ISSN: 1992-8645 www.jatit.org E-ISSN: 1817-3195

AUV PATH PLANNING BASED EFFICIENT ROUTING FOR UNDERWATER LINEAR SENSOR NETWORKS

[1,3]ZAHOOR AHMED, [1]KAMALRULNIZAM ABU BAKAR, [2]MUHAMMAD ZAHID ABBAS, [3]MUHAMMAD AYAZ, [3]EL-HADI M. AGGOUNE

[1]Faculty of Computing, Universiti Teknologi Malaysia (UTM), Johor Bahru, Malaysia.

[2]COMSATS Institute of Information Technology, Vehari, Pakistan.

[3]Sensor Networks and Cellular Systems (SNCS) Research Center, University of Tabuk, Tabuk, KSA.

zahoorahmad390@gmail.com

ABSTRACT

The Linear Sensor Networks (LSNs) have gained much attention of the researchers due to their several positive aspects including easy deployment for linear structures and robustness in various environments. Although, such types of LSNs are suitable for many applications and scenarios but considered ideal for oil, gas, and water pipeline monitoring. In the previous studies, Autonomous Underwater Vehicles (AUVs) are used to receive data from every sensor on the LSNs which leads to longer delays and routing overhead. Also, only homogeneous sensors have been considered in the previous studies, which is not realistic in the real life scenario of sensor deployment. This research focuses on heterogeneous LSNs to monitor underwater pipelines where data is collected from the sensor nodes and transmitted to a surface sink using an AUV. In proposed network architecture which is called AUV Path Planning-based Efficient Routing (APPER), AUV only receives data from sensor nodes with higher resources, hence leads to balance the nodes resources ultimately helping to increase the network life. The impact of AUV usage is high unlikely pure multi-hop approaches as other than offering reduced delays and better delivery ratio with better network lifetime, most importantly it can be extended for hundreds of kilometers. Simulation results exhibit that APPER achieved improved network performance in terms of network topology distribution, packet delivery ratio, end-to-end delays, and routing overhead as compared to the existing routing techniques including Dynamic Addressing Routing Protocol for Pipeline Management (DARP-PM) and AUV-based Linear Sensor Networks (ALSN) respectively.

Keywords: *Underwater Pipelines Monitoring, Autonomous Underwater Vehicles (Auvs), Linear Sensor Networks, Heterogeneous Node Deployment, Data Forwarding*

1. INTRODUCTION

Underwater Linear Sensor Networks for pipeline monitoring are getting significant attention recently as the protection of these resources and facilities have become an important objective of many countries whose economies largely depend on these vital resources. In this regard, Wireless Sensor Networks (WSNs) are being used commonly for such kind of applications in order to collect information from the underwater pipelines [1-3]. Due to very short range of radio signals in such environment, acoustic communication is a feasible option to communicate and forward data from for any section of the pipeline. A network based on wireless sensors is usually installed on the pipeline for this purpose. Normally, in underwater environments, higher reliability of the monitoring process is achieved by dividing the whole pipeline network into multiple segments. Where, in each segment, a surface buoy is deployed that is directly linked with one of the underwater sensor nodes through wire or some similar mechanism. All acoustic sensor nodes need to transfer their sensed information to the closet nearby node linked to one of the surface buoys.

In this paper, we presented a routing technique named AUV Path Planning-based Efficient Routing (APPER) for underwater pipeline monitoring LSNs. Multiple types of nodes are defined such as Basic Sensing Node (BSN), Data Relay Node (DRN), Data Definition Node (DDN), the surface sinks and most importantly an AUV is introduced. In proposed system, BSNs do sensing job, DRN collect

ISSN: 1992-8645 www.jatit.org E-ISSN: 1817-3195

information from BSNs and forward it to DDNs, which are placed at regular intervals between the sinks. This APPER system provides flexibility in the design of the network by adding heterogeneous nodes to minimize the communication delay between each BSNs and sinks. Also it minimizes the workload on BSNs that ultimately reduce considerable energy savings, increase packet delivery ratio and network lifetime. In order to eliminate the multi-hop overhead, the use of an AUV not only increases the network reliability but also solves the problem of the higher latency between BSNs and the sinks. Furthermore, heterogeneous nodes deployment reveals that this approach increases scalability as in [4], helps in efficient packet delivery and failure nodes detection, [5, 6] and provides added reliability support [7]. In this model, connectivity between the DDNs and the sinks is provided by using an AUV which moves on the sinusoidal path between the sinks and collects the sensing data from the DDNs as it comes within range of each node. The AUV can perform multiple functions such as data accumulation, scheduling, sensor operating system and software configuration, programming, updating, as well as localization and synchronization for the DDN nodes. In this case, AUV is also capable to transport the data and programs from the sinks to the DDNs. In this connection, the end-to-end delay for the transmitted data is the main parameter that is significantly affected by the movement of the AUV and the length of the network. Different possibilities to reduce this application-related parameter are considered and analyzed. Moreover, the resulting AUV buffer size requirements are also discussed in details.

The rest of the paper is organized as follows. Section 2 provides the related work proposed with similar attention and the problems they faced are highlighted. Section 3 presents the proposed network model including the algorithms and the necessary relevant details. Section 4 includes the simulation parameters, results and discussions while section 5 concludes the paper.

2. RELATED WORK

There are two kinds of risks that might occur in monitoring of underwater pipeline infrastructures. One is known as intentional risk and other is the occurrence of non-intentional issues. Intentional risk can be caused by human through attacking on the pipeline. For example, pipeline in Middle East has one of the major threats of human attacking. Non intentional risk occurs when a ship strikes into a pipeline, labor mistakes during working in pipeline maintenance or operation, or natural disasters such as earthquakes and volcanoes eruption. On the other hand, it is very challenging and time-consuming process to find the exact location and type of damage occurred its occurring due to some natural disaster like hurricanes. In order to minimize these risks, it is vital to monitor underwater pipelines continuously [8].

For this purpose, several techniques are proposed those used to provide fast and effective detection mechanisms to find faults and fix them timely and in way that are more efficient. In this connection, some researchers utilized mobile nodes for gathering information from WSN like [9] where authors provided a connectivity design of sparse WSNs using existing mobile nodes named MULEs. Here ordinary sensors are assumed to continuously generate sensing data and buffer it until MULE comes within its transmission range. In another study, multiple MULEs are used to collect data presented in [10]; it has set of motions along straight parallel lines in a field with randomly deployed sensors. This divides the field into parallel regions of two types, depending on whether they have sensors in range of a MULE or not. In this regard, authors in [11] introduced a mobile node called a ferry to provide communication between nodes in a highly partitioned ad-hoc sensor network. This ferry is a specially designed node with increased resources such as renewable battery, large memory and higher processing capabilities used in the transportation of messages between nodes, otherwise multi-hop paths might be used between nodes. Similarly, an extension of the ferry scheme was introduced in [12], here authors determine path for the mobility of ferry, where ferry mobility is specifically designed to improve messaging performance. Moreover, another model was introduced for multiple ferries that mainly focus on designing on ferries routes [13]. This model establishes integrated communication network providing the possibility of interaction between the multiple ferries, and handle the problem of ferry route synchronization in order to increase efficiency. Later in a study [14], this ferries communication model is further extended to sparse ad-hoc networks by adding mobile nodes.

Most of the techniques discussed above are designed for multi-dimensional WSNs/ad-hoc network architectures using multi-hop strategies. This paper focuses on an AUV path planning and data collection model for LSN, which to the best of our knowledge, is ignored in the literature. Prior to this research, we conducted a comprehensive survey of LSN routing techniques [15] in

Journal of Theoretical and Applied Information Technology
28th February 2019. Vol.97. No 4

ISSN: 1992-8645 www.jatit.org E-ISSN: 1817-3195

accordance with the comparison of correlation parameters such as linearly homogeneous and heterogeneous nodes deployment issues, communication scheduling, the reliability of the network, an end-to-end delay issues, and different kinds of LSNs routing techniques are discussed. Further, the previous study helped us to find the research gap in reducing the network installation cost, covering scalable network, increasing the reliability and fault tolerance, utilizing heterogeneous types of sensors, and decreasing the communication delay in long range networks etc. While, a summary of major contribution of this work is summarized as follows:

-Define heterogeneous nodes deployment model and functionalities of the nodes.

-Outline the AUV path planning model and data collection algorithm and,

-Compare existing AUV based routing method based on different routing parameters.

3. APPER: PROPOSED ROUTING TECHNIQUE

This section presents the proposed routing technique namely APPER for the efficient monitoring and data collection of the large scale UW-LSN. In such kind of networks, sensor nodes are deployed in linear direction as they monitor the linear structures such as the pipeline. All the necessary details and working procedure of this proposed technique is provided in the following sub sections.

3.1 Network Model

A typical LSN model is utilized in this research; it consists of two integral things including the linear structure (pipeline) and sensor nodes. In case of homogeneous networks, it remains common in LSNs that all the nodes deployed have same the type as shown in figure 1. On the other hand, in heterogeneous networks, nodes belong to different types according to the application requirement such as shown in figure 2.

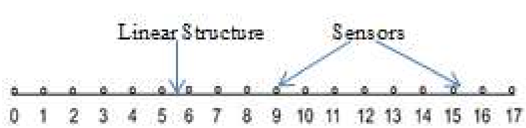


Figure 1: LSN basic structure

Figure 2, presents details about heterogeneous network topology model adopted for Scalable Heterogeneous Nodes Deployment (SHND) deployment scheme [4]. SHND scheme is used as a base of the proposed network topology model of APPER. Here exist three types of nodes BSN, DRN and DDN having unique properties (communication ranges, distances between nodes and levels). SHND distributes total network topology and equally divide the network area into heterogeneous type of nodes using multiple mathematical formulas.

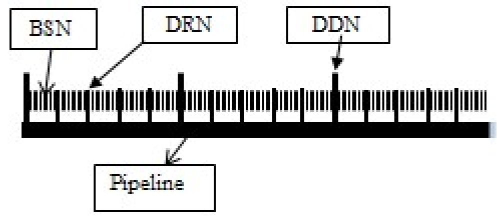


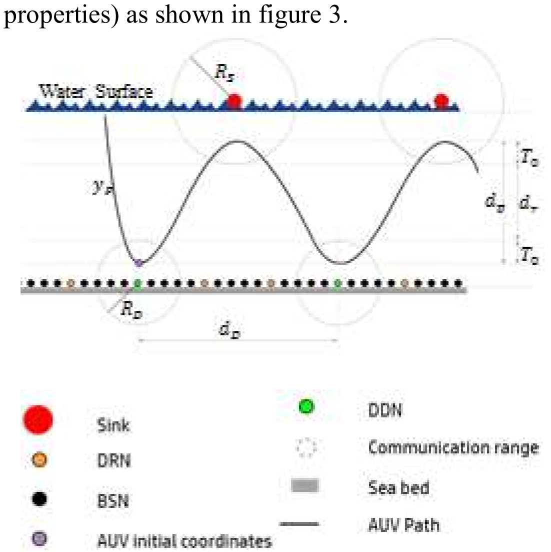
Figure 2 Network topology diagram

Total number of Sinks = 5
Total number of BSN Nodes = 100
Total number of DRN Nodes = 20 Repeated after 4 BSN
Total number of DDN Nodes = 6 Repeated after 4 DRN

These parameters are assumed during the testing of SHND algorithm. Due to limitation of simulator, more nodes cannot be applied in evaluation process but the node deployment ratio is scalable according to the SHND algorithm. Nodes deployment starts from left end of the pipeline and continues till right end of the pipeline.

3.2 AUV Path Planning Algorithm

Algorithm 1 is designed for the deployment of different type of the nodes, sinks and AUV. It consists of step-by-step calculation for each type of node position calculation. (Sinusoidal wave properties) as shown in figure 3.



ISSN: 1992-8645 www.jatit.org E-ISSN: 1817-3195

Figure 3 AUV Mobility Route

The sine wave play important role in many fields of applied sciences because it has the property to maintain its wave shape at the same frequency, arbitrary phase and magnitude. It is the only periodic waveform that has this property. This property leads to its importance in Fourier analysis and makes it acoustically unique [16].

The beginning of the AUV is from the starting point of the AUV movement which actually follows the sinusoidal wave. Based on this, in step 51 to step 57 the algorithm explain that if there is an increase of pipeline length then the nodes can be distributed based those steps. The R_D represent the signal range distance, which is the radio of the network coverage. The range of signal coverage of the sink node at the water surface is represented as R_S. The distance between two DDN in the deployment process is represented as d_D. The d_p is the amplitude of the sine wave path and T_o is the intersection of signal coverage of both AUV and DDN. The difference between the d_p and T_o is the d_r. The y_P is the sinusoidal value obtained for the AUV path planning movement.

The sinusoidal path movement has an advantage of traversing both the top of the sea level and the deep depth of the sea, which makes it suitable for the underwater data collection with the help of sensor nodes. This property leads to its importance in the acoustic environment [17]. In our work, AUV follows the sinusoidal path, for the development of the AUV path some parameters are utilized such as R_d, R_s, Y_p, d_x, d_y, d_r and d_p. Fowling, the complete procedure is explained in Algorithm 1.

Algorithm 1: AUV Path Planning, Sinks and Nodes deployment

Input Variables:

1. N: Total number of BSN nodes
2. Set different distance, neighbor density and type of nodes
3. L: Total Pipeline length
4. S: Set of sinks (s1, s2, s3……)
5. Yp= Path of UAV on y-axis
6. Y_{max}= Maximum value of the y-axis (Water surface
7. X_{max}= Maximum range of the x-axis
8. R_s= Range of each sink
9. R_d= Range of each DDN node
10. d_D= distance between two DDN nodes
11. d_P = Distance between two peaks of UAV path
12. T_o= Overshoot threshold
13. X initial= x coordinate of first DDN
14. D_n = total number of DDN nodes

Mathematical formula to determine AUV path:

$$y_P = R_D - T_o + d_p\left[\sin^2\left(\frac{\pi x}{d_D}\right)\right]$$

Process:

```
1.  Procedure 1: Nodes placement
2.  for i = 0 to N
3.      create an ordinary node
4.      set x, y, z ← 0
5.      set x ← i * d_m

6.  endfor

7.  Procedure 2: Nodes initialization
8.  set nn ← 126

9.  set o1 ← 1
10. set o2 ← 0
11. set o3 ← 0
12. set o4 ← 0
13.
14. for k = 0 to nn
15.     incr o4
16.     if k mod 5 = 0 AND o4 != 0 AND k!=0 then
17.             incr o3
18.             set o4 ← 0
19.     endif
20.     if (o3 mod 5 = 0 AND o3 != 0) OR k=0 then
21.             incr o2
22.             set o3 ← 0
23.             set o4 ← 0
24.     endif
25.     if o4 != 0 AND k!=0 then
26.       set node_type ← BSN
27.       set range ← 100 M
28.       set node_size ← small
29.     elseif o3 !=0 then
30.       set node_type ← DRN
31.       set range ← 500 M
32.       set node_size ← medium
33.     else
34.       set node_type ← DDN
35.       set range ← 2500 M
36.       set node_size ← large
37.     endif
38.     set node[k] address ← o1.o2.o3.o4
39. endfor
```

40. ***Procedure 3: Sinks deployment***
41. ***dowhile (n ≠ Dn)***
42. $S(i) \leftarrow$ n-*1 then* $\sum_{s=1}^{Dn-1} \left(\frac{D(s+1)x-Dsx}{2}\right)$

//ith Sink deployment formula

43. ***end while***
44. ***Procedure 4: AUV Path Calculation***
45. *intial:* $x \leftarrow 0$
46. *move AUV to initial position*
47. ***dowhile*** $(x \neq X_{max})$
48. *calculate next y position of AUV:* $y_P \leftarrow R_D - T_o + d_p \left[\sin^2\left(\frac{\pi x}{d_D}\right)\right]$
49. *move AUV to coordinate* (x, y_p)
50. ***endwhile***

51. ***AUV complete mobility path Y (p) is based on values of x varies from 0 to*** X_{max}.
52. ***If*** *more BSN, DRN, DDN nodes added in LSN Network*
53. *Repeat Procedure 1 and 2*
54. ***Update total coverage formula of complete network by repeating step 30***
55. ***else*** *all heterogeneous nodes are deployed at proper path is developed for AUV*
56. ***endif***
57. *Stop nodes and AUV deployment process, go to data collection and packet forwarding process*

Output: "All nodes and sinks are localized at their places. A sinusoidal path is developed for movement of the AUV over the total pipeline area"

Algorithm 2: Data Collection Algorithm

Data Packet (*dp*) ready to send (BSNs initially generate dp and forward it to the next hop then the same procedure is repeated by each next hop till dp arrives at any DDN.

1. ***Procedure*** *DATA FORWARDING (dp, next hopIDs)*
2. *p = PacketReceived*
3. ***if*** *existInCache(p)* ***then***
4. *drop (p)*
5. *return*
6. ***elseif*** *p_type = pkt_fwd* ***then***
7. *addCache (p)*
8. ***if*** *packet source side = this node side* ***then***
9. ***if*** *this = DDN* ***then***
10. *Update packet p details*
11. ***if*** *AUV passed from this node* ***then***
12. *Forward packet p to next DDN*
13. ***else***
14. *Wait for AUV and then pass packet p to AUV*
15. ***endif***
16. ***elseif*** *this = BSN* ***then***
17. ***if*** *source is BSN* ***then***
18. *Goto step 24*
19. ***else***
20. *drop (p)*
21. ***endif***
22. ***else***
23. ***if*** *source is DRN* ***OR*** *BSN* ***then***
24. ***if*** *source is not closer to DDN* ***then***
25. *Update packet details*
26. *Broadcast packet p*
27. ***else***
28. *drop (p)*
29. ***endif***
30. ***else***
31. *drop (p)*
32. ***endif***
33. ***endif***
34. ***endif***
35. ***else***
36. *drop (p)*
37. *return*
38. ***Endif***
39. ***End Procedure*** *DATA FORWARDING*
40. ***Repeat*** *PACKET FORWARDING procedures* ***until*** *L≠ Maximum Length of Pipeline*

End all procedure and AUV pipeline monitoring trip completed

In step 1 of Algorithm 2, the data packet is generated and received by BSN. In step 2 to 5, BSN check this packet if it already exists in its cache or not. If yes then BSN drops the packet and if no then the packet is saved. In step 6 and 7, the existing data in BSN will be forwarded to the next node. The next node continues to forward the packet until it gets to the DDN. The DDN receives data packet from both sides of the BSN nodes within it signal coverage. The BSN forward packet to the most closest DDN based on the signal quality between them. The concept of signal quality considers the distance between BSN and DDN. Therefore, the signal quality is estimated based on distance. Both, BSN and DDN exchange hello message after every 5 seconds. Based on the hello message information, BSN and DDN know their respective distance from each other. In step 8 to 15, if the packet is generated by DDN then it will update the packet details and then forward to AUV, which hovers above DDN. To forward a packet to next DDN, DRN serves as a relay node that forward packet to the next DDN and update it cache. In step 16 to 26, if the packet is received by BSN then it will check the source, if the source is DRN or itself that (BSN) then it will drop this packet otherwise forward to next BSN which is closer to DRN and DDN. Continue to use the same procedure until packets are collected from the entire pipeline length.

4. RESULTS AND DISCUSSIONS

This section presents the simulation setup and parameter details. We have established simulation setup of the APPER routing technique in AquaSim –a NS-2 based simulator. AquaSim provides underwater environment for the simulation of UWSN and helps in testing and evaluation at different parameters.

APPER is evaluated by different parameters in multiple scenarios with different traffic loads as mentioned in table 1.

Table 1: Simulation Parameters

Parameters	Values
MAC	Underwater MAC
Transport layer protocol	UDP
Antenna	Omni-Directional
Propagation Model	Underwater Propagation
AUV Speed	0.1-0.3
Channel Bandwidth	25Khz
Number of Sinks	5
Number of nodes	20-180
Network dimension	12600m × 500m
Primary sinks location	At both end of the pipeline
Types of nodes	BSN, DRN, DDN
Ranges of nodes	100,250,400,500 m
Maximum Pipeline length	12600 m
Hello packet size	12 byte
Simulation time	1000 sec

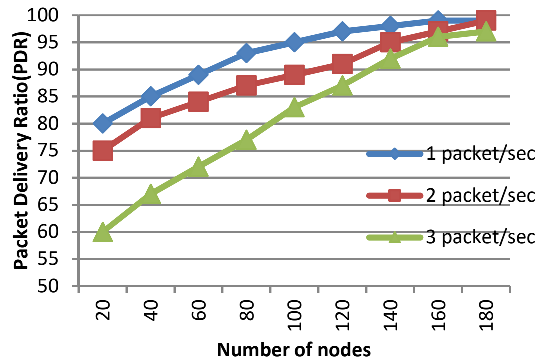


Figure 4: PDR Load APPER

APPER evaluation at different load: After a couple of experiments, it is concluded that APPER offers much better results considering different network traffic loads such as 1, 2 or 3 packets/sec. As highlighted in figure 4, packet delivery ratio increases when traffic load is less while in contrary, when network traffic load moves up to 3 packets/ second, then the packet delivery ratio decreases. The main reason behind these findings is that APPER remains less effective with different network load and data collection mechanisms.

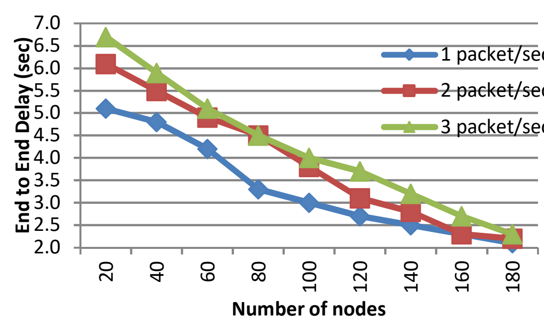


Figure 5: APPER E2E Delay evaluation

APPER end-to-end delay: APPER performance about the end to end delay at different network traffic loads is presented in figure 5. As we can observed that, different traffic loads put major influence on the end-to-end delay; when network load is lesser then end-to-end delay gets smaller otherwise end-to-end delay becomes higher at the greater traffic load (3-packets/sec). The issue of delay is common in underwater acoustic communication, which is almost five times slower than RF (Radio Frequency) so traffic load has higher impact on the delay. So, when network

Journal of Theoretical and Applied Information Technology
28th February 2019. Vol.97. No 4

ISSN: 1992-8645 www.jatit.org E-ISSN: 1817-3195

traffic load escalates then ultimately delay is increased but APPER remains less effective.

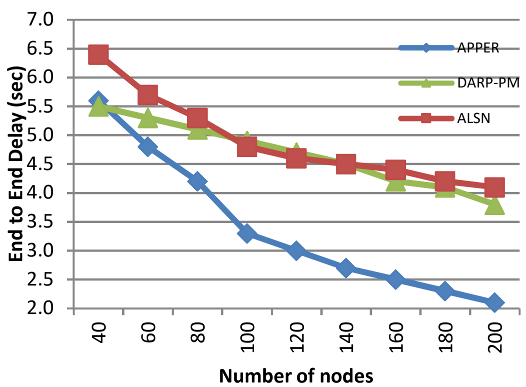


Figure 6: E2E Delay APPER VS DARP-PM & ALSN

APPER Comparison with DARP-PM (Dynamic Addressing based Routing Protocol for Pipeline Monitoring) and ALSN (AUV based LSN): Firstly, we evaluated APPER functionality at different network load and compared it with the aforementioned. After successful experiments of self-testing, we took steps to go ahead and benchmarked APPER's functionality with other existing routing techniques such as DARP-PM [6] and ALSN [17]. It is shown in figure 6 that APPER produce smaller end-to-end delay as compared to DARP-PM and ALSN. The unique property of APPER is the usage of AUV with sinusoidal path planning that helps to collect data efficiently and delivers directly to the floating buoy sinks with minor delay. In DARP-PM and ALSN, Courier Nodes (CNs) and AUV are used to collect data from basic sensors that are not capable to forward the data directly to the sink because their sinks deployment does not support to collect data directly.

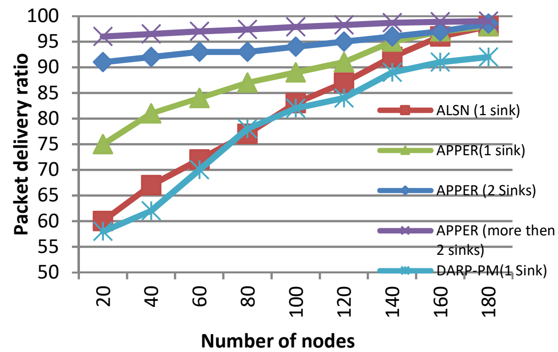


Figure 7: PDR APPER vs DARP-PM & ALSN

Moreover, we compared APPER packet delivery ratio with DARP-PM and ALSN. As shown in figure 7, APPER has higher packet delivery ratio as compared to DARP-PM and ALSN. This happens due to the usage of AUV and multiple sinks where sinusoidal path helps to deliver data efficiently to the closet floating buoy sink. In DARP-PM and ALSN, Courier Nodes (CNs) collect data and buffer it until availability of the sink hence face higher delays.

5. CONCLUSION

This paper presented LSN routing technique applicable for the efficient data collection in the long range underwater pipeline monitoring network. After analysis, it is observed that the proposed AUV path planning and data collection algorithms are found to be more efficient, robust, and flexible in order to collect sensing data from deep sea Underwater Wireless Sensor Network (UWSN). The brief comparison between DARP-PM and ALSN routing techniques concludes that APPER has provided better packet delivery ratio and minimised delay as compared to these routing techniques. Moreover, ALSN technique faces higher end-to-end delay. Similarly, the usage of AUV sinusoidal path is introduced for the first time in this research. It proves to be much beneficial in the routing process although overlooked by other researchers. Finally, it is observed that the proposed solution can provide base for future research directions in the field of UWSN for pipelines monitoring. This study has arrived at the core conclusion that proper AUV path planning based routing technique is more efficient than the existing

ISSN: 1992-8645 www.jatit.org E-ISSN: 1817-3195

routing techniques for the monitoring of long-range underwater pipeline.

ACKNOWLEDGMENT:

This work was supported by Deanship of Research, University of Tabuk under project No. S-1439-163. Authors, also gratefully acknowledge the support of SNCS research center at University of Tabuk under the grant from the Ministry of Higher Education, Saudi Arabia

REFERENCES:

[1] K. M. Awan, P. A. Shah, K. Iqbal, S. Gillani, W. Ahmad, and Y. Nam, "Underwater Wireless Sensor Networks: A Review of Recent Issues and Challenges," Wireless Communications and Mobile Computing, vol. 2019, Article ID 6470359, 20 pages, 2019.

[6] Abbas, M. Zahid., et al., Hop-by-Hop Dynamic Addressing Based Routing Protocol for Monitoring of long range Underwater Pipeline. KSII Transactions on Internet & Information Systems, 2017. 11(2).

[7] Mohamed, N., et al. Reliability Analysis of Linear Wireless Sensor Networks. in Network Computing and Applications (NCA), 2013 12th IEEE International Symposium on. 2013. IEEE.

[8] Joyce, C., Underwater Pipeline Damage Underestimated in Gulf. All Things Considered, 2006.

[9] Sushant, R.C.S.S.R. Data mules: Modeling three-tier architecture for sparse sensor networks. in Proceedings of the IEEE Workshop on Sensor Network Protocols and Applications. 2003.

[10] Jea, D., A. Somasundara, and M. Srivastava. Multiple controlled mobile elements (data mules) for data collection in sensor networks. In DCOSS. 2005. Springer.

[11] Zhao, W. and M.H. Ammar. Message ferrying: Proactive routing in highly-partitioned wireless ad hoc networks. in Distributed Computing Systems, 2003. FTDCS 2003. Proceedings. The Ninth IEEE Workshop on Future Trends of. 2003. IEEE.

[12] Zhao, W., M. Ammar, and E. Zegura. A message ferrying approach for data delivery in sparse mobile ad hoc networks. in Proceedings of the 5th ACM international symposium on Mobile ad hoc networking and computing. 2004. ACM.

[2] M. Ayaz, M. Ammad-uddin, I. Baig and e. M. Aggoune, "Wireless Sensor's Civil Applications, Prototypes, and Future Integration Possibilities: A Review," in IEEE Sensors Journal, vol. 18, no. 1, pp. 4-30, 1 Jan.1, 2018.

[3] Mohamed, N., et al., Sensor network architectures for monitoring underwater pipelines. Sensors,. Vol. 11, no. 11, 2011

[4] Abbas, M. Zahid., et al., Scalable Nodes Deployment Algorithm for the Monitoring of Underwater Pipeline. TELKOMNIKA, (Telecommunication Computing Electronics and Control), 2016. 14(3): p. 1183-1191.

[5] Mohamed, N., et al. Failure impact on coverage in linear wireless sensor networks. in Performance Evaluation of Computer and Telecommunication Systems (SPECTS), 2013 International Symposium on. 2013. IEEE.

[13] Zhao, W., M. Ammar, and E. Zegura. Controlling the mobility of multiple data transport ferries in a delay-tolerant network. in INFOCOM 2005. 24th annual joint conference of the IEEE computer and communications societies. Proceedings IEEE. 2005. IEEE.

[14] Bin Tariq, M.M., M. Ammar, and E. Zegura. Message ferry route design for sparse ad hoc networks with mobile nodes. in Proceedings of the 7th ACM international symposium on Mobile ad hoc networking and computing. 2006. ACM.

[15] Abbas, M. Zahid., et al., An overview of routing techniques for road and pipeline monitoring in linear sensor networks. Wireless Networks, 2017: p. 1-11.

[16] Boyle, W.J., R.A. Wong, and J.M. Shy, Multiple sinusoidal wave configuration stent. 1997, Google Patents.

[17] Jawhar, I., et al. An efficient framework for autonomous underwater vehicle extended sensor networks for pipeline monitoring. in Robotic and Sensors Environments (ROSE), 2013 IEEE International Symposium on. 2013. IEEE.