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EBVBF: Energy Balanced Vector Based Forwarding Protocol

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ABSTRACT Nowadays, one of the biggest problems of underwater networks is the energy consumption in the communication of sensor nodes. Moreover, sensor nodes rescue operations because of the battery starvation is a high-cost activity. With this in mind, this paper proposes a routing protocol called energy balanced vector-based forwarding (EBVBF), whose main objective is to increase the lifetime of an underwater network and to balance the energy consumption of the sensor nodes, avoiding the creation of void zones that can lead to complete interruption of communication between certain nodes and sink nodes, therefore reducing the number of rescue operations and maintenance in an underwater environment, an element very important in the places of difficult access. A simulated performance analysis is carried out by using the proposed protocol in an environment with nodes in movement showing the gain in energy saving in a balanced way and the increase of network lifetime.

INDEX TERMS Acoustic networks, routing protocol, WSN.

I. INTRODUCTION

A sound wave propagating in an underwater environment consists of the compression and alternating rarefaction of water. These alternations are detected by a receiver in the form of pressure variations. The average propagation velocity of acoustic waves in the submarine channel is 1,500 m/s, which is much lower than the velocity of 299,792,458 m/s of the electromagnetic waves in the radio channel [1], [17]

The main mode of absorption of sound waves is the high viscosity of the water or its resistance to changes caused by external factors. This absorption increases with the increase of the frequency of the wave, similar to the terrestrial radio frequency signals, but with greater intensity. This severely limits the amount of data that can be sent in a channel, as this is proportional to the frequency. Waves with frequencies greater than 1 MHz are rapidly absorbed in an underwater environment [21].

Finally, we have dispersion, which occurs due to the displacement of the reflection points caused by the wind on the surface to which a given wave is subjected and which depends on its direction. A vertically traveling wave will have less dispersion than one traveling horizontally [2], [16]

For this study the BELLHOP propagation model was used [1], [22]. Originally developed in Naval Ocean Systems Center, improved by Naval Research Laboratory and eventually used in many organizations around the world, the model was developed considering the propagation of the acoustic rays in two dimensions, having as output the Cartesian coordinates of the acoustic ray, based on travel time, amplitude, acoustic pressure and path loss.

There are four common types of topology for underwater networks, which can be either 2D or 3D, as well as either mobile or static. 2D networks consider only horizontal, vertical and diagonal planes in a two-dimensional plane, while 3D uses volume's three-dimensional positions.

Static networks are those in which nodes surfaces are anchored and therefore do not have their positions altered over the course of the operation of the network. Mobile networks consider that the nodes are loose and therefore are subject to the natural movement of waters, changing their positions throughout time.

In this study the Mobile 2D topology was used, which is the most widely accepted and employed in projects of this type.

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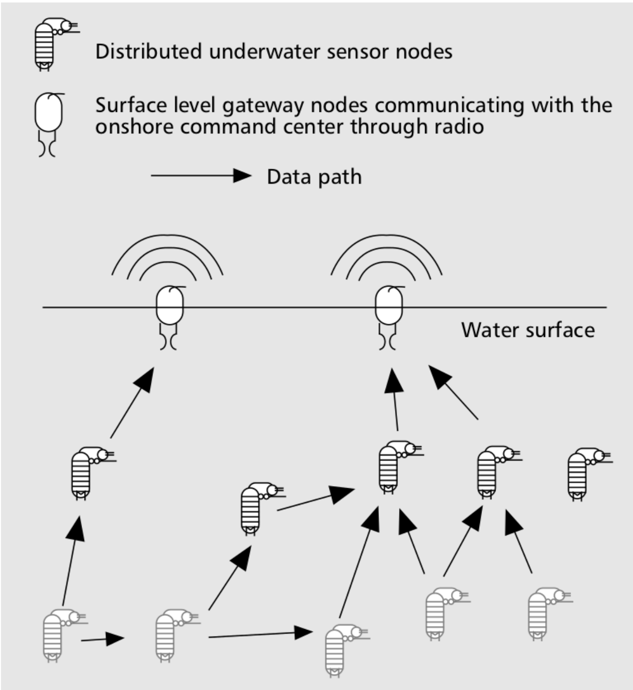


FIGURE 1. **2D topology diagram. Source: [3].**

Figure 1 illustrates this topology. In it, we can observe the nodes divided into three groups according to their depths. At the top (water surface), we have the sink nodes, which are the final nodes and are more robust, the second level are the nodes with certain level of depth and the third one are the nodes that are more deep. A packet is considered as delivered when it reaches any of water surface nodes.

Wireless networks in underwater environments have three main problems:

- Low Range: This is due to the need to use acoustic waves, which have a propagation speed five orders of magnitude lower than the radio waves normally used in terrestrial networks. Conditions of temperature, pressure and, in the case of oceans, salinity of the water, make the RF waves have losses related to the canal, making it sometimes impossible to use them.
- Low Transmission Rate: Transmission rates on wireless networks are related directly to the frequency at which the waves are transmitted. However, acoustic waves transmitted in underwater environments are rapidly absorbed if frequencies exceed 1MHz. For comparison purposes, a common Wi-Fi network uses frequencies greater than 2GHz.
- Node Energy Consumption: The underwater environment and the use of acoustic signals cause a high energy expenditure on the communicating nodes as transmissions used to be in broadcast mode. Since the nodes are distributed in an environment of difficult access, actions of battery recharge or nodes recovery result in a high additional cost of operation. Therefore, it is necessary to adopt measures to avoid the need for such operations. A solution to this last challenge is the main objective of this project, through the use of a routing protocol (EBVBF) and the balancing of the energy expenditure of the transmitting nodes.

In addition to the above problems, underwater networks present some additional challenges. For example, the media access protocols for terrestrial networks cannot predict collisions in a suitable time, since the average signal propagation delay and its standard deviation in underwater networks are very high compared to terrestrial networks.

In broadcast-based wireless networks, routing protocols try to manage and optimize various features and challenges such as increasing delivery reliability, avoiding void zones and managing congestion or energy starvation of nodes among others.

This project proposes EBVBF (Energy Balanced Vector Based Forwarding), a new routing protocol whose main objective is to increase the lifetime of an underwater network, balancing the energy consumption of the nodes and avoiding the creation of "void zones" which can lead to complete interruption of communication between certain sensor nodes and sink nodes, with the great advantage of reducing the operations of rescue and maintenance of the underwater network. This work also takes in consideration the movement of nodes, that is an intrinsic aspect in oceans because of waves. To this end, a performance analysis will be carried out between the proposed protocol and the VBF protocol, using a simulation environment, analyzing the metrics: network lifetime, first node lifetime, transmission delay and number of packets delivered.

The rest of this paper is organized as follows: section II describes the principal proposals of routing protocols to underwater networks; section III describes the proposed routing protocol; section IV shows the simulation performance analysis and in section V we have the conclusions.

II. RELATED WORKS

Here we will outline the most important features of the most known routing protocols to underwater networks.

A. VBF (VECTOR-BASED FORWARDING)

The high mobility of the nodes in an underwater network causes the constant change in the topology which brings with it the need for frequent maintenance and recovery of routes, something very difficult to achieve, especially in 3D topologies.

Created in 2006, the VBF [4], [20] pioneered routing protocols for underwater networks. It uses the position of each node to solve the issue of maintenance and recovery of routes at once in a network, after its convergence, nodes tend to use the same route to reach the surface. Leaving other nodes idle or in some cases using the broadcast transmissions to reach sink node.

Packets are sent through multiple redundant paths between source and destination, mitigating the problem of packet loss and node failures. The protocol is based on the assumption

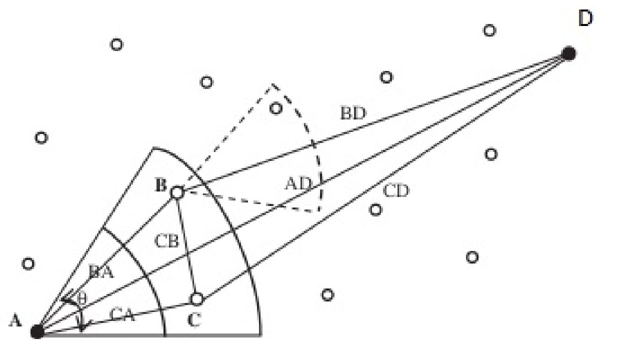


FIGURE 2. Operation of the FBR Routing Protocol. Source: [5].

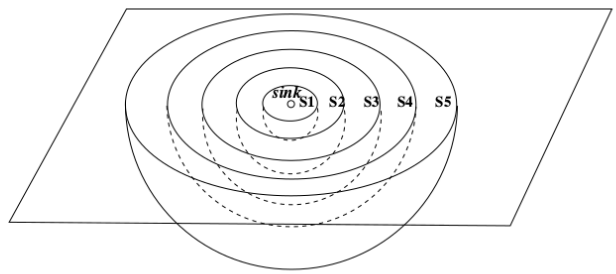


FIGURE 3. Operation of the REBAR routing protocol. Source: [6].

that each node knows its location and that each packet contains the location information of all nodes involved in its transmissions. A virtual routing vector is created in which only nodes next to this vector participate in the transmission. This allows the reduction of network traffic making the management of dynamic topologies easier.

However, VBF presents some problems. The creation of vectors generates problems in non dense networks, since, in case of absence of nodes near to the vector, there will be packet loss and the need for re-transmission. Finally, vectors cause some nodes to be used more frequently, therefore wasting more of these nodes' batteries. Our proposal is just to solve this last problem.

In order to address some of these problems an improved version of the VBR called HH-VBF (Hop-by-Hop Vector-Based Forwarding) [20] has been proposed. It uses the same concept of vectors as VBF but, instead of using only one source vector destination, each node computes a new vector to send the packet to the next node. Thus, there is a decrease in the number of packets lost in sparse networks. However it causes a significant increase in overhead at the nodes, requiring more processing and therefore more waste of energy and an increase in the delay of the delivery of the packet.

B. FBR (FOCUSED BEAM ROUTING)

The lack of location information of nodes causes a large number of broadcasts messages that can cause congestion in the network, reducing the overall throughput. To reduce this flooding the routing protocol FBR for acoustic networks was proposed in 2008 [5], [18].

The FBR, like the VBF, is based in the assumption that each node knows its position and location of the destination node, without the need to know the location of intermediate nodes. With this information, FBR can dynamically establish routes while data travels over the network, where decisions about the next hop is taken node by node.

Figure 2 shows the operation of the transmission method used in the FBR, using cone-shaped geometric spaces in multicast transmissions. Node "A" has the packet that must be sent to destination "D". To do so, it sends a Request To Send (RTS) packet, which contains the locations of "A" and "D". Initially, this multicast transmission will be done with the lowest transmission power, which will be increased if no node is found. To assist in this, a finite number of power rating is used. After this, multicast transmission nodes that receive the packet will calculate their position related to origin. If the node notices that it is inside the transmission cone area, it will respond with a CTS (Clear To Send) message [5].

FBR routing protocol has some problems. FBR causes a high consumption of battery in sparse networks due to the constant use of higher power levels. Lastly, the sending of CTS and RTS packets causes an overload of control packets on the network.

C. REBAR (RELIABLE AND ENERGY BALANCED ROUTING ALGORITHM)

As was mentioned before, the natural movement of the water make the networks very dynamic. In 2008, the REBAR protocol was proposed, which deals with this movement in a positive way [6], [19]. According to the authors, this movement can help to balance the power consumption in the network, since the nodes can alternate in around the destination node.

The REBAR works similarly to VBF and FBR protocols, since it requires that the nodes know their locations and the destination. However, an adaptive scheme where nodes send broadcast messages in small selected domains according to the geographic location information was proposed. Sizes are defined by the distance between nodes and the destination. Nodes that are farther to the destination have lower energy consumption due to a lower participation in the routing process. This scheme is illustrated in Figure 3.

D. ICRP (INFORMATION-CARRYING ROUTING PROTOCOL)

Most of the routing protocols proposed so far send packets of control and data separately. In 2007, the ICRP routing protocol was proposed, a real-time protocol with energy efficiency and scalability where control information is sent together with data [7]. The greatest advantage of the ICRP is that it does not need the location information of nodes.

The route creation process starts at the source node. First, it checks if a previously used route already exists. If not, the data packet containing control information will be broadcast to the nodes until they reach the desired destination. With the path information, the destination can use the same inverse

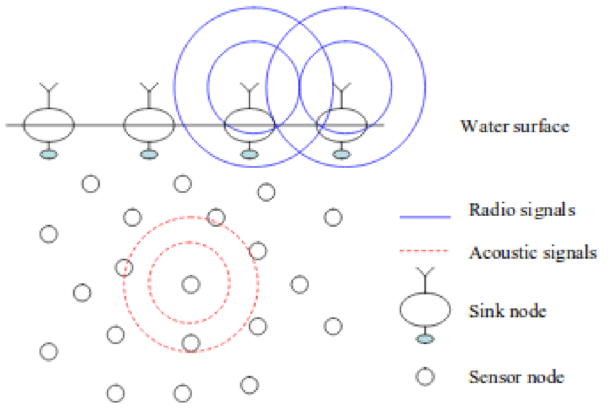


FIGURE 4. Functionality of DBR protocol. Source: [11].

path to send a packet acknowledgment to the receiver. In addition, each route has a different priority, called the route lifetime which denotes how long the route is valid and can be used.

E. DBR (DEPTH-BASED ROUTING)

In 2008 the DBR routing protocol was introduced, which uses depth information of each node, that can easily be obtained with low cost depth sensors, to decide the best route. Several destination nodes are placed on the surface of the water and a packet is considered sent when it reaches any of these nodes. When a node has a packet to send, it will calculate its current depth relative to the surface and will place the value obtained in the package header, which will be sent via broadcast. The node receiving this packet will compare its depth with the present in packet and will resend the packet, also in broadcast mode, if the node is closer to the surface. Otherwise the packet will simply be discarded. The functionality of the DBR is shown in Figure 4.

The DBR protocol has two main problems:

The first is high energy consumption because of all the broadcast messages. For this, EEDBR (Energy Efficient Depth-Based Routing) was proposed, which aims to solve this problem with the definition of two phases, discovery and routing to increase the battery life of each node [9].

The second problem occurs when void zones appear in sparse networks. The DBR protocol cannot adapt when working in greedy mode as packets are only sent to the high levels nodes. In 2015 two modifications of the DBR that aim to solve this problem were proposed: AMCTD (Adaptive Mobility of Co-Launch Nodes in Threshold-Optimized Depth-Based Routing) and DBMR (Depth-Based Multihop Routing) [10].

These alternatives make use of continuous updates in its routing table to the extent that if some nodes are running out of power, the protocol calculates new weights of metrics for each node. This ensures that the remaining nodes' movements cover spaces left by the nodes that were removed from the network [10].

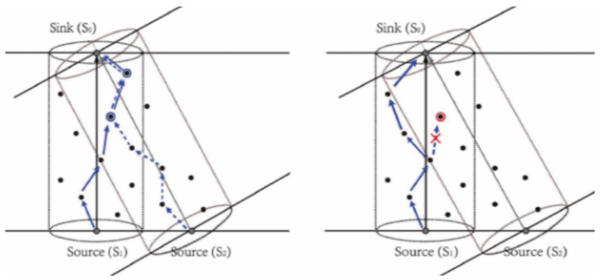


FIGURE 5. Functionality of CL-VBF protocol. Source: [23].

F. CL-VBF (CROSS-LAYER VECTOR BASED FORWARDING)

In 2016, a new proposal for the verification of residual energy was introduced to VBF protocol. With this, there is a balance in energy consumption among nodes, avoiding overloading ones and under-utilizing others [23].

Figure 5 shows, on the left side, the route choice without the energy information. The same packet travels on two different routes, causing unnecessary transmission and the possibility of collisions. On the right side, the CL-VBF protocol, with the residual energy information in the choose of just one route.

G. 2HOP-AHH-VBF (TWO HOP ADAPTATIVE VECTOR BASED FORWARDING)

In 2017, another extension was proposed to the HH-VBF protocol, this time with the intention to minimize the effects of void zones on the VBF proposal. This is done with the collection of residual energy information, as in the CL-VBF, besides the position of the nodes neighbors for the next two hops in the network. Moreover, there is a holding time, so that the same node is not chosen for repeated transmissions, avoiding its energy starvation and consequently mitigating the problem of void zones.

This selection of neighbors is made based on three parameters: first, the neighbor shall be as far as possible from the transmitting node range, so as close to the sink as possible. Then the number of neighbors available to the sink node is evaluated. Finally, the AoA (Angle of Arrival) is calculated from a virtual vector to ensure the optimum position, i.e. the next node chosen for transmission will be the most appropriate one according to the one previously reported [24]. For the collection of these parameters, neighbor beacons are sent at the beginning of the routing process. These beacons have the function of finding neighbors.

H. QF-2HOP-AHH-VBF (QUALITY FORWARD TWO HOP ADAPTIVE VECTOR BASED FORWARDING)

The QF-2Hop-AHH-VBF protocol defines a holding time from the route vectors to decrease the number of transmissions while doing a better neighbor choice for next hop, similarly to 2Hop-AHH-VBF. However, QF-AHH-VBF protocol uses some more information for this calculation: the number of potential neighbors, the distance between the transmitter and receiver of the packet and the distance from the receiver to the vector calculated previously, which may change due to the water movement [24].

The main disadvantage of 2Hop-AHH-VBF and QF-AHH-VBF protocols is the introduction of many control packets, causing a greater number of transmissions without increasing the rate of delivery of data. In addition to the overhead there is also a bigger energy expenditure of the nodes involved, resulting in a reduction of the lifetime of the network.

In [27] an Energy-efficient and Obstacle-Avoiding Routing protocol (EOAR) is proposed not only to address the issue of marine animals acting as obstacles that interfere with communications, but also to balance the network energy according to the residual energy. Results show that proposed protocol can increase the packet delivery ratio by 28.4% and can reduce the energy consumption by 53.4% comparing with HHVBF. This proposal does not take in consideration movement of nodes.

According to [26] HydroCast protocol [25] is similar with DBR, the difference being that HydroCast takes the wireless channel quality into consideration to improve the routing performance under continuous node movement conditions. In this survey authors just cited DBR, VBF and REBAR beside HydroCast as routing protocols that takes in consideration movement of nodes. Our work is based on the VBF protocol.

III. THE ROUTING PROTOCOL PROPOSED

The low price of equipment and antennas used to assess the location of underwater nodes demonstrates that the VBF is a protocol that is cost efficient. Techniques based on TOA (Time of Arrival) and AOA (Angle of Arrival) could also be used to determine the position of nodes like the work of [28] but this issue is out of our scope.

VBF is a protocol without control phase and developed for energy saving. But according to studies published in [20] VBF protocol presents a lower delivery success rate in sparse networks, so HH-VBF was proposed as solution. One challenge of VBF is that the creation of vectors is less effective in dense, since, in the absence of nodes inside the vector, there is no packet forwarding and, as a consequence, there will be loss of packets and need for re transmission. Finally, the vectors may cause that some nodes are used frequently, causing greater battery consumption. In order to address these problems, an improved version of the VBR called HH-VBF (Hop-by-Hop Vector-Based Forwarding) [20] was proposed.

HH-VBF uses the same concept of vectors as VBF but, instead of using only one vector from the origin to the destination, each node computes a new vector up to the destination, aiming for efficient delivery of the package to the next node. Thus, there is a decrease in the number of packets lost in sparse networks. However, the calculations performed cause a significant increase in overhead at nodes, requiring nodes with greater processing power and, therefore, increasing costs of implementation. In addition, the fact that the protocol multiplies the tunnels of communication to the destination, it involves more nodes in the process and, consequently, there is more waste of energy.

Therefore, in order to mitigate problems mentioned before, we propose a new routing protocol EBVBF(Energy Balanced Vector Based Forwarding) that is based on VBF protocol. This protocol increases the network lifetime in low density network, reduces the energy expenditure in a balanced way, avoiding the creation of void zones and thereby increases the reliability of packet delivery.

The VBF protocol tends to choose an optimal node (with lower α) for each packet hop. In this way, nodes involved in the transmission will have their energy depleted until another node can assume the routing task. The EBVBF protocol, with the addition of two priority levels, using a threshold adaptation time, saves the energy of "crucial" nodes. Like this, if another node with more battery can do the transmission it will send the packet first. The result of this new EBVBF referral policy is a balanced and low waste of energy. Recalling that the substitution of nodes is a high-cost activity. In addition, depleting the power capacity of a node that is indispensable for the functioning of the network as a whole can create void zones and so a not suitable functioning of an underwater network.

The EBVBF routing algorithm works similarly to the VBF using (α) (desirableness factor), the virtual tunnel and other characteristics mentioned before.

The most significant contribution of the EBVBF protocol is the creation of a parameter E.O (Energy Optimized), based on the α calculated by the VBF and explained in equation 1 [4], and where, if the energy is less than a predetermined threshold so E.O = α + x, where x ranges from 0 to 3. Otherwise, E.O = α. These levels define different adaptation time for each transmission, decreasing transmission collisions and helping with multipath problem.

$$\alpha = \frac{p}{W} + \frac{R - d\cos\theta}{R} \tag{1}$$

where p is the distance from the node to the vector, W is the radius of the virtual tunnel, R is the maximum distance of transmission, d is the distance between the source and the receiver node and θ is the receiving angle.

As a consequence, we have the establishment of two levels of priorities for nodes, based mainly on the remaining energy in each node. Specifically, the first level works with a parameter αE.O = 0-3, used in the calculation of the adaptation time for each transmission, while the second level presents αE.O = (0 + x) − (3 + x). In the case of x = 3, there is an isolation of the queues (see Figure 6), so that no node will have the same αE, avoiding collisions and improving the multi-path problem. However, depending on the topology and other network factors, a lower value of x may be beneficial, even adding nodes in different positions with the same αE as we have less delay transmission of the packet. Figure 6 gives a view of the operation of the two queues created by the EBVBF protocol.

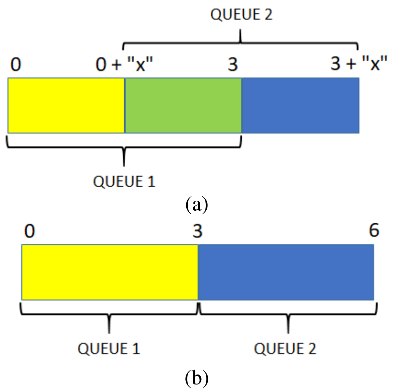


FIGURE 6. **Queues of EBVBF routing protocol. (a) 2 Queues - priorities - EBVBF. (b) 2 Isolated queues (“*xx*” = 3) - priorities - EBVBF.**

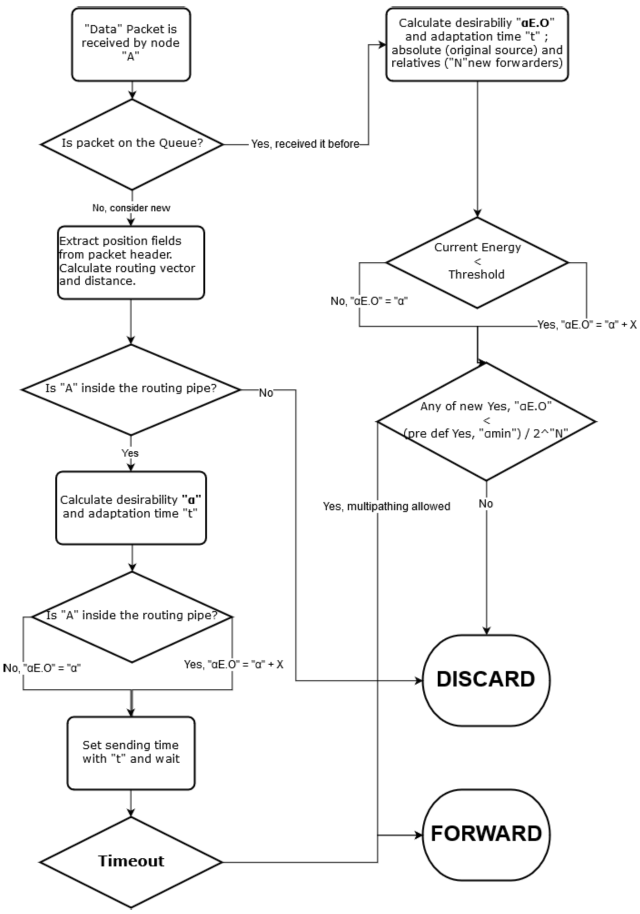


FIGURE 7. **Functioning of EBVBF routing protocol.**

In addition, the functioning of EBVBF can be seen on Figure 7. It emphasizes that the inclusion of the remainder energy in the calculation of the adaptation time based on two priorities is the main contribution of the EBVBF routing protocol.

The new packet forwarding policy will lead to an increase in the delay between the source and the sink node. Therefore the creation of a new type of packet, the emergency packet is proposed. This packet will overlap the reading of remaining energy of the node, so that $\alpha E.O = \alpha$ for all packets of this nature. This feature aims to diminish the transmission delay of packets in the case of priority or urgent transmission.

IV. PERFORMANCE AND ANALYSIS

In the performance analysis of the proposed protocol, the NS-3 (Network Simulator) tool was used with an extension called AquaSim-NG [12].

The NS-3 is a simulator of discrete event networks for internet systems, for educational and research purposes. NS-3 is open source software, licensed by GNU GPLv2 and publicly available for use.

AquaSim-NG is an extension of NS-3 with the purpose of assisting with the acoustic underwater sensor networks. Aqua-Sim can simulate the attenuation of acoustic signals and collisions among packets. In addition, it also can support both 2D and 3D network topologies [13].

The modem simulated in the study was LinkQuest's UWM1000 [14]. This modem has a data rate of 10kbps, with a transmission potency of 2W in a state of a moderate consumption mode, being able to operate at depths of up to 6 km.

Determining the water temperature in the local where the network will be deployed is essential for simulation model, since this characteristic directly influences the velocity of the sound. This is due to the mechanical nature of acoustic waves, which are vulnerable to variations in thermal energy in the transmission medium.

In the simulation the value of 30 Celsius of temperature was used in order to minimize the attenuation following the recommendation of [15].

The aquatic environment has sudden pressure variations. Upon every 10 meters of depth, a pressure is equivalent to one terrestrial atmosphere. With this, the acoustic waves suffer intense scattering as there are pressure variations in the middle of the way, limiting the maximum distance that guarantees a transmission without many errors caused by the physical environment.

In this study, a 2D Mobile topology was used, which is the most used in the studies of the routing protocols mentioned before. Specifically, the topology will be a rectangle, with an area of 1000m × 1010m. Initially, this rectangle will have an uniformity of node location. Other topology will also be evaluated and these scenarios will be explained later.

As is known, the salinity of the ocean is an important factor for any transmission. This is important because salt crystals dissolved in the water spread acoustic waves, causing the attenuation of signal and a decrease in the SNR (Signal-To-Noise Ratio).

In this study, the maximum distance between nodes was 100 m, medium salinity (standard value of the simulator),and the sound velocity 1500 m/s.

Besides these three factors, it is important to highlight the probability of occurrence of problems such as the circulation of boats, as well as the speed of wind moving the water further and causing losses in the signal. In this simulation, this probability will be denoted by “s”. For purposes of this

TABLE 1. Simulation environment configuration.

Antenna	Omnidirectional
TxPotency	2W
Tunnel Radio	100m
RxPotency	0.75W
Movement Probability	0.5
Temperature	30o C
Transmission Interval	5 seconds
Simulation Time	1000 seconds
Maximum distance between nodes	100 m
Sound velocity	1500 m/s
Wind Velocity	1 m/s

simulation, we will use a value of s = 0.5, that is, medium surface activity and wind speed $w = 1\ m/s$.

In the simulation, the following configurations were used aiming to approximate to the actual values of an acoustic network in an underwater environment (see Table 1). All of these values are configurable in AquaSim-NG extension.

In this study a basic On-Off application, standard of the NS-3 simulator, with 50-bit packets (40 data and 10 header automatically added by AquaSim-NG) is simulated. The MAC layer protocol configured in the simulations was Broadcast-MAC. The implemented topology will be a mobile 2D where the nodes will be distributed according to four different scenarios, which will be explained later. The propagation model on the physical medium will be BELLHOP, already implemented by default in AquaSim-NG and discussed earlier. Nodes will move with a velocity of 1.5 m/s to simulate the presence of distortions related to the movement in the surface and waves. Each simulation was executed 100 times, for greater precision in results.

Simulations will use the standard energy model of the AquaSim-NG, with configurable initial energy and wastes related to idle, transmission and reception activities. Values are showed in Table 2 per hour of activity, being proportionally discounted during simulation to the duration of each activity. The initial energy configuration of the devices is described in each scenario.

In addition, we will have a data source and a sink node, with positions being defined according to each scenario, always in order to ensure that the source will have at least two nodes in relation to its neighbors.

The final objective of our protocol is to study the lifetime of the network as the remaining battery energy is the most important performance metric. The success rate of delivery has also been measured. The delay in the delivery of packets was also analyzed even though it was previously known that αE.O would generate an increase in this metric.

The study of the performance of VBF and EBVBF protocols was done in four different scenarios, in order to assess in particular the impact of the new routing policy with respect to the energy waste of the nodes and the lifetime of all network.

A. STUDY OF THE ENERGY THRESHOLD VARIABLE

The scenario contains an area with dimensions of 1000m × 1010m with 625 nodes evenly distributed. The position of the source is (50, 25), while the sink node is at (950, 1010). The initial energy of the nodes will be 15 W/Hr, while the threshold for the proposed protocol will vary from 0 W/Hr to 12.5 W/Hr. These values are deliberately smaller than those found in real situations. This was done in order to activate the energy threshold and decrease the simulation time. The sink source has an initial power of 1000 W/Hr, so they do not interrupt the transmission during the simulation. The factor α will be increased by the value 3, so that αE.O = $\alpha + 3$ as addressed before. Note that when the threshold value is 0 W/Hr, the protocol behaves exactly like pure VBF. The purpose of this scenario is to study the threshold value in relation to network lifetime and delivery rate to determine an adequate value for the all study simulations. The topology used is showed in Figure 8.

TABLE 2. Signal attenuation due to temperature (1km) [15].

Frequency (KHz)	10	10	10	10
Distance (Km)	1	1	1	1
Temperature (Celsius)	4	10	13	30
Attenuation (dB)	1.075	0.8284	0.729	0.3695

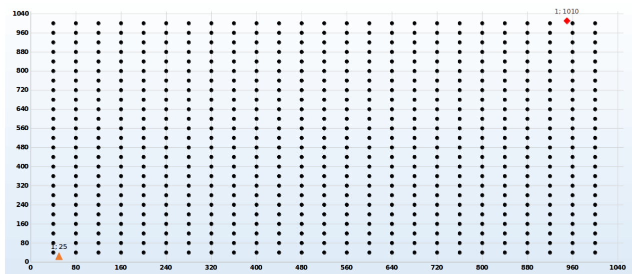


FIGURE 8. Network Topology of 1st Scenario.

Through Figures 9 and 10, it is possible to infer that there is an optimal threshold value that maximize EBVBF battery usage. For very low values, the EBVBF does not remain active enough to save energy. On the other hand, for very high values, the EBVBF activates very early, causing all nodes to migrate to the second level of queues, increasing the delay of packets but not balancing the energy waste. Therefore, for the network lifetime metric, the values of 7.5 W/Hr and 10 W/Hr were more adequate.

According to Figure 11, there is a relation between the threshold value and the increase in the number of packets delivered to the sink node. The variation of the routes and the participation of more nodes are responsible for this increase. However, taking into account the network lifetime, the suitable value for this scenario is 10 W/Hr, which will be used in the next simulations and scenarios.

B. STUDY OF α VARIABLE

As in the first scenario, in this study there is an area dimension of 1000m × 1010m with 625 nodes evenly distributed. The position of the source is (50, 25), while the sink node is at (950, 1010). The initial energy of the nodes is 15 W/Hr, while the threshold for the proposed protocol is 10 W/Hr. Sink and

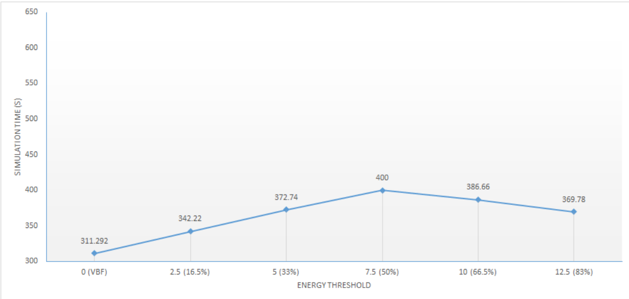


FIGURE 9. First Node lifetime versus Energy Threshold.

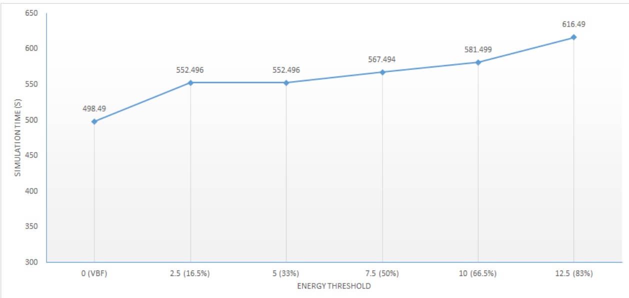


FIGURE 10. Network lifetime versus Energy Threshold.

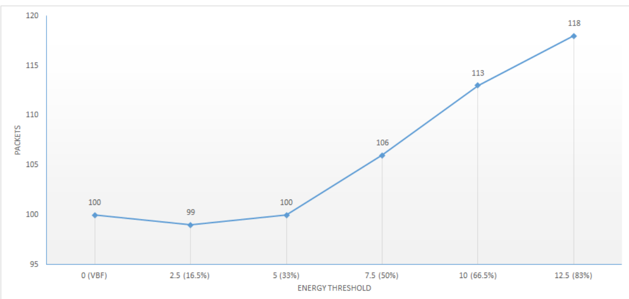


FIGURE 11. Number delivered packets to Sink node versus Energy Threshold.

source nodes have an initial energy of 1000 W/Hr, so they do not interrupt their transmissions during the simulation.

The value of α will be increased from 0 to 3, where α cannot be greater than 3. It should be noted that this behavior is not of the VBF protocol, since the EBVBF protocol for purposes of this scenario has no maximum value.

It is noted that when α is increased by 0 the protocol behaves exactly like the pure VBF protocol. The purpose of this scenario is to rule out any other method of increasing the α factor and determine the impact on the network lifetime as well as define the best value of αE.O. It has also been observed that this simulation determines if the creation of two priority queues (EBVBF) is effective, and if the addition values to α and limiting the sum result to 3 (thus keeping only 2 classes of priority), we will give relevant results.

In this scenario nodes are distributed in a square area of 1000m × 1000m and nodes are statically distributed every 40 meters. Thus, from the source node there are at least four candidates as the first forwarding node.

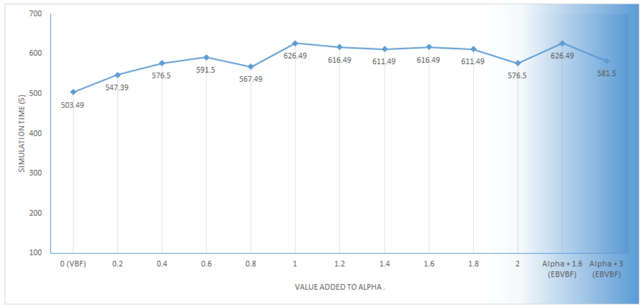


FIGURE 12. Network Lifetime versus α value.

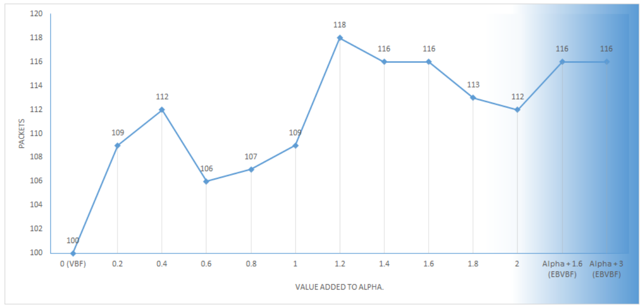


FIGURE 13. Number of packets delivered versus α value.

Figure 11 shows that, with increasing value added to α, the network is generally positive. Because of the network topology, depending on the value, it is not possible to make the node with more energy have priority of transmission in detriment to the node with less energy. Therefore, the value added to α varies the lifetime of the network.

In Figures 12, 13 and 14 when α value is 0, we have the behavior of the VBF protocol. The rest values on X-axis in the graphs are the functioning of the EBVBF protocol.

Figure 12 shows that, just as in the previous result, the value of α changes the lifetime of the first node. It can be seen that the value α of between 1.2 and 1.6 obtained the best result in this metric, a result that remained positive for greater values. The optimal value of α is dependent on the distance between the redundant nodes and the nearest next hop. The determination of the impact of node density will be object of study on the next scenarios.

Figure 13 shows the relationship between the number of delivered packets and the value of α, showing that the energy savings and the new routes generated by the EBVBF protocol increased the delivery rate in relation to the VBF protocol. It was also noted that this rate did not suffer great variations with the α values simulated.

As we can see in Figure 14, the EBVBF average delivery time was higher than that of VBF, since a delay is introduced with the use of αE.O. However, it is worth mentioning that part of the delay for both protocols is due to the delay for acoustic underwater networks. The study of scenario 2 used the values of αE.O equals to 1.5 or 3, since they configured the most balanced choices in relation to the chosen metrics as was shown in previously study. The other values of α did not increase significantly the lifetime of the network compared to

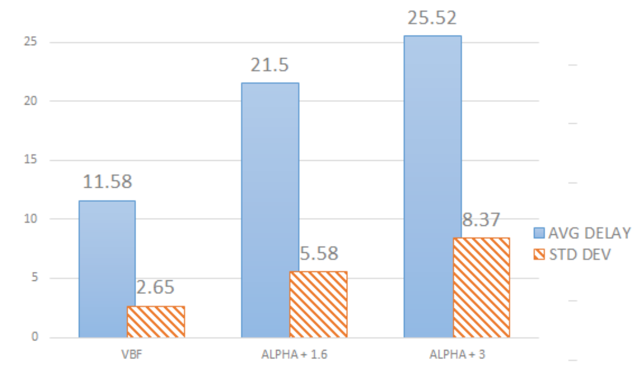


FIGURE 14. Mean Transmission Delay (s).

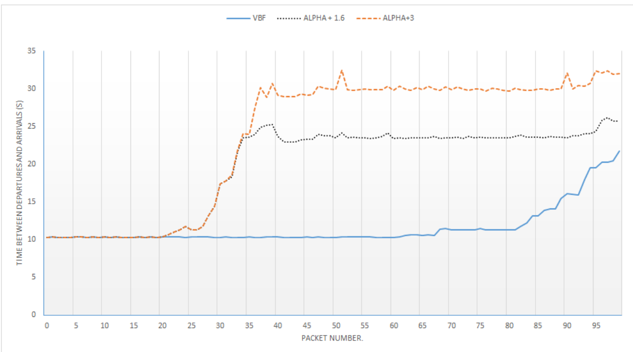


FIGURE 15. Transmission delay (s).

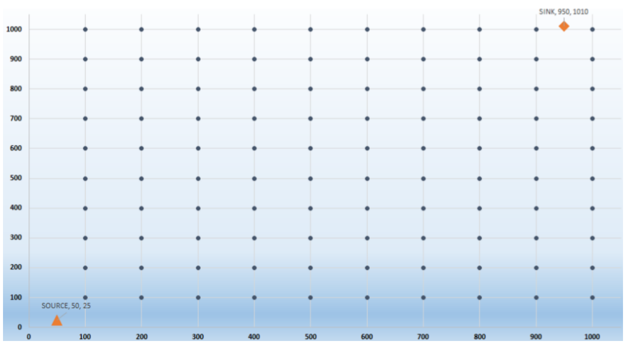


FIGURE 16. Network Topology of 3rd Scenario.

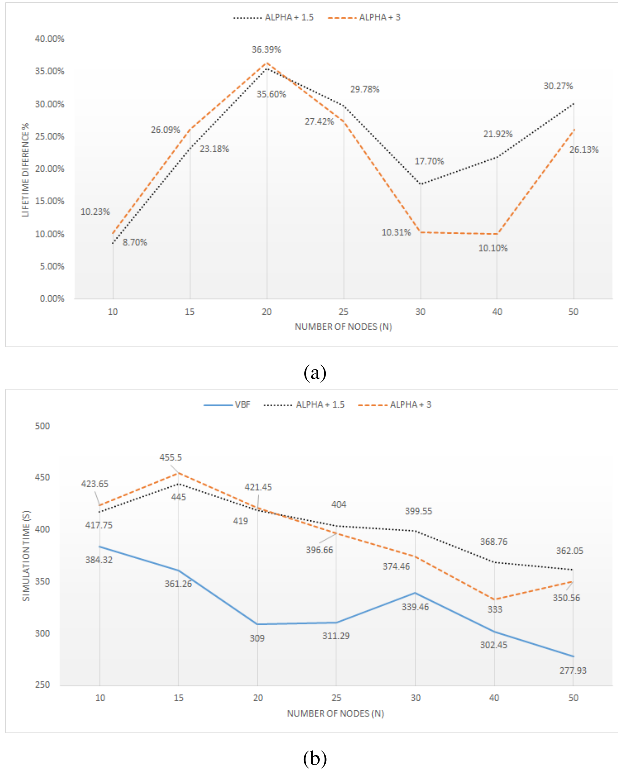


FIGURE 17. Node density Impact evaluation. (a) Network lifetime versus node density. (b) First node lifetime versus node density.

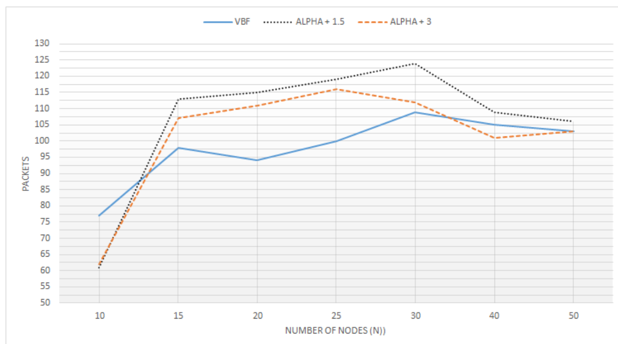


FIGURE 18. Number of packets delivered.

$\alpha + 1.5$, but increases the lifetime of the first node. It should not be ruled out that the greater the α value, the greater the transmission delay according to Figure 15. Therefore, the following scenario will verify the impact of node density using these two αE.O values.

C. DIFFERENT DENSITY OF NODES

In this scenario the area is the same of the second scenario and the positions of source and sink nodes and initial energy are also the same. The VBF and EBVBF protocols will be simulated separately. The number of nodes will be changed in order to establish the relationship between the network density and the network lifetime. The nodes will be distributed in a square with "n" rows and "n" columns. Simulations with the following values of "n" will be made: 10, 15, 20, 25, 30, 40 and 50 (see Figure 16).

The third scenario was created to evaluate the impact of node density in relation to the energy consumption. The results evidenced the increase in the network lifetime with EBVBF protocol with increases of up to 36% for "n" equals to 15 as shown in Figures 17(a) and 17(b).

Figure 18 gives the number of packets delivered to the sink node. In the same way as observed in the previous scenario, EBVBF presented greater reliability for non dense networks. In general, the larger the "n" the greater the similarity between the EBVBF and the VBF in relation to this metric. These results also show that the gain provided by EBVBF is related to the density of the network topology. In the same way that was evidenced in the results of scenario 2, the distance between the nodes and the number of redundant nodes determines the gain obtained by the EBVBF

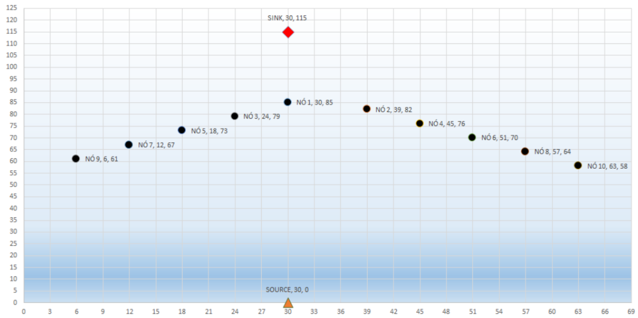


FIGURE 19. Network Topology of 4th Scenario.

protocol, that is, the denser the network, the lower the waste of energy up to a certain limit, where a saturation of redundancy occurs. It is also worth noting that the change in the traditional routes chosen by the EBVBF, in some topology, can allow the adaptation of the routes to multiple source nodes and the possible intersection of its paths.

D. DIFFERENT TOPOLOGY

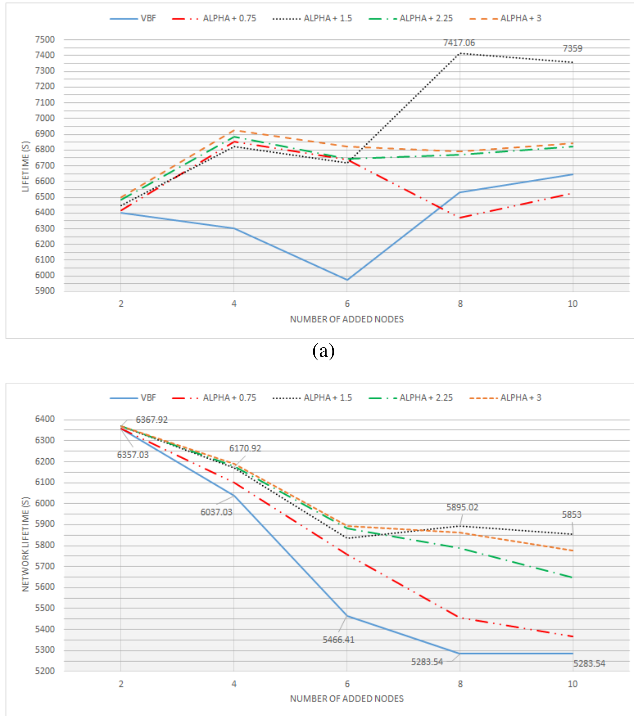
In this study the position of the source is (30, 0), while the sink is in (30, 115). The initial power of the nodes is 150 W/Hr, while the threshold will be 100 W/Hr. The simulation time will be changed to 10.000 seconds, as the goal of this scenario is precisely the waste the energy of all nodes. The sink and the source have an initial energy of 10000 W/Hr so that they do not interrupt their work during the simulation. Nodes will be added according to the equations 2 and 3, where "n" is the number of nodes and "x" and "y" are the coordinates of its position.

$$x = ((3N) * N^{-1} + 33) \quad (2)$$
$$y = 88 - (3N) \quad (3)$$

In this simulation the "n" value will be 2, 4, 6, 8 and 10. The parameter αE.O $= \alpha +$ x, where "x" will have values of 0, 0.75, 1.5, 2.25 and 3. The purpose of this scenario is the study of the network lifetime in relation to the change of numbers of nodes and analyze the functioning of the two priority levels of the EBVBF protocol. Also determine the best value of "x" and the relationship of "n" (redundancy) with the energy profile of the network. The topology of this study is shown in Figure 19.

The third scenario showed how much the increase in the number of redundant nodes affects the gains of the EBVBF protocol.

This study showed that when a node consumed energy up to the threshold, another node started forwarding the packets in that region. Figures 20(a) and 20(b) show how the EBVBF protocol improved the network lifetime. Consequently, it can be observed that the addition of redundant nodes does not have a linear relation with the network lifetime. For each new node, a smaller gain of time is achieved, until the redundancy consumes more energy with re-transmissions than saving it with addition of new nodes.



(a)

(b)

FIGURE 20. Network lifetime improvement with EBVBF protocol. (a) Network lifetime versus number of nodes. (b) First Node lifetime versus number of nodes.

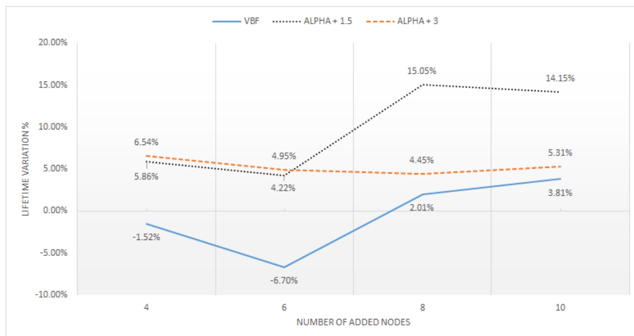


FIGURE 21. Percentage improvement network lifetime versus number of nodes.

Figure 21 points out that, for each node added, the EBVBF protocol demonstrates energy efficiency in relation to the VBF protocol. It is also possible to observe that the increase of the number of nodes reaches a limit where start the decrease of the energy efficiency, since it will force its neighbors to lose energy with receptions and eventually re-transmissions of packets. However, the protocol EBVBF, by balancing energy expenditure, demonstrates better network lifetime management, establishing a better relation between redundancy and energy gain. Meanwhile, the VBF protocol demonstrates always a decrease in the network lifetime.

This fact, for both protocols, the loss of improvement with addition of many nodes occurs due to the nature of broadcasting acoustic transmissions, that is, a large number of nodes will cause each node to receive more duplicate packets, which also causes extra power consumption and eventually overrides the redundancy gain. The ideal number of neighboring nodes for each hop in the EEVBF protocol is lower than in VBF protocol, and for each topology there is a value of "x" that will bring more efficiency compared to VBF protocol.

The VBF protocol tends to choose an optimal node (with lower α) for each packet. This way, the nodes involved in the transmission will have their energy depleted until another node assume the routing task. In contrast, EBVBF protocol seeks to save energy in a balanced mode, with the addition of the two priority levels and the use of a dynamic adaptation time. Like this, if another node with more battery can do the transmission, surely it will have less adaptation time and will send the packet first.

The result of this new routing protocol (EBVBF) referral policy is the saving of the network's energy resources. Recalling that the substitution of nodes is a costly activity, it is desired that the nodes can be exchanged for the least amount of time. In addition, depleting the power capacity of a node can cease the network communication, for example due to the movement of the nodes such node could become indispensable for the routing of packets.

V. CONCLUSION

The results obtained in this study bring the conclusion that the EBVBF protocol balanced the energy consumption between the nodes, increasing the network lifetime. The balancing varied depending on the topology and node density, as well as the number of redundant nodes available at each hop. In the same way as the VBF protocol, the EBVBF protocol has a packet delivery success rate dependent to network density, however the EBVBF protocol has better reliability and delivery rate due to energy balancing. Therefore, the threshold and αE.O parameters can be optimized for each topology and the different needs of each application.

By virtue of its simplicity, where no phase of control or prior knowledge of the network or neighboring nodes is required, the proposed protocol is recommended for short-term applications, since the trade-off between network lifetime and packet transmission delay gived up to 36% of lifetime difference in comparison to VBF protocol. In a real environment, the cost related to the substitution and rescue of sensor nodes can be reduced with the use of an energy gain protocol such as EBVBF protocol. Similarly, gains were observed in relation to the decrease in the number of neighbors, decreasing the cost of the deployment of the underwater sensor network.

On the other hand, EBVBF protocol also seeks to keep as many nodes with remaining batter as possible before exhausting the first node. Therefore, for networks in which nodes change their positions relative to others, great mobility, the maintenance of energy in a node may determine a network's survival, differently to the VBF protocol that wastes energy node by node.

A future work that could be done is a comparison study of performance of the EBVBF protocol with other protocol like DBR, REBAR, CL-VBF and QF-2HOP-AHH-VBF.

The proposed protocol can also be extended with the deployment of an algorithm for dynamic configuration of the α value during the lifetime of the network.

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