EEARP - an Efficient and Energy Aware Routing Protocol for Underwater Wireless Sensor Networks

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ABSTRACT

Recently, Underwater Wireless Sensor Networks (UWSNs) have attracted significant attention from both academia and industry to explore the vast underwater environment. Since UWSNs suffer from long propagation delay, low bandwidth, and high error rate, providing an efficient routing protocol is challenging. This paper proposes EEARP, a series of new routing protocols for underwater networks to improve the performance of existing DBR as a well-known underwater routing protocol. In DBR, upon receiving a new packet, a sensor only forwards it if the packet comes from lower depth. This forwarding mechanism does not care about any energy consumption consideration. Moreover, this greedy behavior of DBR causes a void area problem. EEARP creates a directed acyclic graph rooted at a sink. Each node receives information like depth, energy, and the number of parents from its parents. When forwarding, each node sends a data packet to one or more of its parent nodes. We implemented EEARP in NS2 simulator and evaluated its performance under different scenarios. Results confirm that EEARP outperforms DBR in terms of energy saving, network lifetime, end-to-end delay and packet loss ratio.

Keywords: Underwater Routing, Underwater Wireless Sensor Networks, Energy Efficiency, Depth-based Routing (DBR), End-to-End Delay, Network Lifetime

1. INTRODUCTION

The earth is a water planet, where more than 70% of its area spans over water. Only less than 10% of the water volumes (oceans) have been investigated, while a large area still remains unexplored. The main reason for the investigation is some applications such as environmental monitoring for scientific exploration, disaster prevention, assisted navigation, and oil/gas spills monitoring, and so forth [1], [2]. On one side, traditional approaches used for underwater monitoring missions have several drawbacks and on the other side, these harsh environments are not feasible for human presence as unpredictable underwater activities, high water pressure and vast areas are major reasons for unmanned exploration. For these reasons, UWSNs are a good candidate for gathering information in an underwater environment such as a river, lake, or other water resources. UWSNs assist in the timely gathering of information with higher precision in the vastest area. As shown in Fig. 1, an UWSN consists of several underwater sensor nodes and one or more underwater sink nodes. Underwater sensor nodes spread in a 3D area and send their sensed data to the sinks using acoustic signals. Each sensor node can also receive and forward the data of other sensors toward the sinks. Underwater sink nodes collect the transmitted data from sensor nodes and store or transmit them toward onshore stations using radio signals.

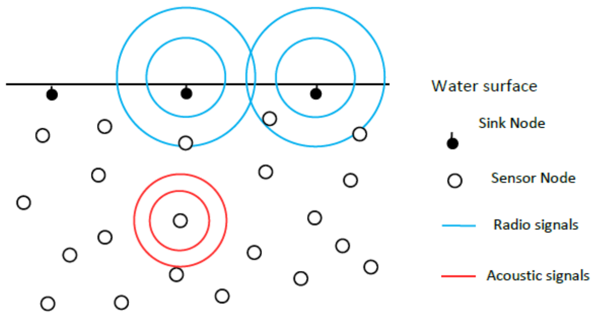

Fig.1: *A sample of UWSN (Adapted from [14]).*

As shown in Fig. 1, the main difference between UWSNs and Wireless Sensor Networks (WSNs) is the transmission media. There are various communication techniques such as optical rays [3], [4] and radio signals [5] for short-range communications. However, these signals attenuate in several meters or several tens of meters in a quick manner, which requires high transmission power and complex signal processing

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techniques. In addition, radio waves do not work properly in underwater due to water-absorption and rapid attenuation. Thus, an acoustic signal is deemed as the only feasible medium which can work satisfactorily in underwater environments and provides longer communication range. On the other hand, using the acoustic signal under water has limitations: propagation speed of acoustic signals in water is very low, i.e., 1500 m/s, which makes long propagation delays [6]. The signal attenuation is very high under water and signal energy is commonly absorbed by the water molecules. Hence, the bandwidth of the associated communication channel is limited. Further, the link quality is severely affected by a lot of factors such as multipath, noise, and path loss. Therefore, the bit error rates are typically very high [7].

Regarding the unique properties of the underwater environment, the approach of forwarding the data packet from a source node to a destination node is vital. Since in UWSN the wireless transmission medium is shared, the neighbor nodes overhear the sent data packet from the sender. A sensor node consumes energy during sending or receiving data and listening to the channel. In underwater sensor networks, energy constraint is a crucial factor because sensor nodes are equipped by a battery, and it is impossible or difficult to recharge them in most application scenarios. Therefore, sensor nodes should avoid sending data packets in an inefficient manner in order to keep their energy for a longer time [8]. In addition, the sensor nodes are developed in three-dimensional architecture and nodes move continuously at 2–3 m/s with the water currents [9]. In such situations, routing protocols should not rely on node position and could send packets to the destination disregarding the position of the prior or current node. Another challenging issue in underwater sensor networks is the void area. Sometimes the suggested path by the protocol will never reach the sink because there is no available node in its neighborhood in the lower depth regarding the current node; this problem is referred to as void area. In this situation, the energy of nodes in network is consumed without providing any fruitful result and therefore the network lifetime is diminished. It is notable when the energy of a node is diminished, the network lifetime will be reduced.

In order to mitigate the aforementioned problems, we propose an efficient energy aware routing protocol (EEARP) to reduce energy consumption and increase network reliability by addressing the void area problem. In our proposed technique, a Directed Acyclic Graph (DAG) in which each sensor node has some parent nodes is created. Then, each node in the forwarding phase selects one or more of its parents based on their residual energy, the number of parent nodes and depths. This process is repeated in each node till the data packet reaches a sink node. Forwarding data packets through multiple parent nodes helps to eliminate void areas. Moreover, selecting parent nodes regarding their depths and energy causes more energy conservation. Simulation results show that EEARP can significantly outperform Depth-based routing (DBR) protocol in terms of some important performance metrics such as energy, end-to-end delay, and packet loss ratio. DBR [14] is a location-free routing protocol in which a sensor node only forwards the received packets based on depth difference between itself and the previous forwarder node.

The rest of the paper is organized as follows. We briefly review some related work in Section 2. Then we present our proposed method in Section 3. Section 4 reports the main results of performance evaluation. Finally, we conclude the paper and discuss some future works in Section 5.

2. RELATED WORKS

Generally, routing is guiding packets from a source node to a destination (one or more sink nodes are usually situated at the water surface). In this section, we review underwater routing mechanisms in two sub-sections: location-based routing and location-free routing.

2.1 Location-Based Routing

Essentially, location-based routing protocols require a precise position of the nodes. In these types of protocols, the underlying assumption is that every node already is aware of its full-dimensional location information, location of one-hop neighbors as well as the sink node. Since the transmission media in underwater environment is not able to efficiently propagate radio signals, estimating an accurate location using GPS satellites encounters serious challenges. As a matter of fact, GPS utilizes radio waves in 1.5 GHz band which do not propagate in water [10]. For this reason, location-based routing protocols use different techniques to estimate the locations of sensor nodes. In the following, we review some location-based routing protocols.

VBF (Vector Based Forwarding) [11] is one of the first location-based underwater routing protocols which considers the consumed energy of sensor nodes and their mobility as well. In this protocol, a virtual vector from sender to receiver is created. Only nodes lying within this cylinder, called the routing pipe, are allowed to forward the receiving data packet. Other nodes simply discard the packet. This policy causes energy conservation because only the nodes lying within the routing pipe will participate in the routing. When a source node has a packet to send, it builds a routing pipe and sends the packet through the pipe. In VBF, each node requires full-dimensional location information for creating the routing pipe. Furthermore, in case of sparse networks in which nodes are too sparsely distributed, and because of the single routing pipe between source and destination, it is possible that no nodes may lie within the virtual pipe for data forwarding. Consequently, data packets are not allowed to forward to the sink even though paths may exist outside the pipe. Moreover, in VBF, the quality of routing depends on the transmission range of each sensor node. The bigger radius results in the inclusion of more nodes in the pipe and improvement of the routing quality. HH-VBF (Hop-by-Hop Vector-Based Forwarding) protocol [12] was proposed to overcome the limitations of VBF. In HH-VBF a virtual routing pipe is created in each hop. In fact, once a node receives a packet from a node, it creates a routing pipe between itself and the sink node. In this way, each node can adaptively make packet forwarding decisions based on its current location. Thus, the probability of finding a routing path in this protocol increases in comparison with VBF.

MFR (Multi-Link Fault-Tolerant Routing) protocol [13] tackles the issues of node and link failure in 3D UWASNs. In MFR, each sensor node has a data structure called backup bin, which allows constructing main backup links and auxiliary backup links for repairing the failed links along the routing path. In this approach, it is assumed that all sensor nodes are cognizant of their own 3D locations through a certain localization service. Each packet carries the positions of the source node, the sink node and the relay node (i.e., the node that transmits the current packet). Upon receiving a packet, a node computes the gravities of its neighbor nodes and chooses the neighbor with the maximal gravity value to be the relay node that is in charge of forwarding the data packet. In gravity computing, residual energy, the intersection angle between the direction of the source to the next node and the direction of the source to the sink is considered. In this protocol, all the one-hop neighbors of the source node are put into a routing table.

Although the simulation results indicate better performance in terms of packet delivery ratio and consumed energy for location-based routing protocols compared to location-free ones, they have some weaknesses. First of all, most location-based routing protocols assume that the three-dimensional position of the nodes is achieved with the assistance of localization services. As we mentioned before, GPS shows a poor performance under water; thus, finding the nodes' position even using anchor nodes is challenging. Furthermore, in an underwater environment, sensor nodes move 3–6 km/h with water currents. This movement makes changes in the positions of the nodes and the routing table needs to be updated. There is a probability of missing the backup links and auxiliary backup links; hence these types of protocols are not suitable candidates for real underwater scenarios.

2.2 Location-Free Routing

These kinds of routings do not require full-dimensional location information of the sensor nodes and only the node's depth is utilized in the routing decision. Depth information can be obtained easily with a depth sensor. DBR [14] is one of the most well-known location-free routing protocols in which a sensor node forwards data packets based on depth difference between itself and the previous forwarder node. In this way, upon receiving packets, the node compares its own depth parameter to that of the sender (extracted from the packet header). If the receiving node is located in a higher depth compared to the sending node, it discards the packet and does not participate in the forwarding process. Otherwise, it replaces its depth into the header of the current packet and broadcasts it. To ensure that a node forwards a given packet only once in a certain time interval, a packet history buffer along with a priority queue are used to diminish the number of forwarding nodes. However, the nodes which are far from each other may not overhear the transmitted packet. Consequently, multiple nodes will probably send the same packet. Therefore, several copies of this packet may reach the destination through more than one route. Although it results in more reliability, it increases the energy consumption. In addition, as only nodes in lower depth participate in forwarding according to DBR, the packet will never arrive at the destination if this area is void; while the packet may be forwarded by the other nodes located in higher depths. This phenomenon is referred to as the void area problem.

FDBR (Fuzzy DBR) is an extension of DBR that uses Fuzzy logic in order to increase energy efficiency of DBR [15]. As a matter of fact, FDBR considers the hop count that the current packet has traversed, residual energy of the current node and depth difference between the previous and current node as the inputs of the fuzzy logic system. Then, it computes the holding time of the current packet. Using fuzzy logic computation in FDBR enables sensor nodes to adapt themselves regarding the network circumstances. For example, if a node has low level residual energy, it has longer holding time compared to the node with higher level residual energy. This policy leads to saving more energy and prolonging the network lifetime. On the other hand, considering depth difference between nodes, leads to a decrease in the end to end delay. Because more depth difference between two relay nodes causes less holding time this leads to less end to end delay. Although, FDBR has better performance compared to DBR, it suffers from computational overhead of the fuzzy computation process.

EE-DBR (Energy-Efficient Depth-Based Routing) [16] is a routing protocol which is proposed to tackle the energy problem in DBR. As DBR only uses the depth of the sensor nodes as a metric for the routing process, packets will be sent over the same path. In this protocol, a node that is close to the water surface has a shorter holding time. Therefore, that node will send the data packet sooner and when other nodes overhear this data packet they renounce from forwarding it. Consequently, because of successive transmissions, compared to other nodes, this node runs out of energy more rapidly which, in turn, leads to a reduction of network lifetime. For computing the holding time, EE-DBR considers the residual energy of sensor nodes to balance energy consumption and achieve more energy saving. This calculation is performed upon receiving a new data packet using Eq. 1 as follows:

$$T = \left(1 - \left(\frac{C}{I}\right)\right) \times max\_T + p \tag{1}$$

where max_T is a predefined value to determine the maximum duration for a sensor node to hold a packet, C is the current energy level of the node, I is the initial energy of the node and p is a priority value. From Eq 1, it is obvious that, in EE-DBR, the nodes with equal residual energy will have equal holding time. This situation leads to forwarding of the packet at the same time by multiple nodes. To prevent this circumstance, EE-DBR uses p parameter as a priority value for each node. In fact, different nodes have different p value and as a result they will have different holding times. In Section 4, we compare our proposed technique with EE-DBR protocol. This protocol operates in two phases: knowledge acquisition and data forwarding. During the knowledge acquisition phase, sensor nodes exchange some information such as depth and residual energy with their single-hop neighbors. While, in the data forwarding phase, data packets are transmitted from the sensor nodes towards the sink node. However, similar to DBR, EE-DBR suffers from the void area problem.

Distance-based Routing [17] is based on the distance between the current node and the sink. This algorithm aims to deliver the packet to the sink through the shortest path. If the packet is forwarded through the nodes with a shorter distance to the sink, it would be likely that a lower number of nodes participate in the forwarding. When a node receives a packet, it forwards the packet to the next node, only if its distance to the sink is shorter than that of the sending node. Otherwise, it simply discards it. The sink node periodically sends a control signal. Other nodes, based on the RSSI (Received Signal Strength Indicator), calculate their distance to the sink node. If a single packet is forwarded by multiple nodes, it leads to energy drain and an increase in traffic. This is avoided by adding a unique-id field to the message. Moreover, to avoid loop, upon arrival of a packet, it is verified to see whether the packet has been forwarded early.

EEF (Energy-Efficient Fitness Based) routing protocol [18] utilizes several metrics including residual energy, depth and depth of intermediate nodes to the sink node for path selection. It is also assumed that each node is aware of the sink's location. In this protocol, when a source node has a data packet to send, it calculates its fitness based on the residual energy, depth, distance from the node to the sink, and the distance from the forwarding node to the sender. It puts the result into the header of the packet and broadcasts it. The one-hop neighboring nodes which receive the packet, calculate their own fitness. If the fitness value is greater than the value incorporated in the packet, this node will forward the received packet via broadcasting. In order to prevent more nodes from forwarding the same packet, the forwarding nodes wait for a time period which is determined based on the fitness. Therefore, the most fitting node sends the packet sooner. The other forwarding nodes overhear this packet and, as a consequence, avoid forwarding it. Since in EEF, the residual energy measure is taken into account at the time of packet transmission, diverse nodes alternatively send data packets, which results in an equally dispersed energy consumption. However, this routing protocol may not be efficient in terms of energy consumption.

EDBR (Efficient Depth-Based Routing) protocol [19] is an improved version of the DBR protocol. In this protocol, a node that is closer to the water surface and has more residual energy is privileged for forwarding the packet. To achieve this goal, upon receiving a packet, each node compares its depth with that of the previous transmitter. If this node is located in lower depth, it holds the packet for a certain time (that is based on the depth and the residual energy) and when the time is over, it sends the packet. A node having high residual energy and low depth has a short holding time and has more chance to forward the packet. The nodes with low energy level do not forward the packet when they overhear its transmission. In terms of network lifetime, end-to-end delay, and residual energy, the operation of this protocol has been improved compared to the DBR protocol. However, it is possible to send a packet through multiple paths. Moreover, in EDBR void area problem has not been resolved. The aforementioned location-free routing protocols face some problems such as unbalanced energy consumption and void area problem. Furthermore, horizontal node movement because of water current is not considered. In these protocols, nodes identification phase is performed at the beginning of the operation, just one time and then

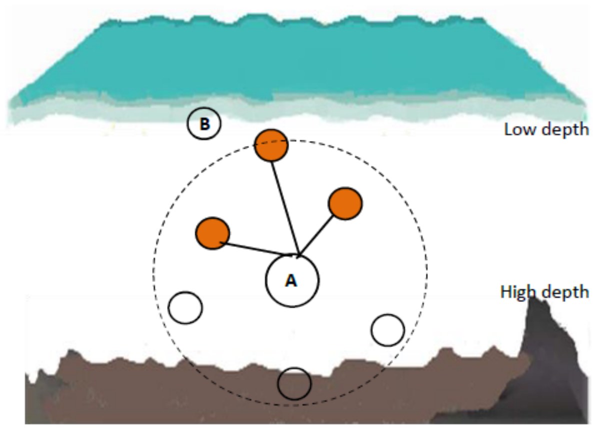


Fig.2: *Node A has three potential parents according to EEARP (the colored nodes). Node B is not in transmission range of node A and is not considered as its parent.*

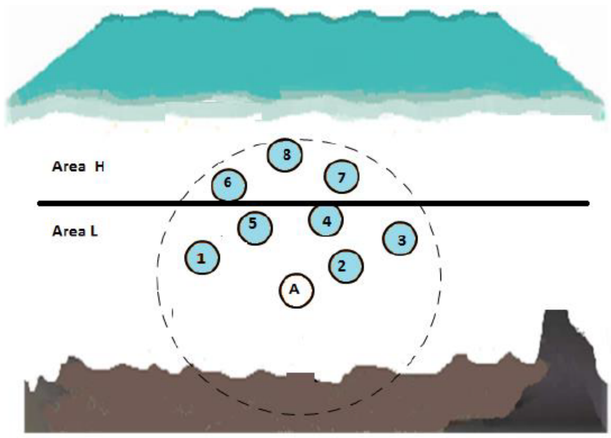


Fig.3: *The nodes in area H can participate in forwarding packets of node A.*

only the energy of the nodes is updated. However, the nodes move with water current and the neighborhood changes. In this paper, we attempt to propose a new routing method based on DBR protocol. We consider several mechanisms to improve the performance of DBR in terms of energy and network lifetime while overcoming the problem of void area.

3. EEARP MECHANISMS

As mentioned in Section 2, both location-based and location-free routing protocols have some limitations in forwarding a packet from source to destination in an underwater environment. In this paper, we propose a new routing protocol EEARP, to improve the performance of DBR mechanism. The proposed technique is based on directed acyclic graph (DAG) principles. EEARP is composed of two phases: notification and data forwarding. In the notification phase, each node encapsulates some information including depth, residual energy and the number of parents (the nodes located in communication range of the current node and having lower depth) in a beacon packet and broadcasts it to its neighbours. As shown in Fig. 2, the coloured nodes are the parent nodes of node A. Although node B is in lower depth, it is not the parent of A as it is out of the communication range of A.

The notification phase is done periodically by sending a beacon packet to each node. The beacon packet includes information such as depth, residual energy, and the number of transmitter node parents. Each node broadcasts the beacon packet and receives and processes the transmitted beacons which have been emitted by the neighbor nodes. Similar to DBR, in EEARP, upon receiving a packet, each sensor node compares its depth with the sender node and discards the packet if it comes from nodes with lower depth nodes. Therefore, each node maintains the information of higher depth nodes in a so-called "parent table". The periodic nature of the notification phase helps sensor nodes to have updated data from their parents even when the neighborhood is changed due to water currents.

In the data packet forwarding phase, based on specific metrics, each node selects one or more parent nodes for forwarding the packet. Therefore, based on the utilized metrics, the number of forwarding nodes is decreased. As a result, less transmission in the network leads to conserving more energy and to increasing the network lifetime. Moreover, if a node does not have any parent, the packet will be sent to a higher node toward the sink through another path. Therefore, it avoids creating a void area. In the following section, four different strategies are proposed for selecting the forwarding nodes.

3.1 First Strategy: Filter Based Forwarding EEARP (EEARP_FB)

In the basic mechanism of DBR and EE-DBR, all the nodes which have lower depth compared with a transmitter node, even their near neighbours, can participate in forwarding the packet. However, packet transmission by the nodes very close to the transmitter can lead to energy consumption and more collision. To improve energy efficiency, our first strategy (EEARP_FB) is to decrease the number of forwarding nodes. It is worth mentioning that, this strategy is valid if the communication and transmission range of all nodes are the same. As shown in Fig. 3, there are 8 nodes, each can potentially be a parent of A. The nodes located in area L have lower depth difference compared to the nodes located in area H. To limit the number of transmissions for a given packet, the first strategy emphasizes that only the nodes located in area H are allowed to be selected as parent node by A.

Parents'Addresses	Depth	Flag	DATA

Fig.4: *Soft start circuit.*

This policy can be implemented by considering a threshold for depth difference value. In this way, upon receiving the information of candidate nodes, node A compares its depth to the depth of each candidate node. Only nodes with depth difference greater than a pre-determined threshold value are allowed to be selected as the parent node. In EEARP_FB, higher threshold values lead to a lower number of potential parents and vice versa. As a matter of fact, a higher threshold value reduces the packet collision probability while decreasing the reliability of delivering data packets to the sink node.

3.2 Second Strategy: Metric Based Forwarding (EEARP_MB)

In this strategy, each node determines the priority of each parent node based on a proposed weighted metric, then places the address identifier of the parent node with the highest priority in the header of the packet and broadcasts it. Fig. 4 demonstrates the format of the new packet. In EEARP_MB, only the node whose address is in the header of the packet can forward the packet. The new node repeats the above action and chooses the parent node with the highest priority.

The proposed weighted metric consists of three important metrics: depth, residual energy and the number of parent nodes. The node that is closer to the water surface delivers the packet to the sink node sooner. Moreover, the residual energy criterion causes the packets to reach the sink node from different paths, which in turn results in balancing the nodes' energy consumption. Moreover, the node with more parents has higher priority because the reliability of the network is increased and causes the next node to choose more paths for forwarding the packet. In summary, EEARP_FB by considering the weighted metric for choosing the most appropriate parent node, reduces end to end delay and energy consumption while increases the reliability of the network.

The proposed weighted metric is calculated as follows:

$$P = w_1 \cdot N_p + w_2 \cdot R + w_3 \cdot d \\ w_1 + w_2 + w_3 = 1 \tag{2}$$

where P is the priority of the candidate parent node, N_p is the number of parents of the candidate parent node, R is residual energy and d is the depth of the investigated node.

As the residual energy is a very important parameter to prolong the network lifetime, we assigned a bigger coefficient to it. However, the effect of the

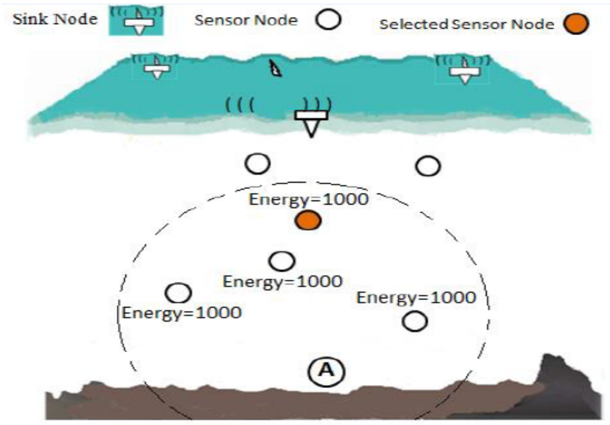


Fig.5: *The coloured node is selected for forwarding.*

number of parents and depth are considered as the same. It is worth mentioning that the weighted metric in Eq. 2 is adjustable and network developers can change the importance of each component regarding the purpose of their networks. In summary, in EEARP_MB, a forwarder node calculates a parent node which has the highest priority and places its address in the target field of the received packet and then broadcasts it. The available nodes in the area receive the packet, but only the node whose address is in the packet retransmits it. For example, in Fig. 5, the A node has four parent nodes and knows the depth, residual energy and the number of parents of each of them. If the amount of energy is equal for the nodes, the coloured node which is in the lower depth and has more parents, is selected as the next forwarding node. However, after several forwarding attempts, the energy of this node will be lower than others and another node may become the candidate for forwarding.

3.3 Third Strategy: Random Based Forwarding (EEARP_RB)

In EEARP_RB, the transmitter only selects one of its parent nodes randomly as the next forwarding node, i.e. preferred parent node. It is obvious that in this technique, the packets are not always routed through a specific path. Indeed, in EEARP_RB, upon receiving a packet, each node randomly selects one of its lower depth neighbours without considering any more conditions and inserts the selected node address into the packet header. It is clear that, since EEARP_RB does not broadcast the data packets, less collision occurs and less energy is consumed in comparison with DBR. On the other hand, it might increase end-to-end delay and decrease network reliability as it does not consider any metric for routing.

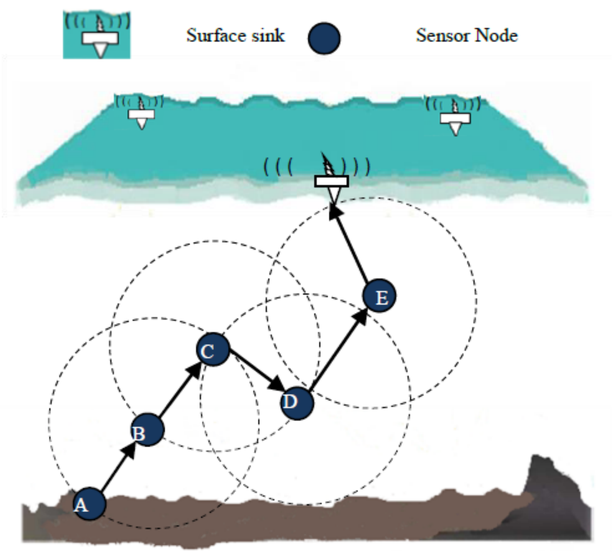


Fig. 6: *Addressing void area problem in EEARP.*

3.4 Fourth Strategy: Selective Parent Based Forwarding (EEARP_SPB)

In EEARP_SPB, each node chooses a number of parent nodes (maximum three nodes) as candidates for forwarding the packet. The priority of the next forwarding nodes is calculated using Eq. 1. The difference between EEARP_SPB and EEARP_MB is that EEARP_SPB chooses three parents instead of one parent. In fact, in EEARP_SPB, after calculating the priority of parent nodes, a forwarder node places the address of three top parents in the header of the packet and broadcasts it.

It is worth mentioning that in EEARP_SPB, similar to DBR, each candidate node does not transmit the packet immediately; rather it waits for a short time that is in accordance with its depth. The node which is at a lower depth waits for a less time and transmits the packet prior to the other two nodes. If the other nodes observe the mentioned packet on the channel, they will refuse to forward the same packet. It is notable that if each of the other two nodes is not in the coverage area of the first forwarding node, after the expiration of waiting time, they will forward the packet like DBR. However, in the worst case, three parent nodes forward the packet.

4. ADDRESSING VOID AREA PROBLEM

As we mentioned before, in DBR protocol, each node discards the received packet from above nodes (i.e. in lower depth). This policy may cause void area problem which prevents a packet from being delivered to the sink.

As shown in Fig. 6, there will be no node above C because the packet transmitted by C will be discarded by D. Consequently, the packet never reaches the target. To address this problem, we propose this modification: when a node receives a packet, it checks the status of its own parents before determining the next forwarding nodes. If the current node does not have any parent, it activates a void flag in the header of the packet and then broadcasts it. Upon receiving such packet, a neighbor forwards it without considering the depth of the transmitting node.

In this way, the packet may reach the target through another path. By applying this strategy to the network shown in Fig. 6, node C activates the void flag of the packet, which is then forwarded by node D towards the sink, passing through node E. Note that, in this scenario, D relays the packet which has been sent by C, while it is placed in a higher depth compared to node C. This slight modification helps in mitigating the void area problem.

5. SIMULATIONS AND PERFORMANCE EVALUATION

To evaluate the performance of our work, we implemented EEARP mechanism along with the four above forwarding strategies in Aqua-Sim [20], a well-known underwater simulator module in NS2. Moreover, to make a fair comparison, we also implemented three popular location-free routing protocols, namely DBR, FDBR and EE-DBR which have been already discussed in Section 2.2.

It is worth mentioning that real experimentations are of high importance as it obtains more accurate results. However, due to the lack of such infrastructure and equipment, we decided to investigate our problem via simulation. The access protocol to the channel in this module is Broadcat_Mac, which broadcasts all data packets at the MAC layer. According to this MAC protocol, when a node has a packet for transmission, it first listens to the channel; if the channel is idle, it would broadcast the packet; otherwise, it would switch to the back-off state.

5.1 Network Configuration

In all simulation scenarios, each node generates a data packet every 10 seconds. We adjusted energy consumption in transmit, receive and idle states to 2 W, 0.75 W, and 10 mW, respectively. The size of each data packet was set to 80 bytes. To investigate the performance of our proposed technique in a fair manner, we considered two different simulation scenarios in three-dimensional topologies with (500*500*500) and (100*100*100) dimensions, respectively. The first scenario was investigated for a varied number of nodes ranging from 200 to 700 and the second one was run for 50 to 200 nodes.

We considered the initial energy of the nodes as 50 Joules. We chose 0.2, 0.6, and 0.2 for coefficients w_1, w_2, and w_3 in Eq. 2, respectively. Each point represents the average of 10 simulation runs with the

Table 1: *Network configuration in the two simulated scenarios.*

	1^{st} scenario	**2^{nd} scenario**
Network dimension	500*500*500	100*100*100
# of sink nodes	3	3
Coordinates of sinks	(50,50,0) (0,0,0) (90,90,0)	(100,100,0) (250,240,0) (400,400,0)
# of source nodes	3	3
Coordinates of sources	(10,10,100) (40,30,90) (90,90,90)	(300,250,490) (240,250,490) (200,150,500)

Simulation parameters

Data generation rate	Packet size	Channel bandwidth	Transmit power	Receive power	Idle power	Physical layer propagation model	Simulation time
0.1 packet per second	80 bytes	10 kbps	2 W	0.75 W	10 mW	Underwater propagation	1000 seconds

confidence interval 95 percent. Table 1 summarizes the network configuration and simulation parameters in both scenarios.

5.2 Performance Metrics

Various measures were employed to demonstrate the performance of our methods and to compare their effectiveness against some existing protocols in the literature:

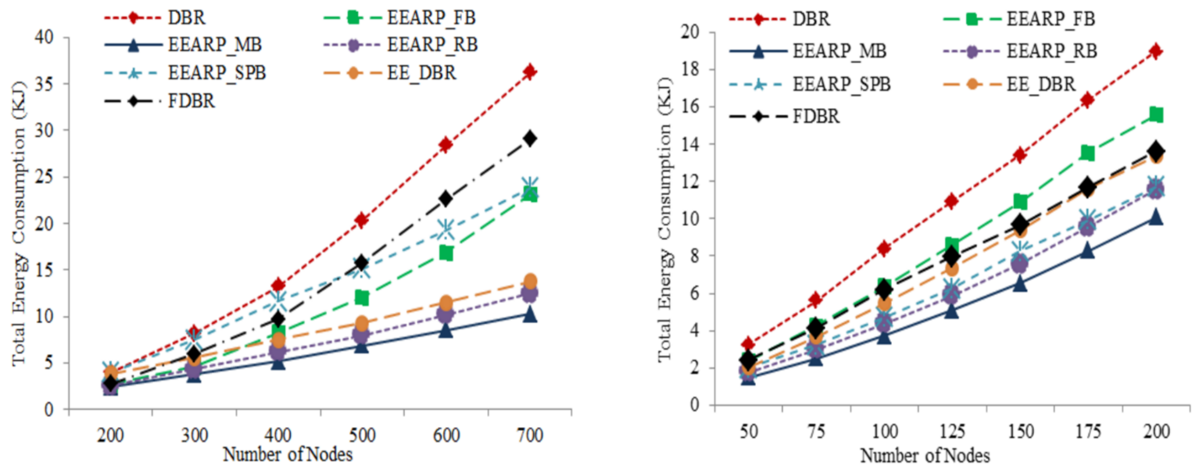
- *Total energy consumption*: The amount of energy which is used by the all sensor nodes in transmitting, receiving, and idle states. This parameter also includes the energy required for forwarding packets in relay nodes.
- *Energy consumption per packet*: This is the average energy which different nodes use for a specific packet to deliver it to the sink.
- *Throughput*: It is the average amount of data received by a group of sinks during the unit of the time.
- *Packet success ratio*: It denotes the ratio of the total number of packets successfully delivered to the sink nodes to the total number of packets generated at the source nodes.
- *End-to-end delay*: It is the average elapsed time between sending a packet at the source node and receiving it at the destination node.
- *Network lifetime*: It is the time until the first node of the network runs out of energy.

5.3 Simulation Results

Fig. 7 delineates the total consumed energy in both scenarios for DBR and proposed strategies. As seen in this figure, in DBR, more sensor nodes take part in the forwarding process and thus, the amount of consumed energy in this method is more than the other suggested methods. This figure also shows that because EE-DBR considers residual energy of sensor nodes, it achieves better energy saving compared to EEARP_FB. Moreover, Fig. 7 confirms that FDBR outperforms EEARP_FB in the second scenario. This is because FDBR considers residual energy of nodes when calculating the holding time. The EEARP_MB method, in which only one node is selected as a candidate for forwarding, has the least amount of energy consumption in both scenarios. Fig. 8, also demonstrates that all of our proposed strategies for parent selecting in EEARP outperform DBR in terms of total energy consumption metric.

Fig. 8 demonstrates average consumed energy per packet for both scenarios. From this figure, it can be observed that for all versions of EEARP, the number of relaying nodes is lower compared to DBR which results in a decrease of energy consumption. Fig. 8 also shows that regarding the parent selection, the performance of EEARP_FB falls behind other strategies. This is because of EEARP_FB attempts to choose more than one parent node and, as a result, more than one node participates in packet forwarding. On the other hand, in EEARP_FB, nodes in the close vicinity of the transmitter do not take part in the packet forwarding. Therefore, the energy consumption per packet is even lower than DBR. Furthermore, Fig. 8 illustrates that EEARP_MB and EEARP_SPB achieve approximately equal performance with EE-DBR and FDBR in terms of average consumed energy per packet. These results indicate energy-awareness of these techniques as good as EE-DBR and FDBR.

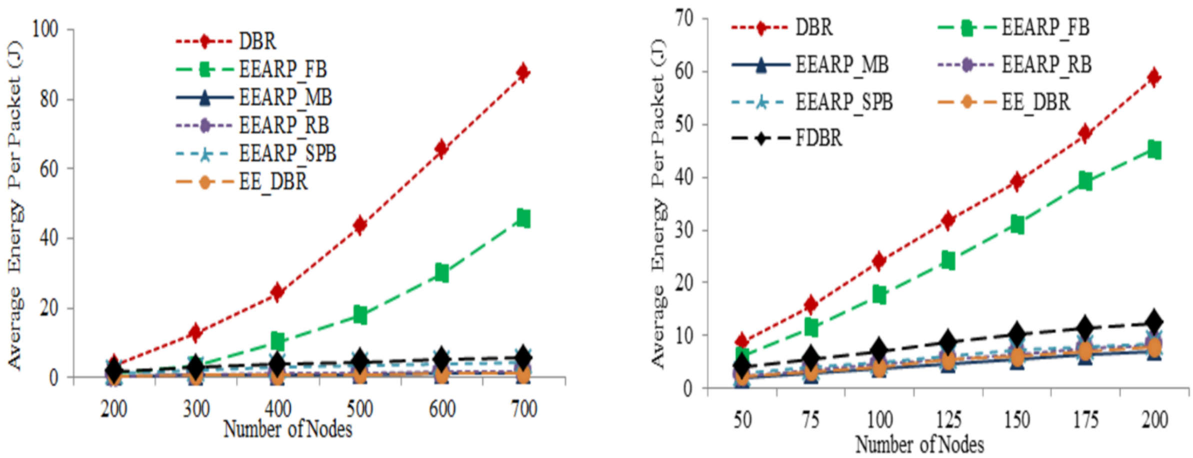
Fig. 9 demonstrates the performance of the protocols in terms of throughput for a period of 600 seconds in both scenarios. In the first scenario with 100*100*100 dimensions, the sensor nodes are



(a) First Scenario with (500*500*500)

(b) Second Scenario with (100*100*100)

Fig.7: *Total energy consumption for different network size with different density.*



(a) First Scenario with (500*500*500)

(b) Second Scenario with (100*100*100)

Fig.8: *Per packet consumed energy for different network size with different density.*

closer to each other leading to a higher collision rate and higher throughput degradation of DBR and EE-DBR. Fig. 9 also shows that in the first scenario, EEARP_FB has poor performance compared to the other proposed strategies in terms of throughput. However, in the second scenario with a larger environment, i.e. 500*500*500, due to the lower density of sensor nodes, the collision rate remains low and hence more packets are received by the sink node using DBR and EE-DBR. Moreover, it can be concluded that EEARP_SPB has better performance compared with the other methods in the first scenario and most cases in second scenario, because it chooses three parent nodes and as a result, it increases the throughput. It can be concluded from Fig. 9 that, although EE-DBR considers p value for calculating the holding time, it might forward a given packet multiple times which leads to throughput degradation in dense topologies. Furthermore, Fig. 9 confirms that EEARP_SPB outperforms FDBR, because unlike FDBR, in EEARP_SPB, fewer nodes participate in packet forwarding leading to a lower collision rate.

Packet success ratio in the two scenarios is shown in Fig. 10. In the first scenario, the number of collisions in DBR is too high which results in a great decrease in the packet success ratio. In EEARP_FB, the success ratio has a little difference from DBR and EE-DBR. Moreover, Fig. 10 shows that EEARP_MB has the best performance in terms of packet success ratio in the first scenario in which the nodes are close to each other. However, again due to the sparseness of the second scenario, the collision rate is lower and as a result, the packet success ratio is high for DBR, EE-DBR and EEARP_FB. The reason is that in DBR, EE-DBR, FDBR, EEARP_FB and EEARP_SPB, more nodes participate in forwarding

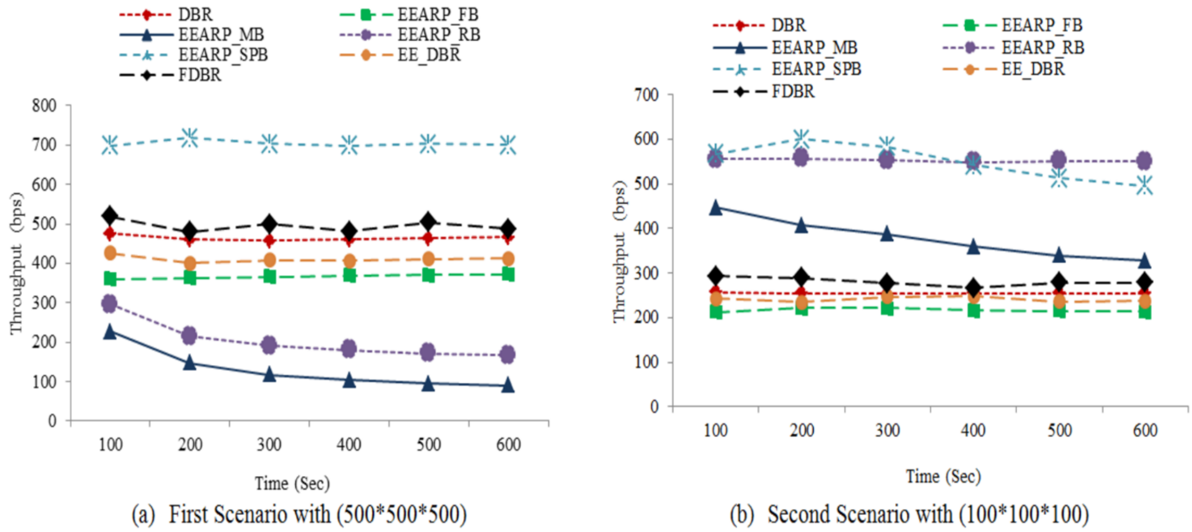


Fig.9: *Network throughput vs. time for networks with different densities.*

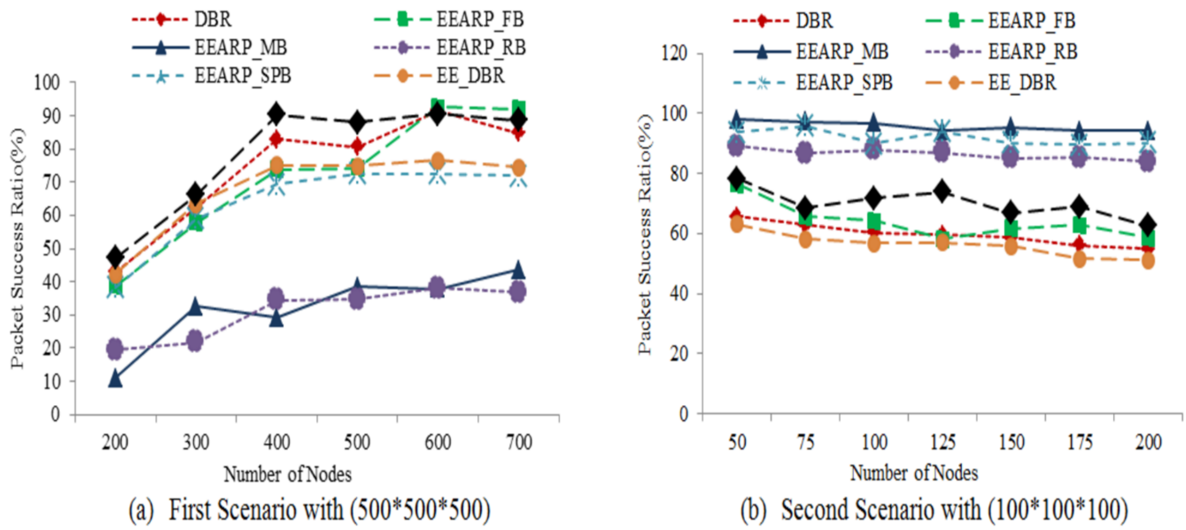
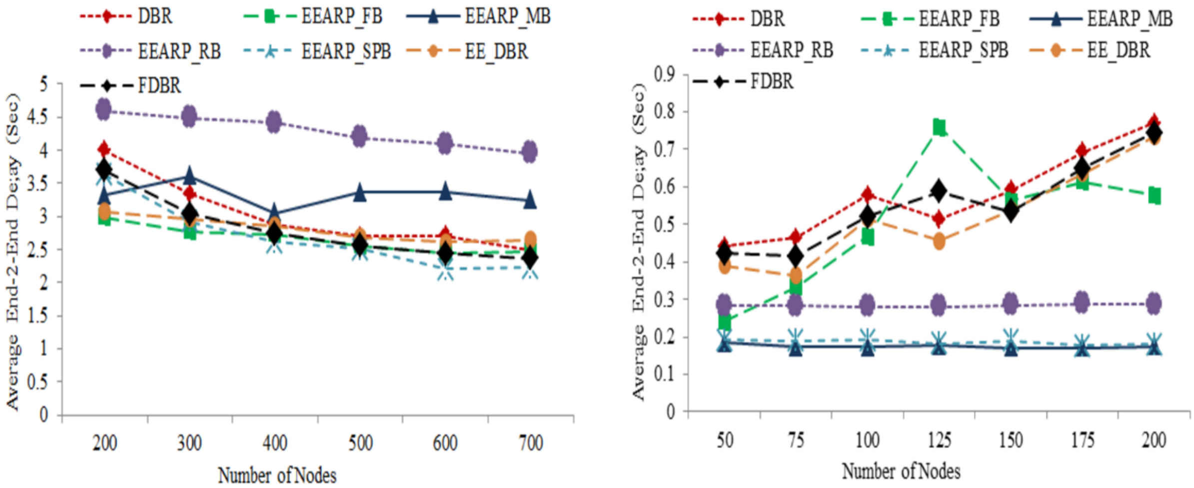


Fig.10: *PSR vs. different network size/density.*

the packets.

As shown in Fig. 11, in the first scenario, end-to-end delay in DBR, EE-DBR and EEARP_FB is more than the other three proposed strategies. This is because of two reasons: first, in DBR, EE-DBR and EEARP_FB protocols more nodes transmit the packet; hence more collision occurs, which in turn results in increased delay time between transmitting the packet and receiving by the sink node. Second, the number of hops that a packet traverses from the source to the sink is high, and as the result the end-to-end delay is relatively high. Moreover, EE-DBR calculates the holding time of a packet by considering the residual and initial energy of the forwarding node. This mechanism increases holding time in nodes which have low energy levels. For FDBR, it can be seen that, this protocol achieves shorter end to end delay in the first scenario. This is because FDBR considers depth difference between nodes to compute the holding time. Since in the first scenario, the distances between nodes are closer compared to the second scenario, the holding time is shorter and as the result FDBR achieves shorter end to end delay. However, in the other three methods, a packet can reach the destination from one or more paths. Therefore, end-to-end delay becomes short. However, in the second scenario, in EEARP_RB the packet reaches the destination later than the other methods. In the second scenario, EEARP_FB and EEARP_SPB achieve better performance in terms of end-to-end delay because in these two protocols the farther nodes are selected as forwarding nodes. This strategy leads to decreasing packet's sojourn time.

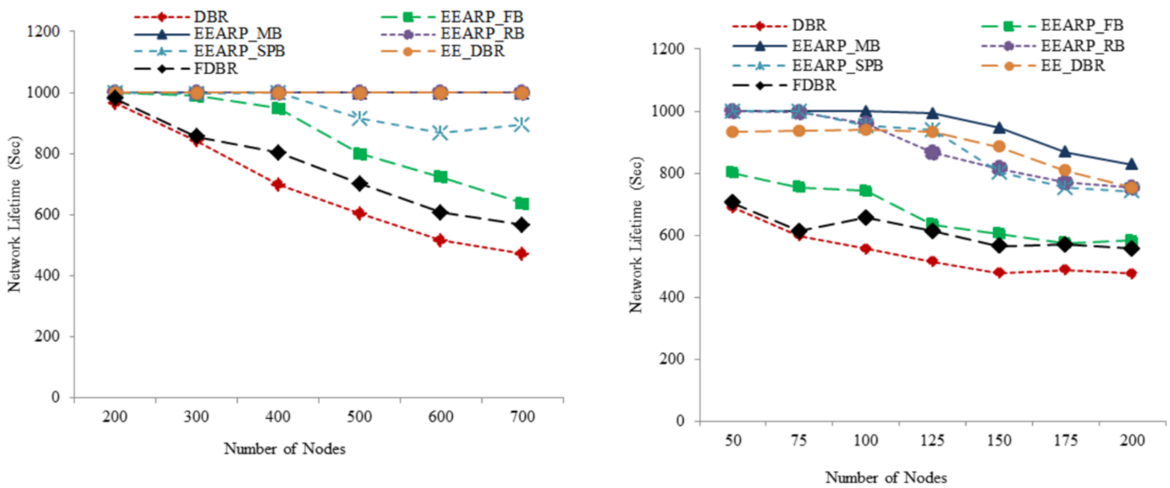
The initial energy of each sensor node is 50 Joules. As shown in Fig. 12, the network lifetime obtained by all versions of EEARP is more than that obtained



(a) First Scenario with (500*500*500)

(b) Second Scenario with (100*100*100)

Fig.11: *End-to-end delay vs. different network size and density.*



(a) First Scenario with (500*500*500)

(b) Second Scenario with (100*100*100)

Fig.12: *Network lifetime vs. different network size and density.*

by DBR. Indeed, in DBR, more nodes take part in forwarding the packet and hence more energy is consumed by the nodes. Since in EE-DBR, each node considers its energy level in the holding time calculation, it achieves reasonable performance in terms of lifetime. Similarly, FDBR considers residual energy of nodes in the fuzzy calculation process. For this reason, it has more lifetime compared to DBR and EEARP_FB. Note that Fig. 7 has already confirmed that DBR consumes more energy compared to EEARP. Furthermore, as EEARP_RD and EEARP_MB employ only one node in forwarding a given data packet, energy consumption remains quite low which, in turn, results in a longer network lifetime compared to other strategies. On the contrary, as EEARP_FB and EEARP_SPB choose more than one node as forwarder, they consume more energy and decrease the network lifetime. Fig. 12, also shows that the lifetime of EEARP_MB, EEARP_SPB and EEARP_RB outperform FDBR and are comparable with EE-DBR which demonstrates the energy effectiveness of them.

6. CONCLUSION

In this paper, we proposed a new underwater routing protocol named EEARP to mitigate the drawbacks of DBR protocol. EEARP attempts to choose suitable nodes as the forwarder in order to reduce energy consumption. To achieve this goal, we proposed four different strategies in which a limited number of nodes are selected as forwarders. In EEARP, each node gathers the required information from its own neighbors and then chooses one or more forwarder nodes regarding the selection strategy. In addition to energy saving, the proposed strategies can diminish packet loss ratio and also can decrease end-to-end delay. Unlike DBR, EEARP mitigates the void area problem in sparse topologies during the routing process. We have implemented EEARP with the four parent selecting strategies in Aqua-Sim and evaluated their performance in sparse and dense topologies. Simulation results confirm that EEARP achieves significantly better performance compared to DBR in terms of total energy and per packet energy consumption. Simulation results also show that EEARP can prolong the network lifetime, decrease end-to-end delay and reduce packet loss ratio in both sparse and dense topologies.

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