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DEPTH BASED FOG ASSISTED DATA COLLECTION SCHEME FOR TIME-CRITICAL IOUT APPLICATIONS

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Abstract
The Internet of Underwater Things (IoUT) primarily relies on acoustic wave communication underwater, while radio signals are utilized at the surface. Integrating IoUT with Fog Computing significantly boosts the performance of applications such as underwater surveillance and pipeline inspection. However, challenges like processing delays at sink nodes due to limited computational capabilities, and energy inefficiencies caused by redundant data transmissions, still persist. To address these challenges, the DFDC protocol employs fog computing to optimize data flow, thereby reducing latency and eliminating unnecessary transmissions. When evaluated against existing methods such as the High-Availability Data Collection Scheme (HAMA) and the Data Gathering algorithm for Sensors (DGS), DFDC demonstrates superior performance by lowering packet delivery ratios, conserving energy, and minimizing duplicate data transfers..

INTRODUCTION

The Internet of Things (IoT) is expanding rapidly across diverse sectors, including smart manufacturing, urban infrastructure, intelligent transportation systems, environmental monitoring, and security applications [4–6]. It incorporates wireless communication and edge device technologies at the network's periphery [7, 8]. The evolution of mobile devices and wireless technologies has further increased the reliance on mobile applications in everyday activities, presenting significant opportunities for Mobile Edge Computing (MEC) [9, 10]. MEC enhances the efficiency of IoT systems by reducing network congestion and improving response times [11].

In parallel, underwater wireless sensor networks (UWSNs) are progressing, propelled by innovations in edge computing and wireless systems [12]. Conventional multi-hop methods for data collection in UWSNs often suffer from high energy demands and imbalanced power distribution across the network [13]. To mitigate these energy-related challenges, mobile edge components like Autonomous Underwater Vehicles (AUVs) are commonly used to gather data from underwater nodes [14].

UWSNs support applications such as underwater navigation, exploration of marine resources, and environmental observation, yet their efficiency requires further enhancement [10]. One of the major issues is the high likelihood of data loss during long-range transmissions in the underwater medium. While multi-hop communication is essential for data delivery, it significantly increases energy consumption [15]. Furthermore, the difficulty of recharging batteries in underwater mobile devices highlights the importance of energy-efficient solutions. Although deploying multiple sink nodes can help reduce transmission distances and energy consumption, it introduces additional deployment complexity. Data processing in UWSNs also encounters delays due to the limitations of underwater computing capabilities and insufficient high-speed connectivity [17].

To overcome these limitations, fog computing emerges as a viable approach. By utilizing intermediate data centers positioned between the end user (EU) and the cloud data center (DC), fog computing shifts data processing closer to the network edge [18]. This proximity enables faster response times, supports mobility, and ensures low-latency communication. It also provides scalability and seamless cloud integration, which are vital for the performance of IoUT systems [19–21]. Designing robust and efficient routing protocols in underwater environments remains a significant challenge. This study focuses on tackling three key problems excessive energy uses during data dissemination, long end-to-end delays during routing and data transfer, and the need to extend network lifetime to improve overall system performance.

Literature Review

Routing Protocols without Mobile Elements

Routing protocols without mobile elements frequently encounter issues of uneven energy consumption, particularly in relay nodes that are located near the receiving node, leading to rapid energy depletion. In underwater sensor networks, this imbalance can result in bottlenecks, delays, and packet loss, ultimately affecting the performance of the network. To resolve this, routing strategies must focus on evenly distributing energy usage to avoid overloading certain nodes. This approach improves network reliability, prolongs its lifespan, and ensures efficient packet delivery, addressing a fundamental challenge in underwater network operations.

Routing Protocols with Mobile Elements

Routing protocols that incorporate mobile elements, such as Autonomous Underwater Vehicles (AUVs), often experience significant delays in data collection due to the requirement for AUVs to visit each node in a sequential order. These delays are further aggravated by the slow pace of AUV movement during data transfer, which is impacted by environmental factors like water flow, pressure, and underwater obstacles. In underwater sensor networks, AUVs gather data by traveling between widely spaced nodes, a task made challenging by their limited speed and the unpredictable underwater conditions. This sequential method of data collection and forwarding introduces delays, particularly in large-scale networks. To enhance the efficiency and overall performance of underwater data collection systems, optimizing routing protocols to reduce these delays is crucial.

Comparison of Routing Protocols without Mobile Elements

Table 2.1: Summary of Schemes

Protocols	Factors	Packet Delivery Ratio	Energy Consumption	End-to-End Delay	Advantages	Disadvantages
Routing Protocols without Mobile Elements						
DBR	Only Depth	Medium	high	high	• Reduce cost (didn't use full location information). • Use multisink (reduce battery drain and high traffic)	Use only one parameter (depth information). • Decrease network lifetime (using the same node many time as a next forwarder node). • High energy consumption (redundant packet transmission). • High end-to-end delay. •Communication void.
DBMR	Depth Node ID Residual energy	Medium	medium	high	Reduce energy consumption (using single best path).	Communication voids (high packet loss). • Didn't use link quality. • Reduce throughput.
EEDBR	Depth Residual energy Priority value	high	low	low	Provide energy balancing (use residual energy with depth information) • High delivery ratio	Communication void. • Delay (adding list of forwarding along the packets). • Didn't use link quality
AEEDBR	Depth Residual energy	Medium	medium	medium	Provide energy balancing (employ residual energy).	Communication void. • Delay (adding list of forwarding along the packets). • Didn't use link quality
EEF	Depth Residual energy Fitness value	Medium	low	medium	Less energy consumption. • Reduce end-to-end delay	Communication void. • Didn't use link quality. • Transmission of same packets (didn't update history of sent packets)
HydroCast	Depth Link quality	high	medium	medium	Reduce end-to-end delay. • High delivery ratio. • Void handling (using recovery path).	High energy consumption (repeating the process of finding detour path). • High overhead (using two hop neighboring nodes).
AMCTD	Depth Courier node Residual energy	high	medium	low	Reduce communication void (courier nodes). • High throughput.	High energy consumption (extra use of hello packets). • High end-to-end delay (increase the waiting time).
VAPR	Depth Hop count Sequence number Link quality	high	high	high	Reduce end-to-end delay. • Void handling (directional opportunistic data forwarding algorithm). • Use multisink (reduce battery drain and high traffic).	High energy consumption (enhance beaconing).

VBRP	based on the routing pipe	high	low	high	Minimizes node energy consumption and enhances packet delivery efficiency	The issues concerning network longevity and coverage gaps remain unresolved.
EBLE	Determined by the remaining energy of the nodes.	Low	low	medium	It equalizes the traffic distribution by considering the remaining energy of the nodes and optimizes data transfers.	The issue of the packet delivery ratio remains unaddressed.

2.5 Comparison of Routing Protocols with Mobile Elements

Protocols	Factors	Packet Delivery Ratio	Energy Consumption	End-to-End Delay	Advantages	Disadvantages
Routing Protocols with Mobile Elements						
(NC)	Based on multiple sub-zones	Medium	low	high	• this protocol exhibits relatively low energy consumption	it has a small coverage ratio. • In the event of a surface mobile node failure, data cannot be delivered to a sink in a timely manner.
MS	determined by the geographical distance to the data collection points.	low	high	high	Improve network lifetime within the specified area. suitable for delay tolerant networks	high packet delivery latency • routing complexity increases with degree of multi-hopping.
(PNLCS-OA)	likelihood of the neighborhood coverage set	high	medium	high	decreases and equalizes the nodes' energy usage based on the likelihood of demand	Data transmission voids occur when communication is lost. In the event of an AUV failure, the nodes are unable to transmit their sensed data to a sink, rendering the algorithm non-operational.
(DGS) and DGA)	Sensors and AUV BASED	HIGH	HIGH	HIGH	The protocol enhances the packet delivery ratio.	Nodes in close proximity to an AUV experience higher energy consumption and shorter lifespans. The network's functionality is compromised in the event of an AUV failure.
(3D-SM)	Utilizing a mobile sink and three cluster heads as its foundation	Medium	low	medium	The operational lifetime of the network can be significantly prolonged through the implementation of this protocol.	In the event of a malfunction or failure of the mobile sink or the cluster heads, the network becomes non-functional.
AEDG	Based on AUV	high	high	medium	Reduce end-to-end	Nodes located near the

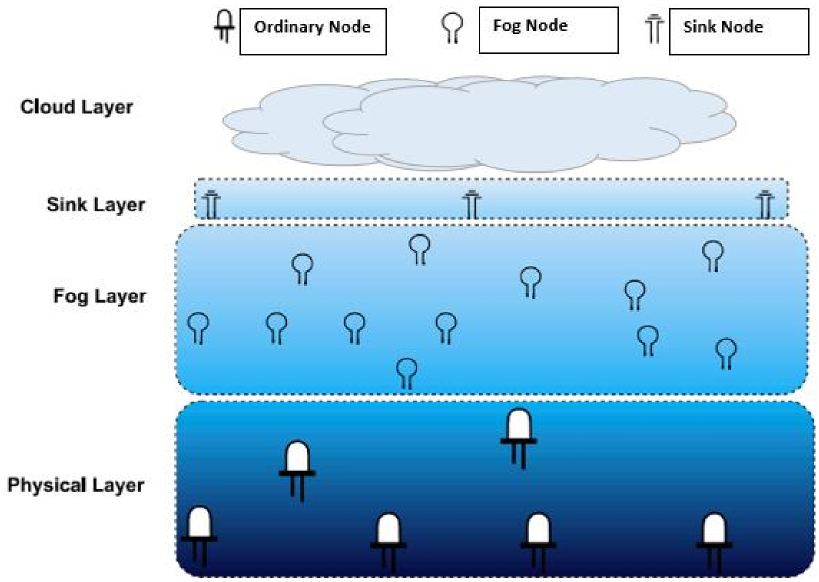
					delay. • High delivery ratio. •	trajectory of the AUV bear a heavier data forwarding load from the AUV. If the AUV experiences a failure, all data may be lost.
AURP	Based on AUV	high	high	medium	This protocol achieves a high packet delivery ratio.	Elevated energy consumption due to a large number of control packets in the network. The protocol does not account for malfunctioning AUVs.
HAMA	Based on Multi-AUVs	high	low	medium	Reduced end-to-end delay and increased reliability due to predefined AUVs and reliable transmissions. The protocol incorporates a malfunction detection and repair mechanism, ensuring high availability even if an AUV fails in data collection.	Multi AUVs are used to collect data. Deployment cost is high
(E2 LR)	based on the routing pipe	high	low	high	controls unnecessary flooding of hello packets to reduce energy consumption regularly updates the energy status	it may not provide a significant reduction in end-to-end delay, which can be a limitation in time-sensitive applications.

Data Collection Scheme for Underwater Sensor Cloud System

The DFDC protocol is structured into four layers: the physical sensor layer, fog layer, sink layer, and cloud layer. Physical layer nodes, which are equipped with acoustic antennas, have limited storage and computational capabilities. In contrast, fog nodes have greater computational and storage capacities. These fog nodes perform localized data processing on the information received from the physical nodes. The data collection mechanism in the DFDC protocol forwards data based on a ratio of depth and energy information. Data is only forwarded if the depth-energy ratio of a node exceeds that of the previous node, helping to reduce end-to-end delays. Fog nodes then process the data by performing computations, dimension reduction, and redundancy elimination before sending the processed data to the central sink node. From there, the sink node forwards the data to the cloud computing center. The primary goals of the DFDC protocol are to minimize energy consumption, reduce delays, and enhance the overall network lifespan.

Architecture of Underwater Sensor Cloud System Based on Fog Computing

An architecture for an underwater sensor cloud system based on fog computing has been designed, as illustrated in Figure 3.2.



Mathematical Illustration of Proposed DFDC scheme

Now we define the holding time based on the criteria. It is assumed that any node A know their coordinates $A(XA, YA, zA)$ and coordinates of the sink node $S(xS, yS, zS)$ and therefore know the distance between these nodes $d(A, S)$ can be calculated by the Euclidean distance

$$d(A,S) = \sqrt{(x_A - x_S)^2 + (y_A - y_S)^2 + (z_A - z_S)^2}$$

The packet is forwarded to those nodes that are at a lesser depth, that is, when a sensor node detects the data; it will broadcast the packet to its neighbors containing its depth information. Any node that receives the packet will compare its own depth with the depth received in the packet and measure the depth difference (dd) by measuring, $dd = zA - zB$. If the depth difference is in negative value, it means that receiving node is closer the Fog node and eligible to forward the packet.

In this way multiple nodes may be recipient of the packets and eligible to forward the received packet. To eliminate redundant packet forwarding. All eligible forwarders nodes (xF, yF, zF) start the timer based on their residual energy ER and their distance to the sink. A node having higher residual energy and shorter distance will have shorter timer that can be calculated by energy to distance ratio

$$T_{hold} = \frac{E_{energy}}{distance} \equiv \frac{E_R}{d(F,s)}$$

where $E_R = KE_{max} + (1-K)E_{min}$ and E_{max} are the minimum and maximum energy of the node and k is the arbitrary parameters

$$0 < k < 1$$

Once the timer for any eligible forwarder expires, it will broadcast the packet. Neighbors on hearing the similar packet they possess from their neighbor will refrain from forwarding that packet to reduce redundant transmission.

3.9 Fog nodes and their distribution

In the underwater sensor network, each fog node has distinct roles: data collection, local computation, and local storage.

The deployment area of the network is represented as a three-dimensional space with dimensions L×L×L.

The number of fog nodes in the network is denoted as N. These fog nodes are distributed across the deployment area.

3.10 Dividing Deployment Area:

To manage the underwater network effectively, the deployment area is divided into M sub-areas, each managed by a specific fog node.

The ith sub-area is managed by the ith fog node, denoted as FNi, and is referred to as Area i.

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The scope of the ith sub-area is confined within a specific range.

3.11 Range of fog nodes'Area

The range of the ith sub-area is confined to:
$[0,0,(i-1)\times L/N]\ )\times[L,L,i\times L/N]$
In more explicit terms, the range of the ith sub-area is confined within the following spatial coordinates:
For the x-coordinate: [0, 0]
For the y-coordinate: [(i - 1) × L/N, L]
For the z-coordinate: [0, i × L/N]
This essentially signifies that the x-coordinates are constrained within the range of [0, 0], indicating that the sub-area is positioned along a single vertical plane. The y-coordinates span from (i - 1) × L/N to L, signifying the vertical extent of the sub-area. Additionally, the z-coordinates are confined within the range of [0, i × L/N], encapsulating the depth-wise scope of the sub-area.
The result of this spatial confinement is that each fog node, designated to manage its respective sub-area, operates within these specified coordinates. This arrangement ensures that data collection, computation, and storage activities are concentrated within a well-defined region, optimizing the efficiency of the fog node's operations while enabling effective coordination with the sensor nodes positioned within this confined sub-area.

3.12 Fog Node Movements and Trajectories

Each fog node moves along a circular trajectory within its designated sub-area. The fog node follows a circular path, making designated stops for a certain duration at specific locations within the sub-area to collect data from sensor nodes. The circular trajectory ensures that the fog node can cover its designated sub-area effectively.

3.13 Equation of Circle Trajectory

The equation that defines the circular trajectory of the fog node in the ith sub-area is provided:

$$(x-L/2)^2+(y-L/2)^2=(\sqrt{2}L/2)^2$$
$$Z=L*2/N+(i-1)*L/N$$

3.15 Forwarding Priority of packets in DFDC

When a sensor node detects data for transmission, it broadcasts the data packet to neighboring nodes, including its depth information, which represents its distance from the water's surface or a reference point. This enables the packet to move toward nodes at shallower depths. Upon receiving the packet, each recipient node compares its depth with the sender's depth using the formula: depth difference (dd) = zA - zB, where zA is the recipient's depth, and zB is the sender's depth. If the depth difference is less than zero, it indicates the receiving node is closer to the Fog node than the sender. This proximity-based evaluation ensures that only eligible nodes forward the packet, optimizing routing and enhancing data dissemination efficiency in underwater environments.

Eliminate redundant packet forwarding in DFDC

In order to eliminate the occurrence of redundant packet forwarding within the network, a systematic approach is introduced. This involves identifying and engaging all qualified forwarder nodes (denoted as (xF, yF, zF)) that are capable of forwarding packets. These forwarder nodes initiate a timer mechanism, which is determined by considering their residual energy (E_R) as well as their respective distances from the sink node.
This timer mechanism plays a vital role in regulating packet forwarding activities and avoiding unnecessary duplications. Nodes with higher remaining energy and shorter distances to the sink are assigned shorter timers. The calculation of these timers is based on the energy-to-distance ratio, aptly denoted as T_"hold " and is defined as:

$$T_{\text{hold}}=\frac{E_{\text{energy}}}{\text{distance}}\equiv\frac{E_R}{d(F,s)}$$

3.17 Compute Holding Time of packet in DFDC

We establish the foundation for determining the holding time using a specific criterion. We assume that each node in the network, denoted as node A with coordinates $A(XA, YA, zA)$, possesses knowledge of its own position and that of the sink node, represented as $S(xS\ ,\ yS\ ,\ zS)$. This knowledge empowers nodes to compute the distance between themselves and the sink, represented as (A, S). This distance calculation is performed using the Euclidean distance formula, which is an established mathematical method.
The Euclidean distance between node A and the sink node S can be calculated using the following formula:

$$d(A,S)=\sqrt{(x_A-x_S)^2+(y_A-y_S)^2+(z_A-z_S)^2}$$

Here, the individual coordinates (x, y, z) represent the positions of node A (XA, YA, zA) and the sink node S (x , yS , zS). The Euclidean distance formula computes the three-dimensional geometric distance between these two nodes.
This distance measurement serves as a key component for determining the holding time, a critical factor in the packet forwarding process. As we established earlier, the holding time influences the timing of packet forwarding by nodes based on their residual energy and proximity to the sink. The Euclidean distance calculation aids in assessing how far a node is from the sink, which, when combined with other parameters, contributes to setting an appropriate holding time.

Simulation Setup

To facilitate this evaluation, we utilize the NS-3 simulation tool, a highly regarded discrete event simulator known for its precision and adaptability.

Table 3.1: Parameter setup

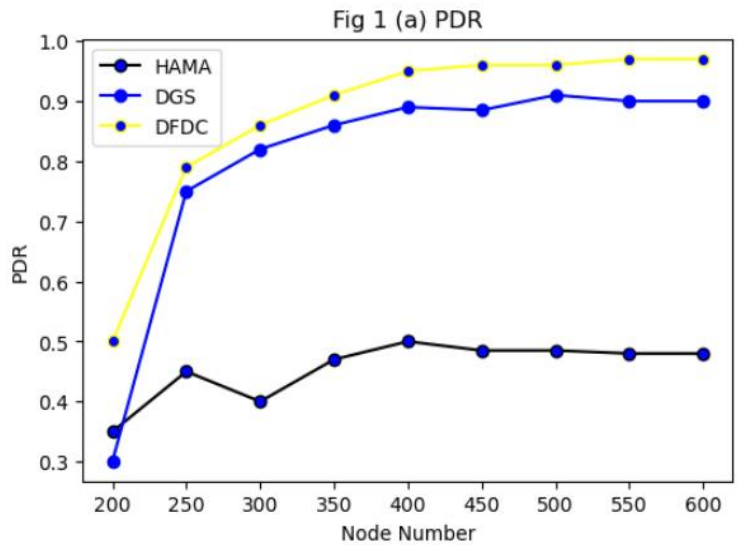
Parameter	Value
Sending energy	50 W, default in NS-3
Receiving energy or idle state	158 mW, default in NS-3
R	2 km
Data rate	16 kbps
Node number	200-500, randomly generate network topology
Deployment region	3D area of $(10\ \text{km})^3$
Fog node number	5
Movement model	Random Walk 2D Mobility Model
Source node	Randomly deploy at the depth of 10 km
Sink location	At the center of the surface
Packet generation model	1 packet per 5 s, Poisson distribution,

RESULT AND ANALYSIS

In the simulation, we evaluate the performance of the proposed data gathering method, specifically the DFDC routing protocol, within the architecture of a fog computing-based underwater sensor cloud system. This analysis is conducted using the NS-3 simulation tool, a discrete event simulator. The simulation compares the performance of HAMA [35] and DGS [56] side by side. Performance measures such as the Packet Delivery Ratio (PDR), end-to-end delay, and energy consumption are assessed to gauge the effectiveness of each protocol.

Packet Delivery Ratio (PDR) Comparison

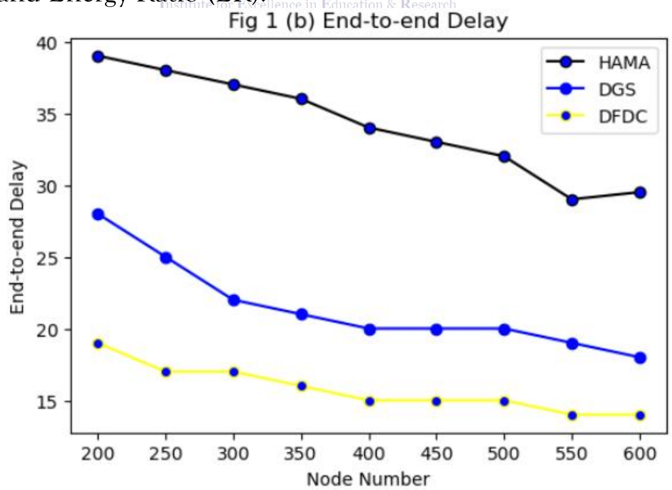
The comparison of Packet Delivery Ratio (PDR) is illustrated in Figure 3(a).



The proposed fog computing-based underwater sensor cloud system architecture enhances the Packet Delivery Ratio (PDR) by utilizing fog nodes for local data processing, thus reducing the transmission burden on the surface sink node. This helps prevent packet loss at the sink node, which is a common issue in traditional protocols. The Depth-based Fog Assisted Data Collection (DFDC) routing algorithm further improves PDR by prioritizing forwarding nodes based on their distance and Energy Ratio (ER). It minimizes forwarding redundancy, particularly in dense networks, and optimizes forwarding decisions by considering node depths. As a result, the proposed architecture outperforms both HAMA and DGS in terms of packet delivery efficiency.

4.3 End-to-End Delay Comparison

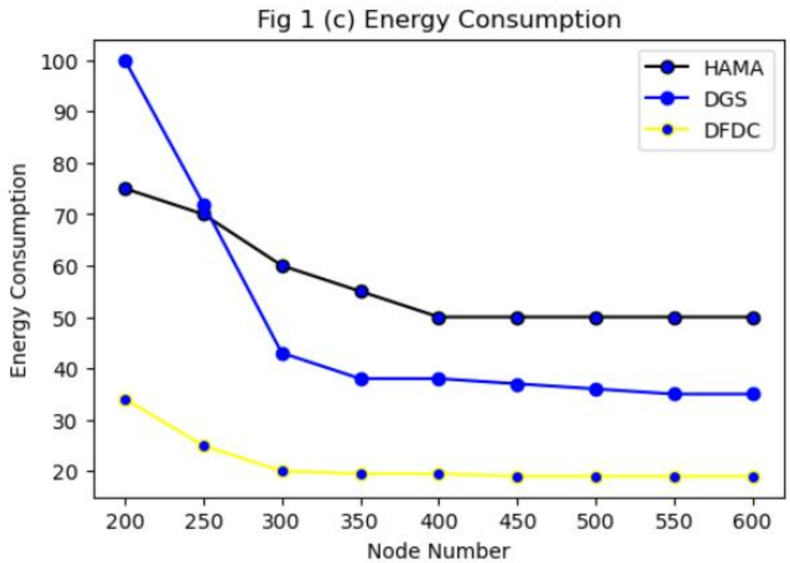
The graph in Figure 3(b) illustrates a comparison of end-to-end delays.



The proposed network architecture reduces both data volume and end-to-end delays by processing collected data to eliminate redundancies. Time-sensitive data is transmitted directly from lower to upper network layers using Autonomous Underwater Vehicles (AUVs), bypassing intermediate relay nodes, which helps minimize delays caused by packet holding or the movement of AUVs. The DFDC routing algorithm further optimizes delays by assigning timers to forwarding nodes based on their residual energy (E_R) and proximity to the sink. Nodes with higher energy and shorter distances to the sink are given shorter timers, calculated using an energy-to-distance ratio. Simulation results demonstrate that DFDC outperforms both HAMA and DGS in reducing delays. HAMA experiences greater delays due to slower AUV speeds and longer paths, while DGS suffers from higher delays as gateway nodes wait for AUVs.

Energy Consumption Comparison

The comparison of energy consumption, presented in Figure 3(c):



This study provides valuable insights into the efficiency of various network architectures. In the proposed system, each fog node is responsible for locally storing and processing nearby data. Time-sensitive data is transmitted to the surface sink node via multi-hop routes, while less critical data is transferred by mobile fog nodes to the surface for further forwarding. By processing data locally, the system reduces the amount of data transmitted, thus minimizing energy consumption. The DFDC routing algorithm improves energy efficiency compared to other protocols through its optimized mechanisms. The HAMA protocol achieves the longest network lifetime due to its design, which utilizes two Autonomous Underwater Vehicles (AUVs). Nodes with lower energy are less likely to be selected for data transmission, ensuring a balanced distribution of energy consumption and maintaining network stability as the number of nodes increases. In contrast, the DGS protocol results in a shorter network lifetime. Nodes situated along the fixed paths of mobile elements, like AUVs, consume energy more quickly, leading to uneven energy usage and a reduction in the overall network lifetime.

CONCLUSION

In summary, this research introduces an innovative architecture and routing scheme to address critical challenges in underwater sensor networks. The fog-computing-based underwater sensor cloud system reduces the load on surface sink nodes, lowering communication delays and energy consumption. By leveraging fog nodes for local data processing and optimized data relay, the architecture significantly improves packet delivery, end-to-end delay, and energy efficiency. The Depth-based Fog Assisted Data Collection (DFDC) routing protocol refines routing decisions, resulting in reduced energy consumption, shorter delays, and greater data reliability. Overall, this study highlights the potential of fog computing and advanced routing protocols to enhance the efficiency, reliability, and sustainability of underwater sensor networks.

Future Work

In the future, there is an opportunity to improve the data transfer process between fog nodes and sink nodes. Fog nodes could collaborate more effectively to optimize how they transmit data. When Autonomous Underwater Vehicles (AUVs) surface, they could communicate and establish a coordinated strategy for data transmission via radio signals. The specific aspects of this coordination are outside the scope of this paper, but such collaboration could help minimize data loss and increase the overall efficiency of the process.

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