In this calculation, the value of energy consumption is obtained through the following equation:

$$\text{Energy Consumption (\%)} = \frac{\text{Used Energy}}{\text{Initial Energy}} \times 100\% \qquad (1)$$

III. RESULT

A. Simulation Result

From the simulation result, based on the specified scenario which has already been mentioned previously in section II, we obtained the following data has resulted in Table 4.

Table 4. Simulation Result

Number of Nodes	Energy Consumption (%)	
	DBR	VBF
5	10.1856	28.0949
6	10.8856	34.0641
7	11.5856	43.3966
8	12.2856	48.2921
9	19.4464	55.9624
10	26.2999	74.2099
11	33.2231	78.7395
12	39.6711	88.4301
13	46.3567	103.3777
14	47.6016	114.6991
15	48.7768	140.1468

As for the data, it can be formed into a graph which resulted in Fig.8 below.

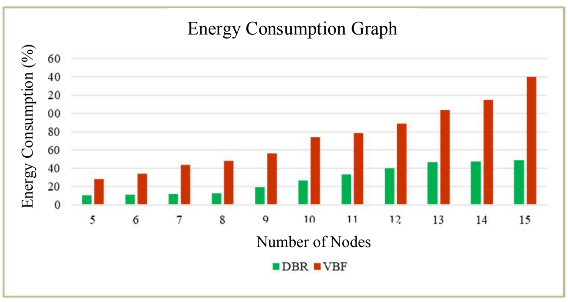

Fig.8. Energy Consumption Graph

In comparison between our research result and previous research result, we provide the previous research result comparison between DBF and VBF routing protocols only as described in Fig 9.

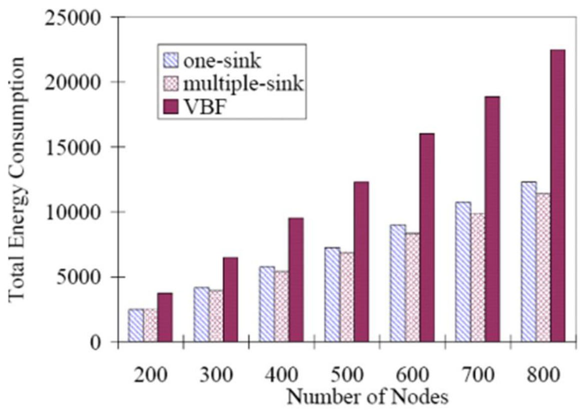

Fig.9. VBF and DBR Energy Consumption Comparison [4]

B. Simulation Visualization

From the scenario that has been determined, the DBR and VBF routing protocol that has been simulated produce the following visualizations at NetAnim which displayed on the Fig.10 and Fig.11.

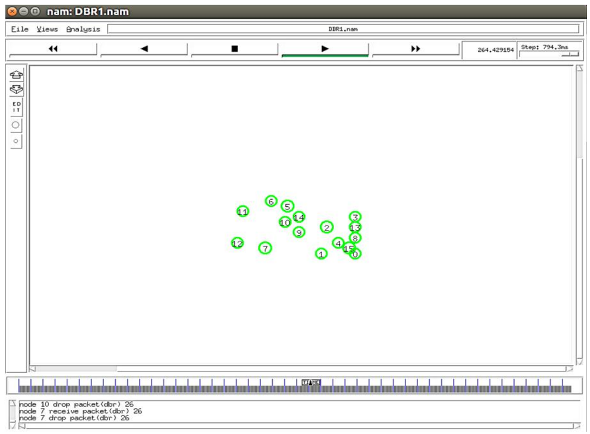

Fig.10. DBR Visualization

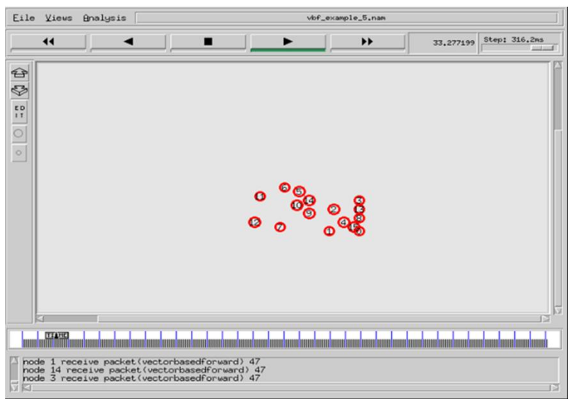

Fig.11. VBF Visualization

IV. DISCUSSION

Based on the results obtained in Table 4 and Fig 8, it can be concluded that the number of nodes whether from DBR or VBF protocol will affect the amount of energy consumption. As it can be seen that energy consumption in the DBR protocol is smaller than the energy consumption in the VBF protocol. This is due to the selection of nodes on DBR protocol tend to forward packets based on the depth of the node, not on the water surface. Meanwhile, the selection of nodes on the VBF protocol tends to approach packets to the closest position to the water surface so that the energy consumption used in the VBF protocol will be higher than the DBR protocol. Otherwise, the energy consumption will be more efficient in DBR protocol than VBF protocol.

The result confirms that the previous research is precise and accurate especially for VBF and DBR protocol in energy consumption parameter. As we can see from Fig 9, the number of nodes applied in previous research was 200-800 nodes which may represent the actual nodes number if it implemented on the real-time situation. Meanwhile, our research focused on the small number of nodes between 5-15 nodes to prove that whether or not when the number of nodes is getting smaller, the energy consumption will also be getting smaller which applies to both DBR and VBF protocol. Also, from previous research, they separated DBR into two sections which are one-sink and multiple-sink while our research did not discuss the division of DBR protocol due to the limitation of DBR source code for Aqua-Sim at NS-2.

The visualization on Fig 10 and Fig 11 are an additional explanation with the visual concept in NetAnim at NS-2. There are 15 nodes in total moving around. The differences between either protocol are the movement. DBR protocol tends to forward packets based on the depth of the node while the VBF protocol tends to approach packets to the closest position to the water surface. We assumed that the water surface is on top of NetAnim while the underwater is on the bottom of NetAnim. From the movement, we can detect which one is using DBR protocol and which one is using VBF protocol for underwater sensor networks.

V. CONCLUSION

Based on the results of the simulation, analysis, and also from the graph where the analyzed number of nodes is directly proportional to the energy consumption used, it can be concluded that the more nodes, the more energy consumption it will be. Also, due to the movement and selection of nodes on DBR protocol tend to forward packets based on the depth of the node, not on the water surface, causing DBR protocol needs less energy consumption than VBF protocol. Meanwhile, the selection of nodes on the VBF protocol tends to approach packets to the closest position to the water surface causing VBF protocol needs almost twice energy consumption than the DBR protocol.

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