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A Priority-based Routing Algorithm for Underwater Wireless Sensor Networks

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Abstract- Advances in low-power electronics design and wireless communication have enabled the development of low cost, low power micro-sensor nodes. These sensor nodes are capable of sensing, processing and forwarding which have many applications such as underwater networks. In underwater wireless sensor networks (UWSNs) applications, sensors which are placed in underwater environments and predicted enable applications in oceanographic data collection, mine reconnaissance, pollution, assisted navigation, distributed tactical surveillance, and ocean sampling. Each sensor uses acoustic signals as its physical medium for communications. This study focuses on a priority-based routing protocol in underwater wireless sensor networks. This routing method tries to improve the QOS requirements with considering high and low priority traffic classes. Through simulation study using the OPNET simulator, we proved that proposed algorithm achieves high performance as compared to GEDAR, in terms of packet loss, end to end delay of data transmission and energy consumption.

Index Terms- wireless sensor network, routing, rate priority, special division.

I. INTRODUCTION

In our earth more than the 70% of the earth's surface is covered with water [1] that could be river and oceans also. Water provides a remarkable part of industrial and human requirements [2]-[3]-[4]. The oil and gas industry move into deeper waters, renewable energy is harvested from the sea, etc. Beside these applications, minerals such as cobalt, nickel, copper, rare earths, silver, and gold are mined from the seafloor. Hence, new infrastructure should be built and maintained.

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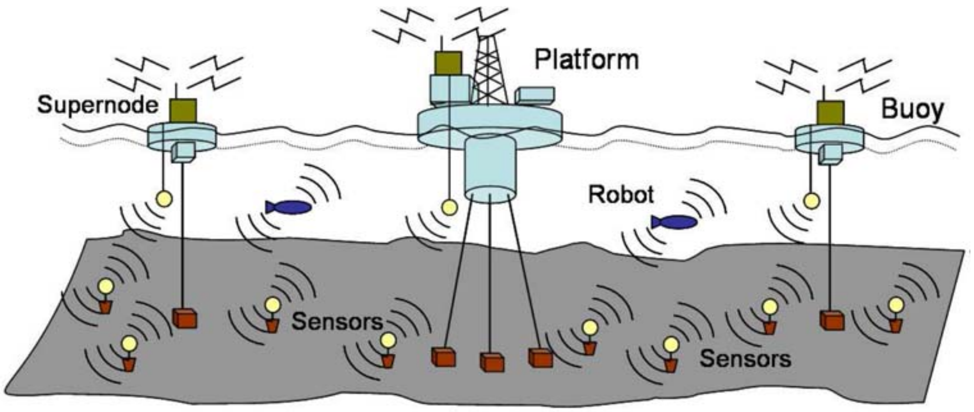

Fig. 1. One possible approach for underwater sensor nodes [6].

Since the ocean is huge and most of the underwater environment is not known to us, research and ocean monitoring are not an easy task. In addition, because of the high level of pressures in deep water, it is not possible for people to work a long time under water.

Therefore, using wireless sensor networks which are composed of a large number of sensor nodes instead of traditional monitoring approaches and ocean exploration is considered as one of the main important issues [5]-[6],(Fig. 1). Security in theses networks is considered too [7].

Underwater sensor nodes communicate with each other using acoustic wave rather than RF wave, because radio frequency (RF) waves are seriously attenuated in the underwater environments [8]. This kind of wireless sensor networks is called the underwater acoustic sensor networks (UASN). One of the main challenges in these networks is routing of data packets from underwater sensors to the surface of the sea and sink node. Different type of routing protocols is designed and deployed in sensors in recent years [9]-[10]. Also in UWSNs, sensor nodes freely drift with ocean currents, which results in dynamic network configurations. Therefore the routing protocol in UWSN should consider dynamic three dimensional (3D) network situations [11]-[12]. The remarkable advancement in current technology is to provide a reliable routing algorithm which is able to send traffics with different QoS requirements using suitable independent paths.

Because of the harsh environmental conditions of underwater places, recharging and replacing the battery of sensor nodes is not economical. In Underwater Wireless Sensor Networks, sensors may monitor the enemy’s movements or smugglers entrance to sea borders which have high priority and need low delay and packet loss. Sensor may also monitor other things with low priority. By the way when data packets are sent from sensor nodes to sink (floating stations on the water level), delay, packet loss and energy consumption are challenging especially in near sink nodes [13]. Therefore, here are the novelties of the proposed algorithm:

- Structuring the network infrastructure by having small cube division that helps us to model the network behavior more efficient (considering the routing).
- Considering special QoS parameters.
- Having a priority-based routing protocol for UWSNs, which is able to transfer different type of data (high and low priority data)

The remainder of this paper is organized as follows: Section 2 consists of related research regarding routing protocol in UWSNs; Section 3 provides details about proposed routing protocol; Section 4 is about the performance evaluations, and comparisons are performed through experiments; Section 5 contains our conclusions and future research directions.

II. ROUTING PROTOCOLS IN UWSNS

The sensors that can send and receive acoustic waves are widely employed in underwater sensor networks because acoustic wave is used as the transmission medium in underwater environments. The deployment of the sensor networks and the techniques adopted for transmitting packets should adapt to the limitation of underwater environment, such as the size of the detection area, the number of deployed sensors and etc. Today different protocols have been proposed for routing in UWSNs [14]-[15]-[16] (Fig. 2).

In UWSN maintenance and recovery of routing paths are very expensive. The Vector based forwarding protocol (VBF) overcome this problem [17]. It helps to improve the low delay and successful rate. In VBF there is a vector similar to a virtual routing pipe and all the packets are transmitted through this pipe from source to sink. There are some drawbacks in this protocol. Firstly, using a path from source to destination leads to creating a virtual pipe line which effects on network routing performance and the density of different nodes. Secondly, this protocol is very sensitive about routing pipe radius threshold and routing performance.

The HHVBF (Hop-by-Hop Vector- Based Forwarding) [18] is a new version and an improvement of VBF. In this method, instead of using a virtual pipeline from source to destination, a virtual pipeline is used per hop. Each intermediate node makes decisions about its pipeline path using its current location. This method can create a path to deliver data packets even using single node, while, the number of available sensors in the neighborhood is small. The performance of HHVBF still is affected by the problem of routing pipe radius threshold. HHVBF has much more signaling overhead compared to VBF, because of its hop-by-hop nature.

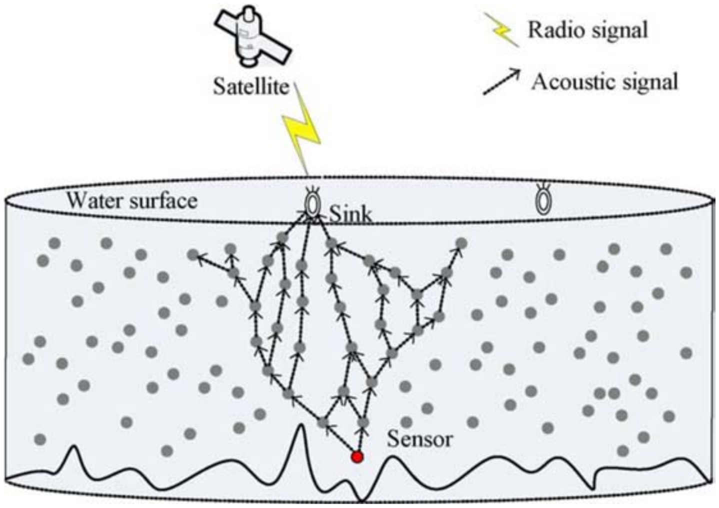

Fig. 2. Routing scenario from a sensor underwater to sink on sea surface.

If there in not any prior information about nodes location, the overall expected throughput will be decreased because of flooding broadcast. Focused Bream Routing (FBR) protocol for acoustic network was presented to reduce the unnecessary flooding [19]. This method assumes that each sensor node knows about its final location. The location of intermediate nodes is not required. The paths are dynamically established when data packets move to their destination. After the appropriate nodes have proposed themselves, the decision about the next hop is made at each step on the path.

The [20] QELAR protocol assumes generic MAC protocols and aims to increase the lifetime of networks by making remained energy of sensor nodes more evenly distributed. The node remained energy and energy distribution among a group of nodes affect in routing process to calculate the reward function. This function helps to select the adequate forwarders for packets and have better lifetime than VBF. In [21] strategies for reducing the operating cost in underwater sensor networks used in seismic monitoring of undersea oilfields is proposed. As replacement of underwater sensor nodes are very expensive and to ensure continuous operation, this paper, developed effective policies to minimize this cost in the seismic monitoring application.

In opportunistic routing in underwater has great potential for mitigating drawbacks from underwater acoustic communication and improves network performance. In [22], two main building blocks for the design of opportunistic routing protocols for underwater sensor networks: candidate set selection and candidate coordination procedures is designed. It propose classifying candidate set selection procedures into sender-side, receiver-side, and hybrid approaches, and candidate coordination procedures into timer-based and control-packet-based methods. Based on this classification, it discuss particular characteristics of each method and how they relate to underwater acoustic communication routing.

In underwater environments applications of Internet of Things such as imaging underwater life, environmental monitoring, and supervising geological processes on the ocean floor, need a prolonged network lifetime. For routing in these places balanced energy adaptive routing (BEAR) is presented to prolong the lifetime of UWSNs [23]. The BEAR protocol operates in three phases as initialization, tree construction and data transmission. In the initialization phase, all nodes share information related to their residual energy level and location. In the tree construction phase, BEAR exploits the location information for selecting neighbor nodes and choosing the facilitating and successor nodes based on the value of cost function. In order to balance the energy consumption among the successor and the facilitator nodes, BEAR chooses nodes with relatively higher remained energy than the average energy of the network.

The [24] is working on network layer of underwater routing protocols. Due to this fact that geographic routing has some attributes, which does not need routing table, two new multi-path methods namely called Greedy Geographic Forwarding based on Geospatial Division (GGFGD) and Geographic Forwarding based on Geospatial Division (GFGD) are proposed. They improves network lifetime, delay and energy consumption. The three dimensional underwater network is first divided into small cube spaces, thus data packets are supposed to be collaboratively transmitted by unit of small cubes logically. All sensor nodes in nearer small cube which have the higher remain energy, the shorter transmission delay, and packet loss rate can be selected as next hob. In both of these algorithms, a sleep scheduler in duty-cycle is considered. In other words, sensor nodes will be awake only when they are needed. Using duty-cycle increase network lifetime and save energy consumption.

GEDAR [25] is a geographic and opportunistic routing protocol that routes data packets from sensor nodes to sinks at the sea's surface. When the node is in a communication void region, GEDAR switches to the recovery mode procedure which is based on topology control through the depth adjustment of the void nodes, instead of the traditional approaches using control messages to discover and maintain routing paths along void regions. GEDAR significantly improves the network performance when compared with the baseline solutions, even in hard and difficult mobile scenarios of very sparse and very dense networks and for high network traffic loads.

III. PROPOSED PROTOCOL

Due to the special nature of underwater environment, in proposed protocol, network is considered as a big cube which is divided into Small Cube (SC) spaces and each of sensor nodes based on their Geographic position are deployed in one of these SCs. This method avoids sending extra packets and

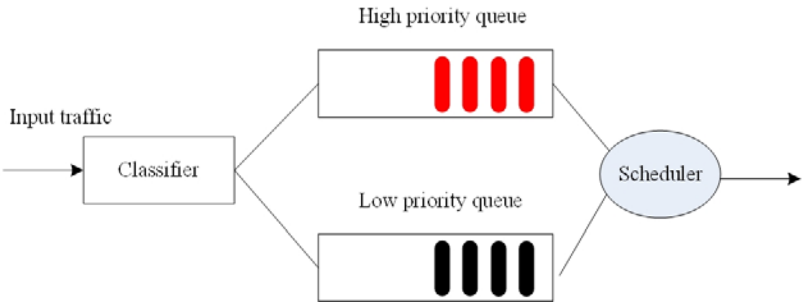

Fig. 3. The structure of an intermediate sensor node.

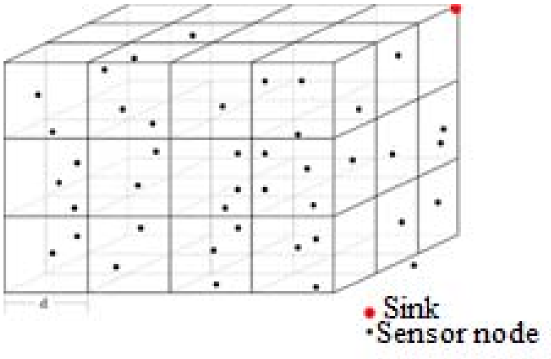

Fig. 4. The underwater network model.

reduces energy consumption. The proposed method supports two traffic classes: high-priority class and low priority class for high and low priority data respectively as in Fig. 3.

High priority data needs low delay and low priority data tolerate some delay. For this we give more share of output scheduler time. Also, there is a priority field in the header of each packet which valued with low or high. The data packets are routed based on their priority.

In this protocol, sensor nodes know their locations by their built-in GPS and each sensor node finds its location based on its geographic location. Logical cubes are formed by network barriers. For instance, if the network area is 400 m* 400m *400m, then 64 SCs with 100 m*100m *100m dimension is needed.

A. Network Model

We model the UWSN as a Large Cube (LC) as Fig. 4 in which the upper side of cube is on the sea surface and the bottom side is on the floor of the sea. There are N sensor nodes with acoustic modems which are deployed randomly in different LC's depths. Furthermore, all sensor nodes are assumed immobile and do not move by sea waves. Also they have the same initial energy and communication range and there are symmetrical communication links between underwater sensor nodes.

A source node provides network information and can be a sensor node or an actuator node. An actuator node presents feedback about an operation. There are two modems in the sink node, namely; acoustic and radio which are placed at the top and right corner of LC. Transmission radius of sensor nodes are equal to r and each node can record sink and its' location. The LC is divided into smaller logical cubes (SC). The number of SCs is depends on sensor's density in the environment. The length of SC is equal *d*, which is related to communication radius *r*. The relationships between each two SCs according to their relative position is as follow:

1. Two SCs may be adjacent to one vertex.
2. Two SCs may be adjacent to one edge.
3. Two SCs may be adjacent to one surface.
4. Two SCs may be completely separated.

These SCs are called vertex- adjacent, edge- adjacent and surface- adjacent neighbor SCs. Each SC has 8 vertex- adjacent, 12 edge- adjacent, and 6 surface- adjacent neighbor SCs.

B. Energy consumption model

When transmitting m bit, the energy consumption of one sensor node E_{tx} is calculated as follows:

$$E_{tx}(m,l) = mE_{elec} + m * T_b CHe^{g(f)l} \tag{1}$$

Here E_{elec} is the radio transmission range, m is the bit length of data packet, T_b is send time bit, H is the water depth of sensor node, I is transmission distance, and g(f) refers absorption coefficient [26].

When receiving m bit, the energy consumption of one sensor node E_{rx} and *g (f)* can be calculated as follows:

$$E_{rx}(m,l) = mE_{elec} \tag{2}$$

$$g(f) = 0.11\,\frac{f^2}{1+f^2} + 44\frac{f^2}{4100+f^2} + 2.75 * 10^{-4} f^2 + 0.003 \tag{3}$$

Where *f* refers central frequency measurement between the upper and lower cutoff frequencies. The seawater is salty, hence the underwater environment is rather corrosive [27]-[28]. T is the temperature of water and *p* is water salinity, thus the propagation delay and loss of path are calculated as follows:

$$1449.05 + 45.7T - 5.2T^2 + 0.23T^3 + (1.333\ - 0.216T +\ 0.009T^2) \tag{4}$$

$$* (s - 35) + 16.3H + 0.18H^2$$

$$L = l^K exp(l * g(f)/10) \quad (5)$$

Where k is an energy propagation factor. The residual energy of a sensor node E_{resi} is calculated as follows:

$$E_{resi} = E_{init} - (E_{rx} - E_{tx}) \quad (6)$$

Hear E_{init} is the sensor's initial energy.

C. Data Routing

Data can be sent to and from each small cube (SC) from six directions. In our proposed approach, we have two data priority. The low priority data is generated by sensors such as monitoring the aquatic environment. Low priority data are less sensitive and can tolerate some delay and packet loss. For this type of data, each cube sends its data on only one side. Selection of this side depends on the geographic location of the sink.

The routing of low priority data occurs in two phases. At First phase we choose next target SC. In this phase according to the sink (x_s, y_s, z_s) and source (x_u, y_u, z_u) coordination's on the z -axis (north or south) and then on the x and y axis (east or west), a next small cube is selected as a target cube. This opens one side of cube to send data packets. At second phase, we calculate the Euclidean distance between existing sensor nodes and sink node, and choose the nearest sensor node to the sink as the next hop. As can be seen, no energy model is considered for this kind of routing, so packets may be lost due to lack of energy.

The high priority data such as sending data through the sensors in water borders of a country, in which case the critical data should be guaranteed to be delivered with a reasonable delay and low packet loss. For this type of data each cube sends its data on all sides. The routing procedure of high priority data also consists of two phases (choose next target SC, choose next target sensor node). At First phase, data sending is limited to a specific range in the network. At the second phase, choosing the sensor nodes with the highest remained energy and the lowest delay can be used to transmit data. This lead to decrease energy consumption and increase network lifetime.

D. High priority Routing algorithm details

In the proposed protocol each sensor node can directly communicate with all other sensor nodes, as vertex-adjacent, edge- adjacent and surface- adjacent neighbor SCs as Fig. 5. In this figure, a node

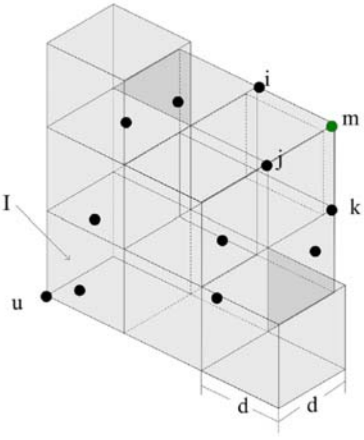

Fig. 5. The relationship between r and d.

b

a

Fig. 6. The transmission space of a sensor node, (a) Logically transmission range. (b) Physically transmission range.

u is the most distant point. .If the length of r (node transmission rage) and d (one side of SC) satisfies the following condition, then all node in adjacent small cubes can receive data from node u:

$$(2d)^2 + (2d)^2 + (2d)^2 = r^2 \tag{7}$$

Where r is constant and d can be obtained as follow:

$$d = \frac{\sqrt{12}}{12} r \tag{8}$$

Fig. 6 shows that 32 SCs can be in the transmission rage of a sensor node. The significant point is that all SCs which are in LC do not have the same number of SC neighbor. If a SC is in the corner of LC or a SC has the same edge or surface with the LC, the number of neighbor SCs is different.

Algorithm 1 shows the first phase of finding the next target SC for high priority data.

High priority Algorithm, phase 1, choose next SC:

1-The sensor node u calculates its location coordinator (x_u ,y_u ,z_u), sink's location coordinator (x_s , y_s , z_s) and its neighbor SCs'ID.
2-The sensor node u calculates the Euclidean distance l_{cs} between current node and sink node.
3- The sensor node u calculates the Euclidean distance between current SC's neighbor SCs and sink node.
4- If l_{cs} is shorter than all the other SCs ($l_{cs\,i}$) , this SC is marked as the next SC and go to step 6.
5- If l_{cs} is not shorter than all the other SCs ($l_{cs\,i}$) , the minimum $l_{cs\,i}$ is selected and sc_i is marked as the closer SC to sink, and go to step 6.
6- Check if there exists any awake node in the marked SC. If no, choose the next closest SC*i*. Repeat this step until there are awake nodes in the current SC.
7- Choose the target next hop sensor node.

In the second phase the sensor node with the most capability, is selected as a next hop node. We define the sensor node u's capability as follows:

$$w_u = \frac{\alpha}{D} + \frac{\beta}{L} + \gamma E_{resi} \tag{9}$$

$$\alpha + \beta + \gamma = 1 \tag{10}$$

Where D is path delay from node to sink, L is the path loss rate, and E_{resi} is remain energy of current node. D and L are dependent on water salty p. These factors show the current node capability and reliability easily. The pentameters α, β and γ are constant (0< $\alpha, \beta, \gamma < 1$) and determine using environment condition.

In our procedure at least one node in the next target SC is chosen, so we select the node with the largest weight value (w) to be the next hop node, and it must be awake (Algorithm1 ,Phase II). The steps in Phase I and Phase II will repeat until there are no more SCs or nodes meeting the route discovery condition. Some SCs can be reused for data transmission if there exists several awake nodes inside.

High priority algorithm, phase 2, choose awake next hop node:

1-Calculating **ω** for each awaking sensor node in SC, using formula (9).
2-Choosing the sensor node as next hop which has more **ω** than other sensor nodes. If there is only one sensor node in SC, choose this node as the next hop node directly. If there are several nodes with exactly the same ω in this SC, choose one node as the next hop node randomly.

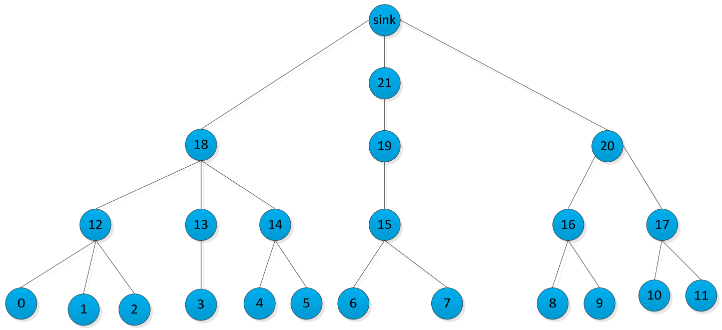

Fig. 7. The topology used in simulation.

Table 1: Simulation parameters.

Network Field	500 m × 500 m
Number Of sensor nodes	100
Number Of sinks	1
Deployment Type	Uniform, Grid
E_{init}	10^{-4}J
E_{elect}	50^{-9} J/bit
Packet size	512 Byte
nodes Simulation time	1000 s
Type traffic	High priority, Low priority
T	$15\ C^0$
r	30 m
T_b	10^3 bit
α, β, ɾ	0.3, 0.4, 0.3

IV. Simulation Results and Analysis

OPNET is the software used in investigating the performance of the proposed protocol. The network topology used in the simulation is shown in Fig. 7 with 21 sensor nodes in the simulation model. A summary of the simulation parameters are shown in Table 1.

In the simulation we implemented GEDAR [26] algorithm for comparison purposes in our simulations.

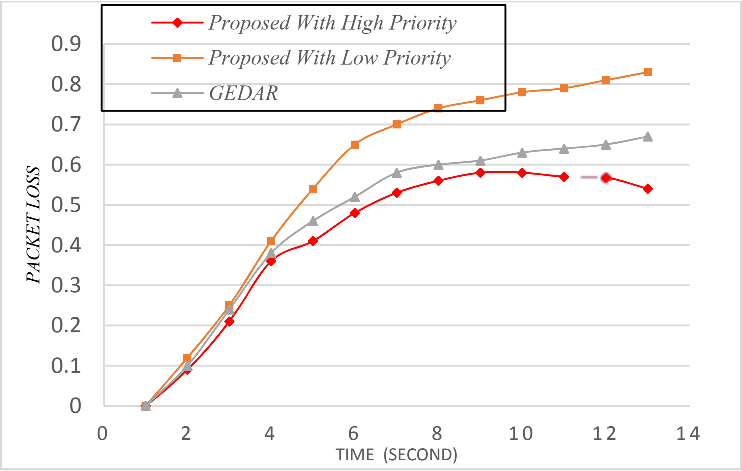

Fig. 8. Packet loss ratio over time for different priority of data packets.

A. *Packet Loss Ratio*

Fig. 8 shows normalized packet loss rate over time for different priority of data packets. In proposed protocol there are two types of traffic, sensitive traffic with high priority and non-sensitive

with low priority. The upper nodes, send sensitive and important data to the sea bed, so the loss of these data packets can cause irreparable problems. Therefore, each type of traffic should route with separate algorithms. As can be seen in Fig. 8 packet loss rate for proposed protocol is less than GEDAR. The proposed protocol, due to using efficient routing paths has less number of packet losses. According to Fig. 8 it can be observed that after about 5 second, differences between our proposed protocol packet loss rate and GEDAR will be greater. GEDAR does not have any classifier at input and scheduler at output of node and does not support priority, so it has the largest number of packet loss. As you can see in the figure 8, as the time goes, the algorithm has the chance to be able to handle the traffic more efficiently. As a result the graph shows a collapse in the line trajectory.

B. *End-to-End Delay*

Another fundamental parameter is an important factor in UWSNs is the end to end delay. It is defined as the time between generation of data packets and reaching the destination. With regard to the fact that GEDAR could not have priority for different traffic type, there exists only one priority for it. Fig. 9 demonstrates the end-to-end delay over time for both high and low priority data as well as GEDAR. High priority traffic has low end-to-end delay as compared to low priority traffic, because in traffic with higher priority all the faces of the cube are opened to send data while in low priority traffic due to the sink location only one cube face is opened to send data packets.

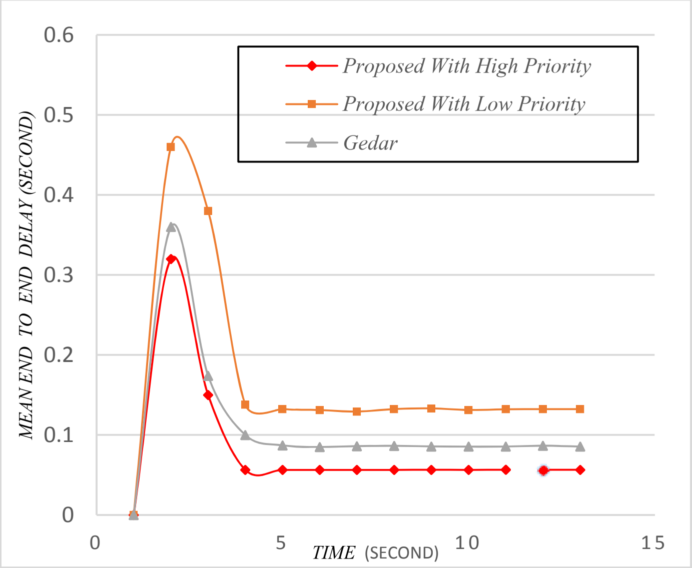

Fig. 9. End to End delay over time.

The proposed protocol transmits more control packets in the first and second phases at the beginning of simulation and this results in more initial end-to-end delay. But with the increase in time and beginning of routing procedure, the end to end delay of the proposed protocol becomes better.

C. *Remain Energy*

Energy consumption is one of the most challenging constraints of UWSNs, because the sensors which are located in underwater environments are related to the security of the country. Under water, charging sensors battery is very difficult and mostly impossible. So, sensors with inadequate energy should be replaced by new sensors to achieve continual, reliable and efficient working network. Due to these difficulties the energy consumption of sensors should be low and should work for long periods of time without battery recharging.

Fig. 10 illustrates the comparison of energy consumption of the closest node to the sink in the proposed protocol with GEDAR in various priority. As it is evidenced, remain energy of packet with lower priority run out faster because it does not consider energy. The lower remaining energy is a result of higher energy consumption. For high priority data we consider nodes remaining energy for next hop selection. This method increase the life time of the network too.

Fig. 11 shows the total residual energy of network as compared to GEDAR. As can be seen in Fig. 11 total remained energy of the proposed protocol is improved in comparison with GEDAR. This mainly because, by using logical cube we do not need complex route discovery process and also

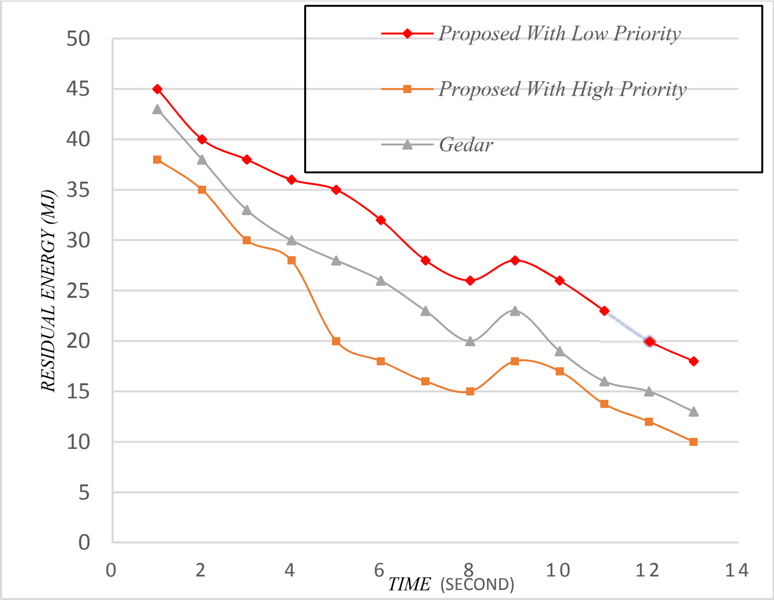

Fig. 10. Residual energy over time with different priority of data packets.

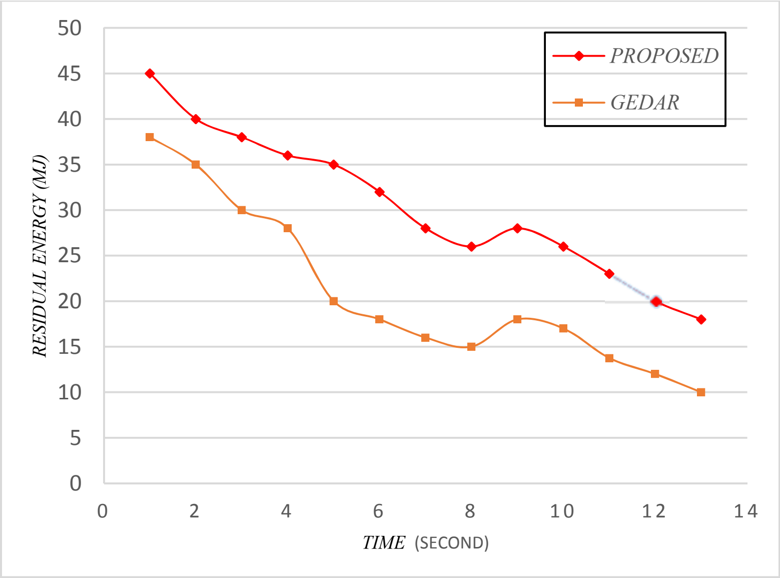

Fig. 11. Residual energy over time.

considering node energy in route selection helps to change new routes. By this way nodes consume most of their energy until the end of simulations and this cause the protocol to be more successful.

D. Packet delivery rate

The packet delivery rate is one of the important parameters in most applications. This parameter plays a significant role in high priority traffics, because these data should be delivered to destination

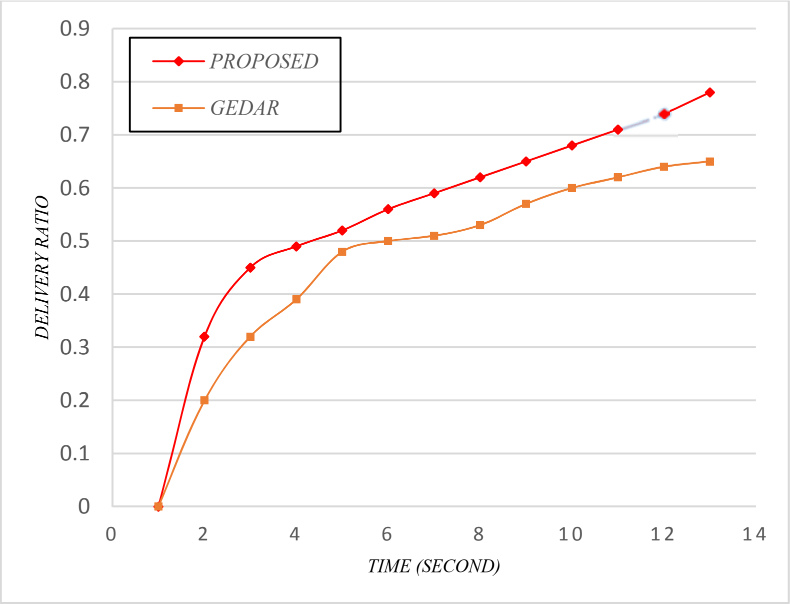

Fig. 12. Packet delivery rate over time.

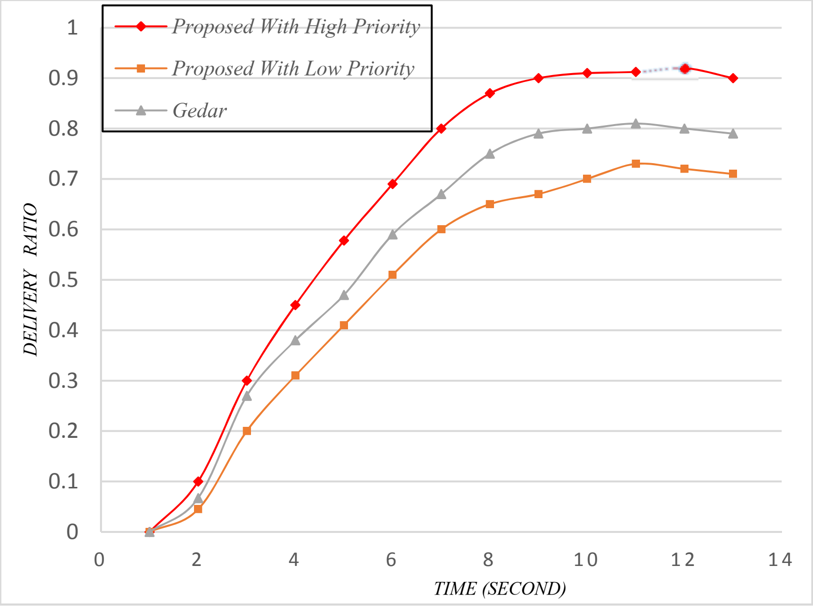

Fig. 13. Packet delivery rate over time with different priority of data packets.

in real time. In fact, time is a sensitive parameter for these traffic. Fig. 12 and 13 show the packet delivery rate over time for total proposed data and for priority-based data, respectively. In proposed protocol because of different algorithms for different traffic types mostly multi route are used to send data. This causes traffic to distribute through multipath. By this way probability of congestion and packet loss decrease and packet delivery rate increases. In GEDAR all traffic route from one path and this cause congestion and low and packet delivery rate.

V. Conclusions

In this paper a priority based routing protocol for use in underwater wireless sensor networks applications has been presented. The proposed protocol supports two traffic classes: high-priority and low priority. The high priority class is used for sensitive and important traffic such as exchanging data through the sensors in water borders of a country, in which case the critical data should be guaranteed to be delivered with a reasonable delay and packet loss. The low priority traffic generated by sensors which monitor the aquatic environment. For this traffic, the proposed algorithm in the first phase selects one of the logical small cubes as a logical target cube. Then in the target cube a sensor node is selected whose distance to sink is minimum. For high priority traffic, target cube and target node are selected as a next hop base on their remained energy. Simulation results show that the proposed protocol is more efficient than GEDAR in terms of packet loss, energy efficiency and end to end delay. For the future we work on real underwater sensors parameters. In this work we took just two priority level, in future we work on multilevel classifier with dynamic weight scheduler. Also we suggest working on intelligent mobile underwater sensors.

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