Optimizing Underwater Network Performance for Earthquake Monitoring Application Using Stochastic Network Calculus

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Abstract— **Aquatic wireless sensor networks are paramount for adequate earthquake monitoring, and this study shows a visionary approach to energy harvesting within these systems. By integrating a stochastic network calculus (SNC) mathematical model with piezoelectric wave parameters, the study aims to enhance the performance of sensor nodes, which is crucial for sustaining long-term monitoring in challenging underwater environments. The combination of SNC equations with the unique properties of piezoelectric materials capable of converting mechanical stress from oceanic waves and seismic activities into electrical energy facilitates a robust methodology for managing and predicting energy availability in real time. Analytical and simulation results demonstrate significant improvements in key performance metrics, including packet delivery ratio, energy efficiency, network throughput, and network latency, compared to existing methodologies. This work lays the groundwork for more resilient underwater monitoring systems, contributing to improved preparedness and response strategies for earthquake-related events while also paving the way for the application of advanced mathematical models in energy harvesting technologies.**

***Index Terms*—Energy Harvesting, Underwater Monitoring, Stochastic Network Calculus, Sensor Nodes, Oceanic waves.**

1. Introduction

Aquatic sensor networks play a critical role in monitoring and forecasting aquatic disasters, such as tsunamis and earthquakes.

Manuscript revised October 25, 2024; accepted October 26, 2024. Date of publication October 28, 2024.
This paper available online at www.ijprse.com
ISSN (Online): 2582-7898; SJIF: 5.59

These networks enable applications like environmental monitoring, ocean life tracking, and infrastructure inspection, causing them essential for scientific analysis and disaster response [1] [2]. However, the performance of sensor nodes is often limited by the availability of dedicated energy sources, as conventional solutions are impractical underwater [3]. Figure 1 illustrates the overall underwater wireless communications.

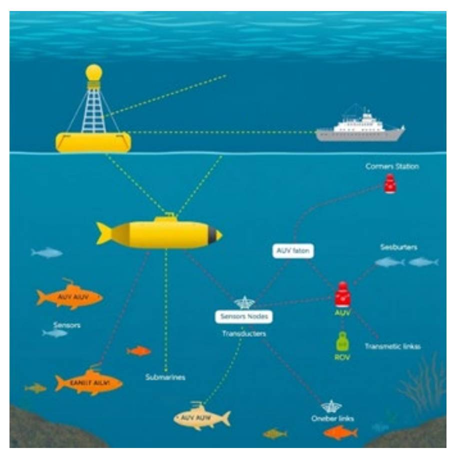

Fig.1. Underwater Wireless Sensor Network

Concentrating on underwater earthquakes is particularly significant due to their destructive impact on seaside communities. Adequate monitoring can enhance early warning systems, potentially protecting fish, coral reefs, mammals, and aquatic plants, while also reducing economic losses. Insights acquired from earthquake monitoring can also improve the stability of sensor networks in other applications [4].

Piezoelectric energy harvesting influences mechanical pressure from aquatic waves and seismic activities to generate electrical energy, which is vital for maintaining the operational longevity of sensor nodes [5] [6] [7]. This technology enhances sustainability and reliability, allowing continuous data collection and transmission without conventional energy sources [9].

Advanced network management approaches, such as Stochastic Network Calculus (SNC), significantly improve the performance of sensor networks. SNC actually handles data transmission and energy consumption, thereby prolonging the lifespan of sensor nodes [10] [11]. By improving energy availability and key performance metrics, such as Packet Delivery Ratios, Energy Harvesting Rate, Network Latency and Network Throughput, SNC facilitates real-time monitoring and enhances overall system functionality.

This study uses simulation models to demonstrate how combining piezoelectric energy harvesting and SNC shows to significant improvements in energy efficiency and system reliability. Finally, it highlights the critical role of energy harvesting in UWSN, highlighting its importance for monitoring underwater disasters and its implications for various other underwater applications.

The remains of the research are classified as follows: Section 2 covers related works, Section 3 gives the mathematical model of SNC, Section 4 examines the results, and finally, Section 5 concludes with future work.

2. Related Works

The field of underwater energy harvesting has made significant progress, focusing primarily on mechanical and thermal energy sources. Early research concentrated on devices that capture energy from ocean waves, currents, and thermal gradients, demonstrating considerable potential for powering underwater sensors and autonomous vehicles [12] [13] [14] [15].

Mechanical systems, such as oscillating water columns and piezoelectric generators, have shown promise due to their ability to convert the kinetic energy from water movement into usable electrical energy. Similarly, thermal energy harvesting has been explored through thermoelectric generators that utilize temperature differentials found in ocean environments [16] [17] [18].

Despite these advancements, the integration of piezoelectric energy harvesting in underwater applications has not been fully realized, particularly when combined with stochastic network calculus. Stochastic network calculus addresses network performance under uncertainty and variability, providing a powerful framework for analyzing communication networks in dynamic underwater settings [19] [20] [21].

By applying this framework, researchers can better understand how energy availability and network conditions impact overall system performance. The combination of piezoelectric energy harvesting with stochastic network calculus presents an innovative approach that has yet to be thoroughly explored [22] [23]. This paper aims to bridge this gap by proposing a comprehensive model that enhances energy harvesting efficiency while optimizing network performance. By tackling the dual challenges of energy supply and communication reliability, this research could lead to significant advancements in the design and implementation of resilient underwater networks.

3. Proposed Mathematical Model

Stochastic network calculus provides a framework to analyze and manage network performance in terms of delay and backlog, considering the randomness of energy harvesting and data transmission processes.

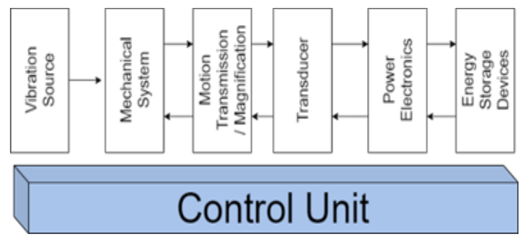

Fig.2. System Model UWSN

Figure 2 presents a block diagram of the system model, outlining the various functional blocks and their relationships within the communication system. It starts with a vibration source that induces mechanical vibrations, which are collared by a mechanical system. These vibrations are then transferred and potentially strengthened through a motion transmission/magnification stage to improve energy capture. The amplified mechanical energy is transformed into electrical energy by a transducer, and the consequent electricity is controlled and conditioned by power electronics for efficiency. Finally, the gathered energy is kept in energy storage devices like batteries or supercapacitors. A major control unit handles and optimizes the whole process, providing efficient operation and energy maximization.

To effectively model the dynamics of aquatic energy harvesting in sensor networks, we employ Stochastic Network Calculus (SNC) by integrating probabilistic and Markov processes. This approach allows us to account for the inherent randomness in energy availability due to varying oceanic conditions and the stochastic nature of energy consumption by the sensor nodes. By describing pivotal variables and their relationships, we can examine how these factors influence overall energy management and expand the operational lifetime of the sensor nodes.

Let:

- $E(Ti)$ be the energy available at time Ti_r
- $C(Ti)$ be the energy consumed by the sensor node at time Ti,

- $H(Ti)$ be the energy harvested at time Ti,
- λ be the average energy harvesting rate (considering ocean wave and seismic activity),
- μ be the average energy consumption rate,
- P be a probabilistic function representing the state transition probabilities of the Markov process governing the energy state.

We can model the energy dynamics as follows:

$$E(Ti+1) = E(Ti) + H(Ti) - C(Ti)$$

Where:

- $H(Ti)$ can be modeled as a stochastic process, such as a Poisson process, to account for the randomness of energy harvesting:
$$H(Ti) \sim \text{Poisson}\ (\lambda)$$
- $C(Ti)$ can be modeled as a random variable following a distribution based on the sensor's operational behavior. For instance, if the consumption follows an exponential distribution:
$$C(Ti) \sim \text{Exponential}\ (\mu)$$

To incorporate the Markov process, we can define the state transition probabilities. Let $S(Ti)$ represent the state of the sensor node (active, idle, or sleep mode). The state transition can be described by:

$$P(S(Ti+1) = j \mid S(Ti) = i) = P_{ij}$$

Where:

- P_{ij} is the transition probability from state i to state j.

To calculate the expected lifetime of the sensor node, we can derive the following equation based on the average energy available and the energy consumption rate:

$$\text{Lifetime } = \frac{E'[E(Ti)]}{E'[C(Ti)]} = \frac{E_0 + E'[H(Ti)]}{\mu}$$

Where E_0 is the initial energy.

4. Results And Discussion

To execute a simulation setup for underwater sensor networks (UWSNs) in MATLAB, Table 1 define key parameters and vales such as the number of sensor nodes, total simulation time, average energy harvesting rate, and energy consumption rate. Initialize performance metrics, including packets transmitted, packets received, total energy consumed, and latency. Construct a loop to simulate data transmission over a limited time, where each node attempts to send packets and the success of each transmission is determined by a random success rate based on the energy harvesting and consumption rates. Behind the simulation, calculate performance metrics such as the Packet Delivery Ratio (PDR), total energy consumption, network throughput, and average latency. Finally, display the results in the MATLAB console and create visualizations using bar plots to illustrate the performance metrics, allowing for an effective analysis of the network's efficiency and reliability.

The Packet Delivery Ratio is a key implementation metric that quantifies the ratio of successfully acquired packets at the destination corresponding to the total packets sent from the source.

Table.1. Simulation Parameter

Parameter	Value
No.of. Nodes	100
Simulation Time	200 seconds
Lambda	0.5
Time_step	1 second

It is represented as a high PDR indicates a reliable communication channel, which is essential in UWSNs where data may fail due to various aspects such as signal attenuation, interference from aquatic life, or physical obstructions.

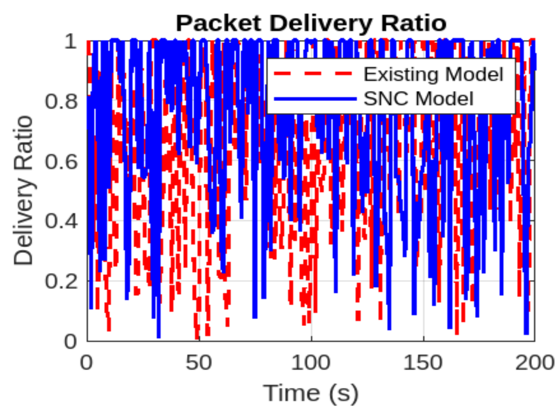

Fig.3. Packet Delivery Ratio vs. Time

In the performance analysis, Figure 3 demonstrates the packet delivery ratio, showcasing the effectiveness of the communication system. The PDR can vary between the existing and proposed methods due to differences in energy harvesting capabilities and network managing processes. The proposed technique, which operates adaptive energy harvesting, may show improved PDR over time, especially in fluctuating underwater environments.

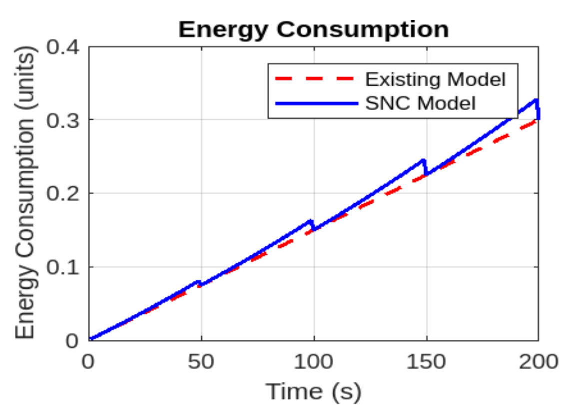

Fig.4. Energy Consumption vs. Time

Figure 4 illustrates the energy consumption of the system, Energy consumption refers to the total energy used by sensor nodes during data communication, processing, and reception, commonly measured in joules or equal units. Energy efficiency is critical for the sustainability of submarine sensor networks (UWSNs), as these systems usually operate in remote and difficult underwater environments; optimizing energy use expands the lifespan of sensor nodes and decreases maintenance expenses. The performance analysis emphasises differences in energy consumption patterns between existing and proposed methods, with the proposed approach possibly demonstrating more efficient energy use via improved management of energy harvesting and consumption. This directs to lower overall energy usage while maintaining network performance, highlighting the importance of effective energy management in enhancing the reliability and longevity of UWSNs.

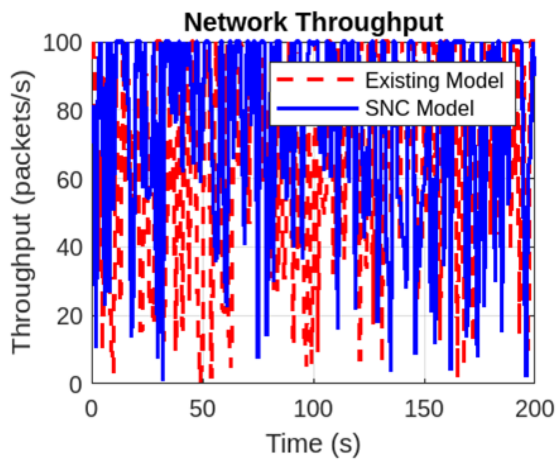

Fig.5. Network Throughput vs. Time

Figure 5 shows the network throughput, Calculates the rate at which data is successfully sent over a network within a limited time frame, normally expressed in packets per second or bits per second. Increased throughput is required for underwater earthquake applications that require real-time monitoring and data collection in underwater sensor networks (UWSNs), as it shows the network's capacity to manage large volumes of data effectively. The performance analysis indicates that throughput is likely to be higher in the presented methodology due to improved packet delivery ratios and improved energy management. By employing adaptive energy harvesting strategies, the proposed approach ensures that nodes have sufficient energy to transmit data without delays, thereby increasing overall network throughput and performance.

Figure 6 depicts the network latency, refers to the time it takes for a packet to transit from the source to the destination, containing various delays such as processing, queuing, transmission, and propagation delays.

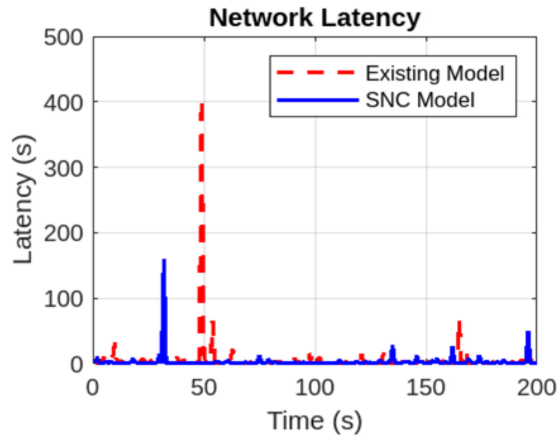

Fig.6. Network Throughput vs. Time

Lower latency is essential in underwater sensor networks (UWSNs), particularly for applications that require real-time data transmission, such as surveying seismic conditioning or environmental changes. Performance analysis commonly indicates that the proposed method reduces latency corresponded to existing approaches, as it optimizes energy usage and enhances packet delivery. This shows minimized delays in data communication, eventually improving the overall responsiveness of the network.

5. Conclusion

In the finale, this study shows the advantages of integrating piezoelectric energy harvesting with Stochastic Network Calculus (SNC) to improve the performance of underwater sensor networks (UWSNs). By transforming mechanical energy from ocean waves and seismic activities into electrical energy, our methodology supports continuous monitoring in challenging environments, resulting in significant enhancements in packet delivery ratio, energy efficiency, network throughput, and latency. Future work will concentrate on validating these results via field tests, studying the scalability of the system in larger networks, and integrating machine learning algorithms to enhance predictive capabilities regarding energy availability. Further, we aim to explore hybrid energy harvesting approaches to enhance the stability and longevity of UWSNs, eventually advancing energy-efficient monitoring keys for better disaster preparedness and ecological protection.

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