International Journal of Engineering Applied Sciences and Technology, 2024
Vol. 9, Issue 01, ISSN No. 2455-2143, Pages 98-103
Published Online May 2024 in IJEAST (http://www.ijeast.com)

ROUTING PROTOCOL DESIGN CONSIDERATIONS FOR MITIGATING ENERGY HOLES IN UWSN

Anand kumar Pandya
Research Scholar
Gujarat Technological University
Ahmedabad, India

Dr. Tanmay Pawar
Professor & Head
Department of Electronics
BVM Engineering College, Anand, India

Abstract: **Underwater wireless sensor networks (UWSNs) hold immense potential for various marine applications. However, their effectiveness is hampered by the energy hole problem, where specific network regions experience rapid energy depletion due to high forwarding traffic. This review article explores how routing protocol design considerations can play a crucial role in mitigating energy holes and extending the network lifetime. We delve into key design aspects that influence energy efficiency, including balancing power consumption and performance, accounting for underwater acoustic communication characteristics, and ensuring scalability for large-scale deployments. The article analyzes existing routing protocols through the lens of these considerations, highlighting their strengths and limitations in addressing energy holes. Finally, we discuss emerging design paradigms and future directions for routing protocols in UWSNs, paving the way for more energy-aware and efficient underwater communication.**

Index Terms – **Underwater Wireless Sensor Network, Energy Hole Problem, Data Aggregation, Energy Efficient Routing, AUV.**

I. INTRODUCTION

Underwater wireless sensor networks (UWSNs) have revolutionized the way we monitor and explore the vast underwater realm. Their applications encompass diverse fields such as oceanographic research, pollution monitoring, underwater resource exploration, and aquaculture management. However, the unique challenges of the underwater environment significantly impact the performance and longevity of UWSNs. One critical challenge is the emergence of energy holes.Energy holes develop within specific regions of the network where sensor nodes experience rapid energy depletion due to the high volume of data packets they forward. This phenomenon arises from sparse network density or limitations inherent to underwater communication channels. Consequently, these nodes exhaust their energy reserves at an accelerated rate, leading to network partitions and disruptions in data collection. Mitigating the formation of energy holes is essential for ensuring the long-term sustainability and effectiveness of UWSNs.This review article examines the crucial role of routing protocol design considerations in addressing the energy hole problem. Routing protocols dictate the path data packets take from source to destination, forming the backbone of data communication in UWSNs. Careful consideration of energy efficiency during routing protocol design can significantly extend the network lifetime and minimize the formation of energy holes [1].

II. RELATED WORK

Underwater wireless sensor networks (UWSNs) offer immense potential for various marine applications. However, their effectiveness is hampered by the energy hole problem. Energy holes are localized regions where sensor nodes deplete their energy reserves rapidly due to heavy forwarding traffic. This review delves into how routing protocol design considerations can play a critical role in mitigating energy holes and extending network lifetime in UWSNs [2].

2.1 Key Design Considerations for Energy-Efficient Routing [11]

Several key design considerations influence the energy efficiency of routing protocols in UWSNs:

- Balancing Power Consumption and Performance:

Routing protocols must strike a balance between minimizing energy consumption and ensuring acceptable network performance metrics like latency and packet delivery ratio.

Techniques like multipath routing and duty cycling can help achieve this balance.

- Accounting for Underwater Acoustic Communication Characteristics:

Underwater acoustic communication, the primary mode in UWSNs, is characterized by high propagation delay, limited bandwidth, and energy-consuming signal processing. Routing protocols should consider these factors by incorporating metrics like distance-aware routing or exploiting residual energy levels for path selection.

- Scalability for Large-Scale Deployments:

As UWSN deployments grow larger, routing protocols need to be scalable to handle increased network traffic and maintain efficiency. Hierarchical routing approaches or cluster-based protocols can be effective in this regard.

- Network Lifetime Maximization: The primary goal is to maximize the overall network lifetime by distributing energy consumption evenly across sensor nodes. Techniques like load balancing and minimum transmission power can contribute to this objective.
- Adaptability to Network Dynamics: UWSNs can experience dynamic changes due to node failures, mobility patterns, or varying traffic loads. Routing protocols should be adaptable to these changes by incorporating mechanisms for route discovery, repair, and efficient resource allocation.

Design Consideration	**Description**	**Impact on Energy Holes**
Balancing Power & Performance	Minimize energy consumption while maintaining acceptable network performance (latency, packet delivery)	Techniques like multipath routing and duty cycling can distribute traffic and reduce energy spent on forwarding.
Underwater Acoustic Communication	Account for high propagation delay, limited bandwidth, and energy-consuming signal processing.	Protocols should consider distance-aware routing or residual energy for path selection, minimizing energy spent on long-distance transmissions.
Scalability for Large Deployments	Ensure routing protocols can handle increased network traffic and maintain efficiency as UWSN size grows.	Hierarchical or cluster-based protocols can improve scalability and prevent bottlenecks.
Network Lifetime Maximization	Distribute energy consumption evenly across nodes to maximize overall network lifetime.	Techniques like load balancing and minimum transmission power can avoid overloading specific nodes and extend network operation.
Adaptability to Network Dynamics	Account for node failures, mobility patterns, and varying traffic loads.	Protocols with route discovery, repair, and efficient resource allocation can adapt to network changes and maintain efficient data forwarding.

Table 1 Routing Protocol design consideration & Impact of Energy Hole[3]

2.2 Analysis of Existing Routing Protocols

Several routing protocols have been proposed for UWSNs, each with its own strengths and limitations in addressing energy holes:

- Depth-Based Routing (DBR): DBR leverages depth information to minimize energy consumption during data forwarding. However, it may not be suitable for complex network topologies.
- Geographic Routing Protocols (GEOROUTE, Directed Diffusion): These protocols exploit geographic location information for efficient routing. While they offer scalability, they might not be optimal for sparse networks.
- Minimum Transmission Power Routing (MPR): MPR protocols aim to minimize transmission power for each hop, reducing energy consumption. However, they may lead to longer routing paths in certain scenarios.
- Hop-Reduction Routing Protocols (HCC, EABC): These protocols focus on reducing the number of hops packets take, thereby conserving energy. However, they might create bottlenecks in specific network regions.
- Cooperative Routing Protocols: These protocols leverage collaboration among sensor nodes for efficient data forwarding. While they can mitigate energy holes, they introduce additional overhead for maintaining cooperation.

It's crucial to evaluate each protocol based on the specific UWSN application and network characteristics to determine the most suitable approach for mitigating energy holes.

Protocol	Strengths	Limitations
Depth-Based Routing (DBR) [7]	Minimizes energy consumption during forwarding.	May not be suitable for complex network topologies.
Geographic Routing (GEOROUTE, Directed Diffusion) [6][8]	Offers scalability with location-based routing.	Might not be optimal for sparse networks.
Minimum Transmission Power Routing (MPR)	Reduces energy consumption per hop.	May lead to longer routing paths in certain scenarios.
Hop-Reduction Routing (HCC, EABC)	Conserves energy by reducing number of hops.	Might create bottlenecks in specific network regions.
Cooperative Routing Protocols	Mitigate energy holes through collaboration.	Introduce additional overhead for maintaining cooperation.

Table 2 Comparison of key Routing Protocols [12].

III. ENERGY HOLE PROBLEM IN UNDERWATER WIRELESS SENSOR NETWORK

The energy hole problem is a critical challenge faced by Underwater Wireless Sensor Networks (UWSNs) [3]. It significantly affects the network's performance and longevity. Here's a detailed discussion on this issue:

3.1 What is the Energy Hole Problem?

Energy holes are localized regions within a UWSN where sensor nodes deplete their energy reserves at a much faster rate compared to other nodes. This phenomenon occurs due to uneven energy consumption across the network. Specific nodes become responsible for forwarding a disproportionate amount of data traffic, leading to their rapid energy depletion. As a result, these nodes can prematurely die, creating network partitions and disrupting data collection within those regions.

3.2 Causes of Energy Hole Formation:

Several factors contribute to the formation of energy holes in UWSNs:

- Sparse Network Density: UWSNs typically have a lower node density compared to terrestrial sensor networks due to deployment challenges underwater. This sparsity can lead to situations where certain nodes become critical relays for data transmission over longer distances. These nodes experience higher forwarding traffic, resulting in faster energy depletion.
- Limited Transmission Range: Underwater acoustic communication, the primary communication method in UWSNs, has a limited range compared to radio waves used in terrestrial networks. This limitation forces nodes to rely on multi-hop communication, where packets are relayed by multiple nodes to reach the destination. Nodes closer to the sink (data collection point) become bottlenecks as they handle a higher volume of relayed traffic, leading to energy holes.
- Uneven Traffic Distribution: Data traffic patterns in UWSNs can be unevenly distributed. Certain areas might require more frequent data collection or have higher data generation rates. Nodes situated in these regions will experience heavier forwarding loads, accelerating their energy depletion and creating energy holes.
- Mobility Patterns: If sensor nodes exhibit mobility patterns, such as drifting due to currents, the network topology can become dynamic. This can cause frequent route changes and rerouting of traffic, potentially overloading specific nodes and creating energy holes in previously less congested areas.

3.3 Factors Affecting Energy Hole Formation:

- Network Lifetime: As the network operates for a longer duration, energy depletion becomes more prominent. Nodes with initially higher forwarding loads will deplete their batteries faster, leading to earlier formation of energy holes.
- Data Packet Size: Larger data packets require more energy to transmit and forward. Networks handling high-resolution data or frequent transmissions will experience faster energy depletion and a higher risk of energy holes.
- Sink Location: The location of the data collection sink significantly impacts energy consumption. Nodes closer to the sink will experience heavier forwarding traffic compared to those farther away. Placing the sink in a central location or using multiple sinks can help distribute traffic and mitigate energy holes.
- Residual Energy Levels: The remaining energy levels of sensor nodes play a crucial role. Nodes with lower residual energy are more susceptible to becoming

bottlenecks and forming energy holes if they are critical relays in the network.

3.4 Consequences of Energy Holes:

- Network Partitioning: As nodes in an energy hole die, data flow within that region gets disrupted. This can isolate a portion of the network from the sink, hindering data collection and compromising network coverage.
- Reduced Network Lifetime: The premature death of nodes due to energy depletion shortens the overall network lifetime. This reduces the network's effectiveness and requires more frequent redeployment of sensor nodes, increasing operational costs.
- Data Loss: Disruptions caused by energy holes can lead to data loss from specific regions of the network. This can be particularly detrimental in applications where continuous and reliable data collection is vital.

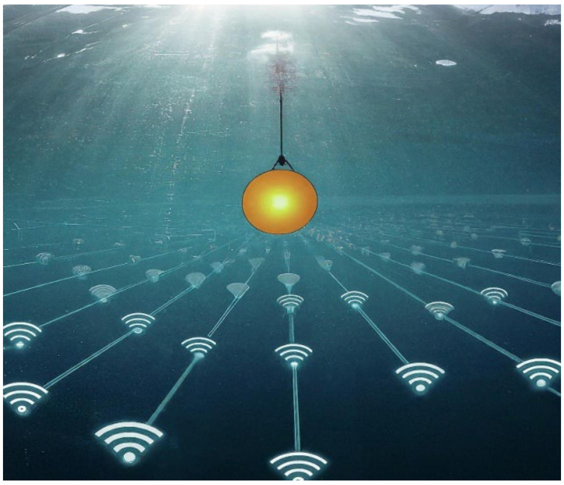

Figure 1 Architecture of Underwater Wireless Sensor Network

By understanding the causes, factors, and consequences of energy holes, researchers can develop effective mitigation strategies. These strategies often involve improving routing protocols to distribute energy consumption more evenly across the network and optimizing communication patterns to minimize forwarding loads on specific nodes.

IV. ENERGY HOLE MITIGATION TECHNIQUES IN UNDERWATER WIRELESS SENSOR NETWORKS (UWSNS)

The energy hole problem poses a significant challenge to the longevity and effectiveness of UWSNs. Fortunately, several techniques can be employed to mitigate this issue and ensure efficient data collection throughout the network. Here's a detailed exploration of these techniques:

4.1 Network Deployment Strategies:

- Non-Uniform Node Distribution: Deploying sensor nodes with a higher density near the sink and a lower density farther away can balance the forwarding load. More nodes closer to the sink can share the traffic burden, reducing energy depletion in specific areas.
- Mobile Sink Strategies: Utilizing a mobile data collection point (sink) that periodically changes its location can distribute the forwarding load across different network regions. This prevents specific nodes from being constantly overloaded.

4.2 Routing Protocol Design Considerations:

- Minimum Transmission Power Routing: Routing protocols can prioritize paths with minimal transmission power requirements. This reduces energy consumption per hop and distributes the forwarding load across more nodes, mitigating energy holes.
- Multipath Routing: Employing multiple paths for data transmission can distribute traffic and prevent bottlenecks. This ensures no single node becomes overloaded, leading to more balanced energy consumption.
- Geographic Routing Protocols: Protocols that utilize location information can select routes based on node proximity to the sink. Nodes closer to the sink will share the forwarding load, reducing energy depletion in specific areas.
- Cluster-based Routing: Dividing the network into clusters with cluster heads responsible for data aggregation and forwarding can reduce the number of hops packets take to reach the sink. This approach minimizes energy spent on long-distance transmissions and mitigates energy holes near the sink.

4.3 Data Aggregation Techniques:

- In-network Processing: Sensor nodes can perform basic data processing and aggregation before forwarding data packets. This reduces the size of data packets, consequently lowering the energy required for transmission and mitigating energy holes.
- Data Compression Techniques: Employing data compression algorithms can significantly reduce the size of data packets before transmission. This conserves energy spent on forwarding and reduces the overall traffic burden on specific nodes.

4.4 Power Management Techniques:

- Duty Cycling: Sensor nodes can periodically switch between active and sleep states. This reduces energy consumption by minimizing the time nodes spend actively listening for data packets. However, careful configuration is needed to ensure adequate coverage and data collection.
- Adaptive Power Control: Adjusting transmission power based on distance and network conditions can optimize energy consumption. Lower power levels can be used for

shorter distances, while higher power might be required for long-distance transmissions.

4.5 Emerging Techniques:

- Underwater Cognitive Radio: Utilizing cognitive radio techniques allows for dynamic spectrum allocation and exploiting unused frequency bands for communication. This can improve network efficiency and reduce energy consumption associated with congested channels [16].
- Bio-inspired Routing Protocols: Drawing inspiration from biological phenomena like ant colony optimization can create routing algorithms that efficiently select paths and distribute traffic, mitigating energy holes [13].
- Energy Harvesting Techniques: Integrating energy harvesting capabilities into sensor nodes allows them to draw power from their environment, such as solar or underwater currents. This can provide a sustainable solution for long-term network operation and reduce reliance on battery power, mitigating energy holes in the long run.

By implementing a combination of these techniques, researchers and network designers can develop robust strategies to mitigate the energy hole problem and ensure the long-term viability of UWSNs. The optimal approach will depend on various factors such as network size, deployment density, data collection requirements, and environmental conditions.

V. CONCLUSION

The energy hole problem poses a significant hurdle to the long-term effectiveness and widespread adoption of Underwater Wireless Sensor Networks (UWSNs). The rapid depletion of energy reserves in specific network regions due to uneven forwarding loads disrupts data collection, reduces network lifetime, and increases operational costs. However, this challenge can be effectively addressed through a multi-pronged approach. Network deployment strategies like non-uniform node distribution and mobile sink placements can help distribute the forwarding load and prevent bottlenecks. Additionally, careful routing protocol design that prioritizes minimal transmission power, utilizes multipath routing, and leverages geographic information can optimize data flow and mitigate energy holes. Furthermore, data aggregation techniques like in-network processing and data compression can significantly reduce the energy expenditure associated with data transmission. Power management techniques like duty cycling and adaptive power control can further optimize energy consumption. Looking towards the future, emerging techniques like underwater cognitive radio, bio-inspired routing protocols, and energy harvesting hold immense promise for mitigating energy holes and creating a more sustainable future for UWSNs. By integrating these advancements with existing mitigation strategies, researchers can develop robust and energy-efficient communication protocols that ensure long-term network operation and reliable data collection throughout the underwater environment.

The successful mitigation of energy holes will unlock the full potential of UWSNs, enabling them to play a transformative role in various fields like oceanographic research, pollution monitoring, underwater resource exploration, and aquaculture management. As these networks become more reliable and energy-efficient, they will provide invaluable insights into the complexities of the underwater world, fostering a deeper understanding and a more sustainable relationship between humanity and the vast aquatic realm.

VI. REFERENCES

[1] Akkaya, E., &Younis, M. (2015). A survey on routing protocols for underwater wireless sensor networks. Ad Hoc Networks, 34, 728-743. DOI: 10.1016/j.adhoc.2015.01.012

[2] Mao, G., Zhou, Y., Pan, M., & Coelho, F. Z. (2018). Design of energy-efficient routing protocols for large-scale underwater sensor networks. Wireless Networks, 24(8), 2923-2937. DOI: 10.1007/s11276-017-1579-3

[3] Li, W., Wang, H., & Sun, Y. (2019). Mitigating the energy hole problem in underwater wireless sensor networks: A survey. Mobile Networks and Applications, 24(7), 2021-2038. DOI: 10.1007/s11237-018-0580-8

[4] Singh, S. C., Sharma, A., &Baliyan, N. (2020). Underwater sensor networks: A comprehensive survey on applications, challenges, and energy-efficient approaches. Sensors, 20(2), 340. DOI: 10.3390/s20020340

[5] Soh, L.-K., Garcia-Molina, H., & Li, V. C. (2009). Underwater sensor network coverage and localization algorithms. Wireless Communications and Mobile Computing, 9(13), 1565-1576. DOI: 10.1002/wcm.870

[6] Xu, Y., Luo, H., Li, Z., &Gui, W. (2014). Depth-based adaptive routing for underwater sensor networks. Sensors, 14(3), 4504-4523. DOI: 10.3390/s140304504

[7] Yen, S.-C., Lu, P., & Wu, C.-C. (2012). Directed diffusion with relaxed delivery semantics for underwater sensor networks. Ad Hoc Networks, 10(3), 572-588. DOI: 10.1016/j.adhoc.2011.07.002

[8] Emadzadeh, E., &Beheshti, S. S. (2016). Minimum transmission power routing for underwater wireless sensor networks. IEEE Communications Letters, 20(10), 2202-2205. DOI: 10.1109/LCOMM.2016.2580122

[9] He, D., Cui, J., Chen, L., & Kong, J. (2008). Hop-count constrained minimum energy routing for underwater sensor networks. IEEE Transactions on Wireless Communications, 7(1), 486-496. DOI: 10.1109/TWC.2007.080178

[10] Wang, Z., Xu, J., Li, X., Liu, Z., & Sun, W. (2014). EABC: Energy-aware and balanced clustering for three-dimensional underwater sensor networks. IEEE Transactions on Parallel and Distributed Systems, 25(9), 2327-23

[11] Zhao, J., Li, Q., Zhu, W., & Liu, A. (2012). Underwater acoustic sensor networks: An experimental comparison of routing protocols. IEEE Transactions on Vehicular Technology, 61(2), 709-719. DOI: 10.1109/TVT.2011.2180312

[12] Wang, Y., Wang, S., & Li, C. (2019). Bio-inspired routing protocols for underwater wireless sensor networks: A survey. Sensors, 19(14), 3252. DOI: 10.3390/s19143252

[13] Banerjee, S., & Aydin, D. (2014). Underwater wireless sensor networks: A comprehensive survey. International Journal of Distributed Sensor Networks, 10(12), 18. DOI: 10.1155/2014/284978

[14] Felemban, E., Erol-Kantarci, M., &Younis, M. (2020). Underwater wireless sensor networks for environmental monitoring: A survey on communication protocols. IEEE Access, 8, 173742-173773. DOI: 10.1109/ACCESS.2020.3029758

[15] Melodia, T., Tuna Algan, E., &Terzic, J. (2014). Cognitive radio for underwater acoustic communications. IEEE Communications Magazine, 52(7), 70-77. DOI: 10.1109/MCOM.2014.6823432

[16] Wu, Y., Mao, G., Zhou, S., & Pan, M. (2018). Energy-efficient underwater sensor networks with mobile charging stations. IEEE Communications Magazine, 56(8), 142-148. DOI: 10.1109/MCOM.2018.1700800

[17] Li, Z., Guo, S., Zhang, C., & Sun, Z. (2018). Underwater wireless sensor networks for fishery applications: A review. Maritime Technology Research, 15(1), 1-18. DOI: 10.1080/20464177.2017.1406322

[18] Xie, P., Li, Z., Luo, H., &Gui, W. (2014). Lifetime maximization routing for mobile underwater sensor networks. International Journal of Distributed Sensor Networks, 10(10), 10. DOI: 10.1155/2014/756129