

Energy Optimized Cross-Layer Routing Protocol for Underwater Acoustic Sensor Networks

Nisha A Somani¹, Nirbhay Kumar Chaubey²

¹Research Scholar, Computer Engineering Department, Gujarat Technological University, Ahmedabad, Gujarat, India

²Dean of Computer Science, Ganpat University, Gujarat, India

Abstract

UAWSNs are severely bandwidth-constrained with high propagation delay, highly dynamic topology and limited battery resources. The Channel-Aware Routing Protocol (CARP), which enhances reliability at the cost of link-quality-based forwarding, causes periodic traffic regardless of environmental events, thereby causing high energy consumption. This paper presents an Energy Optimized Cross-Layer Routing Protocol for Underwater Acoustic Sensor Networks (EO-CLR) that incorporates environmental temperature threshold zones into the routing process. The temperature goes off the normal status, the data will be sent. We deploy and evaluate the proposed scheme using ns-3 with Aqua-Sim-NG. Simulation results indicate that the proposed technique outperforms conventional CARP in terms of residual energy, network lifetime, and channel congestion.

In this paper we study the cross layer routing in multisource under water sensor networks under analyzing energy efficient Cross layer Routing Protocol and simulation using network simulator (ns3) along with temperature.

Keywords: UWSN, USN, Cross layer routing, Energy efficient, CARP, ns3, temperature

1. Introduction

UWSNs are facilitated in the marine environment to collect data for environmental monitoring, offshore exploration, and disaster prevention. Different from Li-Fi and 5G networks, underwater communication is established using acoustic waves which lead to long propagation delay, low data rate, elevated bit error rate and power-hungry transmission. Thus, routing protocols must consider energy efficiency while ensuring reliability. Although the traditional CARP[2] selects the proposed and perceived channel to access its quality and hopcount number, it does not focus on sensed data application-layer significance. When environmental conditions are normal, redundant data packet transmission occurs which increases the rate of energy exhaustion for periodic sensing and transmission. To cover up this limitation, we propose Energy Optimized Cross-Layer Routing Protocol (EO-CLR) that embeds an environmental parameter of temperature, as threshold in routing decisions to control unwanted transmissions thus prolonging the network lifetime.

2. Related Work

Underwater Wireless Sensor Networks (UWSNs) have received a lot of attention lately owing to their applications in ocean monitoring, environmental sensing and aquaculture, but they also introduce several

challenges such as limited energy, huge propagation delay, dynamic topology and unreliable acoustic communication. These challenges have led to the proposal of some Routing Protocol. Ahmed et al. proposed an energy-efficient clustering and redundant transmission control scheme, which minimizes inessential retransmissions and prolongs the network lifetime. Basagni et al. proposed the Channel-Aware Routing Protocol (CARP), which chooses routes according to link quality, thus enhancing packet delivery performance. Khalid et al. proposed the E2MR multipath routing protocol to achieve more reliability and energy efficiency, whereas Wadud et al. These include an energy-balanced routing protocol by Yang et al. Zhu et al. have suggested opportunistic and vector-based routing strategies and Thiagarajan, respectively, to enhance scalability and decrease energy consumption. Zhang et al. proposed a routing protocol for delay-sensitive applications considering real-time constraints regarding the communication time. Martin et al. proposed a tracer-assisted named data routing method to accommodate and reduce routing overhead, which otherwise perturbs the efficiency of retrieving data. Khalid et al. also proposed a guiding network based routing protocol for improving energy consumption and net lifetime. Additionally, Uddin et al. - provided an overview of different routing protocols for wireless sensor networks and their performance factors, while ICAR and FAO highlighted the usefulness of underwater monitoring in fisheries and aquaculture. However, challenges still exist involving reliability, throughput and reality implementation remains open research problems highlighting the potentiality of UWSN routing protocols. Shortcomings and research gaps evident from these studies include: many proposals reduce redundancy through similarity, depth, or energy metrics rather than by prioritizing semantically important sensor readings; relatively few explicitly integrate application layer significance into forwarding decisions.

CARP is intended to handle dynamic underwater acoustic channels by incorporating estimation of link quality in the routing selection. Forwarders are chosen based on channel link quality and residual energy level allowing to reach higher reliability than pure geographic protocols [2]. Standard routing protocols prioritize link quality and hop count. Unfortunately, they provide no built-in event driven mechanism to minimize unnecessary transmissions.

Wireless sensor networks employ an event-driven protocol design approach for energy-efficient communication, where periodic data transport is used only when a relevant event has occurred (Liu et al., 2015). However, in underwater environment, it has been found that continuous sensing and infrequent reporting caused multiple redundant transmissions with a huge amount of energy consumption leading to the congestion of the channel as well as reduce network lifetime. To overcome this challenge, an event-driven mechanism with a temperature threshold is presented whereby sensor nodes only send data once the sensed temperature exceeds or falls below a given threshold value.

This is a prevalent issue in aquaculture [12] and natural aquatic environments since keeping water temperature within the proper range is crucial to ensure healthy life. The ideal thermal environment necessary for the best physiological performance and health tolerance of numerous warm-water fish species lies within a temperature range of 21 °C and 29 °C. Within this range, metabolic processes such as digestion, respiration, growth and the immune response are optimal promoting faster growth rates and lower stress levels. Below 20°C, metabolic processes run slower, appetite decreases and immunity to pathogens weakens — above 30°C oxygen demand increases which causes decreased levels of dissolved oxygen and cause thermal stress thereby rendering the fish more susceptible to microbial infections. Thus, water temperature in the range of 21–29°C keeps metabolic activities in balance and maximizes feed conversion efficiency and overall survival rates. This is a particularly important aspect of fish

health management, and sustainable fish production can be dramatically improved with the addition of temperature as part of a bio-physical factor triad when other environmental requisites are considered (e.g., major water quality parameters) to monitor aquaculture systems. During the stable environmental period, such a threshold-based decision process can effectively suppress undesirable transmissions so that battery power can be saved and end-to-end delay caused by channel contention is avoided. Furthermore, the algorithm may be complemented with adaptive threshold tuning, allowing it to adaptively set its level of sensitivity depending on background changes for higher reliability and responsiveness. The proposed protocol limits the communication to critical events that can significantly enhance the packet delivery ratio, improves throughput efficiency, extends overall network lifetime so that it be efficient for underwater acoustic sensor networks and environmental monitoring applications. The new protocol EO-CLR includes temperature thresholds (20 °C–30°C). Such temperature-dependent limits can enhance reliability when critical environmental changes are taking place and save energy during non-critical communication times, by allowing data transmission only in case sensed temperature exceeds these bounds.

3. Proposed Algorithm

Temperature thresholds between 20°C and 30°C are enabled in the EO-CLR framework for event-driven communication. Instead of repeatedly transmitting every period, the sensor nodes transmit their data only when the measured temperature 30°C. Such a mechanism also eliminates unnecessary traffic and improves channel efficiency. A multi-parameter metric based on channel quality, hop count, residual energy and temperature priority indicator is used to decide routings. It gives more weight to nodes that find abnormal environmental situations, they can be assured of timely and reliable delivery of critical data with greater energy efficiency.

Mathematical Model

Transmission Trigger Function:

$T_trigger = 1$, if $(T < 21^{\circ}\text{C}$ OR $T > 29^{\circ}\text{C})$;
else 0

Proposed Algorithm

Energy Optimized Cross-Layer Routing Protocol (EO-CLR)

Step 1: Sense temperature T .

If $T_trigger = 0$

End; Step 2 otherwise

Step 2: Network Setup phase N :number of nodes in the network

Sink node broadcast $\langle\text{Hello}\rangle$ pkt , hopCount $H_C = 1$

For each node N_i in N that reply

returns $\langle\text{Link Quality}(L_{qik})\rangle$

Forwarder Selection:

Compute Link Quality L_q ,

Residual Energy E_{res} ,

Hop Count H_c of all candidate nodes.

Select node with maximum score.

Step 3: Forward packet.

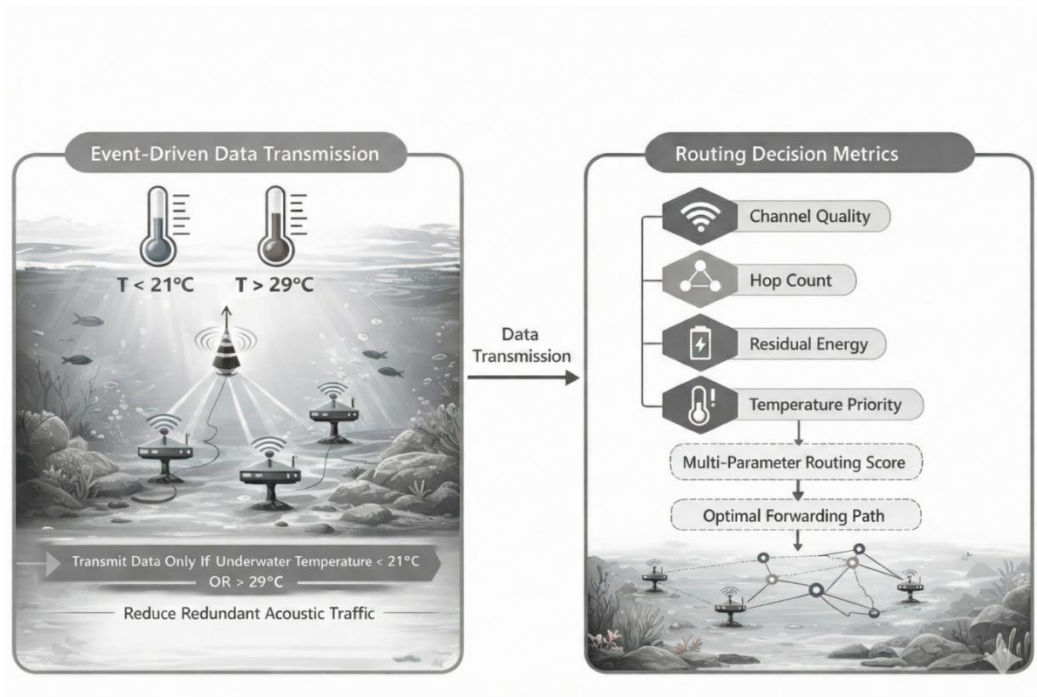


Fig 1: Energy Optimization Framework

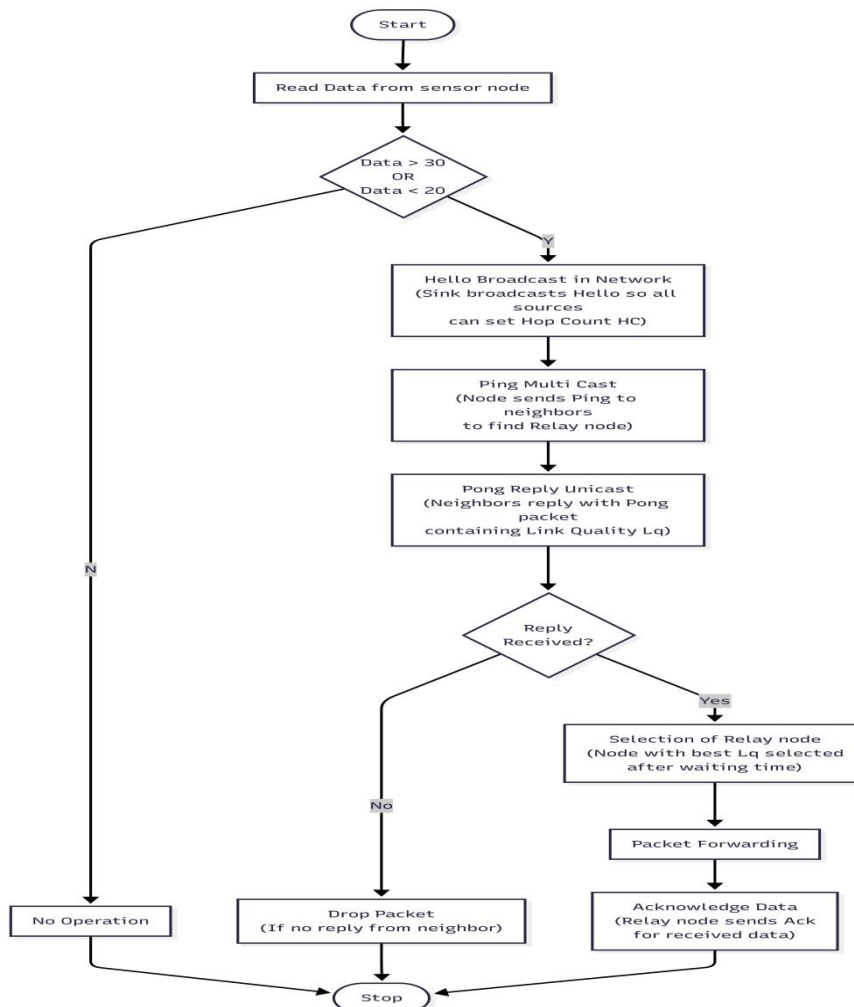


Fig 2: EO-CRP Flowchart

The implementation and evaluation of the proposed algorithm is performed using the NS-3 network simulator[14]. The parameters of the simulation for the experimental setup are shown in **Table 1**. In our study, we analyze scalability and performance by varying the number of sensor nodes from 50, 75 to 100 in different simulation runs. We compare the performance of our proposed EO-CLR protocol with that of the conventional CARP protocol. The performance metrics such as throughput, packet delivery ratio (PDR) and energy consumption are measured and analyzed. Findings show that EO-CLR outperforms CARP in terms of network performance and energy efficiency under different node density levels.

Table 1: Simulation parameters

Deployment depth and area	100 X 100 X 100m ³
Sink node at surface or edge	3
Number of nodes N	50
Initial Energy	250J
Transmission Power consumption	1.6W
Receiving power consumption	1.2W
Idle power consumption	0.008W

4. Results and Performance Metric

Throughput is defined as the amount of data successfully delivered by the network in a given time interval, typically expressed in bits per second (bps) or as a percentage of successful data transfer. It indicates how efficiently and effectively the network can manage data transfers. Without a doubt, high throughput is associated with better use of network resources and great communication quality. Simulation Results: As seen, EO-CLR gives much higher throughput as compared to CARP, it handles increased network load and node density effectively than the CARP algorithm.

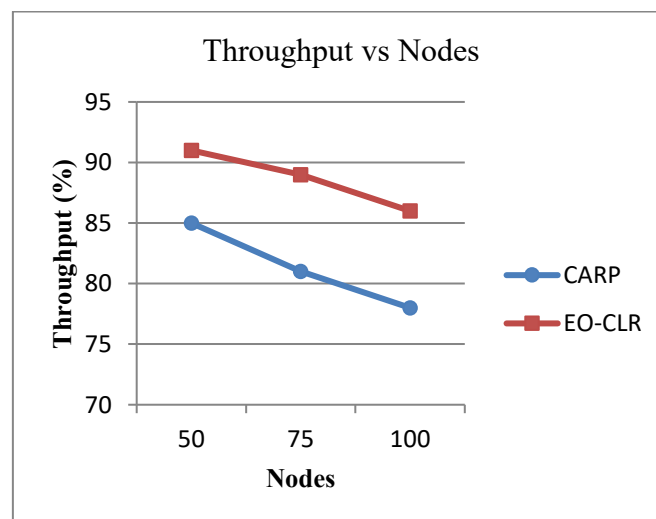


Fig 2: Throughput Vs Nodes

Energy consumption is an important factor in sensor networks, since nodes are usually battery operated and have limited energy that is hard to recharge or replace. It is the cumulative energy consumed by nodes in communication activities like transmission, reception and routing operations. The energy

consumption of the protocol is said to be low, which in turn increase the lifetime of network through increased energy efficiency. Finally, the predicted protocol (EO-CLR) has successfully decreased energy consumption as compared to CARP by reducing repetitive transmissions and improving routing decisions in order to increase the operational lifetime.

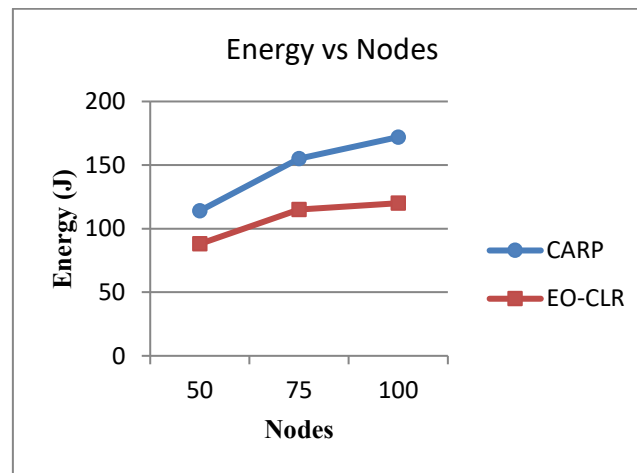


Fig 3: Energy Vs Nodes

Conclusion

In this work, an energy-optimized cross layer routing protocol, EO-CLR, was proposed and evaluated using the NS-3 simulator. The performance of the proposed protocol was compared with the conventional CARP protocol under varying node densities of 50, 75, and 100 nodes. Simulation results demonstrated that EO-CLR achieves higher throughput and packet delivery ratio while significantly reducing energy consumption. The improved performance is mainly due to optimized routing decisions and reduced redundant transmissions. Overall, the proposed EO-CLR protocol enhances network reliability, efficiency, and lifetime, making it suitable for large-scale sensor network deployments. Future work include AI-based routing optimization and real-world deployment testing.

References

1. Ahmed G, Zhao X, Fareed MMS, Fareed MZ. An energy-efficient redundant transmission control clustering approach for underwater acoustic networks. *Sensors*. 2019;19(19):4241. doi:10.3390/s19194241
2. Basagni S, Petrioli C, Petrocchia R, Spaccini D. CARP: A channel-aware routing protocol for underwater acoustic wireless networks. *Ad Hoc Networks*. 2015;34:92-104. doi:10.1016/j.adhoc.2014.07.014
3. Khalid M, Ahmad F, Arshad M, Khalid W, Ahmad N, Cao Y. E2MR: Energy efficient multipath routing protocol for underwater wireless sensor networks. *IET Networks*. 2019;8(5):321-328. doi:10.1049/iet-net.2018.5203
4. Martin R, Cui JH, Han S. Tracer assisted passive named data routing for underwater sensor networks. In: *Proceedings of OCEANS 2014 Taipei*; April 2014. doi:10.1109/OCEANS-TAIPEI.2014.6964560

5. Thiagarajan R, Balajivijayan V, Krishnamoorthy R, Mohan I. A robust, scalable, and energy-efficient routing strategy for UWSN using a novel vector-based forwarding routing protocol. *J Circuits Syst Comput.* 2022;31(15). doi:10.1142/S0218126622502656
6. Tran-Dang H, Kim DS. Channel-aware energy-efficient two-hop cooperative routing protocol for underwater acoustic sensor networks. *IEEE Access.* 2019;7:63181-63194. doi:10.1109/ACCESS.2019.2916185
7. Wadud Z, et al. An energy balanced efficient and reliable routing protocol for underwater wireless sensor networks. *IEEE Access.* 2019;7:175980-175999. doi:10.1109/ACCESS.2019.2955208
8. Zhang S, Wang Z, Liu M, Qiu M. Energy-aware routing for delay-sensitive underwater wireless sensor networks. *Sci China Inf Sci.* 2014;57(10):1-14. doi:10.1007/S11432-013-4957-8
9. Zhu R, Huang X, Huang X, Li D, Yang Q. An on-site-based opportunistic routing protocol for scalable and energy-efficient underwater acoustic sensor networks. *Appl Sci.* 2022;12(23):12482. doi:10.3390/app122312482
10. Energy-efficient guiding-network-based routing for underwater wireless sensor networks. *IEEE Internet Things J.* 2022;9(21):21702-21711. doi:10.1109/JIOT.2022.3183128
11. Uddin MA, Mamun M, Rashid M, Rahman MM. Performance analysis of routing protocols for wireless sensor networks. *Int J Comput Netw Inf Secur.* 2013;5(12). doi:10.5815/ijcnis.2013.12.01
12. Indian Council of Agricultural Research. *Handbook on Fisheries and Aquaculture.* New Delhi, India: ICAR Publications; 2011.
13. Food and Agriculture Organization. *Development of Aquaculture: Reproduction and Gamete Manipulation.* FAO Fisheries Technical Paper. Rome, Italy; 2018.
14. ns-3 Simulator. Accessed February 2026. <http://www.nsnam.org>
15. Aqua-Sim Next Generation Documentation. Accessed February 2026. <https://github.com/rmartin5/aqua-simng>