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Scalable Heterogeneous Nodes Deployment Algorithm for Monitoring of Underwater Pipeline

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Abstract

Underwater Wireless Linear Sensor Networks (UW-LSNs) possess unique features for the pipeline monitoring as compared to the terrestrial sensor networks. Other than long propagation delays for long range underwater pipelines and high error probability, homogeneous node deployment also makes it harder to detect and locate the pipeline leakage efficiently. In order to tackle the problem of delay in large scale pipeline monitoring and unreliable underwater link quality, many algorithms have been proposed but the scalable nodes deployments still need focus and prime attention. In order to handle the problem of scalable nodes deployment, we therefore, propose a dynamic nodes deployment algorithm where every node in the network is assigned a location in the quick and efficient way without needing any localization scheme. It provides an option to handle the heterogeneous types of nodes, distribute topology and mechanism in which new nodes are easily added to the network without affecting the existing network performance. The proposed distributed topology algorithm divides the pipeline length into segments and sub-segments in order to manage the higher delay issue. Normally nodes are randomly deployed for the long range underwater pipeline inspection yet they require proper dynamic nodes deployment algorithm assigning unique position to each node.

Keywords: *scalability, heterogeneity, nodes deployment algorithm, underwater pipeline monitoring*

1. Introduction

Underwater environments do not remain feasible for human operators due to the harsh underwater activities, high water pressure, hazardous underwater creatures, vast areas for exploration and lack of high frequency signals propagation [1]. Due to the underwater acoustic communication, the signal propagation speed is decreased to the speed of sound. Although in underwater, sound waves travel longer and faster than the air but still they are five times slower than the electromagnetic waves [2]. Most of deployment algorithms and routing protocols do not remain suitable for such environments as they necessitate random nodes deployment, joint topology, 2D area, higher data rate, and outcomes in large end-to-end delays [3]. Although significant areas of improvement are highly required to be there in UW-LSN monitoring techniques like scalable nodes deployment, distribution of large network, minimization of the delay in communication and efficient data deliveries to the sink; but the available data rates for the long range underwater applications is very low and not feasible for the real time communication. In short, it seems to be hard to increase the data rate for the long range underwater communication where scalable and efficient nodes deployments in distributed topology are highly supportive in this regard.

In fact, UW-LSNs and terrestrial sensor networks have many common properties including deployment of large number of nodes and energy constraints; but UW-LSN stays unique in many aspects from the terrestrial sensor networks [4]. Firstly, most of the times homogenous types of sensor nodes are deployed randomly that are not scalable for extension of underwater pipelines monitoring coverage. Secondly, UW-LSN requires special deployment algorithms that assign proper nodes positions in 3D dynamic underwater environment. Thirdly, sensors are linearly deployed to maintain the linear topology and distributed topology network [5] that divides the pipeline length into sub-zones and ranges of heterogeneous sensors.

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Fourthly, a proper node deployment has also impact on the communication delay that is another issue in underwater environment because acoustic communications remains the only feasible way of communication in underwater. The better solutions to tackle these problems is development of proper nodes deployment algorithm rather than remote sensing technologies such as robots are not able to achieve precise results about the events occurring in unstable underwater environment. A scalable UW-LSN can contribute as a promising solution for exploration of the underwater environment, monitoring underwater pipelines and boarders. Besides, it can also function in different kinds of other linear applications under many important constraints.

2. Related Work

It is hard to find an article related to scalable nodes deployment algorithm that efficiently deploys heterogeneous types of nodes in order to cover the large scale monitoring area of the underwater pipeline. Further, in underwater environments, it is also difficult to separate the critical monitoring areas and maintaining of communication between the nodes with high energy constraint, common topology changes and nodes failures. For such types of environments, many deployment schemes have been proposed to monitor the underwater pipelines. Among these, most of them need special network setups like automotive tools/robots/vehicles and they generally are divided in different categories [1-2], [6]. Deployment Schemes are classified as those that require special network setups and extra automotive tools [7-11] and use homogenous types of sensors. All these protocols require extraordinary system and multiple types of robots/AUVs equipped with special sensor moves over the pipeline. The drawback of such kind of schemes are that these are not appropriate for long term and large scale underwater pipeline monitoring process as they use to increase cost and delay.

Secondly, chain based deployment schemes mostly involves neighbour nodes location details for the each sensor of complete network. For the sake of ease, most of these types of schemes assume that all nodes in the network already have details of their own location and destination location. These types of deployment schemes [18-20] and their requirements are not easy to be implemented appropriately in underwater as efficient nodes deployment is still a challenging task in UWSN. For comparative analysis perspective, a short summary of some pipelines monitoring deployment schemes is described in Table 1. Further, pipelines monitoring is highly important as there is a broad network of pipelines carrying oil and gas that play an integral role for the energy management and economy of many countries. Such as Nigeria has around 5,000 kilometres oil pipelines consisting of more than 4,000 km of different products carrying pipelines while the remaining length belongs to crude-oil pipelines [21]. The average depth of oceans lays around 2.5km to 3km and pipelines length is more than 100 km. In underwater environment, acoustic communication is considered an ideal but the range of underwater sensor nodes is not preferred more than 1 km. However, if we divide the pipeline length into subzones of 1000 meter each, then less number of nodes is required to deliver the data packets from the middle of the pipeline and from bottom to the surface at different ocean depths [3].

It is important to be noted that the performance of our protocol depends on the number and types of sensors. The proposed deployment algorithm support easily heterogeneous types of sensors but if we increase the number of sensors it will increase the cost of the network. If we use homogenous types of sensors in that case the acoustic communications will give support up to the range of 5 km; but it is not desirable as long distance communications utilize more energy. In order to cover maximum length of the pipeline with low energy and more network life time, we have defined the different ranges of acoustic communication for each types of sensor varying from 200 meter to more than 1000 meter. It is found that acoustic communications work best for the short range applications because it support bandwidth of 20-30 KHz [22-24] in 1 km distance. Although, in special cases, we can increase this range of sensors [25], but in normal acoustic communication it is suggested to use the discussed ranges of sensors.

Table 1. Short summary of the requirements and limitations of existing deployment schemes

Algorithm	Requirements and Limitations
SPAMMS[7]	i) Robot moves in the pipeline to collect data from RFID sensors deployed at the inner wall of the pipeline for the detection and repairing of defected pipeline place. ii) SPAMMS is only suitable for small-scale monitoring and have no any deployment algorithm.
PIPENET[12]	i) Special fixed nodes having static address are required equipped with acoustic pressure sensors. ii) Sink nodes are deployed only on manholes of the pipeline so it is difficult to find the exact leakage place.
SewerSnort[13]	i) All the sensors drift inside the sewerage pipelines have specific coverage area. ii) The beacons are required to assign nodes addresses and increase their respective signals strength. iii) It works only for sewerage pipe having fluid flowing at specific speed but not suitable for UWSN.
TriopusNet[8]	i) It needs special nodes deployment algorithm to release pool of robots in the pipeline. ii) It is not suitable for long range underwater pipeline monitoring as it requires special tools and setup.
KANTARO[9]	i) It doesn't require node address as it consists of a fully automatic robot having intelligently motion control tool in it with a scanner and camera that needs to move inside the pipeline. ii) It is a manual way of inspection where vehicle moves over pipe and it can’t be installed in UWSN.
SCADA [14]	i) It needs special network design and Node-IDs where all clients are attached to the main terminal. ii) This approach involves more manual deployment of sensors therefore not suitable for UWSN.
SWATS [15]	It requires cross check on the part of the neighbouring nodes along the trajectory of the fluid to validate the nodes. It integrates SCADA and assumes the static addressing for nodes and control units.
Distributed topology algorithm[5]	i) It is topology discovery algorithm for LSNs that require an ordered list of the nodes addresses deployed in the network with their relative geographical positions. ii) It works only for same types of sensors and does not capable to handle heterogeneous sensors.
AUV based algorithm[10]	i) It requires autonomous underwater vehicles (AUV) inside or outside of the pipeline that coordinate with each other according to the application requirement. ii) It only manage trajectory of the AUV no any details about pipeline sensors deployment.
Road Monitoring Algorithm[16]	i) It is based on the addresses and placement of nodes. It is also based on the way of data transmission that makes this technique more effective and efficient for LSN. ii) It is only feasible for homogeneous sensors so heterogeneous types of nodes can’t be deployed.
SRJ Algorithm [17]	i) It needs neighbour discovery tables and dynamic signal strengths to bypass failure nodes. ii) Random deployment model and complex routing tables boost delay in communication.
Chain based algorithm[18]	i) It requires all the nodes connected by wire or virtually bonded in a chain. ii) All nodes deployed in a chain and they generate communication overhead to select forwarder node and keep record of all the neighbour nodes.

3. Network Architecture and Contributions

Network Operation Centres (NOCs) are installed on ground at the both ends of pipeline collecting data from the pipeline sensors and courier nodes. The pipeline sensors are deployed linearly on upper surface of the pipeline. Nodes near the NOCs have a closer distance and the distance increases as the nodes go far from NOCs. The nodes positions are assigned dynamically by linear equations designed separately for each type of nodes according to the length of pipeline and each sensor range. The four types of nodes are deployed in this network i.e. Basic Sensing Node (BSN), Data Relay Node (DRN), Data Definition Node (DDN) and Courier Node (CN); BSN has a minimum range while CN the maximum. Nodes are deployed in such a way that they could cover the maximum pipeline length with less utilization of nodes. Most of the ordinary nodes are anchored at allotted position of the pipeline surface except CN that is mobile and is often introduced in network by using hydraulic tool. The courier nodes are helpful to utilize the better network resources, increase the reliability and minimize the delay. These courier nodes can collect data packets from the middle nodes being far from the NOCs. After collecting the data, they deliver these packets directly to the NOCs.

Although some inspiring distributed topology nodes deployment schemes like [5], [26-27] exist in literature but their implementation is thought to be cumbersome in underwater long range pipeline monitoring. In this paper, we propose a novel deployment algorithm for the long range underwater pipeline monitoring. Being scalable and efficient, it makes use of heterogeneous types of sensors with multi-sink architecture. Being designed on multi-sink architecture, the proposed algorithm is going to be helpful in increasing the monitoring coverage, packet delivery ratio and minimizing the delay between nodes and sinks. The courier nodes deployed as surface sinks are equipped with radio and acoustic modems; they use radio frequency to communicate mutually and with the NOC while underwater pipeline sensors have only acoustic modems to communicate with other sensor of same or different category. These heterogeneous sensor nodes are deployed according to LSN thin model [6] but they are placed at specific location according to deployment algorithm. These nodes are deployed in horizontal direction along with pipeline length, they can't move freely with the water currents but the courier nodes have vertical movement with a special hardware [28]. By following these patterns, all nodes are deployed in one line starting from the one corner of pipeline and ending at another. The deployments of courier nodes stand flexible being able to be installed on any place of the pipeline, at any depth level of the ocean, and as well as at the surface level. Due to the harsh underwater environment and heavy currents it is not easy to monitor some area of pipelines in deep and dark sea, so we assume that any courier node that reach any area of the pipeline, it would come back at any area on the surface. According to the underwater environment conditions and underwater pipeline requirements, the contributions of this deployment algorithm are as follows.

1. **Scalable deployment of sensors:** The proposed algorithm is scalable in performance; it deploys heterogeneous sensors having no any restriction of network size.
2. **Designing of dynamic linear equations:** Each type of node obtains its position dynamically by using of linear equations specified to differentiate the types of sensor, sink address and maintain distance. There is no need of any static or manual nodes deployment procedure.
3. **Maximizing of monitoring coverage:** It provides efficient monitoring coverage for the long range pipeline by using different types of sensors, ranges and by passing the damaged nodes.
4. **Robustness:** It is robust as it can be easily adopted in any network size; it accommodates new nodes, damaged nodes or replacing the network nodes without making any serious effect on the rest of network.

4. Proposed Nodes Deployment Algorithm

After a broad literature review, it is revealed that UWSN nodes deployment is a challenging task including the localization of underwater sensor nodes [4]. For this purpose, the algorithm completes its task in three phases. In the **first phase**, it sets the ranges of heterogeneous types of sensors and calculates the required total number of nodes according to total length of the pipeline. In the **second phase,** it sets the frequency and types of neighbour nodes. In the **third phase,** all nodes are assigned specific location on the pipeline surface according to the function of their linear equations in deployment algorithm.

4.1. Types of Sensors and Hierarchical Network Model

We have proposed a hierarchical network model of LSN for the deployment of pipeline nodes. The reliability analysis of different kinds of LSN network architecture [29] preceded the designing of this model. LSN is considered an ideal network for the pipeline monitoring application having specific types of nodes deployment topologies. In this regard, different types of LSN nodes deployment models exist like thin, thick and very thick that are mostly used in flat network models and applications [6]. The hierarchical network model advantages over the flat network models are multiple i.e. the hierarchical network has the ability to develop more reliable and robust model [5-6]. It provides help to distribute the network topology, divide and control the traffic load, and overcome the network failures based on different types of attacks, nodes failures, and battery exhaustion. These kinds of network also support routing protocols to communicate quickly, reduce latency, assign autonomous regions, and control network failures efficiently. In this model, the following four types of nodes are discussed. All of these nodes are deployed linearly on the pipeline surface. Figure 1 presents heterogeneous types of the nodes having unique functions to accomplish such as basic sensing and data collection, packet forwarding and data dissemination to the sinks.

Basic Sensing Nodes (BSNs): These are the most common nodes in our network deployed on the pipeline. Their main task is to sense the pipelines status like any leakage, corrosion, etc. and forward that data to the closest data relay node, data dissemination node, and courier node or directly to sink.

Data Relay Nodes (DRNs): These nodes function as intermediate nodes that gather data from BSNs and forward it to the closest DDN, CN or NOC. Their main role is in routing the data toward the NOC at the shortest path and in less delay. The distance between these nodes is determined by comparing the neighbour nodes addresses.

Data Dissemination Nodes (DDNs): These nodes perform the function of delivering the collected data to the NOC. The technology used to transfer the data from these nodes to the NOC is varied such as usage of underwater vehicles. This implies that each of the DDN nodes have a higher communication capability.

Courier Nodes (CNs): These are the higher frequency nodes in the network. Their objective is to collect data from nodes being far from the NOC by establishing secondary path. After data collection, they directly forward this data to the NOC by using RF communication.

Figure 1. Heterogeneous types of sensors

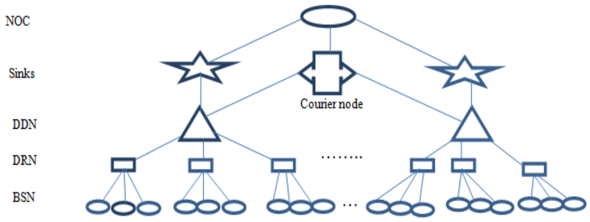

Figure 2. A hierarchical representation of heterogeneous types of nodes in proposed network model

Figure 2 presents the hierarchical relationship between the various types of nodes in the proposed sensor network. BSNs consist of sensing tools like pressure sensing in order to perform the basic sensing process; multiple BSNs forward their data to the nearest DRN and similarly, DRNs transfer their data to the nearest DDN nod; finally, all DDNs transmit their data to the NOC directly or via CN. BSNs, DRNs, and DDNs are equipped with batteries and acoustic antennas for underwater communication. BSNs, DRNs, and DDNs are logically chained with each other and used for designing of integrated acoustic sensor network [30]. In this case, the nodes are equipped with rechargeable batteries that can be recharged from a wire. In addition, the acoustic communication is used to send the data to the next hop neighbour either towards the sink node or the CN. In this scenario, NOC can be installed on the boat standing in water or placed on ground near the coastal area. All sinks and courier node are also equipped with RF antennas to coordinate with NOC at high speed.

4.2. Proposed Network Topology

The proposed network topology in this research is shown in Figure 3.

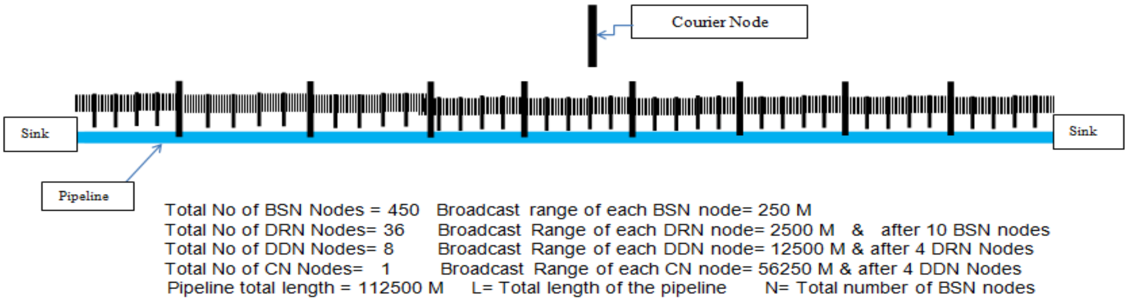

Figure 3. Network topology diagram

4.3. Nodes Deployment Algorithm

Input:

1. Heterogeneous types of pipelines Sensors with different communication ranges
2. Set frequency and types of neighbor nodes
3. Total Pipeline length

Process:

```
Algorithm Steps                                                        Descriptions

1.  If  i=1 then L/N*1 =250 M                                          // i= 1 1st BSN node number
2.    { i=2 then L/N*2 =500 M                                          // i= 2 2nd BSN node number
3.      i=k then L/N*k = $\sum_{i=1}^{k} (\frac{L}{N} * i)$ }          // i-k = total BSN nodes deployment formula
4.  Else If  I<1 & j=1 then L/N*10*1 =2500 M                           // j= 1 1st DRN node number
5.    { i<1 & j=2 then L/N*10*2 =5000 M                                // j= 2 2nd DRN node number
6.      i<1 & j= r then L/N*10*r = $\sum_{j=1}^{r} (\frac{L}{N} * 10 * j)$ }   //j-r = Total DRN nodes deployment series formula
7.  Else If  I<1 & j<1 & p=1 then L/N*50*1 =2500 M                     // p= 1 1st DDN node number
8.    { i<1 & j=2 & p=2 then L/N*50*2 =5000 M
9.      i<1 & j= r &p= t then L/N*50*t = $\sum_{p=1}^{t} (\frac{L}{N} * 50 * p)$ }   //p-t = Total DDN nodes deployment formula
10. Else If  I<1 & j<1 & p<1 & m=1 then L/N*225*1 =12500 M             // m= 1 1st CN node number
11.   { i<1 & j<1 & p<1 &m=2 then L/N*225*2 =250000 M
12.     i<1 & j<1 &p<1 & m=q then L/N*225*q = $\sum_{m=1}^{q} (\frac{L}{N} * 225 * m)$ }   //m-q = Total CN nodes deployment formula
13. End IF
14. Total coverage formula/equation = step 3+step 6+step 9+step 12     // add all formulas
15.       If  more BSN nodes added in LSN Network
16.             Repeat step 1-3
17.       ElseIf  more DRN nodes added in LSN Network
18.             Repeat step 4-6
19.       ElseIf  more DDN nodes added in LSN Network
20.             Repeat step 7-9
21.       ElseIf  more CN nodes added in LSN Network
22.             Repeat step 10-12
23.       Update total coverage formula of complete network by repeating step 14
24.       Else all heterogeneous nodes are deployed at proper place of the pipeline
25.     End IF  "Stop nodes deployment process"
```

Output: Total pipeline length is covered and all heterogeneous types of nodes have assigned specific location on the pipeline.

5. Performance Metrics

We used monitoring coverage, types of sensors and ranges of sensors as the metrics in order to check the performance of the proposed deployment algorithm. Monitoring coverage is based on nodes deployment equations discussed in algorithm and lengths of different pipelines. Type of sensor is defined as heterogeneity nature of a sensor. Range of sensor is defined as the broadcast domain of the each type of sensor. Topology distribution percentage is calculated by dividing the total pipeline length and ranges of different types of sensors especially in the presence of courier node.

5.1. Results and Discussions

Node deployment and coverage: We used different number of nodes and pipelines lengths in order to test our algorithm; Figure 4 explains the heterogeneous types of nodes deployment frequencies in different lengths of the pipelines. Figure 5 shows that total number of heterogeneous nodes are varied according to their application requirement while total number of homogeneous nodes are always deployed at fixed ratio like in Almazyad model [4]. The drawback of homogeneous nodes deployment is that it is expensive utilizing more resources and facing higher latency due to usage of same range sensors. The proposed algorithm distributes the network topology into segments according to hierarchical network model and ranges of the sensors. Figure 6 highlights the comparison of proposed algorithm nodes deployment frequency showing lower frequency in one segment than the ROuting protocol for Linear Structures(ROLS) [31]. The proposed algorithm utilized heterogeneous types of sensors having different broadcast ranges shown in Figure 7. For example, the total pipeline length is considered as 1000M and each BSN node covers 100M length, each DRN covers 250M, each DDN covers 400M while CN covers half length of the pipeline showing better monitoring coverage.

Network Topology Distribution: Imad proposed a distributed topology nodes deployment model [5] for pipelines monitoring; it requires to maintain and update the two lists regularly causing increase in the workload and computational overhead on sensors. This kind of distributed topology discovery does not look feasible for monitoring of long range underwater pipeline. The proposed algorithm considering this issue distributed the network into hierarchical model according to different ranges of heterogeneous sensors. It introduced courier nodes considered as higher frequency nodes; they are capable to communicate with other sensors as secondary sink which divides the network topology into independent segments. If we don't use courier node then whole network will be considered as one unit. In current scenario, we have used 1 courier node that divides the network into two segments and more than 50% of network load is distributed. By following the same deployment pattern, it is also possible to add two or more courier nodes that can further distribute the network into small segments. The comparison of courier nodes and topology distribution is shown in Figure 8.

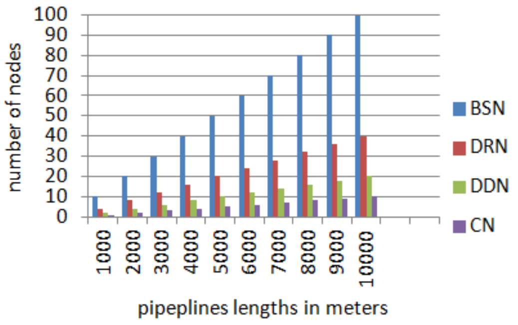

Figure 4. Nodes deployment frequency in different pipelines

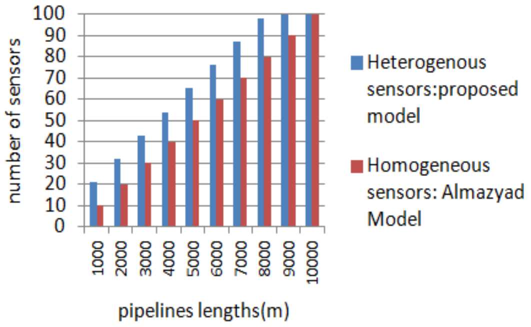

Figure 5. Heterogeneous vs Homogeneous nodes deployment

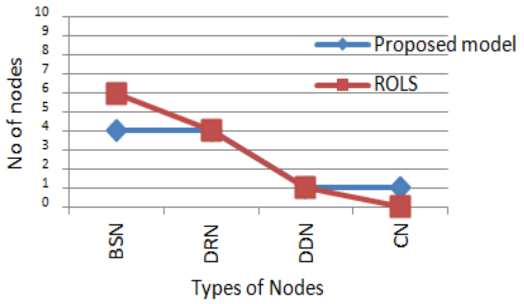

Figure 6. Nodes deployment frequency in one segment

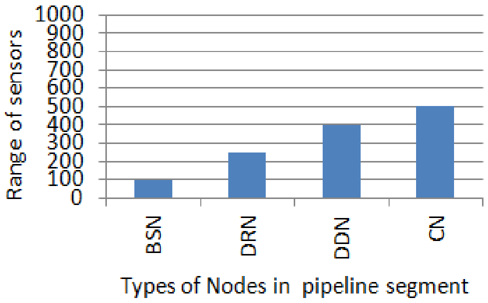

Figure 7. Proposed broadcast range of each sensor

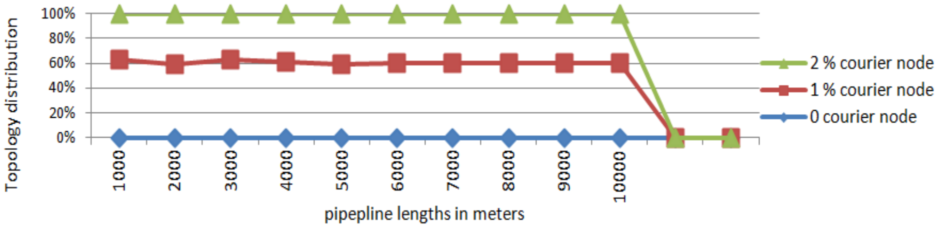

Figure 8. Proposed topology distribution using courier nodes

6. Conclusion

We have proposed a scalable nodes deployment algorithm based on mathematical equations and heterogeneous types of sensors. Novelty of this deployment is its efficient coverage of the different lengths of the pipelines. It has introduced distributed topology model in which total pipeline length is divided into segments. This approach is robust enough for the addition of new nodes; besides, it is scalable as well for any size of network in which new nodes get their relative positions. An important aspect of this algorithm is that it is dynamic in nature. It develops mathematical equations for heterogeneous types of nodes deployment and calculates their position relative to the total pipeline length. Most importantly, it helps to minimize the issue of delay in finding a damage or leakage position of underwater pipeline. This algorithm gives support in detecting the defected position of pipeline and as well as proves helpful in the addition or replacement of nodes. Further, the proposed deployment model minimizes the computational overheads as usually underwater acoustic communication supports extremely low data rates. Furthermore, this algorithm is flexible enough to be used for the long term pipeline monitoring applications. Moreover, it supports the coverage of long range pipelines with less number of nodes having no any limitation of network size. In future, we plan to integrate this dynamic deployment algorithm with dynamic addressing based routing protocols in order to investigate its relative performance.

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