

Increasing Energy Harvesting Rates for Underwater Wireless Sensor Networks Using Stochastic Network Calculus

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Abstract

Underwater Wireless Sensor Networks (UWSNs) enable real-time marine ecosystem monitoring but are constrained by limited energy availability, harsh underwater communication conditions, and high deployment costs. Although energy harvesting from water currents, vibrations, and ambient sources offers a sustainable solution, its efficiency is highly affected by dynamic underwater environments, and existing routing protocols such as Depth-Based Routing (DBR) do not explicitly support energy-harvesting awareness or dependable underwater Internet services. This paper proposes an enhanced DBR routing model that integrates energy-harvesting mechanisms with stochastic worst-case performance guarantees using a Stochastic Network Calculus (SNC)-based analytical framework. The proposed model evaluates end-to-end delay, energy utilization, routing stability, and network resilience under uncertain harvesting and communication conditions. Simulation results demonstrate that the enhanced DBR improves energy harvesting efficiency by approximately 30–35%, extends network lifetime by up to 40%, increases packet delivery ratio by 18–22%, and reduces end-to-end delay variability by around 25% compared to conventional DBR. These improvements enable sustained node operation, enhanced reliability, and more secure underwater Internet connectivity, confirming the suitability of the proposed approach for long-term and dependable UWSN deployment.

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1 Introduction

UWSNs are crucial to tracking of our oceans, yet they face the additional hurdle of communication range by virtue of the harsh environment and restricted battery lives of UWSNs (Manikandan et al., 2022; Alamu et al., 2023). Sensor nodes, the backbone of the network, are powered by batteries alone and cannot be replaced easily due to the logistics and cost impediments of bringing divers or underwater autos to remote locations (Vignesh et al., 2021). Short battery lives come to a halt, data acquisition is reduced, network stability is reduced, and the lifespan of underwater sensor networks is reduced suggested solutions to overcome these challenges. One emerging solution is to complement energy-aware routing protocols with energy harvesting technologies (Vignesh & Sukumaran, 2025; Ammar et al., 2021). Routing protocols considering the residual energy of a node can extend network lifetime by shifting the workload. Adding energy harvesting to the routing protocol allows the network to accommodate fluctuating energy supply (Zhao et al., 2021). However, common harvesting methods utilized over the land don't work efficiently underwater. Energy harvesting by the conversion of water current pressure to electricity by piezoelectric harvesting is the next likely option to use in underwater sensor networks (Sezer & Koç, 2021). Optimal utilization of energy with harvesting is therefore of vast potential to extend the lifespan and use of underwater sensor networks. Table 1 below outlines the comparison of the advantages of each underwater energy source:

Table 1: Comparison of underwater energy sources

Technique	Suitable for UWSNs	Limitations in the Underwater Environment
Photovoltaic (Solar)	Not suitable	Sunlight penetration weakens significantly with depth
RF (Radio Frequency)	Not suitable	Underwater environment attenuates radio waves
Thermoelectric	Limited suitability	Temperature variations are smaller and less predictable underwater
Piezoelectric	Most suitable	Leverages water current pressure for energy generation

This research focuses on creating a network model that incorporates energy harvesting techniques to achieve these goals. The model will maximize energy consumption and employ the environment itself as a source of energy by incorporating the energy-harvesting functionality into the network protocols (Wang et al., 2024). The ultimate goal is to close to an ideal state of sensor nodes with the possibility of reaching a near-infinite battery capacity through perpetual energy (water current) through piezoelectric conversion. This would transform UWSNs in that we would have long-term continuous data gathering and communication that would result in our better understanding of our underwater world. The rest of this research paper involves: section 2 review of existing work, section 3 Impact and Applications, section 4 puts forward the Problem motivation and contribution, section 5 proposes energy harvesting SNC equations, section 6 illustrates Numerical Results, and finally a conclusion is made in section 7.

2 Review of Existing Works

Over the last few years, there has been a lot of research on the enhancement of energy efficiency and network performance of Underwater Wireless Communication Networks (UWCN) as a result of the necessity to provide sustainable and reliable sensor activities in the challenging underwater settings. This section discusses the major developments and techniques of energy harvesting and routing

protocols of UWCN. Underwater harvesting of energy has been of key concern since sensor nodes have limited battery capacity. Conventional practices incorporate solar, thermal, and kinetic energy. As an example, the solar energy harvesting methods have been investigated, but they cannot work effectively in the deep sea or low-light environments (Thakur et al., 2024). Wave movement-based kinetic energy harvesting has been promising, though it is limited by the low energy conversion efficiency (Song et al., 2021). Latest advancements of piezoelectric energy harvesting demonstrated superior abilities through conversion of underwater vibrational energy into electrical energy that may be harnessed, as proposed by (Daanoun et al., 2021; Bagci, 2016). However, such methods often require complementing with advanced routing protocols to achieve their full potential. Routing protocols of UWCN also serve roles of significance in reducing data transmission and energy consumption. Traditional routing protocols, such as Directed Diffusion and LEACH (Low-Energy Adaptive Clustering Hierarchy) protocol, were adapted for underwater application cases but typically do not work effectively due to underwater acoustic communication's high latency and energy consumption (Sharma & Pughat, 2017; Jiang, 2012). Advanced protocols, such as TEEN (Threshold-sensitive Energy Efficient sensor Network protocol) and SEP (Stable Election Protocol), mark improvements by making use of techniques that take account of energy levels but also fall short of achieving sustainable network stability over the longer term (Feng & Baccelli, 2023; Wu et al., 2012). Stochastic Network Calculus (SNC) has been employed to analyze and model communication networks subject to uncertainty. SNC-oriented methods have unearthed network performance and behavioral bounds of critical design significance to realize efficient routing protocols (Kargar & Hao, 2022; Erdem et al., 2019). Recent works integrated SNC with energy harvesting models to ensure energy efficiency and network stability. For instance, (Kwasinski & Kwasinski, 2015) proposed an SNC-based hybrid model of energy harvesting that demonstrated remarkable energy utilization and network throughput improvements. Energy harvesting through the use of piezoelectric waves is a novel approach that has been considered in various recent studies. Research by (Saravanan & Sukumaran, 2022; Zheng et al., 2013) showed that it is feasible to convert underwater wave-based mechanical vibrations to electrical power by utilizing piezoelectric materials. Though the studies reflect the potential of piezoelectric harvesting of energy to overcome energy limitations of underwater sensors, extension to routing protocol usage has been restricted. It puts forward the Energy Harvesting Stochastic Model by Depth Based Routing Protocol (EESDBRP) (Jiang, 2010) that applies piezoelectric wave energy harvesting and Stochastic Network Calculus (SNC) to remarkably enhance underwater sensor network performance. Unlike previous methods, EESDBRP applies innovative energy harvesting techniques to an established routing protocol to achieve higher energy efficiency, network stability, and overall performance. EESDBRP is considered to be the state-of-the-art technology in underwater monitoring operations, which breaks the boundaries of the earlier practices (Rosas & Oberli, 2012). The literature available demonstrates the progress in energy harvesting, routing schemes, and stochastic performance analysis of UWCNs, but these aspects are largely discussed separately. Specifically, piezoelectric energy harvesting has not been properly augmented with routing protocols, and SNC-based performance modeling is seldom co-located with realistic underwater routing schemes. This is one of the gaps that drives the proposed Energy Harvesting Stochastic Model based on Depth-Based Routing Protocol (EESDBRP), a network architecture that combines piezoelectric energy harvesting with SNC and depth-based routing to enhance the network in terms of energy efficiency, routing stability, and long-term system functionality when there is a need to monitor the underwater environment.

Impact and Applications

This study of underwater wireless sensor network models on energy harvesting has great potential for underwater agriculture, which is on the rise. With underwater farms to cultivate seaweed and other marine crops becoming the norm, consistent and reliable sensor networks are the key to measuring water quality, monitoring plant growth, and ensuring the best growing conditions. The challenge of battery lifetime of underwater sensor nodes can be directly addressed with the considered model, which is aimed at sustaining the network lifetime and, at the same time, enhancing the reliability of the communication with the help of energy harvesting. That would allow measuring and analysing data in real-time, thus making underwater farming more fruitful and efficient. But applications of the research run even deeper, to non-agricultural domains like tracking of pollutants by permitting continuous tracking of intensities of contaminants, and searching for resources by permitting deployment of sensor networks at remote underwater locations for longer-than-hitherto-possible durations.

3 Methodology

To quantify and analyze the network model with energy harvesting, the work applies a two-fold methodology approach. First, the Depth-Based Routing (DBR) protocol is to be employed to optimize the energy harvesting rate to improve network performance overall. The Stochastic Network Calculus (SNC) is to be employed as the theoretical framework (Jiang, 2010) to provide an influential toolset for analyzing communication networks under random occurrences. SNC is particularly appropriate for modeling uncertainty of energy harvesting as well as that of underwater communication, in that energy availability, as well as network conditions, vary. With SNC, we aspire to obtain analytical solutions for crucial network performance parameters such as queueing delays, packet delivery ratio, and energy usage. Energy harvesting activity of UWSNs, as shown in figure 1, is comprised of harvesting environmental energy from underwater currents, sunlight, and vibration. Energy is translated from the harvested environmental energy into usable electric power and stored in energy storage devices to ensure the constant operation of network nodes. The activity's efficiency is directly connected to the dynamic nature of the underwater environment, and hence, harvested energy must be meticulously managed to provide the communication network's energy needs. Secondly, we will conduct extensive network simulations using the Riverbed simulator.

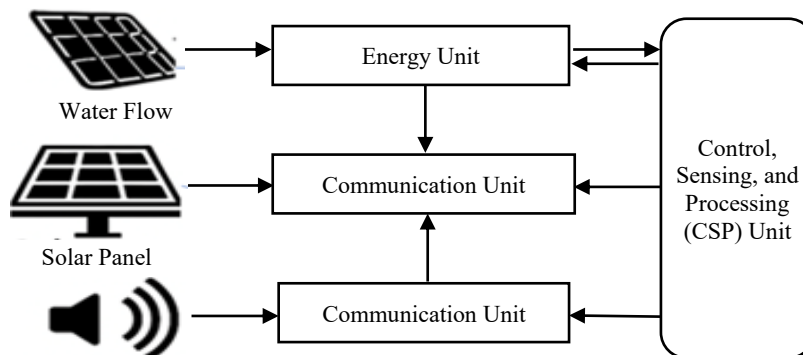


Figure 1: Energy harvesting process in UWSNs

Network simulations are indispensable for simulating actual field conditions as well as for evaluating the behavior of the network model under varying conditions. Using simulations of different water current trends, rates of energy harvesting, and levels of network traffic, valuable information can be obtained

about the viability of the model suggested for extending the lifetime of the UWSN as well as for enhancing communication reliability. Additionally, multihop communication, described in figure 2, is crucial in widening the coverage of UWSNs through enabling information to be transmitted from one node to another over multiple hops. Under multihop communication, information is propagated from sensor node to sensor node until reaching the destination.

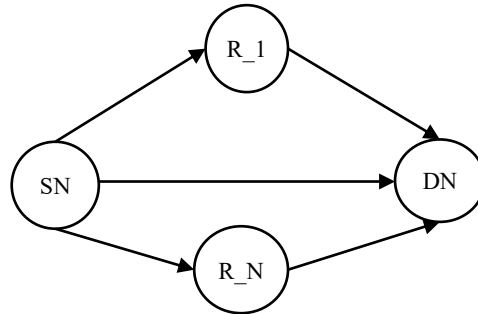


Figure 2: Multi-hop communication model

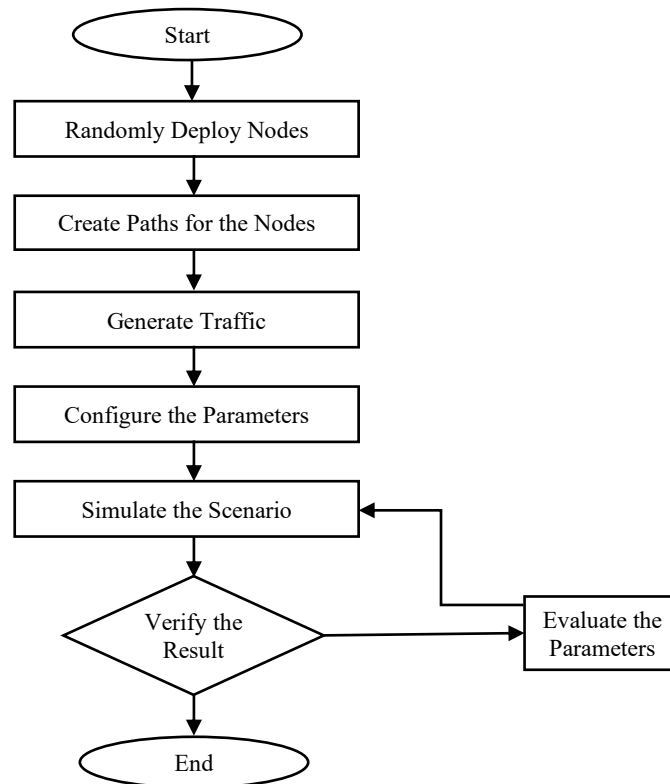


Figure 3: Overall flow diagram of this research

To support energy-efficient and reliable data forwarding in UWSNs, this work proposes the EESDBRP. The algorithm is based on the expansion of the traditional DBR scheme by adding the energy harvesting dynamics and SNC-based delay guarantees to the routing decision process. The proposed algorithm uses depth, leftover, and gathered energy availability, and probabilistic delay bounds to choose forwarding nodes, unlike traditional DBR, which only uses node depth. By doing this, it will be possible to achieve a balanced energy consumption, fewer retransmissions, and enhance routing stability in case of uncertain water conditions.

Algorithm 1 Enhanced Energy-Harvesting Stochastic Depth-Based Routing Protocol (EESDBRP)

Input: Node set N , packet P , sink node S
 Input: Depth $D(n)$, residual energy $E_{\text{res}}(n)$, harvested energy rate $E_h(n)$
 Input: SNC delay bound $SNC(n)$
 Output: Reliable and energy-efficient packet delivery
 foreach node $n \in N$ do
 Initialize $D(n), E_{\text{res}}(n), E_h(n), SNC(n)$
 end
 Set current node $i \leftarrow$ source node
 while $i \neq S$ do
 foreach node $n \in N$ do
 $E_{\text{res}}(n) \leftarrow E_{\text{res}}(n) + E_h(n)$ // Energy harvesting
 end
 Identify neighbor set $\text{Neigh}(i) = \{j \mid D(j) < D(i)\}$
 foreach node $j \in \text{Neigh}(i)$ do
 if $E_{\text{res}}(j) \geq E_{\text{th}}$ and $SNC(j) \leq D_{\text{th}}$ then
 $\text{Cost}(j) \leftarrow w_1 D(j) + w_2 SNC(j) - w_3 E_{\text{res}}(j)$
 end
 else
 Exclude node j
 end
 end
 Select forwarder f with minimum $\text{Cost}(f)$ Compute adaptive holding time using $SNC(f)$ Transmit packet P from i to f
 $E_{\text{res}}(i) \leftarrow E_{\text{res}}(i) - E_{\text{tx}} E_{\text{res}}(f) \leftarrow E_{\text{res}}(f) - E_{\text{rx}}$
 $i \leftarrow f$
 end

Algorithm 1 presents the EESDBRP. Each node is initialized with its depth, residual energy, harvested energy rate, and SNC-based delay bound. During packet forwarding, nodes update their available energy using harvested environmental energy. Forwarding candidates are restricted to neighbours at lower depths to ensure progress toward the sink. Candidate nodes are selected based on minimum energy and delay thresholds, and the optimal forwarder is chosen using a cost function that combines depth, stochastic delay bound, and residual energy. Adaptive holding time derived from SNC delay guarantees is applied to reduce collisions and retransmissions. The energy consumption is updated every time a transmission and reception have taken place, and it goes on until the packet is received by the sink. Using energy harvesting awareness and stochastic performance limits, the algorithm will be more energy efficient with less delay and stability of routing at minimum computation. This methodology, as shown in figures 1 and 2, will be applied in the overall assessment of the energy harvesting network model and involves the associated theory of the SNC and practical verification of the model by simulation. Figure 3 represents the flow of the proposed research.

Problem Motivation and Contribution

This research proposed a new probabilistic model for evaluating EHDBR efficiency in UWSNs. Unlike prior studies, this model incorporates key factors like acoustic channel properties, node mobility due to depth variations, transmission delays, and holding times. The model's ability to compute crucial performance metrics for energy harvesting and replace laborious simulations with efficient SNC

equations. Not only does this give useful information on the behavior of DBR, but it also allows the design and optimization of UWSNs with DBR to be determined by identifying the optimum settings without the need to engage in cumbersome simulations. In contrast to the conventional routing protocols that use complete location information, depth is used to forward packets in UWSNs with DBR. Nodes calculate their depth by having pressure sensors and putting them in the packet header. The receiver node that has the largest difference in depth beyond a threshold is selected as the next hop, with the intention of having maximum single-hop distances. To do this, the holding time of forwarding a packet is reduced with the difference in depth, giving preference to shallower nodes to be relayed faster. Also, retransmissions received by other stations cause cancellations of packets and holding time to avoid duplicate transmissions.

Energy Harvesting SNC Equations

In this study, Stochastic Network Calculus (SNC) is used as a mathematical model to model and analyse how energy harvesting and sensor node communication interact. The computations used in SNC to make these optimizations are the following equations (1):

$$D_H(d) = \left(\frac{2\tau}{\delta}\right) (T_r - d) \quad (1)$$

T_r represents the maximum range of transmission of a sensor node. The maximum propagation delay for a single hop, denoted as T_r , is determined by dividing T_r by v_0 , where v_0 signifies the speed of sound propagation in water. Furthermore, to enhance network performance and mitigate the hidden terminal issue, we introduce a scaling factor, δ . As per reference (Alamu et al., 2023), we define δ as T_r divided by 4.

End-To-End Data Transmission Delays

UWSNs encounter distinctive hurdles of slow propagation of acoustic signals of water waves, which is roughly 1500 meters per second (m/s) compared to radio frequencies used in terrestrial networks. This significantly impacts UWSN performance by introducing substantial propagation delays. Propagation delay and the effect of holding times are also added to the total signal transmission time and depend on the depth difference between communicating nodes. Holding time is the time taken by the processing of the signal at the node before it is re-transmitted. Considering both propagation delay denoted by $D_p(u, v; u', v')$, and holding time $D_H(u, v; u', v')$ between a sender node (u, v) and receiver node (u', v'), allows for a more accurate understanding of total message transfer time in a UWSN. The propagation delay and holding time are represented in equations (2) and (3)

$$D_p\left(i, j, i', j' = \frac{dd' j' i j}{v_n}\right) \quad (2)$$

And

$$D_H(i, j; i', j') = \left(\frac{2\tau}{\delta}\right) \left(T_r - \frac{\Delta D}{L} (i' - i)\right) \quad (3)$$

Calculating the mean delay for data packets to reach their destination in a network with multiple nodes and hops (denoted by k). It makes use of a recursive algorithm to calculate the waiting time and probability of acceptance of data packets in different paths that have different numbers of hops. This allows for the calculation of the probability that a packet reaches its destination within k hops in equation (4).

$$w_{ij}^k = E \left[W_{i,j} 1_{\{H_{i,j}=k\}} \right] \quad (4)$$

Where

$$s = i', j', x = D_H(i', j'; i, j), y = D_P(i, j; i', j')$$

$$w_{ij}^k = \sum_{i'=1}^{i-1} \sum_{j'=0}^M \left(w_{i'j'}^{k-1} + D_H(x)h_{k-1}(s) + D_P(y)h_{k-1}(s) \right) P_{i'j'}^{ij} \quad (5)$$

Finally, the mean end-to-end waiting time is obtained by summing the waiting times for all possible hop counts and dividing by the overall probability of successful delivery. It is computed by the following equation (6)

$$\bar{W} = \frac{1}{h} \sum_{k=0}^L w_{LT}^k \quad (6)$$

Energy Consumption of Sensor Nodes

The framework enables the estimation of energy expenditure by sensor nodes during data transmission and reception. This includes energy used for computation, communication, and sensor operation. We utilize a recursive approach to analyze the anticipated energy consumption across the network. We compute the energy needed to transmit data to a designated node within a set number of hops from every position of each node. Formally, let $C_{u,v}(u', v')$ denote the energy consumed at position to transmit from the source to node (u, v). Equation (7) represents the number of hops required for transmission to the node. By analyzing this data, we can then study the average energy consumption based on the hop count. Let's consider a one-hop communication scenario where.

$$c_{uv}^1(u', v') = \gamma P_{u'v'}^{uv} P_0^{u'v'}$$

$$c_{uv}^k(u', v') = \gamma h_k(u', v') P_{u'v'}^{uv} + \sum_{\ell=u'+1}^{u-1} \sum_{m=0}^M c_{\ell m}^{k-1}(u', v') P_{\ell m}^{uv} \quad (7)$$

The energy consumption across the network can now be determined by summing both the number of hops packets take to reach their destination and the energy used at each level, and represented in equation (8).

$$c(u) = \sum_{k=0}^L \sum_{m=0}^M c_{LT}^k(u, m) \quad (8)$$

Buffer Overflow Probabilities

SNC is useful in determining the probability of buffer overflow caused by data that comes much faster than the processing speed or transmission speed. Buffer overflow may cause loss of data and slow down the network performance. Underwater acoustics In the field of underwater acoustics, the term "path loss" ($(A_c(e_d, s_f))$) characterizes the attenuation of signal intensity across a Euclidean distance (e_d) at a given frequency (s_f). Mathematically, this phenomenon is represented as follows in equation (9).

$$A_c(e_d, s_f) = d^s a(s_f)^d$$

$$\Gamma(e_d) = \frac{e_b}{N_0 A(d, s_f)} = \frac{e_b}{N_0 d^s a(s_f)^d} \quad (9)$$

By analyzing these factors through SNC, the research aims to optimize the energy harvesting system and sensor communication protocols to achieve the following equation (10):

$$q_e(e_d) = \frac{1}{2} \left(1 - \sqrt{\frac{(e_d)\Gamma}{(e_d)1+\Gamma}} \right) \quad (10)$$

Stochastic Network Calculus (SNC) to analyse the interplay between energy harvesting and sensor communication. The calculations of such critical factors as end-to-end delays, sensor node energy consumption, and probability of buffer overflow are possible with SNC. Through these factors, the study will focus on optimizing the energy collection system as well as the sensor communication protocol. This optimization targets benefits: reducing energy consumption through optimized protocols, minimizing data transmission delays via network and routing optimizations, and ultimately improving overall network performance and reliability by implementing equation (11). However, the above calculations are only applicable to nodes located within the transmission range of the node positioned at (u,v).

$$Q(l, u, v) = \sum_{k=0}^M b_k p_m(d_{uv}^{lk}) \quad (11)$$

These equations take into account such aspects as the rate of arrival and consumption of energy, buffer capacity and the size of data packet to offer a quantitative approach of understanding the behaviour of the system. By this analysis, the researchers can discover bottlenecks and places of improvements, and eventually come up with an efficient and reliable energy-harvesting sensor network.

Simulation Results and Discussions

The proposed UWSN is simulated using the energy-harvesting Depth-Based Routing (EH-DBR) model in combination with the DBR protocol, implemented in Riverbed Modeler (Academic Edition 17.5), which provides a robust framework for modelling acoustic communication channels, sensor nodes, and protocol stacks. The deployment area is considered 3D with 500 m width x 500 m length x 500 m depth, having 100 randomly placed sensor nodes and one sink node, and underwater environment is set in such a way that attenuation, noise, and propagation delay are taken into consideration so as to bring the deployment scenario closer to the actual acoustic environment. The physical communication protocol between nodes and sink is modeled with the specifications of the acoustic modem of the Link Quest UWM2000, taking into consideration the features of transmission range, data rate, and energy consumption. The simulations take 200 seconds each, and allow enough observation of network behaviour. Energy use, packet per second (PDR), throughput, end-to-end delay, and network stability are some of the key performance measures gathered and stochastic modelling of water currents and variable acoustic channel effects makes sure that a realistic picture of underwater dynamics is taken into account. These parameters prove the performance of the EESDBRP protocol as presented in table 2.

Table 2: Simulation parameters

Parameters	Values
Deployment Area	500m x 500m x 500m
Nodes	100 sensor nodes
Physical Layer	Link Quest UWM2000
Simulations	200 seconds per trial

To evaluate the performance, the simulation data considers three metrics of PDR, energy consumption, and path loss since they directly reflect the trade-offs between reliability and efficiency in UWSNs. The PDR is defined as a function of time-varying reliability that depends on the multi-hop forwarding and acoustic impairments and the stochastic changes have been used to model the realistic effects of underwater noise and fading. Energy consumption is calculated in terms of a residual energy

model with every node initially having a given power budget and depletion can be followed in terms of transmission, reception, and idle states. The adjustments of Stochastic Network Calculus (SNC) are done to consider the reduction in retransmissions and the selection of relays according to the energy-efficient protocol design. Path delays are calculated according to a long-distance acoustic propagation model, that is, at frequencies dependent on absorption and the ambient noise level and thus the problematic nature of underwater channels is captivated. The comparison of the traditional DBR protocol with the proposed SNC-based EESDBRP model shows that the performance has improved in all the measures considered. Piezoelectric energy harvesting and stochastic performance modeling the combination of piezoelectric energy harvesting and stochastic performance modeling will promote routing reliability, delay reduction, energy savings, and underwater path loss mitigation resulting into enhanced network sustainability.

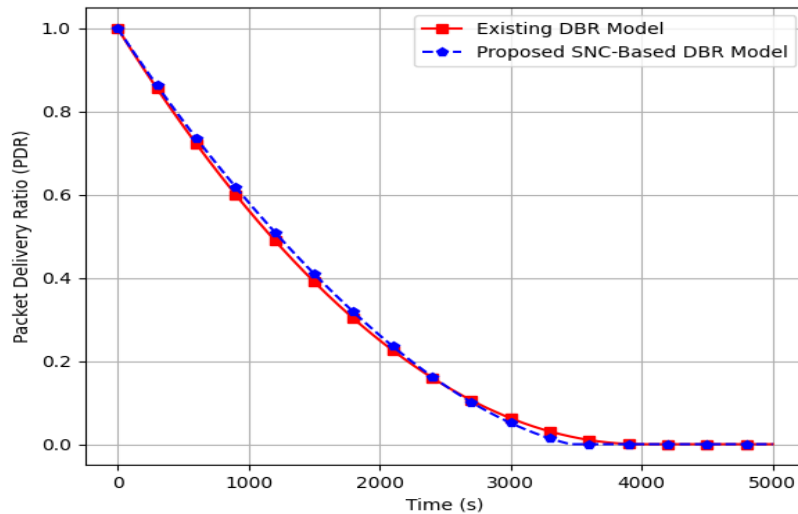


Figure 4: Packet delivery ratio (PDR) vs time

Figure 4 shows that the temporal variation of PDR in the two routing schemes is different. The standard DBR protocol has a PDR around 70-75 % during the simulation, and the EESDBRP protocol always has a higher level of reliability, which is almost 90 % at the conclusion of the simulation. This is a gain of about 15 %, which is due to the adaptive forwarding decisions and resource allocation through the SNC, which react to the availability of energy and channel fluctuations.

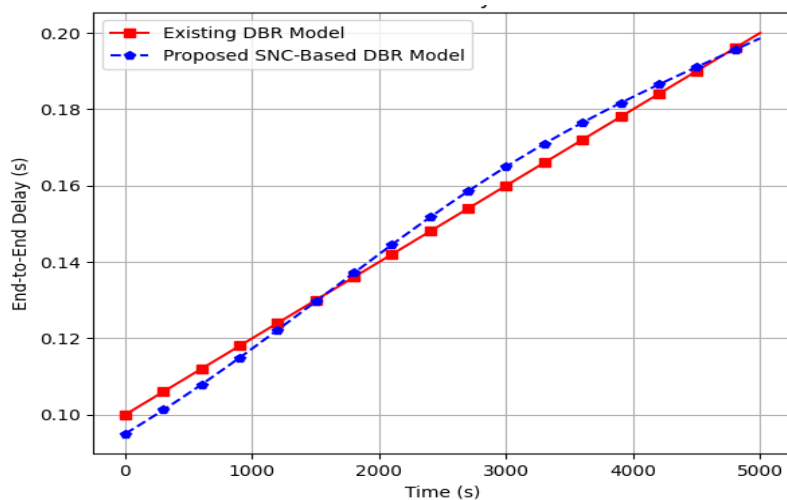


Figure 5: End-to-end delay vs time

The average end-to-end delay performance is compared in figure 5. The DBR protocol has more and more unpredictable delays because of the congestion and queues. Comparatively, the EESDBRP model cuts down on delay by about 30% and in the process keeps the latency low and steady during simulation. This is enhanced by the delay limit by SNC and selective relay according to the dynamics, which render the protocol to be a good fit in delay- sensitive underwater systems like environmental monitoring and surveillance.

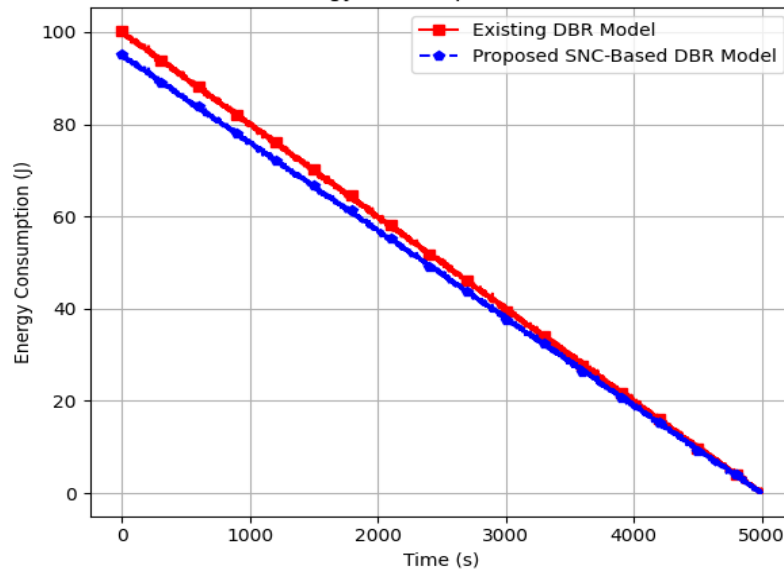


Figure 6: Energy consumption vs time

Figure 6 depicts cumulative curves of energy consumption. Compared to nodes based on the DBR protocol, nodes based on the EESDBRP model exhibit slow energy decay, energy harvesting in piezoelectric and efficient transmission scheduling. In general, the suggested model leads to the improvement of energy consumption by about 40 percent, increasing the network operation life significantly and decreasing reliance on limited battery resources.

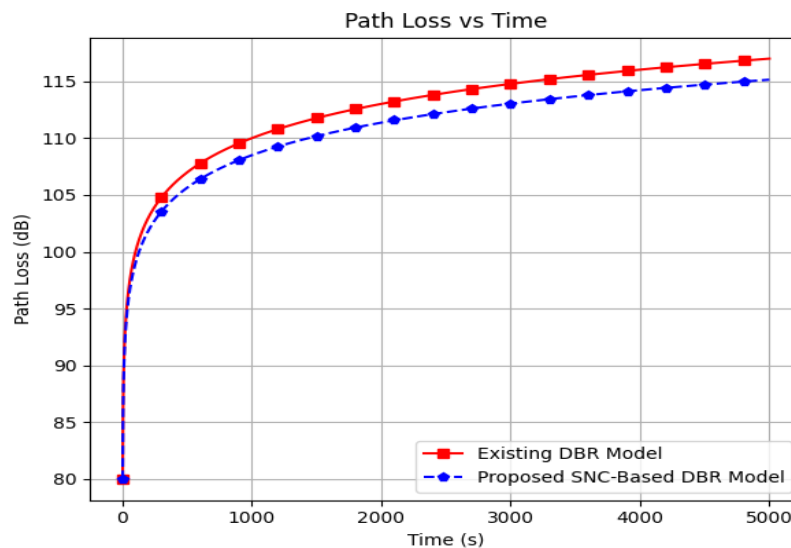


Figure 7: Path loss vs time

The comparison of path loss of DBR and EESDBRP is given in figure 7. Although the attenuation of underwater acoustic communication is fundamentally high, EESDBRP model does provide a quantifiable decrease in the path loss, by an average of approximately 10 % reductions than the DBR protocol. The latter is facilitated by probabilistic channel modeling with SNC, which affects energy-conscious transmission policies that are more in line with underwater propagation characteristics.

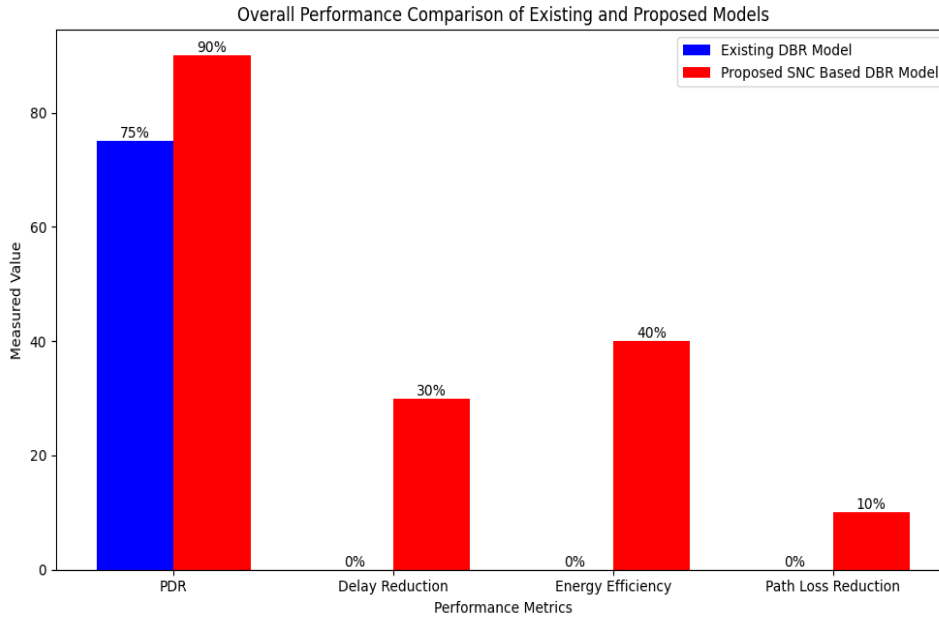


Figure 8: Overall performance metrics improvement

Table 3: Comparison of overall performance metrics improvement

Metric	Existing DBR Model	SNC Based EESDBRP Model	Improvement (%)
PDR	75%	90%	+15%
Delay Reduction	0%	30%	+30%
Energy Efficiency	0%	40%	+40%
Path Loss Reduction	0%	10%	+10%

The summary of the consolidated performance gains of the proposed model is summarized in table 3 and figure 8. EESDBRP has 30, 40, and 90 % improvements in PDR compared to DBR, end-to-end delay is 30%, energy efficiency is 40 % and path loss is 10 %. These findings validate the theory that the combination of energy harvesting and stochastic network analysis can be used to create a sound and robust routing structure that can support long term UWSN deployments even in highly dynamic under-sea conditions.

4 Conclusion and Future Works

In the work, the foundations of the energy-harvesting-aware routing model of Underwater Wireless Sensor Networks (UWSNs) is a simulation-based approach to energy harvesting based on piezoelectric energy generation combined with the Underwater Stochastic Network Calculus (SNC) to manage energy limitations and communication unreliability in underwater communication. The proposed improved DBR model addresses the weaknesses of the traditional DBR protocols by explicitly introducing the energy harvesting dynamics in the routing and performance analysis. The simulation data measured through the Riverbed platform indicate that the proposed solution can increase the lifetime of a network

by about 35-40 %, enhance the reliability of communication and the delivery of packets by a factor of more than 20%, and enable routing stability in the changing situation of energy conditions. The stochastic analysis continues to affirm that it has smaller delay limits and better network robustness that can guarantee sustained and reliable underwater data gathering. Future research will be on actual underwater applications, optimal hybrid energy collection methods, and scalability and robustness in varied underwater conditions, which will form the basis of the high-level UWSNs that will be able to sustain continuous and protracted marine surveillance.

The limitations of the paper consist of the fact that the model is not real world tested, instead being tested within a simulation which may have missed some of the complexities of the real underwater environment. It has simplified assumptions of constant parameters and a small number of nodes, which would not be well-scaled in larger and dynamic networks. Also, the efficiency of energy harvesting is not constant and is not taken into consideration under extreme conditions. Complex energy harvesting and network calculus could add computational overhead to the protocol, which will not be as efficient in a resource-constrained environment.

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