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A Comprehensive Review on Cluster-Oriented Routing Protocols for Underwater Wireless Sensor Networks

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Abstract: Underwater Wireless Sensor Networks (UWSNs) have emerged for various tasks in marine environments. Routing Protocols (RPs) in UWSNs face challenges such as high propagation delay, Energy Consumption (EC), low bandwidth, and low throughput compared to Terrestrial WSNs (TWSNs). UWSNs operate autonomously without human intervention, and the limited energy of sensor batteries poses a significant challenge. Uneven energy resource utilization reduces network longevity, which is a major issue in UWSNs. To combat these issues, a promising approach involves the design of RPs employing clusters for efficient packet routing from source to destination. This paper systematically reviews recent Cluster-oriented RPs (CRPs) in UWSNs, organizing them chronologically. It assesses their merits, drawbacks, and overall network performance, offering insights into future directions for improvement in this domain.

Keywords: UWSN, Marine environment, Cluster-oriented routing, Acoustic communication, Energy efficiency, Network lifetime

I. INTRODUCTION

Oceans are vital for human survival and provide natural resources and marine defense. Scientists are increasingly using UWSNs to monitor oceanic regions. Underwater Optical Wireless Communication (UOWC) technology uses Radio-Frequency (RF), acoustic, and optical waves to transmit data in aquatic environments. However, TWSNs are ineffective in underwater environments due to unique properties like temperature and pressure. Underwater optical communication, like BlueComm and Ambalux, has a data transmission range of around 100 meters [1]. Acoustic communication is suitable for long-distance communication in deep water but is attenuated in saltwater, causing delays.

A. Architectures of UWSN

UWSNs have four types of architectures [2], as illustrated in Figure 1, including:

- **One-Dimensional (1D)-UWSN:** 1D UWSN describes sensors that independently sense, process and transmit data to the Base Station (BS). A buoy that senses the qualities of the water is an example of this; it can submerge for a set amount of time to gather data, then float back to send a signal to the BS.
- **Two-Dimensional (2D)-UWSN:** It consists of clusters of sensor nodes submerged in water. Each cluster has a Cluster Head (CH), or anchor node, and is fixed in place at the water's surface. Data collected by the cluster members is transmitted to the anchor node, which then sends the data to the surface buoyant nodes. Communication in a 2D-UWSN occurs in two dimensions: horizontally between cluster members and their anchor nodes, and vertically between anchor nodes and surface buoyant nodes.
- **Three-Dimensional (3D)-UWSN:** This type of building consists of clusters located at different sea depths. Communication takes place between nodes within the clusters, between CHs, and ultimately between the CHs and the surface. This scenario is not limited to 2D-UWSN.
- **Four-Dimensional (4D)-UWSN:** Similar to 3D-UWSN, 4D-UWSN consists of clusters and Remotely Operated Underwater Vehicles (ROUVs) located at different sea depths. The ROUV collects data from the CHs and transmits the signals directly to the buoy or relays them based on their position.

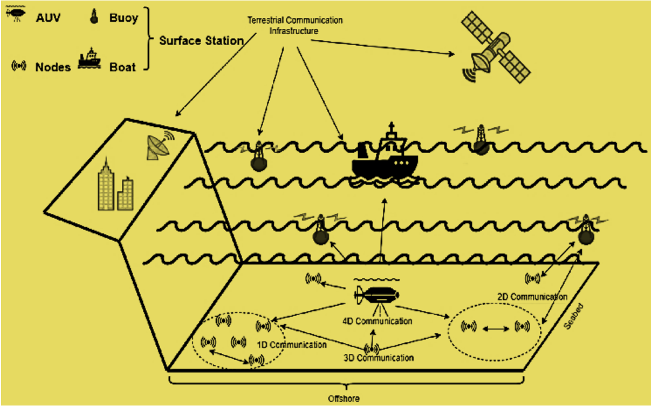

Figure 1. Architecture of UWSN

B. Requirements of UWSN

According to Fattah [3], the fundamental requirements for acoustic communication include:

- **Lifetime:** When deploying UWSN, the lifespan of nodes and the network is critical. Harsh marine conditions make it challenging to replace nodes, impacting performance and cost.
- **Transmission range:** UWSN sensor nodes are grouped and rely on communication with each other, so deployment strategy and communication technique depend on the nodes' transmission range. Acoustic signals are commonly used for underwater communication, but they have drawbacks such as

low data rate, propagation, latency, delay, and potential harm to aquatic life.

- **Node placement:** It is crucial for routing, as algorithms determine the best route for message transmission. Simple methods and optimal node placement are essential to conserve energy and prolong the lifespan of nodes and networks, as complex algorithms consume more energy.
- **Security and privacy:** In high-risk situations, nodes face threats and attacks. Building trust between communication nodes is essential to protect data.
- **Ecological sustainability:** UWSN's main goal is to monitor marine life, so it's important to implement the network without harming any organisms. The variables on the list are mainly related to the chemical and physical properties of the water, such as temperature, salinity, density, and their changes over time and space.

C. *Features of Communication in UWSN*

TWSNs and UWSNs aim to meet application requirements and facilitate data transfer between nodes. However, radio waves weaken in underwater environments, and optical signals have a limited range due to environmental factors [4]. Acoustic signals, which can travel up to 1.5 km, are suitable for underwater communication due to their low attenuation over long distances. Table I compares optical, acoustic, and radiofrequency communication characteristics.

Table I. Various Characteristics of UWSN Transmission

Features	Optical transmission	Acoustical transmission	RF transmission
Bandwidth	10 – 150 MHz	~1 Hz	~ 1 kHz
Frequency band	~1014 – 1015 Hz	~1 kHz	~1 MHz
Propagation speed	3×10^8 m/s	1.5×10^3 m/s	3×10^8 m/s
Signal attenuation	High	Low	Very high
Antenna size	0.1 m	0.1 m	0.5 m
Operational range	10 – 50 m	1000 m	10 m
Communication range	10 – 100 m	1500 m	30 m
Qualities	Low power utilization, high data rate, and low equipment cost	High power utilization, medium data rate, and high equipment cost	

TWSNs and UWSNs require active network nodes for smooth data flow. TWSNs have a constant power source, while UWSNs have a limited power supply and can be shortened due to high consumption [5]. Factors like node density, data integration, sleep time, energy-saving algorithms, and direction-finding rules must be investigated to extend UWSNs' lifespan. Table II outlines the key characteristics that distinguish TWSNs from UWSNs, all of which are crucial for enhancing network functionality and longevity.

Table II. Major Variations between Features of TWSNs and UWSNs

Characteristics	TWSN	UWSN
Localization	GPS assistance	GPS non-assistance
Link stability	Stable	Unstable
Communication range	10 – 100 m	Up to 2 km
Transmission speed	3×10^8 m/s	1.5×10^3 m/s
Energy utilization	High	High
Data rate	High	Low
Bandwidth	Limited	Limited
Bit per second rates	High	Low
Transmission delay	Small and steady	Extended and flexible
Noise	Low-influence	High-influence
Collective association method	Radio signals	Acoustic signals

D. *Applications of UWSN*

UWSNs are increasingly utilized in various sectors, as shown in Figure 2, such as deep sea surveillance, resource discovery, offshore oil and gas production, military surveillance, pollution monitoring, natural disaster forecasting, and coral reef monitoring [6].

- **Monitoring applications:** Underwater monitoring uses a network of sensors to observe the undersea environment, including habitat conditions, water quality, and underwater expeditions. It is crucial for the survival of living organisms. Also, it is used for ecosystem monitoring, resource exploration, and underwater cable and pipeline monitoring.
- **Disaster:** UWSNs are crucial for monitoring and mitigating the impact of natural disasters, including floods, earthquakes, tsunamis, and oil spills. They provide timely flood alerts, detect seismic changes, and aid in prompt cleanup efforts for marine life.
- **Military:** UWSNs are utilized in military applications for detecting underwater mines, securing ports, and locating submarines, providing a cost-effective alternative to traditional methods.
- **Assisted navigation:** Underwater navigation is challenging due to dark, unpredictable landscapes, necessitating assistive navigation technologies like UWSN to aid in navigation in this challenging environment.
- **Sports:** Underwater sports use UWSN applications, utilizing RF transceivers and optical signals, with 2D architectures and CHs for communication in low-coverage areas like pools.

E. *Routing Protocols for UWSNs*

UWSNs are essential for defining isolated subsurface directing procedures, which are categorized based on their methodologies [7], including:

- **Flooding-based Protocols:** It communicates data to all sensor nodes in a specific region, requiring minimal system data, but consuming more energy due to packet communication.
- **Multipath-based Protocols:** It enhances system reliability by reducing the number of paths from source to destination and increasing the packet conveyance proportion.
- **Cluster-based Protocols:** Sensor nodes are grouped into clusters, consisting of CHs and cluster member nodes. The cluster member nodes collect data and send it to their respective CH, which then coordinates the transmission schedule for its member nodes. Figure 3 illustrates the structure of cluster-based UWSNs.

Numerous routing schemes have been created to achieve energy-efficient data collection and routing in underwater environments [8-9]. This paper focuses on the comprehensive review of CRPs for UWSNs designed to improve energy-efficient data collection and routing. The main objective is to enhance understanding of current CRPs for UWSNs and identify open research problems for further analysis and research. The rest of the article is structured as follows: Section II reviews recent CRPs in UWSNs. Section III concludes the review and suggests potential future directions in this field.

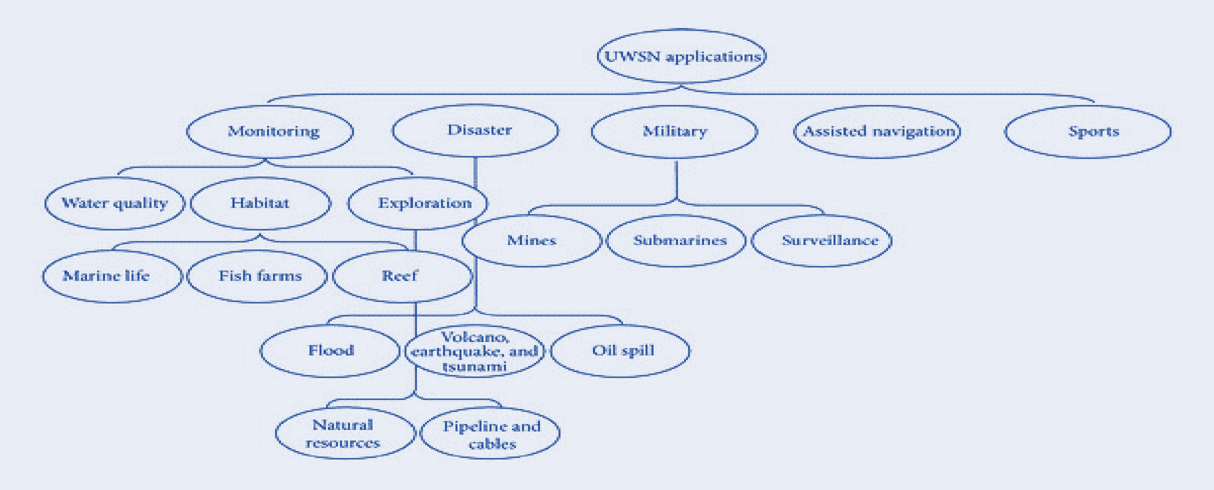

Figure 2. Taxonomy of UWSN Applications

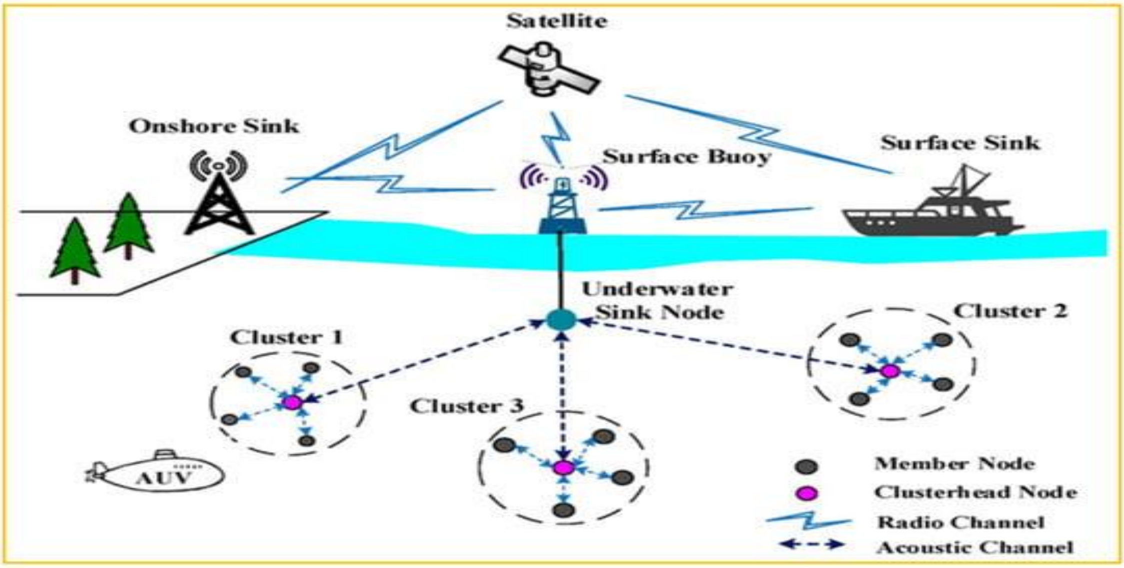

Figure 3. Structure of Cluster-Based UWSN

II. COMPARATIVE REVIEW OF CLUSTER-ORIENTED ROUTING PROTOCOLS IN UNDERWATER WSN

Karim et al. [10] developed two network architecture schemes with multiple sinks: Anchor Nodes assisted CRP (ANCRP) and Void Handling technique in ANCRP (VH-ANCRP). The network space was divided into clusters, with each cluster assigned an anchor node as the CH. In ANCRP, source nodes sent data to their designated CH, which then transmitted the data to the next-hop CH until it reached the surface sinks. The VH-ANCRP used a void handling technique to reconnect void nodes with the network operations by creating ad-hoc CHs.

Omeke et al. [11] introduced a novel protocol known as distance- and Energy-constrained K-means Clustering (DEKCS) for CH selection in UWSNs. Initially, optimal CHs were chosen based on their location and remaining battery level. Then, the residual energy thresholds for optimal CHs were adjusted dynamically to prevent network disconnection. Additionally, the elbow method was utilized to dynamically determine the optimal number of clusters based on the network size, thereby ensuring network scalability.

Nguyen et al. [12] proposed an Energy-Efficient Clustering Multi-hop Routing (EECMR) scheme for UWSNs to extend the network lifetime by balancing EC. The network area was divided into layers based on depth level, and data sensed by nodes was transmitted to a sink using a multi-hop routing path. The CHs were selected based on node depth and residual energy, and they aggregated data packets from cluster members before forwarding them to the sink.

Chinnasamy et al. [13] proposed an Energy-Aware Multi-level Clustering (EAMC) algorithm for UWSNs to improve the network lifespan. Clustering was performed based on residual energy and distance to the block center. When the energy fell below a certain threshold, CH rotation was carried out to balance the load. Subramani et al. [14] developed a Metaheuristics-based CRP for UWSN, called MCR-UWSN, to select efficient CHs and paths to the destination. The protocol includes the Cultural Emperor Penguin Optimizerbased Clustering (CEPOC) method for cluster construction and Multi-Hop Routing with the Grasshopper Optimization (MHR-GOA) algorithm using multiple input parameters.

Mohan et al. [15] developed the IMCMR-UWSN protocol, an Improved Metaheuristics-based Clustering with Multihop RP for UWSNs. The protocol utilized the Chaotic Krill Herd Algorithm (CKHA) to choose CHs based on the residual energy, intra- and inter-cluster distance. Additionally, the Self-Adaptive Glowworm Swarm Optimization (SA-GSO) scheme was employed to determine the optimal multi-hop routes by considering the residual energy, delay, distance, and trust.

Li et al. [16] proposed a Location and Energy-aware K-means Clustered Routing (LE-KCR) scheme. This scheme takes into account the location of a candidate cluster-head, its remaining energy, and the distance to the sink node in the cluster-head selection process. Additionally, it utilizes a dual-hop routing technique for the edge nodes to address the issue of some nodes being inaccessible to the entire UWSN due to the limited transmission range of their clusters.

Lilhore et al. [17] developed a depth-controlled, energy-balanced RP for UWSNs using an improved genetic algorithm (IGA) to find the best multi-hop routing paths for CHs. The protocol focuses on a modified encoding method that uses chromosomes to encrypt routing paths and genes to represent nodes. In addition, they enhanced the data fusion operation using a Back Propagation Neural Network (BPNN) with a highly optimized momentum technique to improve energy efficiency by reducing data duplication and transmission.

Rizvi et al. [18] proposed the Energy Efficient Circular Spinning (EECS) dynamic clustering technique for UWSNs to optimize cluster setup and reduce EC. Bai & Jin [19] developed a routing algorithm for UWSNs using a combination of K-means and Ant Colony Optimization (KACO). First, the underwater area was divided into layers based on depth, and nodes within each layer were clustered using an optimized K-means algorithm. Then, the CHs were selected based on node energy and distance from the sink node. Also, the ACO algorithm was improved by introducing the Gini coefficient for inter-cluster routing.

Shah et al. [20] proposed a Cluster-based cooperative Energy Efficient Routing (CEER) protocol for UWSNs. The main concept was to enhance network lifetime and energy efficiency through clustering and cooperation mechanisms. The network was partitioned into clusters with CHs responsible for data collection and transmission. Node cooperation was employed to optimize data forwarding and achieve load balancing. Kaveripakam & Chinthaginjala [21] developed a Clustering-based Dragonfly Optimization (CDFO) algorithm for decentralized forwarding in UWSNs. Initially, the fitness of each dragonfly was evaluated by considering EC and network coverage. Subsequently, the algorithm determined the optimal number of clusters for effective data transmission in UWSNs.

Bharany et al. [22] introduced an energy-efficient clustering algorithm for UWSNs that utilizes optimized GSO. The algorithm incorporates a method for determining the optimal number of clusters and selecting the most suitable CH. Additionally, an aggregation technique was employed to transmit information to the BS with minimal redundancy. A novel fitness function was developed, taking into account luciferin value, residual energy, and overall network EC, which was then utilized to select CHs.

Ragavi et al. [23] proposed a Clustered Distance Vector-based Geographical Opportunistic Routing (CDVGOR) protocol for UWSNs to efficiently transmit data. If the clustered data was transmitted over a non-communicating range or a sensor node with minimal energy, it was considered a void node or dead node. Initially, the shortest path with a minimal hop count was determined, and the void node was updated with an infinite hop count. Then, the proposed model incorporates sleep/wake scheduling, a waiting mechanism, and a periodic beaconing algorithm to achieve a higher Packet Delivery Ratio (PDR) with minimal EC.

Sathish et al. [24] proposed the Member Nodes Supported Cluster-Based RP (MNS-CBRP) for UWSNs to ensure reliable data transmission rates using the network's member nodes. The protocol involved creating clusters by dividing the network's space into small circular sections and selecting the CH for each circle. Source nodes in the MNS-CBRP were responsible for transmitting the collected data to the CH, which then forwarded the data to the next CH until all data packets reached the surface sinks.

Vahabi et al. [25] introduced a novel Cluster-Based Depth Source Selection Routing (CBDS2R) protocol for UWSNs. The network utilized a 3D architecture with mobile sink nodes located on the surface, while sensor nodes were randomly deployed underwater. Clustering was performed based on the link quality between nodes. Within each cluster, nodes at lower depths were chosen as source nodes for data sensing and transmission. Routing was determined by selecting adjacent nodes with good link quality and the highest remaining energy. Table 3 compares the advantages, limitations, and network performance of CRPs in UWSNs.

Table III offers a detailed overview of CRPs in UWSNs, emphasizing their impact on energy efficiency. Each protocol has distinct advantages and drawbacks, shedding light on the routing complexities in UWSNs. The assessment of these protocols has centered on key metrics including PDR, network lifetime, EC, and packet reception.

Table III. Comparative Study of Cluster-oriented Routing Protocols in UWSNs

Ref. No.	Protocols	Advantages	Limitations	Network Performance
[10]	VH-ANCRP	It achieved reliable data transmission and solved the void node problem.	EC was still high.	Mean PDR = 99%; Mean network throughput = 475Kbps; Mean End-to-End (E2E) delay = 2.85sec; Mean EC = 650J; Mean network lifetime = 785sec
[11]	DEKCS	It leads to a lower number of dead nodes per unit interval.	It did not consider the trade-offs between coverage, delay, and reliability.	No. of nodes alive = 168; No. of dead nodes = 40; Residual energy = 140J
[12]	EECMR	It resulted in higher residual energy, longer network lifetime,	Multi-hop routes can cause high latency, and the high EC at the cluster	Total dead nodes = 30; Residual energy = 3.1J; Received packets at the sink = 800

		and more packets received at the sink.	relay between depth levels may lead to frequent re-clustering.	
[13]	EAMC	It improved network lifetime and energy efficiency.	Finding the best number of CHs was difficult, and static clustering can result in unbalanced clusters when nodes fail.	Network lifetime = 2580 rounds; Mean residual energy = 0.69J; EC = 3.8×10^{-3}J
[14]	MCR-UWSN	It reduced EC and extended the network's lifespan.	High node mobility may impact network performance.	First node dies = 852 rounds; Last node dies = 1187 rounds; Total EC = 68%; No. of received packets = 27500
[15]	IMCMR-UWSN	It increased the network lifetime and throughput.	EC was still not efficient.	No. of alive nodes = 230; No. of dead nodes = 80; Total EC = 78%; No. of packets received = 22187
[16]	LE-KCR	Reduced EC and extended network lifetime.	The limited transmission range can reduce scalability and connectivity for larger networks.	No. of dead nodes = 3; Residual energy = 1.9mJ; Death rate of nodes = 0.44
[17]	IGA and BPNN	It can reduce redundant transmissions, resulting in low EC.	Data fusion can cause delays for time-critical data. Also, time complexity and overhead were high.	Total EC = 16%; PDR = 88%; Packet loss ratio = 21%; No. of nodes alive = 50;
[18]	EECS	It can reduce EC per round efficiently.	High latency for multi-hop clustered UWSNs.	EC = 47J; Network lifetime = 777 rounds
[19]	KACO	It can improve the efficiency of energy and packet transmission.	It was limited to isomorphic networks.	No. of dead nodes = 45; Mean residual energy = 3J; No. of packets received at the sink = 600
[20]	CEER	It improved network lifetime and energy efficiency.	The PDR was low due to high node mobility.	Mean E2E delay = 17.39s; Mean total EC = 9.273J; PDR = 53.95%;
[21]	CDFO	Improved network lifetime and packet reception.	It did not consider the impact of the EC, PDR, and residual energy.	No. of packets received = 9311; Network lifetime = 1120 sec
[22]	Optimized GSO	Prolonged network lifespan and preserved energy.	The performance depends on stationary node positions and low mobility.	First node dies = 704 rounds; Last Node Dies = 987 rounds; Total EC = 48%; No. of packets received = 23234
[23]	CDVGOR	Improved PDR and reduced mean EC.	Frequent rediscovery of routing paths was necessary due to high mobility and topology changes.	Network lifetime = 79%; Mean EC = 20nJ; PDR =85%
[24]	MNS-CBRP	Reduced EC and transmission delay.	It did not consider the impact of network throughput and PDR.	Mean transmission delay = $58\mu s$; Received EC = 0.15mWh; Transmitted EC = 0.15mWh; Idle EC = 0.85mWh; Time spent for transmission = 28ms
[25]	CBDS^{2}R	It was suitable for both small and large-scale networks due to high PDR and low latency.	High overhead was caused by the periodic broadcasting of Hello packets to calculate link quality between nodes.	Residual energy = 5100J; Mean E2E delay = 22ms; Mean PDR = 98%; Mean network lifetime = 5000 rounds; No. of nodes alive = 390

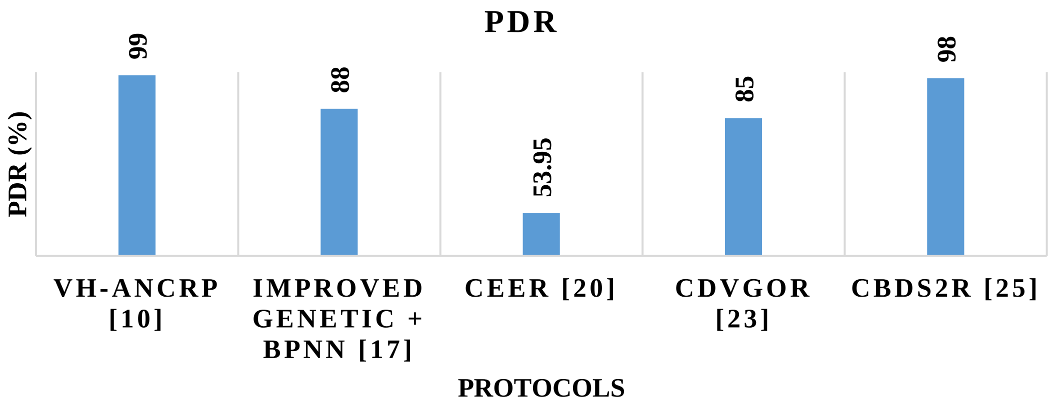

Figure 4. Comparison of PDR for Different CRPs in UWSNs

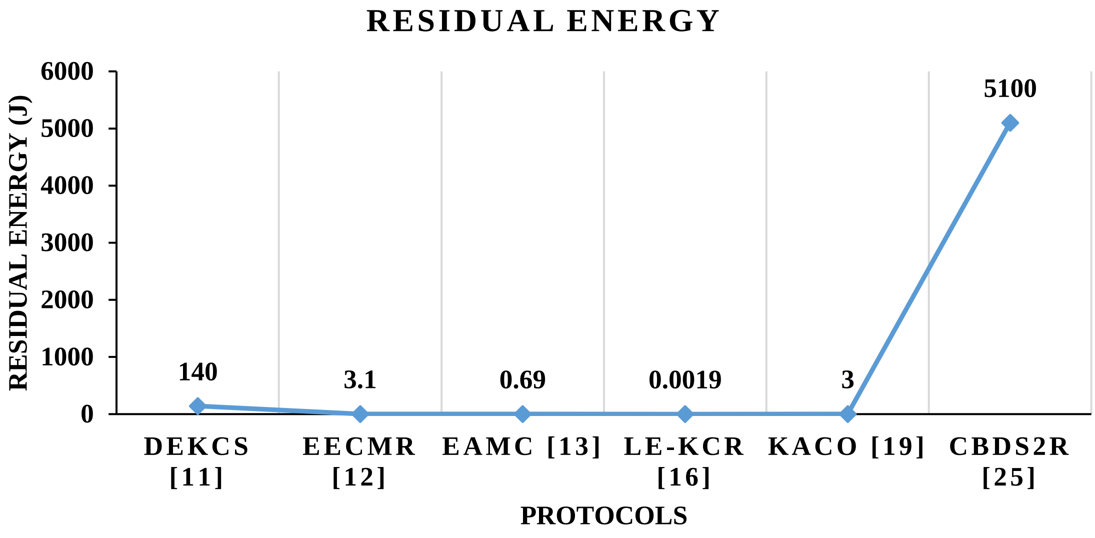

Figure 5. Comparison of PDR for Different CRPs in UWSNs

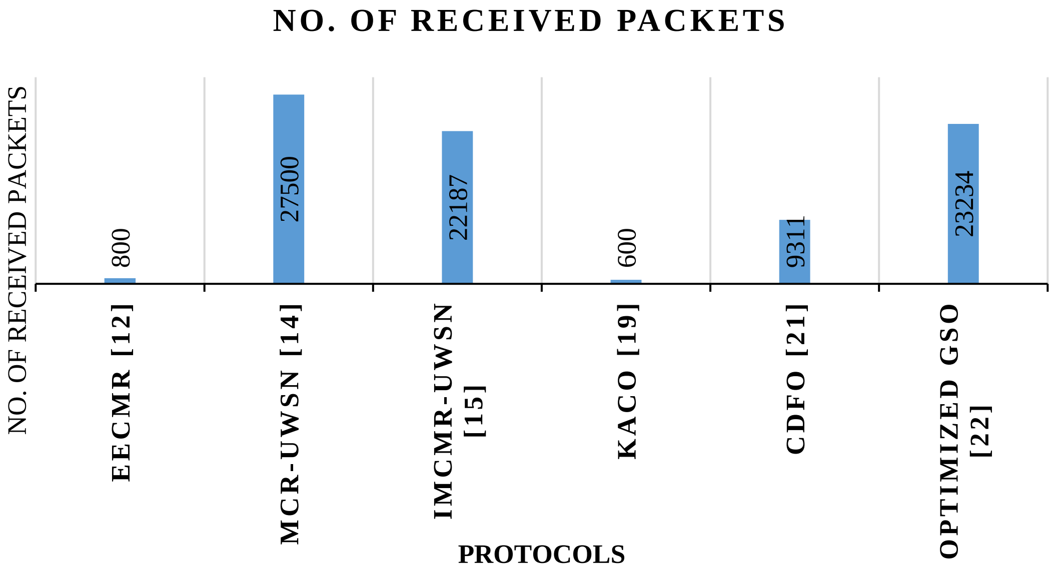

Figure 6. Comparison of No. of Received Packets for Different CRPs in UWSNs

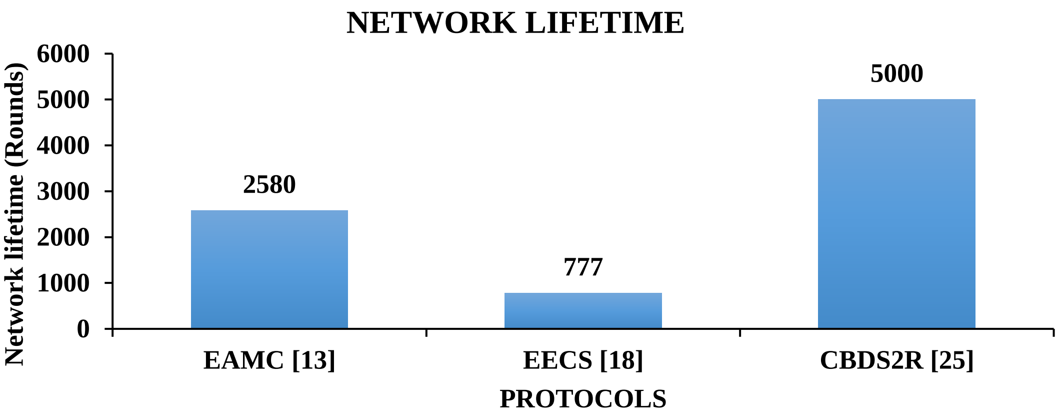

Figure 7. Comparison of No. of Received Packets for Different CRPs in UWSNs

Figure 4 – 7 illustrates the importance of selecting the most suitable protocol based on specific context and data characteristics. The VH-ANCRP achieved a high PDR, and the MCR-UWSN achieved a higher number of received packets compared to other protocols. However, these protocols lack the utilization of link quality between nodes, leading to excessive EC and reduced network lifetime. The CBDS2R protocol achieved a high network lifetime and residual energy, improving network measures significantly.

III. CONCLUSION

RPs for UWSNs are crucial for conserving energy in underwater applications due to limited sensor node battery life. This paper provides a detailed comparison of recent CRPs in UWSNs, examining their advantages, disadvantages, and performance. The analysis evaluates the protocols based on residual energy, received packets, PDR, and network lifetime. The results show that the CBDS2R protocol outperforms others for both small and large-scale UWSN applications. Nevertheless, the periodic broadcasting of Hello packets for link quality determination may lead to high overhead. Future advancements could involve intelligent routing in UWSNs using artificial intelligence models, such as machine learning and deep learning algorithms, to enhance network performance by considering more network parameters and reducing the Hello packet broadcasting.

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