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A Survey on Efficient Routing Strategies for The Internet of Underwater Things (IoUT)

Manal Al-Bzoor, Walaa Ayyad, and Ola Alta'ani

***Abstract*—The Internet of Underwater Things (IoUT) is an emerging technology that promised to connect the underwater world to the land internet. It is enabled via the usage of the Underwater Acoustic Sensor Network (UASN). Therefore, it is affected by the challenges faced by UASNs such as the high dynamics of the underwater environment, the high transmission delays, low bandwidth, high-power consumption, and high bit error ratio. Due to these challenges, designing an efficient routing protocol for the IoUT is still a trade-off issue. In this paper, we discuss the specific challenges imposed by using UASN for enabling IoUT, we list and explain the general requirements for routing in the IoUT and we discuss how these challenges and requirements are addressed in literature routing protocols. Thus, the presented information lays a foundation for further investigations and futuristic proposals for efficient routing approaches in the IoUT.**

***Keywords*—IoUT; UASN; Routing**

I. Introduction

ALMOST two-thirds of Earth's surface area is covered by water. This large area of the world needs to be explored, monitored, and connected to the smart land Internet of things. To achieve this, the Internet of Underwater Things (IoUT) was introduced. Underwater acoustic sensor network (UASN) is a fundamental platform for enabling IoUT applications in underwater exploration, oilfield utilization, and underwater navigation [1]. Efficient and timely routing and broadcasting of packets from the underwater sensor nodes to the surface is of crucial importance for connecting these applications to the land internet. However, acoustic waves are used in UASN as the best alternative for the severely attenuated radio waves in water medium. Nevertheless, acoustic links come with its own drawbacks including high bit error rate (BER), high propagation delay, low bandwidth, and high energy consumption of acoustic transceivers [2]. Due to such unique characteristics and dynamicity of the underwater environment, routing over acoustic links should have lightweight signaling and the ability to cope with the variation in the quality of the link to provide better data delivery [3].

There are only few studies that addressed the protocol requirements of an IoUT application. Like an IoT, an IoUT protocol designer focus on three performance metrics which are energy efficiency, reliability, and security. In this paper, we discuss the specific issues and challenges imposed by the usage of acoustic communications for enabling IoUT. We further discourse the issues of mobility and localization difficulty of underwater nodes [4]. Moreover, we categorize the existing UASN routing protocols and discuss the advantages and disadvantages of each category. We further give examples on each category from recent and state of the art routing techniques. Our work will help future protocol designers decide on the most appropriate routing category given a specific performance requirement.

The rest of this work is organized as follows: In section 2, we present and analyze the unique challenges imposed by using the UASN. In section 3, we discuss the performance requirements of IoUT routing protocols. We categorize and discuss in literature methodologies in Section 4. Finally, in Section 5, we conclude this work and lays future research directions.

II. CHARACTERSTICS AND CONSTRAINTS OF UASN

IoUT applications are viable via the use of UASN for largescale underwater environments. However, this type of network suffers from unique constraints and challenges that affect the operation and efficiency of any application.

A. Acoustic Communication

As mentioned earlier, electromagnetic waves (EM) are highly attenuated in water medium. It can be only used for communication between surface sinks and land internet or can be used for communication between nodes in shallow water. On the other hand, acoustic signals can travel long distances for up to few kilometers without losing the information it carries. However, acoustic channels suffer from frequent packet drops, multi-path fading, and dispersion. It also suffers from long propagation delays due to the slow speed of sound of 1500m/s, low bandwidth in the order of tens of kilobits per second, and high bit error rate. Moreover, acoustic transceivers consume much higher power while in transmission mode that is in orders of watts compared to that in milliwatts for radio transceivers [1][2].

To face the challenges raised by the usage of acoustic channel, energy efficient and cross layer routing protocols are preferred.

B. Underwater Devices

Underwater devices are heterogeneous in nature with different communication capabilities. A smart underwater sensor node is either anchored to the sea bottom with limited mobility or can be floating with water current with uncontrolled mobility. All nodes are battery-operated, equipped with an acoustic transceiver, a processor to perform simple

Manal Al-Bzoor, Walaa Ayyad, and Ola Alta'ani are with Yarmouk University, Computer Engineering Department, Yarmouk University, Irbid, Jordan (e-mail: (mbzoor@yu.edu.jo, 2019997001@ses.yu.edu.jo, olataani@yu.edu.jo).

computations, and can communicate with other underwater nodes or with a Surface Sink. A surface sink is either mounted on a ship or floating on a buoy. Surface sinks are capable of both acoustic communication with the underwater world and EM communication with a satellite or with onshore control stations.

Recently, Autonomous Underwater Vehicles (AUVs) were also employed to improve the overall communication process in an underwater network. However, AUVs are expensive, slow, and can be only used to collect unurgent data [5].

C. *Deployment Architecture*

UASN are usually three-dimensional (3D), where nodes are deployed at various depths with one or more sinks deployed at the surface as shown in Fig. 1. Autonomous underwater vehicles can be also used for data collection in IoUT applications. Underwater Nodes are either deployed at fixed locations in the bottom of the ocean, can be anchored at various depths with constrained mobility or can be floating with surface buoys. Such unique and constant mobility of underwater topology invalidate the benefits of routing protocols that depend on fixed topology information. Moreover, remote deployment of nodes in deep oceans raises the challenge of underwater nodes battery recharging difficulty. Therefore, reducing energy expenditure and extending the network lifetime are crucial requirements for routing protocols in the UASN.

It is also hard to obtain the location of underwater nodes where the global positioning systems (GPS) fails to work in water medium and obtaining the location information needs costly localization techniques [2]. Thus, a routing strategy that doesn't rely on location is preferred.

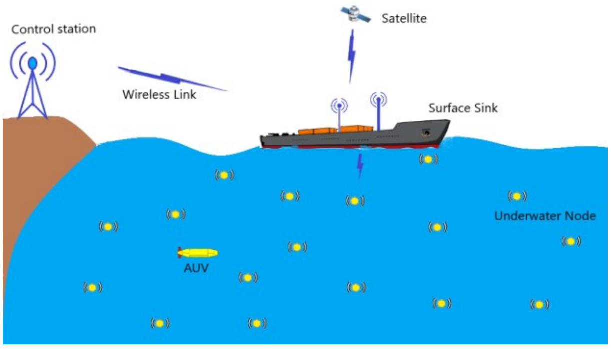

Fig.1. Internet of Underwater Things Architecture [6]

III. ON EFFICIENT ROUTING FOR THE IOUT

Like IoT, an efficient routing strategy for the IoUT depends on the requirement of the application it serves and can combine one or more of the followings, energy efficiency, reliability, robustness to mobility, and security. It is hard to achieve all these requirements on one protocol as there is always a trade-off. In this section we discuss each of these requirements.

A. *Energy Efficiency*

Since the replacement of underwater nodes batteries is tedious and not always feasible, energy efficiency is one of the most important metrics to be considered for routing in the IoUT. Moreover, balancing the energy consumption of individual nodes should also be achieved to prolong the network lifetime and avoid any disconnection in the network. This is hard in multi-hop routing favored by UASN since nodes closer to the surface usually depletes their energy faster by forwarding other nodes' data. Hence, new energy-saving, and balancing strategies need to be introduced to improve energy efficiency [7].

B. *Reliability*

Reliability is a key requirement for any communication system. Methods to increase reliability in an error-prone acoustic channel with a sparse deployment have been addressed by almost all protocol stack layers. Dynamic multi-path and multi-hop routing and cross-layer techniques were proposed in the literature to enhance reliability. However, there is always a tradeoff between enhancing reliability and reducing energy expenditure [4].

C. *Robustness to Mobility*

The mobility of underwater sensor nodes caused by water currents needs to be considered by routing strategies. Due to the continuous movement of underwater nodes, static and fixed routes are not suitable for such environment. On the other hand, adaptive routing techniques are preferable for routes that change frequently because of mobility. However, adaptive routing usually consumes extra energy and requires more processing time to recover or rebuild routes. Thus, a routing protocol that takes node mobility into consideration while lowering energy consumption and reducing end-to-end delays is needed. Mobility of nodes also affects the link quality which should also be taken into consideration. A class of mobility-aware routing algorithms is introduced to overcome this problem [8].

D. *Security*

Security requires consistent research to combat all sorts of threats coming from the outside world to keep operations of UASN secure and error-free. Various cryptographic techniques when integrated with routing protocols are helpful for end-to-end routing and may prevent disruptions from all sorts of attacks like Man-in-the-middle attack, DoS attack, and DDoS attack [9]. Since it is usually handled at higher protocol stack layers, only few secure routing strategies were proposed in literature [10,11].

IV. IOUT ROUTING STRATEGIES

Due to the unique challenges mentioned for underwater communication, routing protocols utilized for land based WSNs aren't appropriate for UASNs. In general, UASN researchers favors multi-hop geographic routing because multi-hopping achieves a better trade-off between energy consumption and delay reduction while geographic routing has lower overhead when compared with proactive and reactive routing strategies [12]. However, geographic routing still has the problem of routing void region formation because of the imbalances in energy consumption [13]. In this paper, we categorize the existing routing protocols as Location-based, location free, cluster-based, and AUV aided. We discuss these categories with examples in the following subsections.

A. *Location Based Routing*

In location-based geographical routing, nodes forward data in a greedy fashion to nodes closer to the surface sink. In this type of routings, three-dimensional location of nodes is an inevitable requirement and is obtained via complex localizations algorithms that adds to the extra energy expenditure and longer delays in the network.

One of the first and state of art protocols that requires the full location of nodes is the Vector-Based Forwarding (VBF) protocol [14]. In VBF, a vector pipeline is predefined between the source and destination/sink nodes. The forwarding nodes are selected from the nodes located in the vector pipeline where the nodes closer to the vector center are selected as forwarders. In dense networks, the width of the vector pipeline is fixed which eliminates several qualified nodes to act as forwarders. Therefore, Hop-Hop VBF(HH-VBF) protocol was proposed in [15] to solve this problem.

In a Focused Beam Routing protocol (FBR) [16], position information is assumed to be always known by all underwater and sink nodes. Next hop forwarders are selected from those nodes located within the section of a focused beam of a predefined angle θ. In this protocol, source node sends a multicast RTS packet request and nodes hearing this message and lies within a cone of angle $\pm\theta/2$ are selected as potential forwarders.

Sector-Based Routing with Destination Location Prediction (SBR-DLP) routing protocol [17] differs from VBF and FBR in that sink nodes are assumed to be mobile with multiple relay nodes. To select the optimal next hop, the source node sends a message that includes its location and packet ID. Each node receiving this message will compare whether its distance to the destination is shorter than the source node. Nodes satisfying this condition will send a reply packet to the source node. Thereafter, the source node will have all the information of its neighbors to decide on the best node to act as the forwarder.

Depth-Controlled Routing (DCR) protocol was proposed to overcome the problem of void regions in geographic routing [13]. In DCR, every node is equipped with a topology controller. The topology controller modifies the depth information based on location information obtained in real-time. Updating the depth information helps successful delivery of packets when the greedy geographic routing would fail. This protocol is unique since it controls the network topology based on the delivered data ratio by reducing the number of disconnected nodes in void regions.

Another location-based routing protocol is the Link Expiration Time-Aware Routing (LETA) protocol [18]. In this protocol, the expected forwarder node is found according to a bias theory. The performance metrics used to find the best next hop forwarder are the depth information, residual energy, and distance.

In [19] a Level Based Adaptive Geo-Routing (LB-AGR) protocol is proposed. The next hop in LB-AGR protocol is selected according to a function combining residual energy, density, and location.

In a Directional Flooding-Based Routing (DFR) proposed in [20] multiple forwarders are selected within the range of a predefined vertical angle to guarantee lowest delay toward the sink node.

Another example of location-based routing protocols is HydroCast [21]. This protocol uses a greedy heuristic to reduce redundant forwarding and hence reduce energy expenditure.

In all the mentioned location-based protocols, each node is supposed to be always aware of the three-dimensional coordinates of all neighboring nodes. However, obtaining the location of mobile nodes and frequently broadcasting it to neighbors is expensive and time-consuming. Although the performance of some location-based protocols surpasses other routing protocols categories, still accurate localization is the main drawback, especially in real-time scenarios.

B. Location Free Routing Protocols

An assumption of obtaining full location information of underwater nodes is not mandatory in this type of routing protocols. The depth-Based Routing (DBR) is a simple, efficient and state of art example [22]. In DBR, each sensor node chooses whether to forward the data based on the depth information of the current node and the depth of the previous node. The depth information of a node is obtained from an attached pressure sensor. Receiving nodes with less depth are the only qualified nodes to forward packets. DBR does not require full-dimensional location information. Its performance in terms of energy efficiency is good for dynamic scenarios. On the other hand, void region formation, long delays, data redundancy, and high energy consumption still need to be enhanced in DBR.

An Energy-Efficient and Depth-Based Routing (EEDBR) protocol was proposed in [23] to reduce the energy consumption in DBR. EE-DBR is used to decrease multiple paths forwarding redundancy. The authors used the time of arrival ranging technique to check whether a node existed in a void region or not. Then, nodes that located in the blind zones are not used as forwarding packet. Furthermore, a Directional DBR Protocol (D-DBR) is also proposed in [24] to guide the packets to be forwarded to the sink node via an optimal route. Thus, this protocol reduces the number of next hops and reduces the propagation delay and enhances the delivery ratio.

Another protocol proposed in [25] to solve the problems in DBR is Shortest Path Routing Protocol Based on the Vertical Angle (SPRVA) to improve both energy efficiency and end-to-end delay. In this protocol, the best forwarder is chosen depending on the main priority indicated by the residual energy and vertical angle between propagation orientation and depth orientation. An alternative priority is utilized when the main priorities of candidate nodes are equal and are denoted by the link quality. Furthermore, to prevent nodes in void regions from participating in forwarding, a recovery algorithm is proposed. to solve the problems of the void region and long detour in DBR.

A Distance Vector-based Opportunistic Routing (DVOR) algorithm proposed in [3] relies on a query approach to establish the distance vectors for underwater acoustic nodes and store the smallest node counts towards the sink. DVOR has the functionality to eliminate the problem of the blind zone and long detours. In addition, DVOR accomplishes opportunistic forwarding without complex signaling to choose relay candidates and direct data forwarding among potential relays.

Another routing protocol that does not rely on location information is Channel-Aware Routing Protocol (CARP) [26]. This protocol uses power control to select a robust path and avoid control loops and void regions.

[8] proposed an enhanced version of the Channel-Aware Routing Protocol (E-CARP) to improve energy efficiency and cope with the mobility of nodes. E-CARP allows a previous-hop to be chosen as a forwarder even if it may not be the best forwarder.

An adaptive Mobility of Courier nodes in Threshold-Optimized DBR (AMCTD) protocol is proposed [27]. AMCTD predefined several depth thresholds for numerous nodes based on the network intensity to reduce the number of forwarding nodes. AMCTD protocol is not appropriate for data-sensitive applications. Thus, an Improved-AMCTD (I-AMCTD) was developed in [28]. I-AMCTD joined both the soft depth threshold and hard thresholds. Moreover, the forwarding node sends the depth threshold information combined with the "hello" packet. This causes extra overhead.

A localization-Free Interference and Energy Holes Minimization (LF-IEHM) routing protocol were proposed in [29] to overcome the problem of energy hole. However, the delay problem still exists. Therefore, a Delay-Sensitive Depth-Based Routing (DSDBR) was proposed in [30] to solve the delay problem.

Authors in [4], proposed two routing protocols for UASNs to ensure both stability and reliability: A Reliable and Stability-Aware Routing (RSAR) and Cooperative Reliable and Stability-Aware Routing (CoRSAR). In Reliable and Stability-Aware Routing, energy is assigned to a node based on the depth information where high power is assigned to nodes with the lowest depth. This power assignment is called the energy grade of a node where five energy grades are formed from top to bottom. The forwarder node is chosen according to the energy grade along with residual energy and depth. This protocol utilizes just one link to send data, but this link might not be reliable all the time. Thus, the Cooperative Reliable and Stability-Aware Routing is proposed. In this proposed protocol, the destination receives several copies of packet symbols. This reduces the effects of the inverse channel on data packets, also makes the extraction of data more convenient at the final host. Compared to the traditional scheme.

C. Cluster Based Routing

Clustering was long used in wireless sensor networks to balance energy consumption and hence prolong the network lifetime. Nevertheless, if the size of the cluster is large, then nodes located away from Cluster Heads (CHs) require much power to forward packets to their CH. On the other hand, small-sized clusters will cause extra communication overhead. Therefore, an optimal cluster size should be carefully selected to enhance the network lifetime and reduce power consumption [31].

In terrestrial wireless sensor networks, a cluster-based routing was an approach taken by the Low Energy Adaptive Clustering Hierarchy protocol LEACH-L in [7]. It was adopted by the Clustering Vector-Based Forwarding (CVBF) algorithm for UASN [32]. An I-Kmeans technique which is the most common clustering approach for time series data transformed by a multiresolution dimensionality reduction method was also presented and used for clustering in UASN [33].

In [34], an energy efficient routing protocol selection for Cluster-based Underwater Wireless Sensor Network (CUWSN) was proposed. Underwater relay nodes (URNs) are selected based on hop count. To send packets to the base station multi-hop or direct transmission method is used. In the perspective of power consumption, multi-hop transmission surpasses the direct transmission method.

An Adaptive Clustering Habit (ACH2) protocol for land based WSNs is proposed in [35]. In this strategy, a free association technique is used where nodes are associated with CHs. The power consumption is minimized, and network lifespan is maximized by reducing the propagation distance. In this method, the CHs are selected based on a predefined threshold. Then, the number of CHs is chosen based on the optimum distance within them. Consequently, the load is balanced between CHs. Although this method improved the network lifetime for WSNs, the transmission delay has increased.

In [36], Free Space Optical (FSO) and Electromagnetic (EM) wave-based communication approaches are proposed to select the optimal optimum range of clusters. The outcomes are calculated by modifying the location of the sink at three different positions (center, corner, midpoint). Furthermore, this method reduces energy consumption, but the end-to-end delay is increased.

ATR-WDFAD-DBR and CB-WDFAD-DBR algorithms are proposed in [30]. In the proposed schemes, 3D multi-sink architecture model is assumed. This 3D model consists of the anchored, relay, and sink nodes. Anchored nodes placed at the seafloor to sense and collect data. Relay nodes are deployed at a random underwater location to forward data to the sink node. The network is split into clusters to reduce interference where data is gathered at a local head node before being forwarded to the surface sink. CHS is selected based on maximum residual energy. problem of void holes, the ATR-WDFAD-DBR scheme is used to overcome the void whole problem by modifying the transmission range. On the other hand, CB-WDFAD-DBR scheme is used to maximize the network lifetime by selecting the CH with maximum residual energy.

Cluster based routing where also combined with multi-hop location free routing in an energy-efficient clustering multi-hop routing protocol (EECMR) [37]. Authors in this work have combined the advantages of both approaches such as in balancing energy expenditure increasing network lifetime, while avoiding costly localization overhead. In their approach, depth information is used to divide the topology into layers where each cluster is selected based on residual energy and depth at each layer. Data is then forwarded via multi hop routes from one CH in each layer to another CH in the layer above until it reaches the surface sink.

D. Routing Protocols Aided by Autonomous Underwater Vehicles (AUVs).

One major disadvantage of multi-hop routing is that energy for sensor nodes closer to the surface will be depleted quickly because of relaying data packets of other nodes. As a result, these nodes will die early, affecting the network connectivity and overall performance. To balance and save underwater nodes energy, AUV aided routing was proposed. When an AUV moves closer to the nodes and collects data using the lowest power levels, nodes energy is preserved. In this type of algorithms, End-End delays from source nodes to the surface sink is usually not taken into consideration due to the slow speed of AUV.

To reduce the long delays, AUV assisted routing is usually combined with a clustering approach as presented in [5]. This work, authors combined a smart genetic based AUV path selection with a simple clustering technique to enhance the network performance.

In [38], the researchers tried to reduce the energy expenditure of nodes closer to the AUV path. They suggested an AUV location prediction (ALP)-based data collection scheme to overcome this problem. The AUV trajectory is changed periodically to balance energy consumption. They also used a reliable time mechanism to ensure effective communication between nodes and AUV and thus improves network performance. It guarantees that the nodes near the AUV trajectory have sufficient time for communicating its data with the AUV.

A heterogeneous channel of both acoustic and radio is adopted in AUV-Aided Underwater Routing Protocol (AURP) [39]. They use multiple AUVs with controlled mobility as relays for underwater gateways to minimize total data transmissions.

In an Advanced AUV-Aided Energy Efficient Routing Protocol for Underwater WSNs (AAEERP) [40] and in AUV Aided Efficient Data Gathering (AEDG) [41], authors used a shortest path tree algorithm to find the best energy efficient and reliable path for an AUV to collect data from underwater gateways. Energy balancing in this approach is achieved by rotating the roles of the gateways.

A Routing Void Prediction and Repairing Technique (RVPR) employed AUVs to solve the problem of routing voids creation [42]. A particle swarm optimization is used in this strategy to adjust the AUV position for maximal connectivity in the void region while minimizing the distance the AUV needs to travel.

We summarize the advantages and disadvantages of each mentioned routing category in Table 1.

CONCLUSION

In this paper, we presented the most challenging factors that affect the protocol design for IOUT that is facilitated by UASNs. We also discussed major requirements for efficient routing and how they are affected by underwater networking's unique characteristics. Then we categorized existing underwater routing protocols, discussing each category and what performance metrics it enhances, we also gave relevant examples from literature on each category. For instance, the main drawback of location-based protocols is getting the three-dimensional coordinates of nodes which is not an easy task since GPS doesn't work underwater. Location unaware techniques were proposed to solve this problem. However, they usually suffer from excessive overhead that also affects energy consumption and delays. Cluster-based routing was proposed to compensate for energy imbalance in both location-aware and location-unaware routing techniques. Moreover, researchers opted to use AUV aided routing to reduce underwater nodes' energy expenditure. This is done by sending to the AUV when it moves at a close distance to nodes.

TABLE I
COMPARISON OF ROUTING

Routing Category	Advantages	Disadvantages
Location Based	Low energy expenditure and high delivery ratio for statics network	High localization cost for mobile network
Location Free	Robustness to mobility, Avoids costly localizations	Control message overhead
Cluster Based	Scalability, Reduced and balanced energy expenditure	Cluster formation overhead
Aided by AUV	Enhanced network life, High delivery ratio, Avoids routing voids	Long end to end delays, Complexity of AUV path planning algorithm

In future work, we will expand this work to include secure and reliable routing strategies and will survey and compare all existing routing protocols in terms of achieving better performance for IoUT.

REFERENCES

[1] M. Jouhari, K. Ibrahimi, H. Tembine and J. Ben-Othman, "Underwater Wireless Sensor Networks: A Survey on Enabling Technologies, Localization Protocols, and Internet of Underwater Things," in IEEE Access, vol. 7, pp. 96879-96899, 2019, https://doi.org/10.1109/ACCESS.2019.2928876
[2] Tuna, G, Cagri Gungor, V. A survey on deployment techniques, localization algorithms, and research challenges for underwater acoustic sensor networks. Int J Commun Syst. 2017; 30:e3350. https://doi.org/10.1002/dac.3350
[3] Guan, Quansheng, Fei Ji, Yun Liu, Hua Yu, and Weiqi Chen. "Distance-Vector-Based Opportunistic Routing for Underwater Acoustic Sensor Networks." IEEE Internet of Things Journal 6.2 (2019): 3831-839.
[4] Ali M, Khan A, Mahmood H, Bhatti N. Cooperative, reliable, and stability-aware routing for underwater wireless sensor networks. International Journal of Distributed Sensor Networks. 2019;15(6). https://doi.org/10.1177/1550147719854249
[5] Al-Bzoor, M, Al-assem, E, Alawneh, L, Jararweh, Y. Autonomous underwater vehicles support for enhanced performance in the Internet of underwater things. Trans Emerging Tel Tech. 2021; 32:e4225. https://doi.org/10.1002/ett.4225.
[6] Manal Al-Bzoor, Ahmed Musa, Khawla Alzoubi, Taha Gharaibeh, "A Directional Selective Power Routing Protocol for the Internet of Underwater Things", Wireless Communications and Mobile Computing, vol. 2022, Article ID 3846621, 13 pages, 2022. https://doi.org/10.1155/2022/3846621
[7] Xia Li, Shi-liang Fang, and Yong-chun Zhang. "The Study on Clustering Algorithm of the Underwater Acoustic Sensor Networks." 2007 14th International Conference on Mechatronics and Machine Vision in Practice (2007).
[8] Zhangbing Zhou, Beibei Yao, Riliang Xing, Lei Shu, Shengrong Bu. E-CARP : an energy efficient routing protocol for UWSNs in the internet of underwater things. IEEE Sensors Journal, Institute of Electrical and Electronics Engineers, 2016, 16 (11), pp.4072 - 4082. https://doi.org/10.1109/JSEN.2015.2437904
[9] Guang Yang, Lie Dai, Guannan Si, Shuxin Wang, Shouqiang Wang,Challenges and Security Issues in Underwater Wireless Sensor Networks,Procedia Computer Science, Volume 147,2019, Pages 210-216, https://doi.org/10.1016/j.procs.2019.01.225
[10] Du X, Peng C, Li K. A secure routing scheme for underwater acoustic networks. International Journal of Distributed Sensor Networks. June 2017. https://doi.org/10.1177/1550147717713643
[11] Ahmadi, M., & Jameii, S. M. (2018). A Secure Routing Algorithm for Underwater Wireless Sensor Networks. International Journal of Engineering, 31(10), 1659-1665.
[12] Zhang, Wenyi, Milica Stojanovic, and Urbashi Mitra. "Analysis of a Linear Multihop Underwater Acoustic Network." IEEE Journal of Oceanic Engineering 35.4 (2010): 961-70.
[13] Coutinho, Rodolfo W., Luiz F. Vieira, and Antonio A. Loureiro. "DCR: Depth-Controlled Routing Protocol for Underwater Sensor Networks."2013 IEEE Symposium on Computers and Communications (ISCC) (2013).
[14] Xie, Peng, Jun-Hong Cui, and Li Lao. "VBF: Vector-Based Forwarding Protocol for Underwater Sensor Networks." NETWORKING 2006. Networking Technologies, Services, and Protocols; Performance of Computer and Communication Networks; Mobile and Wireless Communications Systems (2006): 1216-221.
[15] Chen Wang, Gang Zhang, Lei Zhang, and Yang Shao. "Improvement Research of Underwater Sensor Network Routing Protocol HHVBF." 11th

International Conference on Wireless Communications, Networking and Mobile Computing (WiCOM 2015) (2015).
[16] Jornet, Josep Miquel, Milica Stojanovic, and Michele Zorzi. "Focused Beam Routing Protocol for Underwater Acoustic Networks." Proceedings of the Third ACM International Workshop on Wireless Network Testbeds, Experimental Evaluation and Characterization - WuWNeT '08 (2008).
[17] Chirdchoo, Nitthita, Wee-Seng Soh, and Kee Chaing Chua. "Sector-Based Routing with Destination Location Prediction for Underwater Mobile Networks." 2009 International Conference on Advanced Information Networking and Applications Workshops (2009).
[18] Uddin, Md. Ashraf, and Mamun-or-Rashid. "Link Expiration Time-Aware Routing Protocol for UWSNs." Journal of Sensors 2013 (2013): 1-9.
[19] DU, Xiu-juan, Ke-jun HUANG, Sheng-lin LAN, Zhen-xing FENG, and Fan LIU. "LB-AGR: Level-based Adaptive Geo-routing for Underwater Sensor Network." The Journal of China Universities of Posts and Telecommunications 21.1 (2014): 54-59.
[20] Daeyoup Hwang, and Dongkyun Kim. "DFR: Directional Flooding based Routing Protocol for Underwater Sensor Networks." OCEANS 2008 (2008).
[21] Noh, Youngtae, Uichin Lee, Saewoom Lee, Paul Wang, Luiz F. Vieira, Jun-Hong Cui, Mario Gerla, and Kiseon Kim. "HydroCast: Pressure Routing for Underwater Sensor Networks." IEEE Transactions on Vehicular Technology 65.1 (2016): 333-47.
[22] Yan, Hai, Zhijie Jerry Shi, and Jun-Hong Cui. "DBR: Depth-Based Routing for Underwater Sensor Networks." NETWORKING 2008 Ad Hoc and Sensor Networks, Wireless Networks, Next Generation Internet (2008): 72-86.
[23] Wahid, Abdul, Sungwon Lee, Hong-Jong Jeong, and Dongkyun Kim. "EEDBR: Energy-Efficient Depth-Based Routing Protocol for Underwater Wireless Sensor Networks." Communications in Computer and Information Science (2011): 223-34.
[24] Diao, Boyu, Yongjun Xu, Zhulin An, Fei Wang, and Chao Li. "Improving Both Energy and Time Efficiency of Depth-Based Routing for Underwater Sensor Networks." International Journal of Distributed Sensor Networks 2015 (2015): 1-9.
[25] Li, Meiju, Xiujuan Du, Xin Liu, and Chong Li. "Shortest Path Routing Protocol Based on the Vertical Angle for Underwater Acoustic Networks." Journal of Sensors 2019 (2019): 1-14.
[26] S. Basagni, C. Petrioli, R. Petroccia and D. Spaccini, "Channel-aware routing for underwater wireless networks," 2012 Oceans - Yeosu, 2012, pp. 1-9, https://doi.org/10.1109/OCEANS-Yeosu.2012.6263538
[27] Jafri, Mohsin Raza, Muhammad Moid Sandhu, Kamran Latif, Zahoor Ali Khan, Ansar Ul Yasar, and Nadeem Javaid. "Towards Delay sensitive Routing in Underwater Wireless Sensor Networks." Procedia Computer Science 37 (2014): 228-35.
[28] Javaid, N., M. R. Jafri, Z. A. Khan, U. Qasim, T. A. Alghamdi, and M. Ali. "IAMCTD: Improved Adaptive Mobility of Courier Nodes in Threshold-Optimized DBR Protocol for Underwater Wireless Sensor Networks." International Journal of Distributed Sensor Networks 10.11 (2014): 213012.
[29] A. Khan, I. Ahmedy, M. Anisi, N. Javaid, I. Ali, N. Khan, M. Alsaqer, and H. Mahmood, "A Localization-Free Interference and Energy Holes Minimization Routing for Underwater Wireless Sensor Networks," Sensors, vol. 18, no. 2, p. 165, Jan. 2018.
[30] M. R. Jafri, M. M. Sandhu, K. Latif, Z. A. Khan, A. U. H. Yasar, and N. Javaid, "Towards delay-sensitive routing in underwater wireless sensor networks," Procedia Computer Science, vol. 37, pp. 228-235, 2014.
[31] Khan A, Javaid N, Latif G, Jatta L, Fatima A, Khan W. "Cluster based and adaptive power-controlled routing protocol for underwater wireless sensor networks". In 2018 21st Saudi Computer Society National Computer Conference (NCC) 2018 Apr 25 (pp. 1-6). IEEE.
[32] Ibrahim DM, Eltobely TE, Fahmy MM, Sallam EA. "Enhancing the vector-based forwarding routing protocol for underwater wireless sensor networks: a clustering approach". In International conference on wireless and mobile communications 2014 Jun 22 (No. 10, pp. 98-104).
[33] JIANG, Peng, and Bin-feng RUAN. "Cluster-based coverage preserving routing algorithm for underwater sensor networks." ACTA ELECTONICA SINICA 41.10 (2013): 2067.
[34] Bhattacharjya K, Alam S, De D. CUWSN," Energy efficient routing protocol selection for cluster based underwater wireless sensor network". Microsystem Technologies. 2019 Aug 13:1-7.
[35] Ahmad A, Javaid N, Khan ZA, Qasim U, Alghamdi TA."Routing Scheme to Maximize Lifetime and Throughput of Wireless Sensor Networks". IEEE Sensors Journal. 2014 Jun 4;14(10):3516-32.
[36] Yadav S, Kumar V." Optimal clustering in underwater wireless sensor networks", acoustic, EM and FSO communication compliant technique. IEEE access. 2017 Jul 4;5:12761-76
[37] N.-T. Nguyen, T. T. T. Le, H.-H. Nguyen, and M. Voznak, "Energy-Efficient Clustering Multi-Hop Routing Protocol in a UWSN," Sensors, vol. 21, no. 2, p. 627, Jan. 2021.
[38] G. Han, X. Long, C. Zhu, M. Guizani, Y. Bi and W. Zhang, "An AUV Location Prediction-Based Data Collection Scheme for Underwater Wireless Sensor Networks," in IEEE Transactions on Vehicular Technology, vol. 68, no. 6, pp. 6037-6049, June 2019, https://doi.org/10.1109/TVT.2019.2911694
[39] Yoon S, Azad AK, Oh H, Kim S. "AURP:An AUV-aided underwater routing protocol for underwater acoustic sensor networks". Sensors. 2012 Feb;12(2):1827-45.
[40] Ahmad, A., Wahid, A., & Kim, D. "Workshop on Performance Monitoring and Measurement of Heterogeneous Wireless and Wired Networks "- PM2HW2N '13. the 8th ACM workshop, (2013). AEERP. Proceedings of the 8th ACM.
[41] Ilyas N, Alghamdi TA, Farooq MN, Mehboob B, Sadiq AH, Qasim U, Khan ZA, Javaid N. "AEDG: AUV-aided efficient data gathering routing protocol for underwater wireless sensor networks". Procedia Computer Science. 2015 Jan 1;52:568-75.
[42] Z. Jin, Q. Zhao and Y. Luo, "Routing Void Prediction and Repairing in AUV-Assisted Underwater Acoustic Sensor Networks," in IEEE Access, vol. 8, pp. 54200-54212, 2020.