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The Effect of Routing Protocols on the Performance of Wireless Networks in Versatile Underwater Applications

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ABSTRACT

Underwater Sensor Networks (UWSNs) have attracted the research community due to their critical applications, such as environmental monitoring, hurricane tracking, and disaster analysis, to mention a few. This kind of network struggles with many challenges, such as propagation delay and limited energy resources. Many efforts in the literature try to overcome these challenges. However, there is still a need to perform more investigations aiming to obtain more reliable approaches for UWSNs. Therefore, this article suggests an Efficient Energy-Depth Hybrid Routing Protocol (EEDH-RP) that addresses the aforementioned issues. The proposed method integrates energy-efficie and depth-based routing strategies, aiming at optimizing packet delivery and minimizing consumption of powe. The proposed routing involves a hybrid forwarding metric in a way that assumes residual energy and depth information, as well as adaptive transmission power control to improve reliability.The proposed routing is assessed against three well-known routing protocols, namely Vector-Based Forwarding VBF, Depth-Based Routing DBR, and HydroCast Routing HCR. The evaluation involves metrics such as packet delivery ratio, energy consumption, end-to-end delay, network lifetime, and throughput. According to the results, EEDH-RP performed better than the benchmark. It gains 92% for packet delivery ratio, energy consumption of 450 joules (with improvements of 25%, 18%, and 10% for VBF, DBR, and HCR, respectively), and 1.2s for end-to-end delay. Our proposal also extends network lifetime by 28% compared to VBF, and 12% compared to DBR.

Keywords:

Underwater Sensor Networks (UWSNs), Routing Protocols, Hybrid Routing, Vector-Based Forwarding VBF , Depth-Base Routing DBR

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1. INTRODUCTION

UWSNs are considered an important technology that is used for monitoring and exploring underwater environments. This technology has been involved in a wide range of applications (e.g., ocean monitoring, data collection, disaster tracking, and pollution monitoring) [1]. These networks contain sensor nodes distributed in underwater environments, aiming to collect and transmit data to surface stations, as shown in Figure 1. However, the nature of underwater environments (e.g., high propagation delays, limited bandwidth, and harsh communication conditions) may lead to significant challenges for reliable communications [2]. Moreover, cloud systems struggle with security issues, such as centralized trust and tampering. One of the technologies that can be used to address this issue is the use of blockchain. It solves such security issues with immutability and transparent verification procedures and avoids traditional security measures.

As a result, designing effective routing strategies is considered one of the most critical research areas. The routing process is considered one of the most important key factors that affect the performance of UWSNs (e.g., energy efficiency and scalability). Routing in UWSNs differs from traditional WSNs due to the use of acoustic communication that struggles with high attenuation, multipath propagation, and Doppler effects [3]. These kinds of issues may cause an increase in packet loss and energy consumption. Moreover, the mobility of nodes caused by water currents and the 3D deployment of nodes complicate the routing process [4]. Traditional routing protocols are unsuitable for UWSNs, which increases the demand for specialized protocols that address these unique challenges.

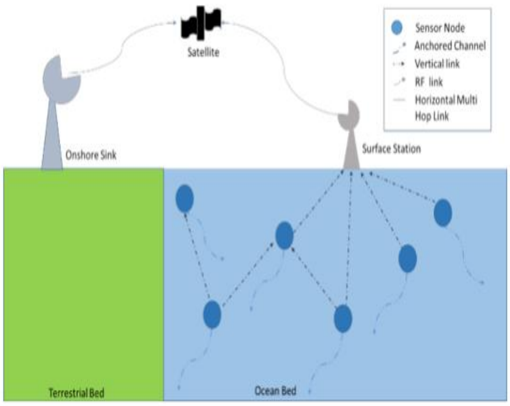

Fig.1. Typical 3D Underwater Wireless Sensor Network [1].

The currently available routing protocols for UWSNs are categorized into location-based, depth-based, and energy-efficient. Location-based (e.g., VBF) that is based on geographic information to forward packets has issues related to high energy consumption and low adaptability in dynamic environments [5]. The depth-based (e.g., DBR) that uses depth information to send packets to the surface may cause energy imbalances and void areas [6]. Energy efficiency (e.g., HCR), which optimizes energy consumption, is considered complex due to the computations needed [7]. Although these categories are considered efficient, there is a critical need to adopt hybrid approaches that integrate the strengths of multiple strategies to achieve better performance. According to the aforementioned, this research suggests an Efficient Energy-Depth-Based Hybrid Routing Protocol (EEDH-RP) for underwater environments. The main idea of the proposed routing comes from the integration of energy efficiency and depth-based routing. This integration can optimize packet delivery and minimize energy consumption. Moreover, the suggested routing strategy involves a hybrid forwarding metric that utilizes nodes' residual energy and depth information, which can be considered (as shown in the results section). The reason for this adaptation is to make routing decisions wiser. Moreover, the proposed routing also involves adaptive transmission power control to improve energy efficiency and reliability. Therefore, this design adopts proactive and reactive strategies for optimal routing. It also tries to balance the trade-off between overhead and performance. These features make it appropriate for dynamic and resource-constrained underwater environments. This work's contributions are summarized as follows:

- Design an effective routing protocol for UWSNs and present its mathematical representation of the residual energy, depth-based forwarding, and adaptive transmission power.
- Perform a comprehensive assessment of the proposed protocol using simulation-based experiments. Also, benchmark the proposed protocol with the literature (e.g., VBF, DBR, and HCR). The selection of these benchmarking protocols lies in their nature, which is close to the proposed design. The assessment metrics are packet delivery ratio, energy consumption, end-to-end delay, and network lifetime.

The proposed approach is different from the works in the literature by integrating energy-depth hybrid metrics with adaptive power control, as well as eliminating GPS dependency.

The remaining sections are as follows: Section 2 explores the literature and summarizes it. Section 3 illustrates the design approach and mathematical modeling of the proposed design as well as the evaluation measurements. Section 4 demonstrates the findings and discuss them. Section 5 presents the conclusions and outlines this work's future directions.

2. LITERATURE REVIEW

The literature of UWSNs is rich with contributions that thrive in this field but still have gaps that need to be filled or mitigated. Energy is a critical concern when it comes to UWSNs because of the energy limitations of underwater nodes. Other issues, such as delay, network lifetime, and throughput, are also considered critical issues in UWSNs. The energy of the nodes in UWSNs is limited due to the difficulties in replacing the batteries at deep levels, as well as the cost of installing new batteries. The delay in the communications between two nodes may affect the whole Network performance. Moreover, network lifetime should be maximized, aiming to have longer network availability. The throughput of the network reflects the efficiency of the UWSNs design and should be maximized. This section presents the efforts in the literature that try to optimize the aforementioned issues in UWSNs. The authors of [8] suggested an Energy-Efficient Depth-Based Routing (EEDBR) protocol. It utilized residual energy and depth information to forward packets. However, since it frequently exchanges control messages, it struggles with issues related to the high overhead. This limitation restricts its scalability in large networks. In the same context, [9] proposed a Reinforcement Learning-based Energy-Efficient Routing (RL-EER) protocol that dynamically adjusted routing decisions based on node energy levels. However, it needs significant computational resources that make it inappropriate for resource-constrained underwater nodes. On the other hand, depth-based routing protocols use depth information to send packets to the surface and avoid void areas. In this regard, [10] developed the DBR protocol that uses depth gradients to forward packets. As mentioned, this protocol yielded energy imbalances. Therefore, [11] improved DBR and overcame this issue. They suggested the Weighted Depth-Based Routing (WDBR) protocol considering both depth and node density. However, WDBR struggles in sparse networks where node density is low. Furthermore, hybrid protocols integrate multiple strategies to improve performance in dynamic underwater environments. [12] proposed a hybrid protocol that combines location-based and cluster-based routing to improve packet delivery. Their protocol depends heavily on GPS for localization. This was considered an issue in deep underwater scenarios. [13] developed a Hybrid Energy-Aware Routing Protocol (HEAR) that merged energy-efficient and geographic routing. However, it did not adequately address void areas. Void areas, where no forwarder nodes are available, are considered a significant challenge in UWSNs. [14] tried to develop a void avoidance technique that used opportunistic routing. It dynamically selected forwarders based on node density. However, this approach increased the delay between two nodes due to the time consumed in the forwarder selection. Another work addressing this issue was performed by [15], who suggested a Void-Aware Routing Protocol (VARP). They used historical data to predict void areas. In their experiments, VARP required significant memory and computational resources. Adaptive transmission power control optimizes energy consumption by manipulating transmission power based on distance and environmental variations. [16] proposed a protocol that adjusted transmission power dynamically. They did not take into consideration the residual energy. This caused the premature node to be consumed. [17] designed an Adaptive Power Control Routing Protocol (APCRP) that utilized fuzzy logic to optimize transmission power. Their approach showed more complexity and overhead. Table 1 summarizes the presented works and demonstrates their strengths and limitations, aiming at detecting the gaps in the literature.

Table. 1 summarizes the literature and focuses on the main strengths and limitations.

Aspect	Ref.	Strengths	Limitations
Energy-Efficient	[8]	Improves energy efficiency using residual energy and depth metrics.	High overhead due to frequent control message exchanges.
	[9]	Uses reinforcement learning for dynamic routing decisions.	Requires significant computational resources.
Depth-Based	[10]	Avoids void areas by routing packets toward the surface.	Leads to energy imbalances and overutilization of surface nodes.
	[11]	Considers depth and node density for improved performance.	Struggles in sparse networks with low node density.
Hybrid Routing	[12]	Combines location-based and cluster-based routing for dynamic environments.	Relies on GPS, which is impractical in deep underwater scenarios.
	[13]	Combines energy-efficient and geographic routing.	Does not adequately address void areas.
Void Avoidance	[14]	Dynamically selects forwarders based on node density.	Increases end-to-end delay due to forwarder selection time.
	[15]	Uses historical data to predict void areas.	Requires significant memory and computational resources.
Adaptive Transmission Control	[16]	Optimizes energy consumption by adjusting transmission power.	Does not consider residual energy, leading to premature node depletion.
	[17]	Uses fuzzy logic to optimize transmission power.	Introduces additional complexity and overhead.

Based on the literature, several gaps need to be addressed. As a result, a routing protocol that should achieve the following is required:

- Reduce the overhead and maintain energy efficiency.
- Balance the consumption of energy across the network.
- Incorporate void avoidance into a hybrid forwarding metric.
- Reliable packet delivery of minimum delay and resource usage.
- No excessive overhead.

3.RESEARCH METHOD

This section detail the proposed research method, benchmarking approaches, and performance evaluation approaches.

3.1 Proposed Method

A hybrid routing protocol for UWSNs called the Efficient Energy-Depth-Based Hybrid Routing Protocol (EEDH-RP) is proposed. This protocol combines the strengths of energy-efficient routing and depth-based routing to address the issues of UWSNs, such as energy constraints, mobility of nodes, and high latency. It uses a hybrid approach to optimize packet delivery while minimizing energy consumption. The main features of the proposed protocol are:

- **Energy-Efficient**: This is performed by prioritizing the nodes with higher residual energy for forwarding packets.

- **Depth-Based**: It uses depth information to avoid void areas and ensure reliable packet delivery.

- **Hybrid Feature**: Involve proactive and reactive strategies for routing, aiming to balance the overhead.

- **Adaptive Transmission Power**: Adjusts transmission power based on distance and environmental conditions.

The step-by-step of the proposed routing is:

Step_1: Initialization: Each node initializes its parameters, such as residual energy, depth, probability of forwarding, and forwarding metric.

Step_2: Forwarding Decision: When node i has a packet to send, the node calculates the Forwarding Metric (FM) based on:

$$FM(i) = \beta \cdot \frac{E_{res}(i,t)}{E_{init}(i)} + (1-\beta) \cdot P_f(i) \quad (1)$$

Where β Is the weighting factor and ranges ($0< \beta < 1$) to balance the energy and depth. The residual energy (E_{res}) is formalized as follows:

$$E_{res}(i,t) = E_{init}(i) - E_{cons}(i,t) \quad (2)$$

Where E_{init} denotes the initial energy of node i and E_{cons} (i, t) is the consumed energy by node i at time t. The probability of forwarding $P_f(i)$ for node i is given based on its depth as follows:

$$P_f(i) = \frac{D_{max}-D(i)}{D_{max}-D_{min}} \quad (3)$$

Where D_{max} represents the maximum depth in the network, while D_{min} is its minimum depth. Moreover, the energy E_{tx} consumed for transmitting a packet of size L bits for node i over a distance d is given by:

$$E_{tx}(i,L,d) = L \cdot E_{elec} + L \cdot \epsilon_{amp} \cdot d^{\alpha} \quad (4)$$

Where E_{elec} is the energy required to execute the transmitter/receiver circuitry, the amplification factor of the transmit amplifier is represented by ϵ_{amp}, and α It is the path loss exponent, which is usually valued at 2 in underwater environments.

The node selects the neighbor with the highest $FM(i)$ as the next hop. In case of no suitable neighbor is found, the packet is dropped to avoid unnecessary energy consumption.

Step_3: Adaptive Transmission Power Control: The transmission power $P_{tx}(i)$ is adapted and adjusted based on the distance d to the next hop and given by:

$$P_{tx}(i) = P_{min} + (P_{max} - P_{min}) \cdot \frac{d}{d_{max}} \quad (5)$$

Where Pmin represents the minimum transmission power, Pmax is the maximum transmission power, and dmax represents the maximum transmission range.

Step_4: Packet Forwarding: The source node forwards the packet to the selected "*next hop*", then, the next hop repeats the process by recalculating the FM for its neighbors and selecting the best forwarder. This process is repeated until the packet reaches the target.

Step_5: Energy and Depth Update: The nodes periodically update their residual energy and depth information. A test message (e.g., a hello message) is exchanged to ensure that all the nodes have updated information about their neighbors. Figure 2 shows a flowchart that describes the step-by-step workflow.

3.2 Benchmarking Protocols

The benchmarking is performed by comparing the performance of EEDH-RP against three well-known routing protocols for UWSNs. The selection of these protocols is based on their approach to routing, which makes them optimal candidates for benchmarking, as follows:

- VBF: It is a location-based technology that utilizes vectors to forward data packets. It is suitable for sparse networks; however, it struggles with high energy consumption in most situations.

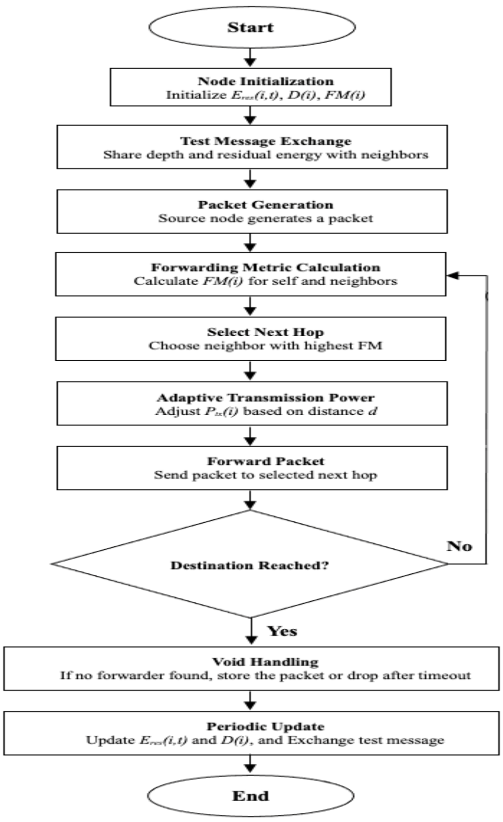

Fig. 2: Flowchart of the proposed routing protocol (EEDH-RP).

- DBR: This protocol involves depth information to forward data packets to the surface. It is considered simple and effective for UWSNs. However, it has a problem related to power imbalance.

- HCR: This protocol is considered pressure-based routing for UWSNs. It focuses on reliability, but sometimes struggles to consume more energy in data transmission.

3.3 Assessment Metrics

Assessing EEDH-RP against the benchmarking, 4 metrics are used:

1- Packet Delivery Ratio (PDR): The ratio of the frequency of packets received (NPR) to the frequency of packets sent (NPS) and given by [18]:

$$PDR = \frac{NPR}{NPS} \qquad (6)$$

2- Energy Consumption: The amount of energy consumed and formalized as follows:

$$E_{total} = \sum_{i=1}^{N} E_{cons}(i,t) \qquad (7)$$

3- End-to-End Delay: The delay between the send and receive and given by [19]:

$$Delay = \frac{\sum_{i=1}^{N}(T_{recv}(i) - T_{send}(i))}{N} \qquad (8)$$

4- Network Lifetime: It expresses the ratio of the time until the first node dies (TD) to the total simulation time (TS):

$$Lifetime = \frac{TD}{TS} \qquad (9)$$

4. RESULTS AND DISCUSSION

This section describes the simulation environment and its main settings. It also demonstrates the results and the performance assessment of the proposed and benchmarking protocols. This section ends with a discussion of the obtained results.

4.1 Simulation Settings

All the simulations are implemented based on the NS3 simulator [20]. The simulation settings are shown in Table 2.It should be mentioned that the simulation includes 100 nodes that are deployed in a 3D underwater environment of 500m (length) x 500m (width) x 500 m (depth). The sink node is positioned at depth =0m, which aims to collect the data from other sensors. Each node has a transmission range of 100m, and the traffic model used is Constant Bit Rate (CBR). The channel model is acoustic with attenuation, noise, and multipath effects. The mobility model used is a Random Waypoint (RW). The data rate used is 10 kbps, which is typical for underwater acoustic communications. In the simulations, sensor nodes sense events and generate packets to further forward them toward the sink node using the routing protocols. The sink node then collects all the data from network sensors. The sink node is a gateway to send data to the external network of interest. It should be mentioned that the settings of UWSNs depend on the purpose of the network and the applications adopted [21, 22].

Table. 2: Simulation setup for the EEDH-RP proposed protocol.

Item	Value	Description
Simulator	NS-3 V3.30	Ubunto OS
Node Hardware	WHOI Micro-Modem	Tx Power: 10-50 W, SNR: 20dB
Network Size	100 nodes	3D deployment (500m × 500m × 500m).
Transmission Range	100m	Max communication distance between nodes.
Initial Energy per Node	100 J	Starting energy for each sensor node.
Packet Size	64 bytes (512 bits)	Data packet size for CBR traffic.
Simulation Time	500 seconds	Total runtime of the experiment.
Traffic Model	1 packet/second	Constant Bit Rate (CBR) traffic.
Channel Model	Acoustic	Attenuation, noise, multipath effects.
Mobility Model	Random Waypoint (RW)	Node movement simulation.
Data Rate	10 kbps	Underwater acoustic communication rate.
Energy Parameters		
E_elec	50 nJ/bit	Energy/bit to run transmitter/receiver circuitry.
ϵ_amp	100 pJ/bit/m²	Amplification energy for transmission.
Path Loss Exponent (α)	2	Underwater acoustic path loss.
Transmission Power		
P_min	0.1 W	Minimum power for short-range comms.
P_max	10 W	Maximum power for long-range comms.

4.2 Experimental Results

The results of this work are presented based on the metrics used as follows:

1- *Packet Delivery Ratio (PDR):* The performance of EEDH-RP compared to the other routing protocols is shown in Figure 3. EEDH-RP obtains the highest PDR compared to other protocols, which is due to its hybrid approach that balances energy efficiency and performs reliable forwarding.

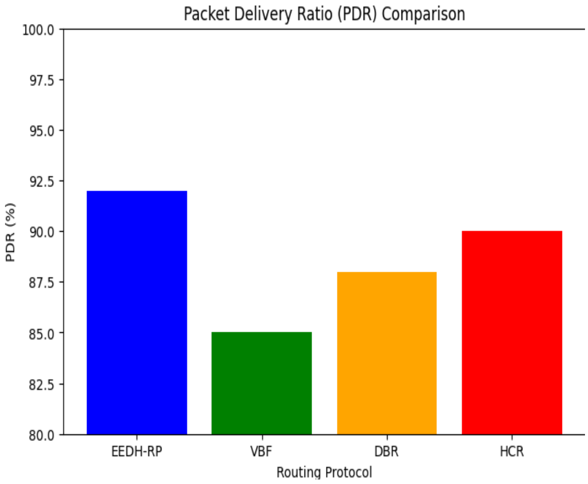

Fig. 3. Performance of Packet Delivery Ratio (PDR) for the proposed and the benchmarking routings.

More analysis is required to prove that the obtained results are statistically significant. Table 3 presents the mean PDR values of the protocols, and Figure 4 demonstrates the variations of PDR of all the protocols. The variations show that fewer variations are obtained from the proposed routing, which reflects its stability. Testing these means is essential to prove that their difference is statistically significant. We use the ANOVA test with the Null hypothesis and Alternative hypothesis [23, 24]. The confidence level we used in this analysis was 95% (α=0.05). The results show that the (*p-value <0.05*), we can reject the null hypothesis. This rejection proves that the difference between the performance of the protocols is statistically significant. The reason behind the VBF gaining a lower PDR is due to the reliance on geographic vectors. This makes it struggle in dynamic underwater conditions.

Table. 3. PDR mean values of the performance of all protocols.

EEDH-RP	VBF [5,10]	DBR [6,11]	HCR [7,12]
92% ± 2%	85% ± 3%	88% ± 2.5%	90% ± 2%

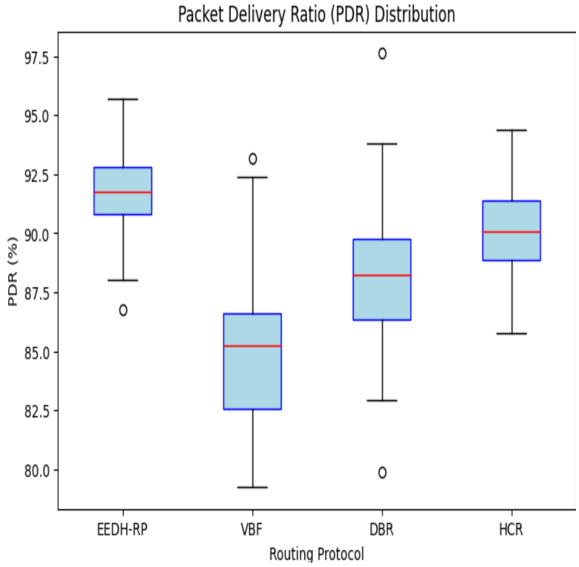

Fig. 4. Boxplots for the PDR variations of all protocols.

2- Energy Consumption: The proposed routing consumes less energy than the benchmarking as shown in Figure 5. This is because of the adaptive transmission power strategy in the proposed routing as well as the energy-aware forwarding behavior.

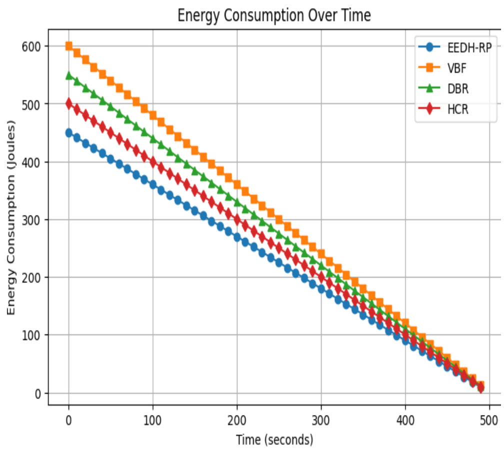

Fig. 5. Performance of energy consumption for the proposed and the benchmarking routings. The energy consumption of all the routing protocols is measured in joules (y-axis).

A Similar analysis method followed in the previous metric needs to be performed for the energy consumption of all the routing protocols. Table 4 shows the mean values of the performance of the protocols. The regression analysis shows that the energy consumption increases linearly as time progresses. Using ANOVA analysis, the null hypothesis is rejected because (*p-value* < significance level). This means that the difference in the performance of all the routing protocols is statistically significant.

Moreover, the pairwise analysis also shows that EEDH-RP consumes significantly less energy than the other protocols. The highest energy consumption was obtained by VBF, which is due to the fixed transmission energy used in sparse networks.

Table 4. Energy consumption means the values of all protocols.

EEDH-RP	VBF [5,10]	DBR [6,11]	HCR [7,12]
450 joules ± 20 joules	600 joules ± 30 joules	550 joules ± 25 joules	500 joules ± 20 joules
Improvement Vs EEDH-RP	25%	18%	10%

3- *End-to-End Delay:* Based on the experimental results, the proposed routing protocol reflects the lowest delay among the other routing Protocols, as depicted in Figure 6. This result can be interpreted as an indicator of using an efficient forwarding mechanism that avoids avoidance.

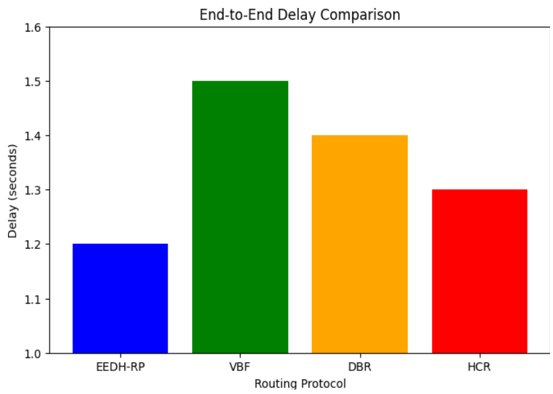

Fig. 6. Performance of end-to-end delay (in seconds) for the proposed and the benchmarking routings.

The mean values of the delay of the protocols involved in this work are presented in Table 5. The analysis shows that the proposed routing has less standard deviation compared to other protocols, which means it is more consistent and stable. The ANOVA test shows that the results of delay are also statistically significant considering the *p-value* and the confidence level. The higher delay was obtained by VBF because of multi-hop vector-based paths and void recovery.

Table 5. Delay means the values of all protocols.

EEDH-RP	VBF [5,10]	DBR [6,11]	HCR [7,12]
1.2s ± 0.1s	1.5s ± 0.2s	1.4s ± 0.15s	1.3s ± 0.1s

4- *Network Lifetime*: The performance in terms of network lifetime shows the superiority of the proposed protocol, as shown in Figure 7. It shows that the proposed protocol extends the lifetime of the network by distributing the energy consumption within the network nodes evenly.

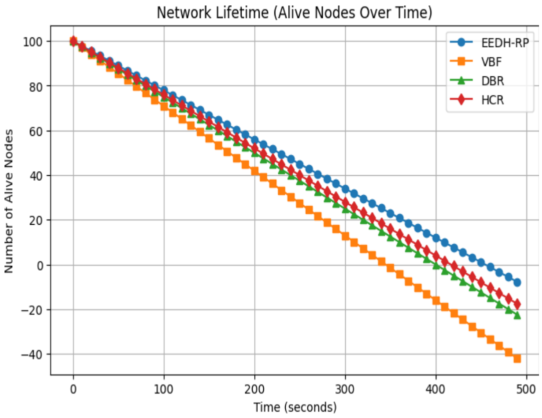

Fig. 7. The number of alive nodes over time for each protocol.

The statistical analysis of the performance of the protocols in terms of network lifetime is also performed. Table 6 presents the mean values of the network lifetime of all the protocols. A survival analysis using the Kaplan-Meier curve is performed [25-27], it shows that the proposed routing reflects the highest survival probability over time, while the VBF shows the lowest. Based on the ANOVA analysis, the obtained results are statistically significant.

5- *Throughput*: The results show that the throughput of the proposed routing is the highest among the other routing protocols. It can be observed in Figure 8 that the reliable feature of the proposed routing approach makes it more efficient compared to other routing methods.

Table 6. Network lifetime means the values of all protocols.

EEDH-RP	VBF [5,10]	DBR [6,11]	HCR [7,12]
450s ± 15s	350s ± 20s	400s ± 18s	420s ± 15s

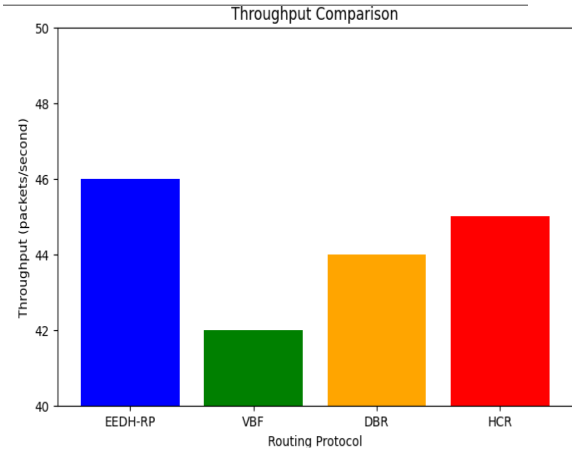

Fig. 8. Performance of throughput for the proposed and the benchmarking routings.

Table 7 presents the throughput mean values of all the protocols. The statistical analysis shows that the throughput of the proposed routing is stable over time. The ANOVA also indicates hat the performance of the throughput of all protocols is statistically significant.

Table 7. Throughput mean values of all protocols.

EEDH-RP	VBF [5,10]	DBR [6,11]	HCR [7,12]
46 packets/second ± 2	42 packets/second ± 3	44 packets/second ± 2.5	45 packets/second ± 2

4.3 Discussion

According to the obtained results, observations can be listed as follows:

- The proposed EEDH-RP outperforms VBF in all metrics. This is very clear when observing the energy consumption and network lifetime. The main reason behind this performance is that VBF depends on geographic information, which is considered less efficient in dynamic underwater environments.
- The proposed EEDH-RP routing improves upon DBR by incorporating energy awareness. This does not allow energy imbalances and extends the network lifetime.

- The proposed EEDH-RP performs slightly better than HCR, which is because of its hybrid approach.
- The proposed EEDH-RP gains 7% higher PDR, 25% lower energy consumption, 20% lower delay, 28% longer network lifetime, and 9% higher throughput compared to VBF.
- The proposed EEDH-RP gains 4% higher PDR, 18% lower energy consumption, 14% lower delay, 12% longer network lifetime, and 4% higher throughput compared to DBR.
- The proposed EEDH-RP gains 2% higher PDR, 10% lower energy consumption, 8% lower delay, 7% longer network lifetime, and 2% higher throughput than HCR.

In general, the findings demonstrate that EEDH- RP is highly effective for UWSNs. The accurate design of EEDH-RP reflect is superior performance in terms of PDR, energy consumption, delay, lifetime of the network, and throughput. Our hybrid design makes it well-suited for dynamic and resource-constrained underwater environments.

5. CONCLUSION

This research proposed a routing protocol that integrates energy-efficient and depth-based strategies. The performance of EEDH-RP was evaluated using simulations. It was benchmarked with VBF, DBR, and HCR routing. The findings showed that EEDH-RP gained a 92% packet delivery ratio. The energy consumed was 450 Joules and the end-to-end delay of 1.2s. These results, in addition to the advanced statistical analysis used, such as ANOVA analysis and hypothesis testing, showed the superior performance of the proposed routing against the benchmark. The proposed routing also extended The network lifetime and reflected its ability to balance energy efficiency, reliability, and scalability. However, it has limitations that can be considered for future work. For instance, the results were simulation-based; testing EEDH-RP in real-world underwater environments is vital to validate its performance. Moreover, adopting machine learning techniques can also be of benefit to optimize routing decisions and adapt to dynamic underwater conditions. Another important future direction of this work is the use of blockchain technology. This work can be extended by integrating blockchain and the proposed approach. This will enhance the security and trust and ensure tamper-proof data logging.

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Authors' Declaration

- Conflict of Interest: There are no other forms of carbon but allotropes.

- The publisher has agreed with the requirement, and we would like to state that all the figures and tables presented in the manuscript are our work.Besides, all the Figures and images are by copy and re-use permissions granted for re-publication and have been included with the manuscript.

- Ethical Clearance: It is important to note that the project was reviewed and approved by the local ethical committee of the Digital Research Center of Sfax (CRNS), Laboratory of Signals and Networks (SM@RTS), and Sfax University and University of Mosul.

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تأثير بروتوكولات التوجيه على أداء الشبكات اللاسلكية في التطبيقات المتنوعة تحت الماء

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الملخص

استقطبت شبكات الاستشعار تحت الماء (UWSNs) اهتمامًا كبيرًا من مجتمع البحث العلمي نظرًا لتطبيقاتها الحيوية، مثل مراقبة البيئة، وتتبع الأعاصير، وتحليل الكوارث، على سبيل المثال لا الحصر. يواجه هذا النوع من الشبكات تحديات عديدة، مثل تأخر الانتشار وموارد الطاقة المحدودة. وتسعى العديد من الجهود في الأدبيات إلى التغلب على هذه التحديات. ومع ذلك، لا تزال هناك حاجة إلى إجراء المزيد من التحقيقات بهدف التوصل إلى مناهج أكثر موثوقية لشبكات الاستشعار تحت الماء. لذلك، تقترح هذه المقالة بروتوكول توجيه هجين فعال للطاقة والعمق (EEDH-RP) يعالج القضايا المذكورة أعلاه. تدمج الطريقة المقترحة استراتيجيات التوجيه الموفرة للطاقة والقائمة على العمق، بهدف تحسين توصيل الحزم وتقليل استهلاك الطاقة. يتضمن التوجيه المقترح مقياس توجيه هجينًا بطريقة تفترض معلومات الطاقة المتبقية والعمق، بالإضافة إلى التحكم التكيفي في طاقة الإرسال لتحسين الموثوقية. تم تقييم التوجيه المقترح وفقًا لثلاثة بروتوكولات توجيه معروفة، وهي: التوجيه القائم على المتجهات VBF، والتوجيه القائم على العمق DBR، والتوجيه القائم على العمق HydroCast. يتضمن التقييم مقاييس مثل نسبة توصيل الحزم، واستهلاك الطاقة، والتأخير من البداية إلى النهاية، وعمر الشبكة، والإنتاجية. ووفقًا للنتائج، كان أداء EEDH-RP أفضل من المعيار. فقد حقق زيادة بنسبة 92% في نسبة توصيل الحزم، واستهلاك طاقة قدره 450 جول (مع تحسينات بنسبة 25% و18% و10% لـ VBF وDBR وHCR على التوالي)، و1.2 ثانية في التأخير من البداية إلى النهاية. كما يُطيل اقتراحنا عمر الشبكة بنسبة 28% مقارنةً بـ VBF، و12% مقارنةً بـ DBR.

الكلمات الداله :

شبكات الاستشعار تحت الماء (UWSNs)، بروتوكولات التوجيه، التوجيه الهجين، التوجيه القائم على المتجهات VBF والتوجيه القائم على العمق DBR