Fuzzy Logic-Based Adaptive Transmission Power Control for Autonomous Underwater Vehicles

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***Abstract*—In this study, we introduced an adaptive transmission power control algorithm, harnessing the potential of fuzzy logic, to address the inherent uncertainties characteristic of underwater Autonomous Underwater Vehicles (AUVs). Capitalizing on fuzzy logic's proficiency in managing uncertain and imprecise data, our approach offers a robust solution tailored to the dynamic and challenging underwater environments. This algorithm dynamically adjusts the transmission power based on real-time input parameters including distance, Received Signal Strength Indicator (RSSI), and energy consumption, optimizing energy usage within AUVs. As a result, the operational efficiency of AUVs is significantly enhanced, promoting longevity and reliability. Simulation outcomes demonstrate that our fuzzy logic-based method delivers a more adaptable and resilient energy management strategy, proving its effectiveness even under unpredictable underwater conditions.**

***Index Terms*—Underwater AUVs communications, Adaptive power control, Fuzzy Logic Control, Energy efficiency**

I. Introduction

Underwater communication is instrumental in a wide array of applications, from environmental monitoring and underwater exploration to under-ice operations [10]. The control of transmission power is crucial, determining the balance between communication reliability and energy efficiency that governs overall system performance. This balance becomes particularly significant for Autonomous Underwater Vehicles (AUVs), which must maintain reliable data transmission while minimizing energy consumption to extend operational life, coordinate with other nodes, and adapt to changing underwater conditions.

However, the intricacies of underwater communication present formidable challenges. Issues like signal attenuation, multipath propagation, and changing channel conditions [4] necessitate solutions that are both robust and adaptable. Traditional approaches, such as modulation schemes, routing protocols, and power control mechanisms, often struggle to fully address these complexities, emphasizing the need for more sophisticated strategies specifically tailored to underwater AUV communication.

Several previous solutions attempted to tackle the issue of power control. For instance, the RECRP routing protocol for underwater wireless sensor networks adjusts transmission power based on inter-node channel conditions and energy consumption [11]. Similarly, the DPower strategy focuses on conserving energy by adaptively selecting the appropriate power level based on the inter-node distance [8]. Yet, these strategies tend to inadequately account for the inherent uncertainties and dynamic nature of underwater environments. Factors such as sound speed variations, AUV mobility, signal attenuation, multipath propagation, and time-varying characteristics result in inconsistencies in determining distance, energy consumption, and channel conditions.

To address these challenges, our work introduces an adaptive power control mechanism based on fuzzy logic. Fuzzy Logic Control (FLC) is a sophisticated approach capable of handling uncertain and imprecise data [3], making it an ideal fit for our problem characterized by inherent uncertainties. Our mechanism optimizes transmission power levels based on factors like inter-node distance, energy consumption, and channel conditions. We leverage a robust underwater channel model to estimate these parameters, utilizing beacon messages to determine distances and evaluate energy and channel conditions.

Despite these robust models, uncertainties in real-world scenarios can still occur due to model inaccuracies, environmental changes, and dynamic factors like water currents and node mobility. To navigate these uncertainties, we incorporate distance, energy consumption, and channel conditions into our fuzzy logic framework. Through multiple IF-THEN fuzzy rules, we capture the interplay between these factors and infer the optimal transmission power level. This approach enables us to determine the transmission power level as the output of our fuzzy logic control system, striking a balance between energy efficiency and communication reliability. We evaluate the efficacy of our proposed mechanism through key network performance metrics, including transmission power adjustment, packet delivery ratio, and energy consumption, anticipating that our approach will prove effective in the face of unpredictable underwater environments characterized by frequent variations in distance, energy consumption, and channel conditions.

In the remainder of this paper, we present a detailed discussion divided into several sections. In Section II, we review relevant work that has set the stage for our research. Following this, Section III outlines the issues our study seeks to address through the problem statement. The problem modeling is further elaborated in Section IV, which sets the foundation for our proposed solution. We then introduce our Fuzzy Logic-based Adaptive Transmission Power Control in Section V, which is

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the core of our proposed mechanism. In Section VI, we test the performance evaluation of our proposed mechanism, outlining our simulation setup, results, and a comparative analysis. We close our paper with Section VII, where we summarise our key findings and contributions.

II. Related Works

In this section, we talk about related works about the existing proposed protocols or mechanisms for underwater communications in terms of energy efficiency.

A. *Non-fuzzy logic methods*

One of the related work [9] suggests a system that would make underwater swarming possible by using single-transducer, Doppler-based and multi-frequency attenuation-based acoustic navigation without time-synchronization for multi-vehicle swarming. In this solution, a leader with good navigation carries a multi-frequency sound source. Scalable numbers of followers equipped with a custom low-cost acoustic package then adapt heading based on Doppler-shifted frequency and range using multi-frequency difference in absorption.

An energy conserving protocols for use in underwater acoustic networks called DPower [8] is proposed. The method encompasses a straightforward transmission power calibration procedure and adaptive power level selection. The method was evaluated in combination with DFlood, a known and validated constrained flooding protocol developed for underwater applications. However, the method is implemented in a 2-D instead of 3-D environment, and all the simulated nodes are static instead of mobile, which is not suitable for underwater swarming networks.

Efficient Depth-based MAC (ED-MAC) protocol for underwater sensor networks is proposed in work [1]. The main objective of the ED-MAC is to conserve sensor energy by enabling them to enter into sleep mode during certain time slots. However, chaing modes may not be suitable for underwater swarming because it lacks the capability to handle dynamic and unpredictable swarm behavior. Additionally, the protocol may not be able to effectively handle the high node density and frequent topology changes often observed in underwater swarm networks.

A MAC protocol was proposed in [2] with the objective of reducing the energy consumption of sensors. The protocol divides a packet into several sub-packets, which are forwarded to the next sensor, and solves the problem of sensor isolation by utilizing depth adjustment. The proposed approach is shown to achieve significant improvements in energy-saving and packet delivery ratio based on numerical results. However, this energy-saving method cannot be directly applied to underwater swarming due to challenges such as high propagation delay, low bandwidth, high error rate of underwater acoustic channels, and unpredictable swarm behaviors.

B. *Fuzzy logic related methods*

An fuzzy based energy efficient packet forwarding scheme is proposed in work [12]. The fuzzy logic tackles issues in Underwater Wireless Sensor Networks such as node shutdowns, re-transmissions due to packet loss or collision, and incorrect sensor node selection. The scheme considers factors like the number of hops to the gateway node, the number of neighboring nodes, and the distance (or RSSI) in a 3D UWSN setup. While the scheme offers a solution through fuzzy logic, this approach does not explicitly address such uncertainty and cannot handle the real-time environment. However, our approach is designed to address this problem by taking into account distance, received signal strength indicator (RSSI) and energy consumption in real time, which allows our system to better adapt to changing environmental conditions and improve the energy efficiency of the entire network.

A fuzzy logic vector-based routing protocol for underwater networks is proposed in work [6]. However, it does not adequately address the uncertainties of the underwater environment and lacks real-time adaptability. In contrast, our fuzzy logic-based adaptive transmission power control algorithm effectively handles these uncertainties by incorporating real-time parameters like distance, RSSI, and energy consumption. Moreover, it adaptively manages power transmission, thus enhancing the network's longevity even under uncertain conditions. This dynamic, real-time approach differentiates our algorithm, providing a more robust and efficient solution for underwater networks.

III. Problem Statement

A. *Problem Description: The Issue of Uncertainty*

In networks involving Autonomous Underwater Vehicles (AUVs), the dynamic and unpredictable nature of underwater environments introduces significant uncertainties, which can impact network performance adversely. These uncertainties often stem from factors such as varying water currents, unpredictable node mobility, fluctuating signal propagation characteristics, changes in noise levels, and inconsistent energy consumption patterns. Such factors result in inconsistent signal propagation, leading to variability in RSSI, channel conditions, and energy consumption. AUVs, if operating on a fixed transmission power, might either waste energy due to excessive transmission power or fail to maintain reliable communication due to inadequate transmission power, depending on the various conditions. These variabilities could subsequently affect the communication reliability, overall energy consumption, network lifetime, and packets transmission reliability.

B. *Problem Solution: Why Fuzzy Logic*

Given the inherent uncertainties and nonlinearities of underwater communication environments, traditional mathematical models often fall short in capturing the complex interrelationships among these variable parameters. Therefore, a more adaptive and robust approach is required, which is Fuzzy Logic Control. Fuzzy Logic allows us to model complex systems with a high level of abstraction, reflecting our knowledge and experience. It is particularly adept at managing problems with undefined models, ambiguity, and vagueness, which are all characteristic of underwater communication scenarios for

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AUVs. By transforming the inputs, such as distance, RSSI, and energy consumption, into degrees of membership on a continuous scale, Fuzzy Logic can accommodate imprecision and make rational decisions, much like human reasoning. Therefore, Fuzzy Logic becomes an effective tool for our problem, where adaptive transmission power control is crucial to ensure energy-efficient, reliable communication under unpredictable and varying underwater conditions.

C. What is Fuzzy Control (FC) and Its Advantages and Disadvantages

Fuzzy Control (FC) is a control method that utilizes Fuzzy Logic to manage the control processes. Its main advantage is its ability to manage uncertainty and vagueness, making it particularly useful for our underwater swarm network scenario.

- Advantages: (1) Flexibility: FC can model nonlinear functions of arbitrary complexity. (2) Tolerance for imprecise data: FC is not sensitive to precise inputs; it can manage noisy data and works with ranges of values. (3) Scalability: FC is based on natural language, making it easy to scale up or down.
- Disadvantages: (1) It lacks a systematic methodology to construct and optimize fuzzy systems. (2) The performance of FC can be significantly influenced by the definition of the membership functions and rules, which often depend on expert knowledge and are usually developed based on trial and error.

IV. Problem Modeling

This section presents the network, communication, and energy models for the underwater vehicles network. It also describes the objective of our study and the constraints that need to be considered.

A. Network Model

We consider an underwater vehicles network consisting of N nodes distributed in a three-dimensional space. The nodes can move freely within the network area under the influence of water currents and their own propulsion systems. The positions of the nodes are denoted as (x_i, y_i, z_i) for i = 1, 2, ..., N, where x_i, y_i, and z_i are the coordinates of the $i-th$ node. The topology of our model is shown in Figure 1.

In the given network topology, a sink node operates as a beacon, broadcasting its position information periodically to the Autonomous Underwater Vehicles (AUVs) in the network. Upon receiving this beacon message, the AUVs can calculate their distance from the sink node. The AUVs then use this distance information, alongside factors such as Received Signal Strength Indicator (RSSI) and the energy required to transmit data over the calculated distance, to adjust their transmission power. Having optimized their transmission power, the AUVs can then efficiently relay data packets back to the sink node. This system allows for dynamic adjustment of transmission power based on changing distances and environmental conditions, ensuring an energy-efficient network operation.

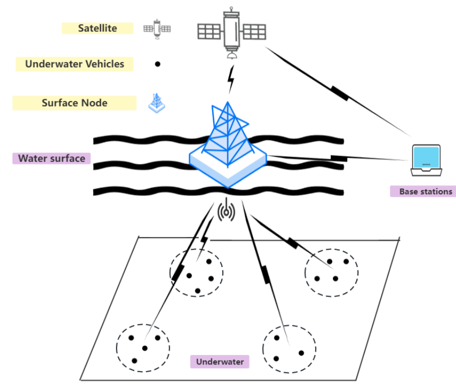

Fig. 1. System overview of the network model

B. Communication Model

Acoustic communication is used as it offers a better range compared to optical or radio frequency communication in underwater environments. The acoustic channel experiences path loss, multi-path fading, and ambient noise, which affects the signal quality and communication range.

The path attenuation model [14], between two underwater nodes at distance d at the frequency of signal f can be expressed as:

$$A(d, f) = A_0 * d_k * a(f)^d \tag{1}$$

Where A_0 is the unit-normalizing constant, k is the spreading factor, $a(f)$ is the absorption coefficient. If to express the attenuation in dB, the path loss is:

$$10 \log^{A(d,f)} = k * 10 \log^d + d * 10 \log^{a(f)} \tag{2}$$

Where the first item on the right means the propagation consumption and the second item represents the absorption of the medium. The absorption coefficient of a sound signal with a specific frequency f in dB/km is typically determined empirically and described by the Thorps formula [5]:

$$10log^{a(f)} = 0.11\frac{f^2}{(1+f^2)} + 44\frac{f^2}{(4100+f^2)} + 2.75\times10^{-4}f^2 + 0.003 \tag{3}$$

Equation (2) represents the reduction in underwater acoustic signal strength without any obstructions along the transmission path. When a hydro-acoustic signal with frequency f is transmitted at power P through an unobstructed path, the received signal strength (RSSI) is given by $P/A(d, f)$. Thus, we can approximate the quality of the underwater channel between two nodes by analyzing the RSSI.

C. Energy Model

Each node in the network is equipped with a limited battery capacity. The energy consumption of a node depends on

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its transmission power consumption, reception power consumption, and idle power consumption [13]. Based on the earlier equations, The anticipated energy consumption for transmitting a packet is:

$$E_{tx}(m, t_{data}, P, A(d, f)) = m \times t_{data} \times P \times A(d, f) \quad (4)$$

where m means the data size in bytes and t_{data} represents the duration for transmitting a data message.

D. Goal and Constraints

The primary objective is to develop an adaptive transmission power control mechanism that minimizes the overall energy consumption in the network while ensuring reliable communication among nodes. Secondary objectives include maximizing the network lifetime, minimizing the transmission delay, and maximizing the packet delivery ratio.

The constraints for the problem include:

- Limited battery capacity: The energy consumption of each node must not exceed its battery capacity.
- Maximum allowable transmission power: The transmission power of each node must be within the predefined limits.
- Minimum required received signal strengh: The RSSI at the receiving node must be above a certain threshold to ensure successful communication.
- Communication range: The transmission power must be sufficient to reach neighboring nodes within the communication range.

In the next section, we will detail the proposed adaptive transmission power control mechanism that addresses these objectives and constraints.

V. Fuzzy Logic-Based Adaptive Transmission Power Control

In this section, we elucidate our proposed fuzzy logic-based adaptive transmission power control mechanism for underwater vehicle networks. Fuzzy logic is renowned for handling uncertain input data and adapting swiftly to changing environments, providing a cogent balance between complexity and optimality. The dynamism and complexity of underwater environments where energy efficiency and communication performance are paramount make fuzzy logic an excellent choice for our study.

A. System Overview

In this system, sink node periodically broadcasts a beacon message with its positional information. Upon receipt of this message, each mobile AUV calculates its distance to the sink node. These distances, combined with the current state of the channel and the energy consumption required for transmission over the calculated distance, serve as the input parameters for a fuzzy logic controller that we employ to optimize the transmission power for underwater communication. The fuzzy logic system is shown in Figure 2, where D is the distance between auv and sink node, E represents the energy consumption, and RSSI is the received signal strength at AUV side.

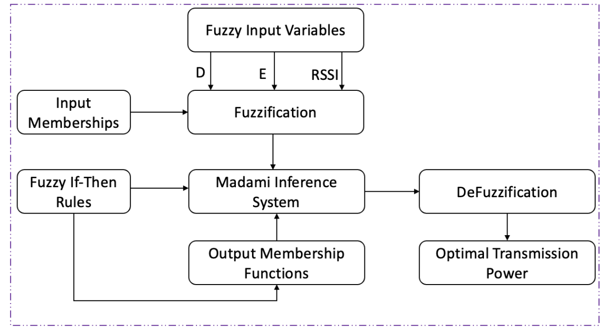

Fig. 2. Fuzzy Logic System

This fuzzy logic controller uses predefined fuzzy membership functions for each input variable and the output variable, transmission power. Based on these membership functions, a set of fuzzy rules is established to govern the relationship between these variables. By continuously recalculating their distances to the sink node and adjusting the input parameters of the fuzzy logic controller accordingly, the mobile nodes dynamically adapt their transmission power. This adaptive power control mechanism thereby ensures efficient communication with the sink node, taking into account the variable underwater channel conditions and distances. In addition to improving communication efficiency, it also helps conserve energy, enhancing the overall performance and sustainability of underwater vehicles systems.

B. Fuzzy Logic Control

Fuzzy logic control is a rule-based control method that employs linguistic variables and fuzzy sets to handle imprecise and uncertain input data [3]. In our adaptive transmission power control mechanism, we use fuzzy logic control to adjust the transmission power of each node based on variables including distance estimation, channel condition estimation, and energy consumption.

The fuzzy logic controller comprises:

- Fuzzy input variables: Distance estimation, received signal strength, and energy consumption.
- Fuzzy output variable: Transmission power.
- Fuzzy rules: If-then rules describing the relationships between input and output variables.
- Fuzzy inference system: A system using fuzzy rules to infer the appropriate output value based on input values.

1) Distance Membership Function: The membership functions for the 'distance' variable are divided into 'near', 'medium', and 'far', which cover the range of 0 to 3000 meters. 'Near' is characterized as a distance up to 2000 meters with maximum membership at distances up to 1000 meters. 'Medium' covers distances from 1000 to 3000 meters, peaking at 2000 meters. Finally, 'far' represents distances beyond 2000 meters, with full membership at 3000 meters. These divisions

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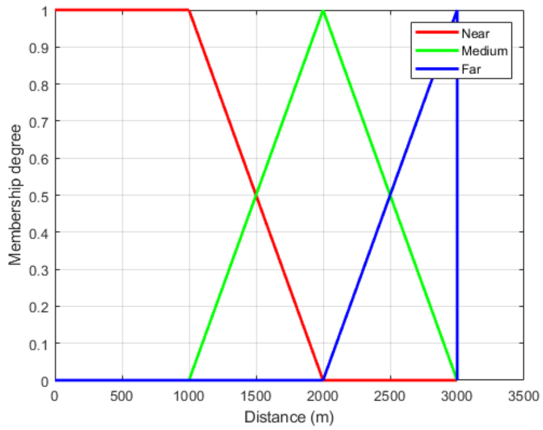

Fig. 3. Membership Function of Distance

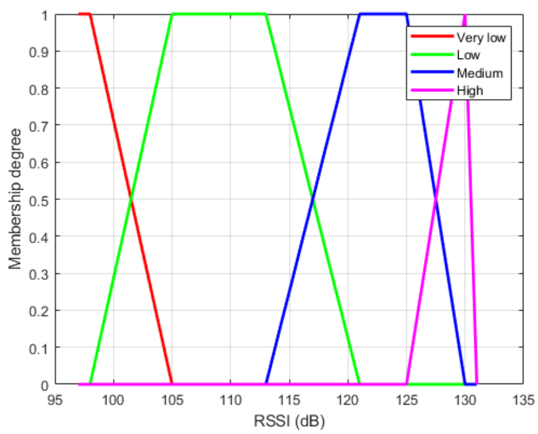

Fig. 4. Membership Function of RSSI

were defined based on extensive simulations. The membership function is shown in the Figure 3

2) RSSI Membership Function: The membership functions for 'rssi' are divided into 'very low', 'low', 'medium', and 'high', which span the range from 97 dB to 130 dB. These divisions reflect the various signal strength conditions the underwater communication devices might encounter, as determined through simulations. It was observed that most devices operate effectively within this range. Consequently, adjusting the transmission power according to the RSSI value allows for optimized communication efficiency and energy conservation. The membership function of RSSI is shown in Figure 4.

3) Energy Consumption Membership Function: The 'energy' variable, representing energy consumption, has membership functions divided into 'low', 'medium', and 'high', ranging from 30 to 128 joules. The divisions reflect the different levels of energy consumption that might occur during the operation of the devices, as observed in simulations. By incorporating energy consumption into the fuzzy logic controller, the system can make more effective decisions to balance communication performance and energy efficiency.

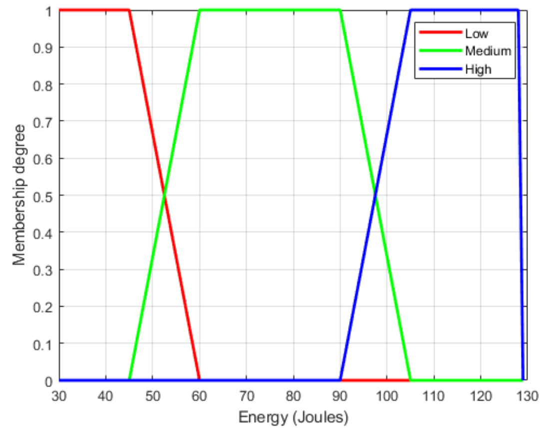

Fig. 5. Membership Function of Energy Consumption

The membership function of energy consumption is shown in Figure 5.

4) Fuzzy Rules: In our designed fuzzy logic system, we have crafted a comprehensive set of if-then rules that illustrate the relationship between the input variables (Distance, RSSI, Energy) and the output variable (Transmission Power). Based on the input values, these rules are used by the fuzzy inference system to determine the appropriate transmission power.

The purpose of these rules is that they provide a near-optimal solution that balances energy efficiency and communication performance in the underwater vehicles network. The fuzzy rules are shown in the Table I. The purpose of these rules is to provide a mechanism for adjusting the transmission power dynamically based on the current communication conditions and energy state. All these rules are encoded in our fuzzy control system, enabling our system to provide optimal transmission power settings under various circumstances.

Distance	RSSI	Energy Consumption	transmission power
far	low	low	high
far	low	medium	high
far	low	high	medium
far	very low	low	very high
far	very low	medium	very high
...	...	...	...
...	...	...	...
medium	high	low	medium
medium	high	medium	medium
medium	high	high	low

TABLE I
ALL POSSIBLE COMBINATIONS OF DISTANCE, RSSI AND ENERGY CONSUMPTION

VI. Performance Evaluation

To evaluate the performance of our fuzzy logic controller in dynamically adjusting the transmission power, a series of simulation experiments were conducted. The objective of these experiments is to validate whether our fuzzy control system can effectively balance energy efficiency and communication performance and provide optimal transmission power settings under various communication conditions and energy states.

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A. Experimental Setup

We utilized an UnetStack simulator to simulate an underwater vehicles network [7]. The simulator facilitates the realistic simulation of underwater acoustic communication and the mobility of AUVs. The primary parameters used in our simulations are listed in Table II.

Parameter	Value
Platform	RealTimePlatform
Channel Model	BasicAcousticChannel
Carrier Frequency	25 kHz
Bandwidth	4096 Hz
Spreading	2
Temperature	25°C
Salinity	35 ppt
Noise Level	60 dB
Water Depth	20 m
Rician K-factor	10
Fast Fading	True
Probability of False Alarm (pfa)	1×10^{-6}
Processing Gain	0 dB

TABLE II
SIMULATION PARAMETERS

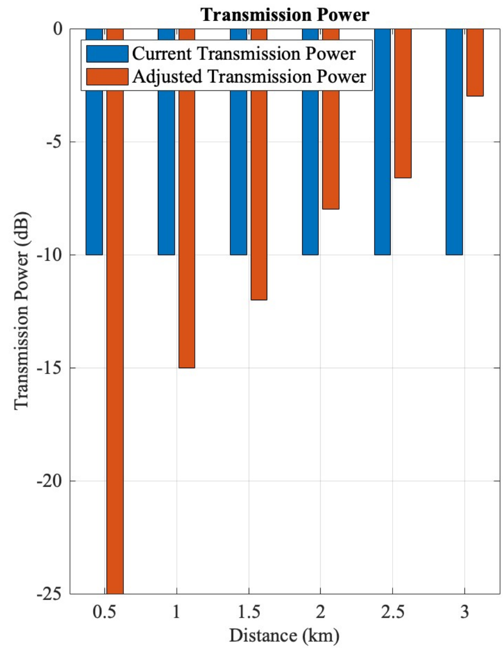

Fig. 6. Fuzzy Logic based Transmission Power Adjustments

B. Performance Analysis

In this section, we present the results of our experiments aimed at analyzing the performance of our power control strategy. Three key aspects were studied in depth: the adjustment of the transmission power, the energy consumption, and the packet delivery ratio.

1) Transmission Power Adjustment: As part of our experimentation, we examined how our power control mechanism adjusts the transmission power. Figure 6 shows the adjustments made at various distances.

The figure shows that the communication distance of the AUV increases from 0.5 kilometers to 3 kilometers, there is a noticeable decrease in the adjusted transmission power compared to the current transmission power. Initially, at a communication distance of 0.5 kilometers, the adjusted transmission power shows the most substantial decrease to -25dB, which is 15dB lower than the current transmission power. Then, as the communication distance increases, this decreasing trend gradually slows down. For instance, at a communication distance of 1 kilometer, the adjusted transmission power is -15dB, which is only 5dB lower than the current transmission power; whereas, at a distance of 2 kilometers, the adjusted transmission power is -8dB, which is merely 2dB lower than the current power. Finally, at a communication distance of 3 kilometers, the adjusted transmission power elevates to -3dB, which is 7dB higher than the current transmission power.

This pattern of power adjustment suggests that our system can dynamically adjust the transmission power based on the communication distance. In short-range communication, the system significantly lowers the transmission power to save energy. However, as the communication distance increases, the system gradually increases the transmission power to maintain a good communication quality. This observed pattern validates the system's capability to optimize transmission power and conserve energy, which is crucial for the AUV's long-term operation.

2) Energy Consumption: The energy consumption of our power control strategy is depicted in Figure 7.

The figure shows an essential trend in energy consumption for the Autonomous Underwater Vehicle (AUV) system. Both current and adjusted energy consumption figures escalate as the communication distance increases from 0.5 to 3 kilometers.

Interestingly, at shorter communication distances, such as 0.5 km, the adjusted energy consumption is significantly lower (17.16 Joules) than the current consumption (30.73 Joules). This improvement is due to our system's ability to efficiently lower transmission power, enhancing energy conservation. However, at a communication distance of 2 km, the adjusted energy consumption (130 Joules) exceeds the current energy consumption (121 Joules). This shift signals a pivotal point where the energy required for maintaining strong communication begins to outweigh the initial energy savings from power adjustments. Finally, at a communication distance of 3 km, the adjusted energy consumption rises further to 190 Joules, outstripping the current consumption of 177 Joules. This trend emphasizes a delicate trade-off in the system design between energy efficiency and communication quality.

In summary, the dynamic power adjustment strategy of our system effectively reduces energy consumption at shorter distances, but faces challenges at longer distances. This information provides a critical foundation for future work on optimizing power management strategies in AUV systems.

3) Packet Delivery Ratio: Based on the adjustments of transmission power, it appears that there is a significant impact

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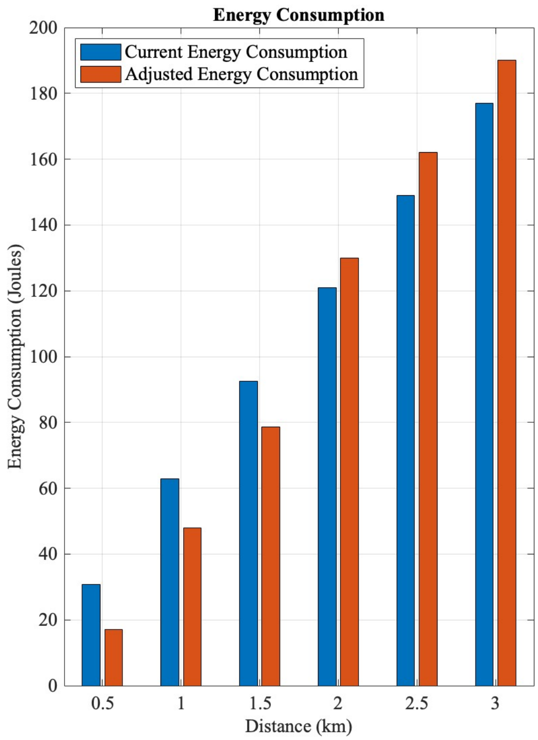

Fig. 7. Energy Consumption Comparison

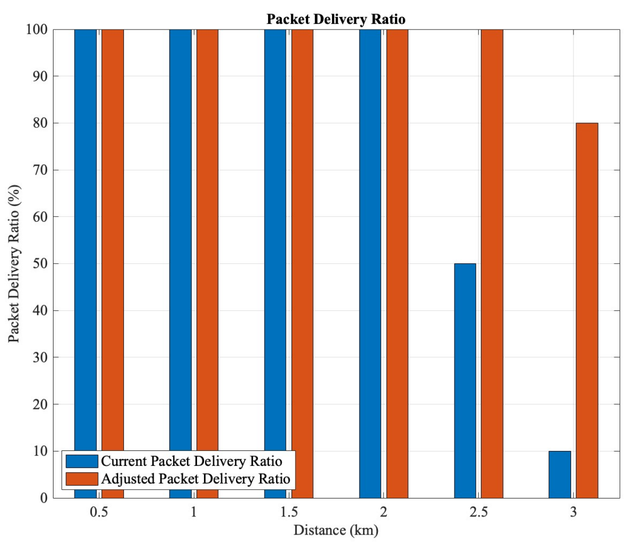

Fig. 8. Packet Delivery Ratio Comparison

on the packet delivery ratio (PDR) due to the adjustment of transmission power. The details are shown in Figure 8.

Initially, at distances ranging from 0.5 km to 2.0 km, there are no observable changes in the PDR - both current and adjusted values stand at 100 percents. This indicates that the adjustment in transmission power does not impact the packet delivery at these distances, suggesting an efficient power management. However, as the communication distance reaches 2.5 km, a noticeable discrepancy occurs. The current PDR drops to 50 percents, while the adjusted PDR remains at 100 percents. This trend suggests that the adjusted transmission power significantly improves the reliability of packet delivery at this distance. Further, at a communication distance of 3 km, the current PDR reduces drastically to 10 percents, while the adjusted PDR falls to 80 percents. Despite the decline, the adjusted PDR is still significantly higher than the current PDR, demonstrating the system's resilience in maintaining packet delivery despite increased distances.

In conclusion, adjusting the transmission power appears to maintain a high packet delivery ratio, particularly at longer distances, improving the overall efficiency and reliability of the communication system.

VII. Conclusion

In this study, we implemented fuzzy logic within Autonomous Underwater Vehicles' (AUVs) communication networks to adaptively modulate transmission power control, aiming to conserve energy and counteract the uncertainties of harsh underwater environments. Our simulation results demonstrate the system's ability to balance energy conservation, communication distance, and channel conditions, effectively enhancing the efficiency and reliability of underwater communication. This research confirms the potential of fuzzy logic as a viable tool for managing uncertainties in AUV communication networks and optimizing energy usage for varying underwater conditions.

Acknowledgements

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