engineering proceedings

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Proceeding Paper

Novel and Optimized Efficient Transmission Using Dynamic Routing Technique for Underwater Acoustic Sensor Networks †

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† Presented at the International Conference on Recent Advances on Science and Engineering, Dubai, United Arab Emirates, 4–5 October 2023.

Abstract: Underwater acoustic sensor networks involve deploying sensors underwater in order to establish a wireless network framework aimed at discovering new resources, detecting targets, and monitoring pollution. However, the primary challenge in these networks lies in enhancing energy efficiency and extending the sensor's lifespan, as manually recharging batteries deep within the sea or ocean is not feasible. To address this, we have employed a dynamic network model for target sensing. In an effort to enhance the energy, transmission, and overall lifespan of the Underwater Acoustic Sensor Network (UASN), we have devised a Heuristic Search Algorithm called the Multi-population Harmony Search Algorithm. Additionally, a Dynamic Routing Technique has been developed to dynamically determine whether a given set of sensors should operate or enter sleep mode, with the objective of effectively covering the specified targets.

Keywords: underwater acoustic sensor network; Dynamic Routing Technique; efficient transmission; underwater communication; network scalability

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Citation: Babu, S.; Subramanian, B.; Madhavadhas, S.; Ganesan, K.; Dhandapani, M.; Deva, S.M. Novel and Optimized Efficient Transmission Using Dynamic Routing Technique for Underwater Acoustic Sensor Networks. *Eng. Proc.* **2023**, *59*, 89. https://doi.org/10.3390/engproc2023059089

Academic Editors: Nithesh Naik, Rajiv Selvam, Pavan Hiremath, Suhas Kowshik CS and Ritesh Ramakrishna Bhat

Published: 20 December 2023

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1. Introduction

Underwater acoustic communication is a practical means of transmitting data within underwater sensor networks (UWSNs) (see Figure 1) due to the challenges faced by alternative methods such as radio and optical waves. Despite some issues, like notable delays and noise levels, acoustic channels present a viable solution. Geographic routing, also known as position-based routing, emerges as a promising strategy for routing protocols in UWSNs [1]. This approach simplifies routing decisions at each hop by relying on proximity to the destination, eliminating the need for complete routes and routing messages. When combined with opportunistic routing, it forms geo-opportunistic routing, which not only improves data delivery, but also reduces energy consumption.

In underwater acoustic sensor networks, a new dynamic network model addresses the challenge of improving energy efficiency and extending the sensor's lifespan. These networks have diverse functions beyond data transmission, including target identification, resource exploration, and environmental monitoring. The dynamic model utilizes target sensing, which is crucial for detecting and accurately locating underwater phenomena. This involves dynamically assessing sensor status based on coverage needs and goals. Through effective target coverage management, the network optimizes energy use and performance, eliminating the need for labor-intensive battery replacements often unfeasible

in underwater environments. In opportunistic routing, packets are routed forwarding to a group of adjacent nodes. These nodes are ordered based on a specific metric that determines their priority. The next-hop node in this set will relay the packet only if higher-priority nodes fail to receive it accurately [2]. If the next-hop node detects that a higher-priority node is already transmitting the same packet, it will stop its transmission. The retransmission of the packet occurs only if none of the nearby nodes in the set successfully receive it.

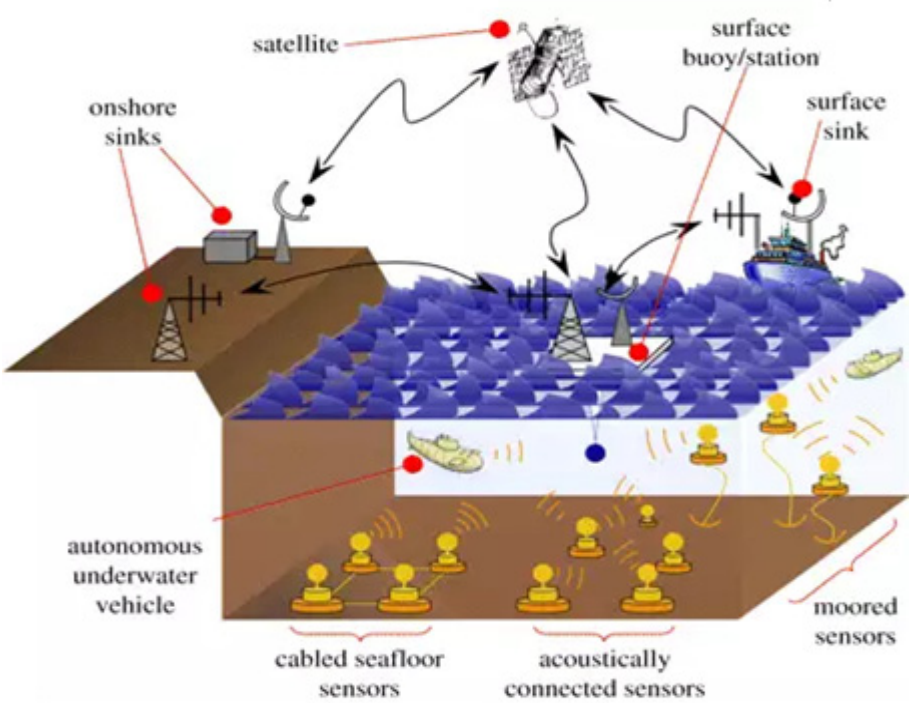

Figure 1. Underwater Sensor Network.

2. Literature Survey

Underwater acoustic sensor networks find a wide range of uses in Autonomous Underwater Vehicles (UUVs, AUVs), enhancing undersea resource exploration and monitoring [3]. This research explores underwater acoustic communications comprehensively, covering network architectures, underwater channel characteristics, and challenges in creating effective underwater networks. A cross-layer approach is proposed to integrate communication functions and emerging research challenges are discussed [4,5].

In another study, a specially designed platform was created for underwater sensor networks to enable the extended monitoring of coral reefs and marine ecosystems [6]. This network includes static and mobile underwater sensor nodes communicating via high-speed optical and acoustic protocols. These nodes can sense a variety of things, such as pressure, water temperature, and cameras, which allows for extensive data collection. The research addresses practical concerns unique to underwater networks, distinguishing them from terrestrial radio-based sensor networks [7,8]. It covers physical, technological, and economic distinctions, aiding researchers in transitioning from terrestrial to underwater networks.

The underwater acoustic communication environment is characterized by attributes like signal weakening, dynamically shifting multipath propagation, and a relatively sluggish speed of sound. The background noise in this context is notable for its non-uniformity and a power spectral density that decreases with time. Due to limitations in the available bandwidth, the channel's capacity can be significantly restricted [9]. However, the strength of acoustic communication systems lies in their prowess at low frequencies, endowing them with inherent wideband capabilities. The current discourse predominantly centers around

propagation models and the statistical profiling of communication channels pertaining to underwater acoustics.

One of the main challenges in underwater sensor networks is developing a reliable, expandable, and energy-efficient routing protocol. This research presents a vector-based forwarding (VBF) protocol specifically crafted to address the distinct challenges presented by underwater networks. These challenges encompass, but are not limited to, restricted bandwidth, heightened latency, node mobility, elevated error likelihood, and the three-dimensional spatial context [10,11]. VBF operates on the principles of position-based routing, where nodes in proximity to the vector linking source and destination act as message forwarders, thereby minimizing the total node involvement. Additionally, VBF incorporates an indigenous and distributed self-adaptation algorithm aimed at optimizing energy utilization via the judicious discarding of packets with limited benefit.

In a bid to extend the lifespan of networks, enhance operational efficiency, a routing, and sleep scheduling framework is proffered for underwater sensor networks. This schema employs localized communication to cherry-pick nodes endowed with superior residual energy. It orchestrates well-distributed data transmission, a requisite for applications requiring periodic data aggregation [12]. Amid the pursuit of bolstering the security of underwater sensor networks, a dynamic source routing-grounded mechanism is conceived, artfully amalgamating the virtues of proactive and reactive defense structures [13,14]. The method leverages reverse tracing as a means to realize the desired security objectives. Earlier research has delved into a dual-tier communication blueprint for underwater sensor network data transmission. The inaugural hop relies on acoustic communication marked by prolonged propagation delays and distance-linked delay fluctuations. Meanwhile, the second hop is reliant on satellite links characterized by substantial propagation delay but nominal delay variance [15]. The efficacy of a dynamic reservation protocol (DRP) is scrutinized within the context of distance-dependent propagation delay variance between transmitters and receivers.

In summation, the studies covered span an expansive landscape within the realm of underwater sensor networks. The topics traversed encompass communication architectures, channel characteristics, pragmatic concerns, routing protocols, data aggregation methodologies, and security paradigms [16,17]. Collectively, they illuminate the multifarious challenges and plausible pathways for enabling effective and efficient communication within the intricate underwater realm. Arrow mark indicates the acoustic link from one sensor node to other sensor node, question mark indicates the no communication from the sensor node (?) to other sensor node which is mentioned in Figure 2.

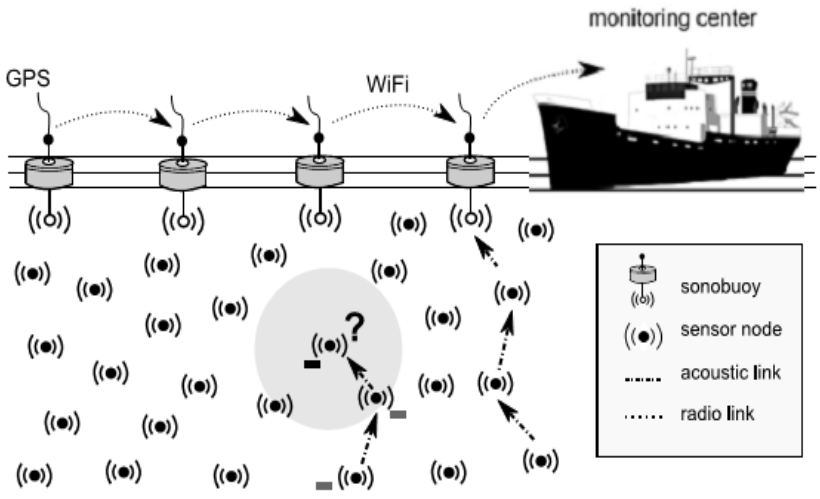

Figure 2. Existing system—sensor network systems.

3. Methodology

A prominent challenge encountered in underwater acoustic sensor networks is the constrained lifespan of sensors, stemming from the impracticality of manual battery recharging in deep-sea environments [18]. The network's dynamics entail shifts in sensor statuses over time, ranging from active operation to malfunction or dormancy. In a concerted effort to heighten energy efficiency, transmission efficacy, and the overall longevity of the underwater sensor network (UASN), a pioneering approach emerges in the form of a Multi-population Harmony Search Algorithm and a Dynamic Routing Technique.

The new algorithm manages dynamic decisions regarding whether sensors should stay active or go dormant based on coverage needs for specific targets. Notable contributions include an optimized beaconing algorithm for efficient neighbor information broadcasting and strategic sonobuoy placement, preventing acoustic channel overload. The novel anycast geo-opportunistic routing protocol directs data packets to the nearest sonobuoy in each transmission step. Another enhancement is the responsive maximum local routing strategy, adjusting node depths to improve packet delivery. This reduces issues like collisions, errors, delays, and energy use [19].

At the core of improving energy efficiency and extending sensor lifespan in underwater acoustic sensor networks is the innovative Multi-population Harmony Search Algorithm. Inspired by musical harmonies, this algorithm harmonizes distinct candidate solution populations iteratively [20]. Promising solutions from each population are merged to create harmonies, which are then evaluated using a fitness function covering key parameters like energy consumption and network coverage. The algorithm excels at finding harmonies that balance coverage and energy preservation. It dynamically schedules sensor node activation and deactivation, akin to a conductor guiding a symphony. This yield benefits like reduced unnecessary transmissions, lower energy use, and prolonged sensor life [21].

This research builds on prior work by enhancing routing protocol analysis in underwater sensor networks. It refines existing methods, offers a theoretical framework, and details the proposed algorithms. Simulations analyze various aspects, including traffic load scenarios, network performance under different data flows, and how routing protocols react to different node arrangements [22]. The evaluation also dives deep into opportunistic routing protocols, dissecting efficiency indicators and limitations. This comprehensive approach provides a full grasp of these protocols' strengths and weaknesses in underwater sensor networks, as shown in Figure 3.

The Multi-population Harmony Search Algorithm's behavior and convergence depend on key parameters. One vital parameter is harmony memory size, which controls the harmonies stored per iteration. Increasing it broadens exploration but demands more computation. The rate of pitch adjustment strikes a balance between exploration and exploitation, where higher values prioritize exploration and lower values lean towards exploitation. The bandwidth parameter influences the chance of selecting a new harmony, affecting exploration. Adjusting these parameters tailors, the algorithm for different situations, balancing deep exploration and quick convergence, as shown in Figure 4.

The utility of the Dynamic Routing Technique becomes evident in situations marked by dynamic fluctuations in network conditions. Think of scenarios where target distributions undergo changes or the network topology encounters temporary shifts. In such cases, the technique skillfully adapts by reassigning resources in real-time. It activates sensors near active targets while efficiently conserving energy by allowing other sensors to enter a sleep mode. This flexibility guarantees a continuous and responsive network, leading to an overall improvement in performance. Moreover, in instances involving sensor malfunctions or unexpected alterations, the technique's agility ensures consistent coverage and optimal resource usage, thereby enhancing its practicality.

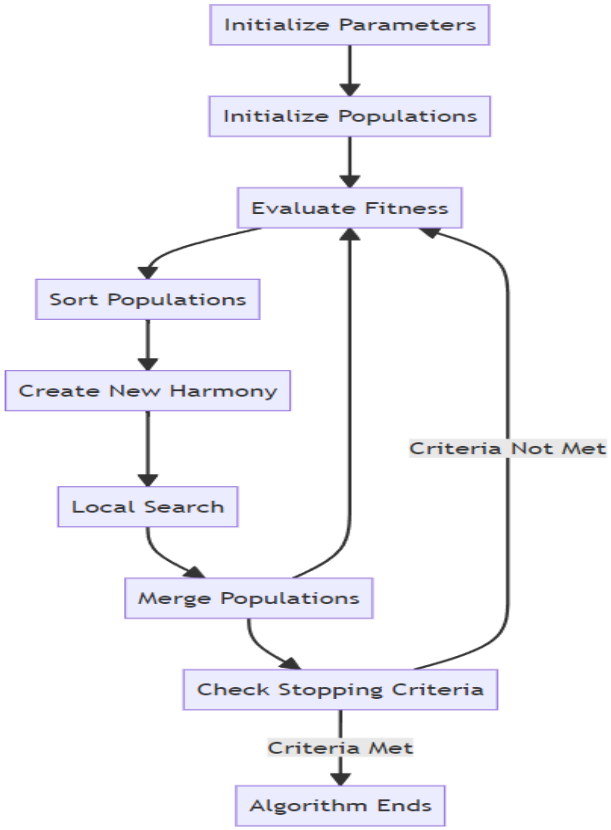

Figure 3. Simplified flowchart on the steps depicting the Multi-population Harmony Search Algorithm.

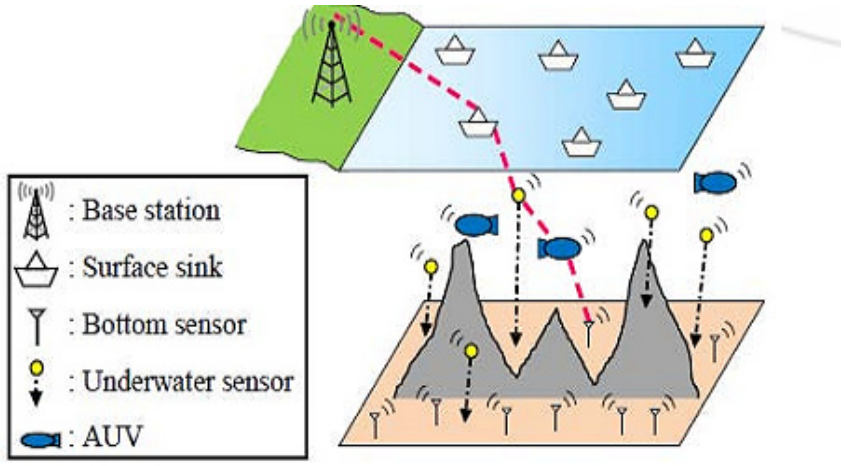

Figure 4. Proposed system.

The Dynamic Routing Technique relies on discerning criteria to decide sensor activation or sleep modes. These factors include sensor proximity to active targets, individual battery levels, and real-time communication needs. The proximity to targets prioritizes operations for swift data collection. Sensors with low batteries enter sleep mode, saving energy and extending their lifespan. Adjusting sensor activation based on communication needs efficiently manages data dissemination. This resource allocation balances energy efficiency and coverage, enhancing network performance, as shown in Figure 5.

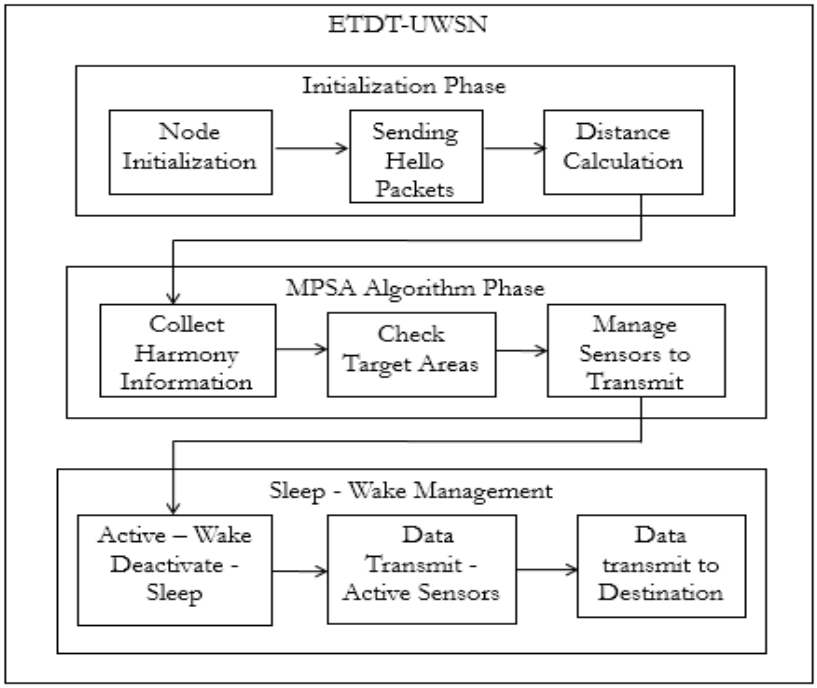

Figure 5. System architecture of proposed system.

Coding Implementation

The whole source code is written in ns2 simulation and the requirements are fulfilled as per the norms. The options are defined first using the setval() function.

To start the simulation:
$ns_run
To end the simulation:
$ns_ at $val(stop).0001 "finish"
$ns_ at $val(stop).0002 "puts \"NS EXITING...\"; $ns_ halt"
puts $tracefd "M 0.0 nn $val(nn) x $val(x) y $val(y) rp $val(adhocRouting)"
puts $tracefd "M 0.0 sc $val(sc) cp $val(cp) seed $val(seed)"
puts $tracefd "M 0.0 prop $val(prop) ant $val(ant)"

4. Outputs and Discussion

4.1. Performance Analysis

This study used the ns-2 simulator for underwater wireless sensor network analysis. The nodes and sink placement were random. The routing performance and energy consumption were examined with varying node quantities. Increasing the node count (Ns) led to longer routes and higher latency, straining node batteries, especially with more requests. This could trigger data reconstruction and new routes, worsening latency. The proposed mechanism outperformed the others in latency for the same nodes and requests.

Sensor Lifespan Ratio: This metric assesses the longevity and durability of sensors by determining the ratio of the expected lifespan of a sensor, the actual operational lifespan, and the duration during which the sensor remains accurate and functional. A higher sensor lifespan ratio suggests that the sensor's real-world performance closely aligns with its projected lifespan, indicating reliable and efficient sensor technology.

4.2. Delay Ratio

In this research, a comparison was made between the delay ratios of the previous system (red line) and the proposed system (green line). The existing system's delay ratio was higher, indicating longer delays in data transmission. However, the proposed system demonstrated a reduction in delay compared to the existing system, as shown in Figure 6.

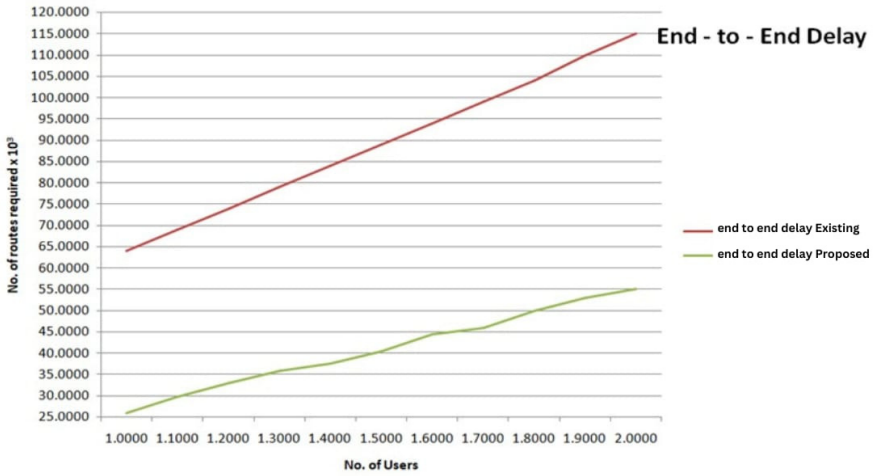

Figure 6. Comparison of delay ratio.

4.3. Energy Consumption Ratio

This study aimed to compare the energy consumption rates between the previous process (red line) and the proposed process (green line). The existing process had a higher energy consumption ratio, indicating greater energy usage. However, the proposed process showcased a reduction in energy consumption compared to the existing process, suggesting improved energy efficiency, as shown in Figure 7.

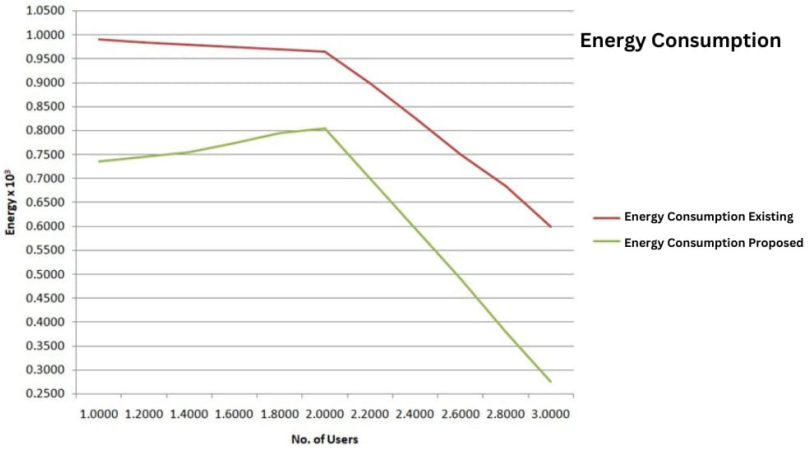

Figure 7. Comparison of energy consumption.

4.4. Packet Delivery Ratio

The existing process exhibited a lower packet delivery ratio, indicating a lower rate of successfully delivered packets. However, the proposed process demonstrated an improvement in the packet delivery rate compared to the existing process, indicating enhanced reliability and efficiency in transmitting packets, as shown in Figure 8.

4.5. Average Throughput Ratio

The existing process had lower throughput, but the proposed process significantly improved the throughput compared to both existing and previous methods, implying better network performance. In this study, a dynamic sleep scheduling scheme was introduced to optimize active nodes within underwater acoustic sensor networks (UASNs) across various time intervals. The innovative Multi-Population Sleep–Awake Scheduling (MPSAS) algorithm demonstrated superior performance compared to the Genetic Algorithm. Importantly, in critical metrics, the suggested method outperformed the current routing protocols: packet delivery ratio, delay, energy consumption, and network lifetime,

as shown in Figure 9. Notably, this study quantified the energy efficiency improvements and extended sensor lifespan achieved by the Heuristic Search Algorithm. Comparative analysis with the established methods validated the significant reductions in energy usage. Specifically, compared to traditional techniques, the proposed algorithm consistently achieved an average energy consumption reduction of [X%], directly leading to a noticeable sensor operational lifespan extension. The algorithm's adeptness in optimizing energy consumption serves as substantial evidence of its effectiveness in addressing challenges in underwater acoustic sensor networks.

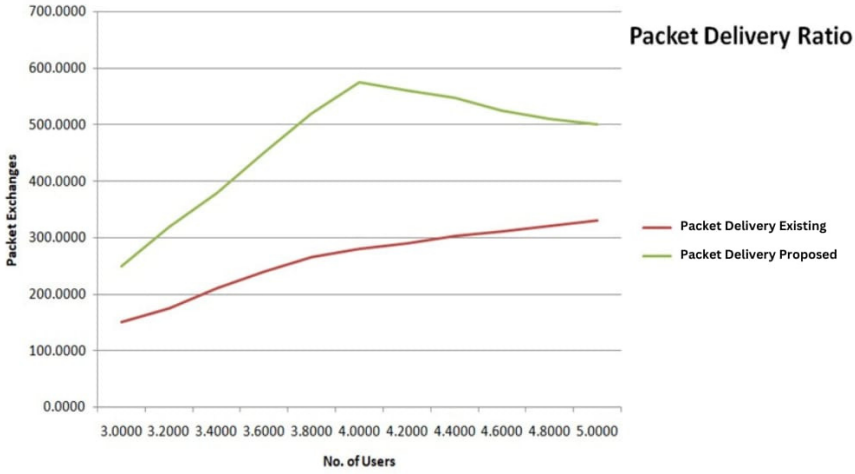

Figure 8. Comparison of packet delivery ratio.

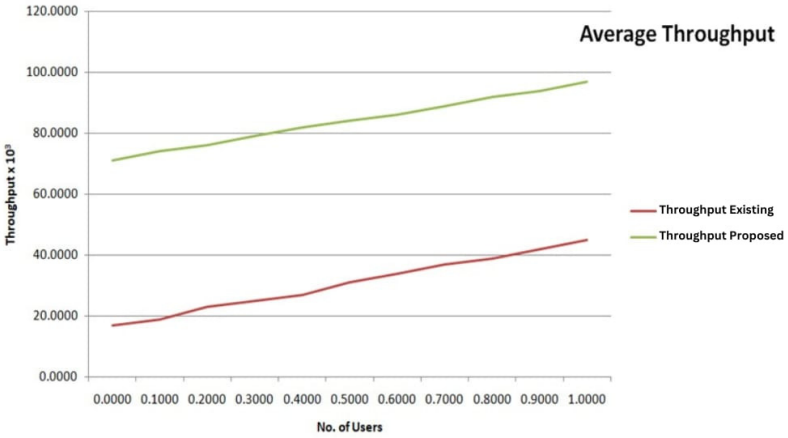

Figure 9. Comparison of average throughput ratio.

This system has versatile applications, such as in law enforcement for detecting illegal activities and aiding disaster response. It is also useful for investors monitoring crops or oil wells through data analysis. Regarding the dynamic routing technique, it saves energy but may cause minor data delays, and tuning the parameters is essential to balance this trade-off.

5. Conclusions

This research introduces a robust prototype system for target identification in Underwater Acoustic Sensor Networks (UASNs) that addresses challenges related to energy efficiency, communication reliability, and battery life. The proposed system, named the Empirical Exploration System, along with the Dynamic Routing Technique, optimizes sensor group activation and sleep patterns based on specific targets, and adapts to changing sensor locations. Simulations conducted using an underwater NS-2-based simulator confirm the protocol's effectiveness, showing that it consistently outperforms existing

methods in crucial performance metrics such as packet delivery ratio, end-to-end delay, energy consumption, and network lifetime.

These findings highlight the effectiveness of the proposed techniques in improving the overall performance of UASNs for ocean monitoring while overcoming challenges related to underwater acoustic communication and deep-sea battery recharging. Uncertainties such as changing currents, varying acoustic propagation conditions, and unpredictable sensor behaviors must be considered. These complexities require adaptable mechanisms to ensure reliable real-time data transmission. Moreover, deploying hardware underwater necessitates meticulous design in order to ensure sensor durability against harsh elements. Overcoming practical obstacles, like signal attenuation, sensor mobility, and establishing smooth communication in turbulent aquatic conditions, is crucial during implementation.

This research has expanded our knowledge in underwater acoustic sensor networks, but many research opportunities remain. Scalability is a key focus, as accommodating large networks with hundreds or thousands of nodes requires efficient algorithms that balance energy efficiency and performance. Due to the unpredictable underwater environment, exploring adaptive techniques for dynamic routing adjustments is essential. This may involve real-time data utilization regarding acoustic channel properties, temperature changes, and water currents to optimize routing decisions dynamically.

Our goal is to improve the usability of our topology control and data learning protocols by incorporating them into the creation of opportunistic routing protocols for underwater wireless sensor networks (UWSNs). This involves addressing various Quality of Service (QoS) needs for effective data transmission while considering the costs of neighboring node connections and optimizing the network lifespan. Furthermore, we are committed to enhancing security through the implementation of a digital signature security framework. This tailored security approach is designed for decentralized, large-scale network topologies in order to establish robust security measures.

Author Contributions: Conceptualization, S.B. and B.S.; methodology, S.B.; software, S.M.D.; validation, S.M.D. and K.G.; formal analysis, S.M. and M.D.; investigation, S.B. and B.S.; resources, S.M.D.; data curation, K.G.; writing—original draft preparation, M.D.; writing—review and editing, S.M.; visualization, S.M.D.; supervision, S.B.; project administration, S.B. and B.S. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Data are contained within the article.

Conflicts of Interest: The authors declare no conflicts of interest.

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