Geographic and Opportunistic Routing for Underwater Sensor Networks

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Abstract—Underwater wireless sensor networks (UWSNs) have been showed as a promising technology to monitor and explore the oceans in lieu of traditional undersea wireline instruments. Nevertheless, the data gathering of UWSNs is still severely limited because of the acoustic channel communication characteristics. One way to improve the data collection in UWSNs is through the design of routing protocols considering the unique characteristics of the underwater acoustic communication and the highly dynamic network topology. In this paper, we propose the GEDAR routing protocol for UWSNs. GEDAR is an anycast, geographic and opportunistic routing protocol that routes data packets from sensor nodes to multiple sonobuoys (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. Simulation results show that 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.

Index Terms—Geographic and opportunistic routing, communication void region problem, topology control, underwater sensor networks

1 Introduction

Oceans represent more than 2/3 of the Earth's surface. These environments are extremely important for human life because their roles on the primary global production, carbon dioxide (CO_2) absorption and Earth's climate regulation, for instance. In this context, underwater wireless sensor networks (UWSNs) [1] have gained the attention of the scientific and industrial communities due their potential to monitor and explore aquatic environments. UWSNs have a wide range of possible applications such as to monitoring of marine life, pollutant content, geological processes on the ocean floor, oilfields, climate, and tsunamis and seaquakes; to collect oceanographic data, ocean and offshore sampling, navigation assistance, and mine recognition, in addition to being utilized for tactic surveillance applications [2], [3], [4].

Acoustic communication has been considered as the only feasible method for underwater communication in USWNs. High frequency radio waves are strongly absorbed in water and optical waves suffer from heavy scattering and are restricted to short-range-line-of-sight applications. Nevertheless, the underwater acoustic channel introduces large and variable delay as compared with radio frequency (RF) communication, due to the speed of sound in water that is approximately 1.5×10^3 m/s (five orders of magnitude lower than the speed of light (3×10^8 m/s)); temporary path loss and the high noise resulting in a high bit error rate; severely limited bandwidth due to the strong attenuation in the acoustic channel and multipath fading; shadow zones; and the high communication energy cost, which is of the order of tens of watts [5].

In this context, geographic routing paradigm seems a promising methodology for the design of routing protocols for UWSNs [6], [7], [8], [9]. Geographic routing, also called of position-based routing, is simple and scalable. It does not require the establishment or maintenance of complete routes to the destinations. Moreover, there is no need to transmit routing messages to update routing path states [10]. Instead, route decisions are made locally. At each hop, a locally optimal next-hop node which is the neighbor closest to the destination, is selected to continue forwarding the packet. This process proceeds until the packet reaches its destination. Geographic routing can work together with opportunistic routing (OR) (geo-opportunistic routing) to improve data delivery and reduce the energy consumption relative to packet retransmissions.

Using opportunistic routing paradigm, each packet is broadcast to a forwarding set composed of neighbors. In this set, the nodes are ordered according to some metric, defining their priorities. Thus, a next-hop node in the forwarding set that correctly received the packet, will forward it only whether the highest priority nodes in the set failed in to do so. The next-hop forwarder node will cancel a

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scheduled transmission of a packet if it hears the transmission of that packet by a higher priority node. In OR paradigm, the packet will be retransmitted only if none of the neighbors in the set receives it.

The main disadvantage of geo-opportunistic routing is the communication void region problem. The communication void region problem occurs whenever the current forwarder node does not have a neighbor node closest to the destination than itself, i.e., the current forwarder node is the closest one to the destination [11]. The node located in a communication void region is called *void node*. Whenever a packet gets stuck in a void node, the routing protocol should attempt to route the packet using some recovery method or it should be discarded.

In this paper, we propose the GEographic and opportunistic routing with Depth Adjustment-based topology control for communication Recovery over void regions (GEDAR) routing protocol. GEDAR utilizes the location information of the neighbor nodes and some known sonobuoys to select a next-hop forwarder set of neighbors to continue forwarding the packet towards the destination. To avoid unnecessary transmissions, low priority nodes suppress their transmissions whenever they detect that the same packet was sent by a high priority node. The most important aspect of the GEDAR is its novel void node recovery methodology. Instead of the traditional message-based void node recovery procedure, we propose a void node recovery depth adjustment based topology control algorithm. The idea is to move void nodes to new depths to resume the geographic routing whenever it is possible. To the best of our knowledge, this work is the first that considers depth adjustment node capabilities to organize the network topology of a mobile underwater sensor network to improve routing task. Simulation results showed that GEDAR is able to reduce the amount of void nodes through the depth adjustment-based void node recovery strategy. Consequently, GEDAR improves the packet delivery ratio and decreases the end-to-end delay for the critical scenarios of low and high densities and diverse network traffic load, when compared with the state-of-the art routing protocols [7], [9] and the simple geographic and opportunistic routing (GOR) without any recovery mode.

This work significantly enhances our previous solutions [12], [13] by investigating the routing problem and the maximum local problem in mobile underwater network scenarios. Moreover, in this work we design an opportunistic routing protocol to cope with underwater acoustic communication impairments. In [12], [13], a static underwater sensor network scenario was considered with sensor nodes attached into buoys and anchors. In those solutions, routing decisions and the topology organization were done in a proactive way, before the monitoring phase. The contributions of this work are *i)* an enhanced beaconing algorithm to disseminate the location of the neighbor nodes and known sonobuoys to avoid overloading the acoustic channel; *ii)* an anycast geo-opportunistic routing protocol advancing the packet, at each hop, in a directed way towards to the closest sonobuoy; *iii)* a novel reactive maximum local routing strategy based on the depth adjustment of the nodes, to improve the packet delivery ratio by avoid long hop paths, which can increase packet collisions and, consequently, the packet error rate, end-to-end delay and energy consumption. Moreover, this work extends our preliminary solution [14] in that we include

1) an enhanced review of underwater sensor network routing protocols,
2) a more detailed theoretical framework and proposed algorithms description,
3) more simulation results including different traffic load analysis and topology related and opportunistic routing protocol related performance evaluation metrics.

The rest of this paper is organized as follows. Section 2 provides an overview of the existing geographic routing approaches and their communication void node recovery strategies. In Section 3, we provide a brief overview of GEDAR. In Section 4, we present some preliminary concepts used by the proposed protocol. Section 5 shows our newly proposed GEDAR routing protocol. The performance evaluation of the proposed protocol is described in Section 6. Finally, Section 7 presents our conclusions and future work.

2 Related Work

Xie et al. [6] proposed the VBF routing protocol. In VBF, data packets are routed along a virtual "routing pipe" of pre-determined radius, calculated from the position locations of the sender and destination nodes. When a node receives a packet, it either verifies its distance to the forwarding vector and continue forwarding the packet whether this distance is less than a predefined threshold or discard it. If the network density is high, many nodes are involved in the forwarding process. This guarantees the existence of redundant paths to forward data, improving the packet delivery ratio. However, it also increases the network energy consumption. In order to cope with this drawback, the authors proposed a self-adaptation algorithm. In this algorithm, each node calculates its desirableness factor which measures the suitability of a node to forward packets. This factor is given as a function of the distance between the current node and the forwarder node, the projection of the node to the routing vector, and the angle between the vectors from the forwarder to the destination and from the forwarder to the current node. If the desirableness factor is less than a defined threshold, the node will schedule the data packet transmission according to its priority.

Depth-based routing (DBR) [7] routing protocol is the first underwater sensor network routing protocol that uses node depth information to route data packets. The basic idea of DBR is to forward data packets greedily towards the water surface. Thus, packets can reach multiple data sinks deployed at the water surface. During the forwarding, the current sender broadcasts the packet. After receiving it, if the receiver is closer to the water surface, it becomes qualified as a candidate to forward the packet. Otherwise, it will discard the packet. Each qualified candidate will forward the packet in a prioritized manner if its distance to the current forwarder is at least d_{th} and it has not previously sent this packet previously. Node priority is given by means of the holding time. The farther the candidate node is on the current forwarder, the lower is its holding time. After the holding time, the packet is broadcast if the node has not received the same data from a neighbor.

RPR [15] routing protocol extends DBR by dealing with malicious attackers, such as spoofing attacks. In RPR protocol, the packet header and payload are encrypted. Each node has a pair of keys (public and secret keys), and a certificate for the key pair generated by a trusted party. Also, a network wide secret key (NSK) is used to encrypt information shared among the nodes. During the packet forwarding process, the sender encrypts the packet payload with a gateway public key (GPK). The packet header, at each forwarder, is encrypted with NSK and signed with the node public key. Upon receiving a packet, the node decrypts the head and checks if the packet is signed by a legitimate node. Only packets with a proper signature are accepted.

VBVA routing protocol [16] extends the VBF routing protocol [6] by including a communication void region recovery mode. Data packets are routed using the same strategy as VBF. During the void node recovery phase, VBVA attempts to route the packet along the boundary of the communication void region by either shifting the forwarding vector or by means of a back-pressure method when the communication void region is convex. In the vector shifting mechanism, the void node asks its neighbors to change the current routing vector. After, the node keeps listening to the channel to check if a neighboring node forwarding the packet is using the new routing vector. If a node is a final node (void node), that is, even with the vector shifting the packet cannot be forwarded, the back-pressure mechanism is used. In the back-pressure mechanism, the packet is routed back in the direction moving away from the destinations. This is performed until the packet reaches a node which can do vector shifting to forward the packet towards the destination.

Lee et al. [8] proposed the Hydrocast routing protocol also exploiting the pressure (depth) level information of the nodes to greedily route packets towards sonobuoys (sinks) at the sea surface. Hydrocast also employs the opportunistic routing paradigm in which the next-hop node priority is given according to the trade-off between the progress of the packet towards the surface and the link cost of reaching the neighbor node. To cope with redundant transmissions, the authors proposed a greedy heuristic to determine a cluster of next-hop forwarders without hidden terminal problems. When a node determines that it is in a communication void region, it performs a search for a node whose depth is lower than its depth by means of controlled flooding and explicitly maintains a path to the node.

Void-aware pressure routing (VAPR) [9] uses the depth information of the nodes to forward data packets towards the sea surface. VAPR is a geographic and opportunistic routing protocol where a next-hop forwarder set to continue the packet forwarding is determined from the greedy pressure strategy. In VAPR, each node is aware of the void nodes from the sonobuoy's reachability information disseminated in the network via periodic beaconing. Each node uses that information to build a directional (upwards or downwards) path towards some surface sonobuoy. The next-hop forwarding set is selected according to the neighbor forwarding direction, that is, those directions in which there is a match of the forwarding direction with the current forwarder (upward or downward).

O'Rourke et al. [17] proposed a multi-modal communication approach. In the proposed approach, a sensor node equipped with acoustic communication modem, surface level radio frequency communication modem, and a depth adjustment system, computes the trade-off network energy cost and data latency based on the amount of data needed to be sent and the cost of surfacing; and, the sensor node then decides what technology should be used to send the data. Once a node decides to surface, nodes that will form the radio link path to the destination, are informed via acoustic communication to surface. The authors proposed and evaluated algorithms to determine the set of surface nodes. The disadvantage of this approach is that all nodes should have both acoustic and RF transmission modems. Moreover, for the typical the application scenario of deepest place monitoring, the multi-modal communication approach can result in high end-to-end delay due to the time required to move sensor nodes until the sea surface to transmit the gathered data.

In [12] and [13], the authors proposed a centralized and distributed geographic routing protocol with depth adjustment based topology control as a void node recovery strategy for long-term underwater monitoring static network architecture. The proposed protocols organize the network topology to reduce the void and the number of disconnected nodes before the beginning of the sensing phase.

Key differences. Herein, we point out some key differences of our proposed protocol to the aforementioned related proposals. VBF, DBR and RPR routing protocols do not employ any communication void region routing recovery procedure. In these protocols, the packet is discarded when it reaches a communication void region. In this paper, we propose a novel depth-adjustment based communication void region routing recovery procedure. Thus, nodes located into communication void region are moved for new depths in order to resume the geo-opportunistic forwarding.

Hydrocast and VAPR explicitly discover and maintain a routing path to forward packets from void nodes. This can be expensive in terms of energy since the high energy cost of underwater acoustic communication and the impairments of the acoustic channel. Moreover, as packets will be routed through more hops to circumvent the communication void region, the acoustic channel can be overloaded, increasing the average end-to-end delay and reducing the packet delivery ratio due to more collisions and retransmissions. In our proposed protocol, we present a novel paradigm to cope with communication void regions in mobile scenarios, taking advantage of the depth adjustment mechanism present in the current sensor nodes. Our idea is to move void nodes to new depths in order to resume the geo-opportunistic routing. With this approach we have an energy cost to move void nodes. However, we can avoid overloading the acoustic channel and the unnecessary energy expenditure relative to the greater number of packet retransmissions.

The works [12], [13], [17] proposed a node's depth adjustment to improve data packet delivery in static underwater sensor networks. Differently, our node's depth adjustment algorithm is devoted to the communication void region routing problem in mobile underwater sensor networks, acting in a reactive way to overcome changes in the network topology. Moreover, we implement an opportunistic routing mechanism to mitigate the impairments of the underwater acoustic communication, which was not considered in those solutions.

3 Basic Idea of GEDAR

GEDAR is an anycast, geographic and opportunistic protocol that tries to deliver a packet from a source node to some sonobuoys. During the course, GEDAR uses the greedy forwarding strategy to advance the packet, at each hop, towards the surface sonobuoys. A recovery mode procedure based on the depth adjustment of the void node is used to route data packet when it get stuck at a void node.

The proposed routing protocol employs the greedy forwarding strategy by means of the position information of the current forwarder node, its neighbors, and the known sonobuoys, to determine the qualified neighbors to continue forwarding the packet towards some sonobuoys. Despite greedy forwarding strategy being a well known and used next-hop forwarder selection strategy, GEDAR considers the anycast nature of underwater routing when multiple surface sonobuoys are used as sink nodes.

We consider that, as in [9], each sonobuoy at the sea surface is equipped with a global positioning system (GPS) and uses periodic beaconing to disseminate its location information to the underwater sensor nodes. We assume that each underwater sensor node knows its location. The location of the neighbors is known through periodic beaconing. Despite the exact knowledge of the node's location being a strong assumption mainly for a mobile scenario, some proposals have been devoted to solve this problem [18], [19], [20]. Moreover, the localization problem in underwater networks continues to attract research efforts due to the importance of nodes' localization to tag the collected data, track underwater nodes and targets, and to group nodes coordinated motion [19].

Furthermore, GEDAR is opportunistic routing aiming to mitigate the effects of the acoustic channel. Thus, a subset of the neighbor nodes is determined to continue forwarding the packet towards some surface sonobuoy (next-hop forwarder set). The research challenge of OR next-hop forwarder set selection is how to determine a list of neighbors such that the hidden terminal problem is reduced. The next-hop forwarder set selection mechanism of GEDAR considers the position of the neighbors and known sonobuoys to select the most qualified candidate neighbors.

When a node is in a communication void region, GEDAR moves it to a new depth to resume the greedy forwarding strategy. To the best of our knowledge, GEDAR is the first routing protocol proposed for mobile underwater sensor networks to consider the depth adjustment capability of the sensor nodes to deal with communication void region problem. The motivations for the use of this new paradigm are threefold. First, the node depth adjustment technology is already available [17], [21]. Second, the communication task in the underwater sensor network is highly expensive. Third, the cost needed to move the nodes to new depths is diluted along the network operation when compared with the case where the node must route data packets along more hops.

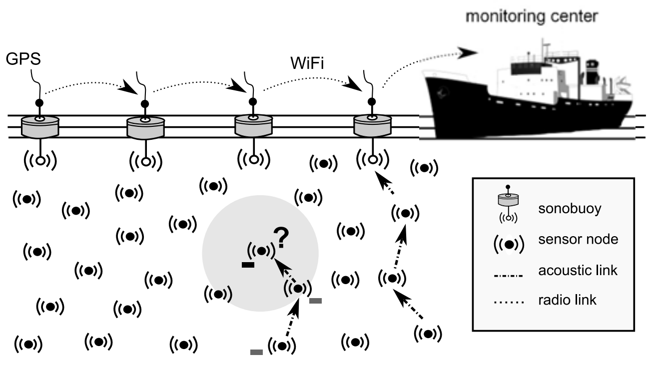


Fig. 1. SEA Swarm architecture and the communication void region problem.

4 Preliminaries

4.1 System Model

In this paper, we consider an underwater wireless sensor network sensor equipped aquatic (SEA) swarm architecture, as shown in Fig. 1. In this architecture, we have a large number of mobile underwater sensor nodes at the ocean bottom and sonobuoys, also named sinks nodes, at the ocean surface. They move as a group with the water current [22]. Our model consists of a set $N = N_n \cup N_s$ of nodes with a communication range of r_c, so that N_n represents the set of sensor nodes, and N_s is the set of sonobuoys.

The sensor nodes $N_n = \{n_1, n_2, \ldots, n_{|N_n|}\}$ are randomly deployed in a geographic area of interest $D \in \mathcal{R}^3$ to provide 4 D (space and time) monitoring. Each node is equipped with various sensor devices and with a low bandwidth acoustic modem which is used to periodically report the sensed data to the destinations (sonobuoys). Underwater sensor nodes can adjust its depth by means of inflatable buoys or winch based apparatus. In a buoyancy-based depth adjustment system, a buoy can be inflated by a pump, bladders or other device to change the buoyancy of the float relative to the water. This system does not use propulsion mechanisms, reducing the energy cost to the depth adjustment. In winch-based apparatus, sensor nodes are attached to surface buoys or anchors by means of cables. A cable is then adjusted to move and maintain a node in a determined depth. Some proposals, which consider depth adjustment capability of the nodes for coverage improvements [23] and localization systems [24], for instance, did not consider the cost relative to this task. In this work, as we consider that sensor nodes can freely drift with ocean current, Drogue [21] is a preferable candidate to be used as a sensor node. However, we have considered the vertical movement speed and energy cost values of the depth adjustment mechanism proposed in [17] as that work provides information about the vertical movement speed and cost. However, it is worth highlighting that winch-based approaches are energy hungry as compared with buoyancy-based approaches. Thus, each sensor node can move vertically with velocity $v = 2.4\,\mathrm{m/min}$ at an energy cost of $E_m = 1500\ \mathrm{mJ/m}$.

The sonobuoys $N_s = \{s_1, s_2, \ldots, s_{|N_s|}\}$ are special nodes randomly deployed at the sea surface. Each sonobuoy is equipped with GPS in order to determine its location. Moreover, they are equipped with both acoustic and radio transceiver modems; each sonobuoy uses acoustic links to send commands and to receive data from underwater sensor nodes, and the radio links are used to forward the data packets to a monitoring center for future processing. Like [7] and [9], we consider that if a packet arrives at any sonobuoy, it can be delivered to the monitoring center. This assumption is reasonable because acoustic communication is more hard than radio frequency communication since sound propagates (speed of $1.5 \times 10^3\,\mathrm{m/s}$ in water) five orders of magnitudes slower than radio (with a propagation speed of $3 \times 10^8\,\mathrm{m/s}$ in air).

We represent the network topology as an undirected graph $G(t) = (V, E(t))$ at time t, where $V = N$ is the set of vertices corresponding to the sensor nodes and sonobuoys; and, $E(t) = \{e_{ij}(t)\}$ is the finite set of links between them. Two nodes u and $v \in V$ are *neighbors* at time t and are *directly connected* via a *link*, if they can directly, mutually, and consistently communicate over an acoustic channel at time t. We define $N_u(t)$ as the set of underwater sensor nodes that are node u's neighbors with $u \notin N_u(t)$ and $S_u(t) = \{n_{s_1}, n_{s_2}, \ldots, n_{s_k}\}$ where n_{s_i} is defined as the quintuple *(sequence number, ID, X, Y,* Λ*)* of the *ID* sonobuoy, located in the (X, Y)-coordinate, known by its *(sequence number)th* beacon. The flag $\Lambda = 0$ indicates that the node has not disseminated this information for its neighbors.

4.2 Underwater Packet Delivery Probability Estimation

In this section, we estimate the underwater packet delivery probability $p(m, d)$ of m bits for any pair of nodes with distance d, which is used in the next-hop subset forwarding selection procedure of the proposed geo-opportunistic routing protocol.

Like [8] and [25], we use the following underwater acoustic channel model [26], [27]. The path loss, that describes the attenuation on a single, unobstructed propagation path, over a distance d for a signal of frequency f due to large scale fading, is given as:

$$A(d, f) = d^k a(f)^d, \tag{1}$$

where k is the spreading factor and $a(f)$ is the absorption coefficient. The geometry of propagation is described using the spreading factor k. Its commonly used values are $k = 2$ for spherical spreading, $k = 1$ for cylindrical spreading, and for a practical scenario, k is given as 1.5. The absorption coefficient $a(f)$, in dB/km for f in kHz, is described by the Thorp's formula [26] given by:

$$10 \log a(f) = \frac{0.11 \times f^2}{1 + f^2} + \frac{44 \times f^2}{4100 + f} + 2.75 \times 10^{-4} f^2 + 0.003. \tag{2}$$

The average signal-to-noise ratio (SNR) over distance d is thus given as:

$$\Gamma(d) = \frac{E_b / A(d, f)}{N_0} = \frac{E_b}{N_0 d^k a(f)^d}, \tag{3}$$

where E_b and N_0 are constants that represent the average transmission energy per bit and noise power density in a non-fading additive white Gaussian noise (AWGN) channel. As in [28] and [29], we use Rayleigh fading to model small scale fading where SNR has the following probability distribution:

$$p_d(X) = \int_0^{\infty} \frac{1}{\Gamma(d)} e^{-\frac{X}{\Gamma(d)}}. \tag{4}$$

The probability of error can be evaluated as:

$$p_e(d) = \int_0^{\infty} p_e(X) p_d(X) dX. \tag{5}$$

Here, $p_e(X)$ is the probability of error for an arbitrary modulation at a specific value of SNR X. In this paper, we use the binary phase shift keying (BPSK) modulation that is widely used in the state-of-the-art acoustic modems [5], [8], [9], [30], [31].

In BPSK, each symbol carries a bit. In [32], the probability of bit error over distance d is given as:

$$p_e(d) = \frac{1}{2}\left(1 - \sqrt{\frac{\Gamma(d)}{1 + \Gamma(d)}}\right). \tag{6}$$

Thus, for any pair of nodes with distance d, the delivery probability of a packet with size m bits is simply given by:

$$p(d, m) = (1 - p_e(d))^m. \tag{7}$$

5 Design of GEDAR

5.1 Enhanced Beaconing

Periodic beaconing plays an important role in GEDAR. It is through periodic beaconing that each node obtains the location information of its neighbors and reachable sonobuoys. Unlike the solutions [12] and [13], where each node can be informed beforehand concerning the location of all sonobuoys (as long-term underwater monitoring architecture is formed by static nodes attached to buoys and/or anchors), we need an efficient beaconing algorithm that keeps the size of the periodic beacon messages short as possible. For instance, if each node n_i embeds its known sonobuoy locations $|S_i|$ together with its location, the size of its beacon message in the worst case, without considering lower layer headers, is $2(m + n) \times |N_s| + 2m + 3n$ bits, where m and n are the size of the sequence number and ID fields, and each geographic coordinates, respectively. Given that the transmission of large packets in the underwater acoustic channel is impractical [33], we propose an enhanced beacon algorithm that takes this problem into consideration.

Algorithm 1 is an enhanced periodic beaconing used by GEDAR to broadcast periodic beacons and to handle received beacons. In the beacon messages, each sonobuoy embeds a *sequence number*, its *unique ID*, and its *X, Y* location. We assume that each sonobuoy at the surface is equipped with GPS and can determine its location. The sequence number of the beacon message does not need to be synchronized among all sonobuoys. It is used together with the ID to identify the most recent beacon of each sonobuoy (line 24). The depth information of sonobuoys is omitted from the beacon message since the sonobuoys are deployed on the surface and vertical movement is negligible with respect to the horizontal movement [34].

Algorithm 1. Periodic Beaconing

```
1: procedure BroadcastPeriodicBeacon(node)
2: m: a new beacon message with the next seq_num
3: if beacon timeout expired then
4:     m.coordinate ← location(node)
5:     if node ∈ N_n then
6:         for s ∈ S_i(node) do
7:             if Λ(s) = 0 then
8:                 m.addSon.(seq_num(s), ID(s), X(s), Y(s))
9:                 Λ(s) ← 1
10:            end if
11:        end for
12:    end if
13:    Broadcast m
14:    Set a new timeout
15: end if
16: end procedure
17:
18: procedure ReceiveBeacon(node, m)
19: if m is from a sonobuoy then
20:    update(S_i(node), m)
21: else
22: update_neighbor(m.seq_num, m.id, m.location)
23:    for s ∈ m do
24:    if seq_num(s, m) > seq_num(s, S_i(node)) then
25:            update(S_i(node), s)
26:        end if
27:    end for
28: end if
29: end procedure
```

Similarly, each sensor node embeds a *sequence number*, its unique *ID* and X, Y, and Z position information. Moreover, the beacon message of each sensor node is augmented with the information of its known sonobuoys from its set $S_i(t)$. Each node includes the *sequence number*, *ID*, and the X, Y location of the its known sonobuoys. The goal is for the neighboring nodes to have the location information of the all reachable sonobuoys. GPS cannot be used by underwater sensor nodes to determine their locations given that the high frequency signal is rapidly absorbed and cannot reach nodes even localized at several meters below the surface. Thus, each sensor node knows its location through localization services, such as [20]. Localization services incur additional costs in the network. However, the knowledge regarding the location of sensor nodes can eliminate the large number of broadcast or multicast queries that leads to unnecessary network flooding that reduces the network throughput [35]. In addition, the location information is required to tag the collected data, track underwater nodes and targets, and to coordinate the motion of a group of nodes [19].

In order to avoid long sizes of beacon messages, a sensor node includes only the position information of the sonobuoys it has not disseminated in the predecessor round (lines 5-12). Whenever a node receives a new beacon message, if it has come from a sonobuoy, the node updates the corresponding entry in the known sonobuoy set $S_i(t)$ (line 20). Otherwise, it updates its known sonobuoys S_i set in the corresponding entries if the information location contained in the beacon message is more recent than the location information in its set S_i. For each updated entry, the node changes the appropriate flag Λ to zero, indicating that this information was not propagated to its neighbors (line 25). Thus, in the next beacon message, only the entries in $S_i(t)$ in which the Λ is equal to zero are embedded (lines 7-10). We add random jitters between 0 and 1 during the broadcast of beacon messages, to minimize the chance of both collisions and synchronization. Moreover, after a node broadcasts a beacon, it sets up a new timeout for the next beaconing.

5.2 Neighbors Candidate Set Selection

Whenever a sensor node has a packet to send, it should determine which neighbors are qualified to be the next-hop forwarder. GEDAR uses the greedy forwarding strategy to determine the set of neighbors able to continue the forwarding towards respective sonobuoys. The basic idea of the greedy forwarding strategy is, in each hop, to advance the packet towards some surface sonobuoy.

The neighbor candidate set is determined as follows. Let n_i be a node that has a packet to deliver, let its set of neighbors be $N_i(t)$ and the set of known sonobuoys $S_i(t)$ at time t. We use the packet advancement (ADV) [36] metric to determine the neighbors able to forward the packet towards some destination. The packet advancement is defined as the distance between the source node S and the destination node D minus the distance between the neighbor X and D. Thus, the neighbors candidate set in GEDAR is given as:

$$\mathcal{C}_i = \{n_k \in N_i(t) : \exists s_v \in S_i(t) \mid D(n_i, s_i^*) - D(n_k, s_v) > 0\}, \tag{8}$$

where $D(a, b)$ is the euclidean distance between the nodes a and b and, $s_i^* \in S_i(t)$ is closest sonobuoy of n_i as:

$$s_i^* = argmin_{\forall s_j \in S_i(t)}\{D(n_i, s_j)\}. \tag{9}$$

5.3 Next-Hop Forwarder Set Selection

GEDAR uses opportunistic routing to deal with underwater acoustic channel characteristics. In traditional multihop routing paradigm, only one neighbor is selected to act as a next-hop forwarder. If the link to this neighbor is not performing well, a packet may be lost even though other neighbor may have overheard it. In opportunistic routing, taking advantage of the shared transmission medium, each packet is broadcast to a forwarding set composed of several neighbors. The packet will be retransmitted only if none of the neighbors in the set receive it. Opportunistic routing has advantages and disadvantages that impact on the network performance. OR reduces the number of possible retransmissions, the energy cost involved in those retransmissions, and help to decrease the amount of possible collisions. However, as the neighboring nodes should wait for the time needed to the packet reaches the furthest node in the forwarding set, OR leads to a high end-to-end latency [25].

For each transmission, a next-hop forwarder set $\mathcal{F}$ is determined. The next-hop forwarder set is composed of the most suitable nodes from the next-hop candidate set $\mathcal{C}_i$ so that all selected nodes must hear the transmission of each other aiming to avoid the hidden terminal problem. The problem of finding a subset of nodes, in which each one can hear the transmission of all nodes, is a variant of the maximum clique problem, that is computationally hard [8].

The next-hop forwarder set selection algorithm of GEDAR is based on the proposed in [8] and [9]. We use normalized advance (NADV) [37] to measure the *"goodness"* of each next-hop candidate node in $\mathcal{C}_i$. NADV corresponds the optimal trade-off between the proximity and link cost to determine the priorities of the candidate nodes. This is necessary because the greater the packet advancement is, the greater the neighbor priority becomes. However, due to the underwater channel fading, the further the distance is from the neighbor, the higher the signal attenuation becomes as well as the likelihood of packet loss. For each next-hop candidate node $n_c \in \mathcal{C}_i$, normalized packet advancement is:

$$NADV(n_c) = ADV(n_c) \times p(d_c^i, m), \tag{10}$$

where $ADV(n_c) = D(n_i, s_i^*) - D(n_c, s_c^*)$ is the n_c packet advancement towards its closest sonobuoy s_c^*; d_c^i is the euclidean distance between the source node n_i and the forwarder candidate n_c and, $p(d_c^i, m)$ is the packet delivery probability of m bits over distance d_c^i given according with Equation (7).

Let $\mathcal{F}_j \subseteq \mathcal{C}_i$ be a set formed by candidate forwarder nodes, ordered according to their priorities (NADV) as $n_1 > n_2 > \cdots > n_k$, that must hear each other. The expected packet advance (EPA) of the set $\mathcal{F}_j$, which is the normalized sum of advancements made by this set [8], [38], is defined by Equation (11). The objective of the greedy opportunistic forwarding strategy is to determine the subset $\mathcal{F} \subseteq \mathcal{C}_i$ such that the (EPA) is maximized.

$$EPA(\mathcal{F}_j) = \sum_{l=1}^{k} NADV(n_l) \prod_{j=0}^{l-1} (1 - p(d_i^j, m)). \tag{11}$$

Algorithm 2 presents a heuristic for the next-hop forwarder set selection. First, lines 2 to 4 determine the NADV of each qualified neighbor according to Equation (10). Second, the neighbor candidate set $\mathcal{C}_i$ is ordered according to the priority of the nodes as a result of the NADV (line 5). Third, lines 8 to 18 determine the clusters from the neighbor candidate set $\mathcal{C}_i$. Each cluster $\mathcal{F}_j$ starts with the greatest priority node from $\mathcal{C}_i$ and is expanded by including all nodes in $\mathcal{C}_i$ which have a distance less than $\frac{1}{2}r_c$. Fourth each cluster $\mathcal{F}_j$ is expanded to include those nodes in $\mathcal{G}_i$ (a copy from $\mathcal{C}_i$) that have a distance of less than the communication radius r_c for all nodes already in the cluster (lines 19-25). The idea is to expand each cluster while maintaining the restriction that each node should hear the transmissions of each other node in the cluster. Finally, the cluster $\mathcal{F}$ with the highest EPA is selected as the next-hop forwarder set.

Algorithm 2. Next-Hop Forwarder Set Selection

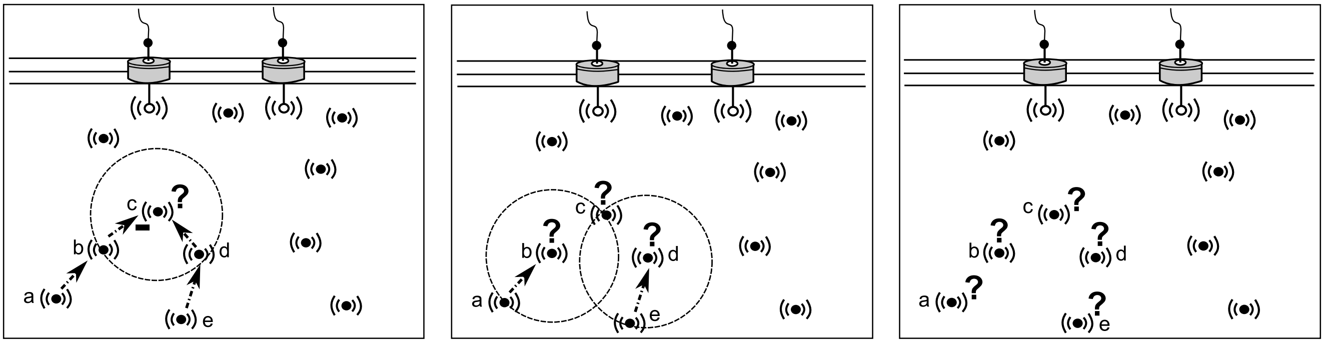
1: **procedure** GetNextHopForwarders(source node n_i)
2: **for** $n_c \in \mathcal{C}_i$ **do**
3: $\quad NADV(n_c) \leftarrow d_c \times p(d_i^c, m)$
4: **end for**
5: Order $\mathcal{C}_i$ according with the NADV of the nodes
6: j ← 1
7: $\mathcal{G}_i \leftarrow \mathcal{C}_i$ {$\mathcal{G}_i$ is a copy of $\mathcal{C}_i$}
8: **while** $|\mathcal{C}_i| > 0$ **do**
9: $\quad \mathcal{F}_j \leftarrow \{n_1 \in \mathcal{C}_i\}$ {n_1 is the highest priority node of $\mathcal{C}_i$}
10: $\quad \mathcal{C}_i \leftarrow \mathcal{C}_i - \{n_1\}$
11: $\quad$ **for** $n_u \in \mathcal{C}_i$ **do**
12: $\quad\quad$ **if** $D(n_1, n_u) < \frac{1}{2}r_c$ **then**
13: $\quad\quad\quad \mathcal{F}_j \leftarrow \mathcal{F}_j \cup \{n_u\}$
14: $\quad\quad\quad \mathcal{C}_i \leftarrow \mathcal{C}_i - \{n_u\}$
15: $\quad\quad$ **end if**
16: $\quad$ **end for**
17: $\quad$ j ← j +1
18: **end while**
19: **for** $\mathcal{F}_j$ **do**
20: $\quad$ **for** $n_k \in \mathcal{G}_i$ **do**
21: $\quad\quad$ **if** $D(n_k, n_t) < r_c \ \forall n_t \in \mathcal{F}^j$ **then**
22: $\quad\quad\quad \mathcal{F}_j \leftarrow \mathcal{F}_j \cup \{n_k\}$
23: $\quad\quad$ **end if**
24: $\quad$ **end for**
25: **end for**
26: Calculate the EPA for each cluster $\mathcal{F}_j$ according to Equation (11)
27: **return** the cluster $\mathcal{F}$ with the highest EPA
28: **end procedure**

After computing the forwarding set, the current forwarder node includes the address of the next-hop forwarder nodes in the packet and then broadcast it. Each node that has correctly received the packet, verifies if it is a next-hop forwarder and then sets the timer to broadcast it according to its priority. The greater the priority of the node is, the shorter is its waiting time. The packet will be discarded by the nodes that are not listed as the next-hop forwarder.

In opportunistic routing, the highest priority node becomes a next-hop forwarder and the rest of the lower priority nodes transmit the packet only if the highest priority node fails to do so. The lower priority nodes suppress their transmissions after listening the data packet transmission of the next-hop forwarder. In GEDAR, when the ith priority node receives the packet, it will wait for the remaining time to complete propagation of the packet plus the time corresponding to the delay propagation between the 1th to the 2th priority nodes, the delay between the 2th to the 3th priority nodes, and so on until the delay between the $(i-1)$th to the ith priority node. After this time, if the ith node does not hear the transmission of the packet, it will broadcast it. Thus, the ith waiting is:

$$T_w^i = T_p + \sum_{k=1}^{i} \frac{D(n_k, n_{k+1})}{s} + i \times T_{proc}, \tag{12}$$

where T_p is the remaining propagation time and T_{proc} is the packet processing time. The remaining propagation time



(a) Example of recovery mode procedure at c

(b) Nodes b and d start the recovery mode procedure after receiving a c's void_node_announcement_message

(c) Scenario after the recovery mode procedure at nodes a, b, c, d, e. All generated data packet from these nodes will be discard.

Fig. 2. Example of a communication void region scenario.

represents the delay needed for the complete propagation of the packet broadcast by the sender node. This time is defined as

$$T_p = \frac{(r_c - D(n_a, n_b))}{s}, \tag{13}$$

where n_a is the receiver node, n_b is the sender node, and s is the speed of sound underwater. The second term in Equation (12) corresponds to the time required for the node to hear the transmission of its predecessor priority node.

5.4 Recovery Mode

Void node recovery procedure is used when the node fails to forward data packets using the greedy forwarding strategy. Instead of message-based void node recovery procedures, GEDAR takes advantage of the already available node depth adjustment technology to move void nodes for new depths trying to resume the greedy forwarding. We advocate that depth-adjustment based topology control for void node recovery is more effective in terms of data delivery and energy consumption than message-based void node recovery procedures in UWSNs given the harsh environment and the expensive energy consumption of data communication.

The GEDAR depth-adjustment based topology control for a void node recovery procedure can be briefly described as follows. During the transmissions, each node locally determines if it is in a communication void region by examining its neighborhood. If the node is in a communication void region, that is, if it does not have any neighbor leading to a positive progress towards some surface sonobuoy ($\mathcal{C} = \emptyset$), it announces its condition to the neighborhood and waits the location information of two hop nodes in order to decide which new depth it should move into and the greedy forwarding strategy can then be resumed. After, the void node determines a new depth based on two-hop connectivity such that it can resume the greedy forwarding.

Algorithm 3 is used for void node recovery. In the recovery mode procedure, the void node changes its status, stops the beaconing, sends a void node announcement message to announce its void node condition to the neighborhood, and schedules the procedure to calculate its new depth (lines 1-7). When a neighbor node receives a void_node_announcement_message, it removes the sender from its neighbor table and, from the updated neighbor table, determines whether it is a void node or not. If the receiver node will be not a void node, it replies the received message with a void_node_announcement_reply message containing its location information and the location of its neighbors. Otherwise, it will start the void node recovery procedure. This strategy is used to avoid cascading effects during the depth adjustment of void nodes. For instance, consider the worst scenario of a "mountain-like" communication void region, as depicted in Fig. 2. The picture shows underwater sensor nodes, such as the a, b, c, d, and e nodes, that should deliver collected data to sonobuoys at sea surface through multihop underwater acoustic communication. In this example, the node c has data packet to be sent. It discovers that it is in a communication void region and then it starts the void node recovery algorithm (Algorithm 3). At this moment, nodes b and d using node c as the next-hop forwarder. During the void node recovery, node c sends a void_node_announcement_message to its neighbor nodes (see Fig. 2a). After receiving that control packet, nodes b and d remove c from its neighbor table and determine whether they can continue forwarding the packet, using the greedy geographic and opportunistic strategy, through other neighbor nodes. In this scenario, as they cannot, b and d start the recovery mode procedure (see Fig. 2b). The same procedure is performed by nodes a and e. At the end, none of them can continue the recovery void node procedure as they have not received any replay of a void_node_announcement_message. Thus, all generated packets from these nodes will be discarded as they do not have a next-hop forwarder candidate, as shown Fig. 2c.

After the waiting time t (line 6), the void node runs the procedure *CalculateNewDepth* (lines 12-33). The set Ω contains the location information of the two-hop connectivity obtained from the void_node_announcement_replay message received from the non-void node neighbors. The new depth of the void node is calculated from two-hop connectivity neighbor set Ω. Let vn be the void node and $u \in \Omega$ a possible next-hop forwarder node. If node u is a one-hop neighbor, the void node vn must determine a new depth such that its distance to the closest sonobuoy is larger than the distance from node u to its closest sonobuoy (lines 15-18). This is done by solving the inequality in line 17. The new possible depth z^*_{vn} is then added to the set of candidate depths $\mathcal{D}$ (line 18). If node u is a two-hop neighbor of nv, nv

determines whether there is a new depth z^*_{vn} such that vn can communicate directly with u and can forward its packet through u using the greedy forwarding strategy (lines 19-25). In line 20, the void node vn determines its euclidean distance to u considering only the X, Y coordinate location. This is because, in the worst scenario, vn will be at the same depth of u. If this distance is less than the communication range r_c, the void node vn determines a new candidate depth z^*_{vn} relative to the node u such that vn can use u as a next-hop forwarder (lines 21-24). This new candidate depth is then added to the set $\mathcal{D}$ (line 23). At the end, the void node vn chooses a new depth from the set $\mathcal{D}$ such that its displacement is minimum (line 27), starts its vertical movement (line 28) and changes its condition of void node (line 29). If vn can not determine a new depth, it restarts the recovery mode procedure (line 31).

Algorithm 3. Void Node Recovery Algorithm

1: **procedure** RecoveryMode()
2: is_void_node $\leftarrow$ true
3: Stop beaconing
4: $\Omega \leftarrow \emptyset$ $\triangleright$ Set of neighbors to topology control
5: Send void_node_announcement_message
6: CalculateNewDepth(t)
7: **end procedure**
8:
9: {n_{vn} is the void node.}
10: {Ω set of neighbors to act as next-hop forwarder.}
11: {$\mathcal{D}$ set of depth candidates to the void node n_{vn}.}
12: **procedure** CalculateNewDepth(time)
13: **if** $|\Omega| > 0$ **then**
14:     **for** $n_u \in \Omega$ **do**
15:         **if** $D(n_{vn}, n_u) \leq r_c$ **then**
16:             $d_u \leftarrow D(n_u, s^*_u)$
17:             $(x_{vn} - x_{s^*_{vn}})^2 + (y_{vn} - y_{s^*_{vn}})^2 + (z^*_{vn} - z_{s^*_{vn}})^2 \geq d^2_u$
18:             $\mathcal{D} \leftarrow \mathcal{D} \cup \{z^*_{vn}\}$
19:         **else**
20:             $d \leftarrow \sqrt{(x_{vn} - x_u)^2 + (y_{vn} - y_u)^2}$
21:             **if** $d \leq r_c$ **then**
22:                 $(x_{vn} - x_u)^2 + (y_{vn} - y_u)^2 + (z^*_{vn} - z_u)^2 \leq r^2_c$
23:                 $\mathcal{D} \leftarrow \mathcal{D} \cup \{z^*_{vn}\}$
24:             **end if**
25:         **end if**
26:     **end for**
27:     $z = \arg\min_{\forall z_i \in \mathcal{D}}\{|z_{vn} - z_i|\}$
28:     n_{vn} moves to new depth z
29:     is_void_node $\leftarrow$ false
30: **else**
31:     RecoveryMode();
32: **end if**
33: **end procedure**

6 Performance Evaluation

In this section, we evaluate the performance of our proposed protocol against the simple geographic and opportunistic routing protocol without recovery mode and the two other most popular previously proposed routing protocols for UWSN: DBR [7] and VAPR [9]. All evaluated routing protocols have been implemented using Aqua-Sim [39]. Aqua-Sim is a high fidelity and flexible packet level underwater sensor network simulator developed on NS-2 to simulate the impairment of the underwater acoustic channel.

In our simulations, the number of sensor nodes range from 150 to 450 and the number of sonobuoys is 45. They are randomly deployed in a region the size of 1,500 $\times$ 1,500 $\times$ 1,500 m. In each sensor, data packets are generated according to a Poisson process with the same parameter $\lambda = \{0.01, 0.05\}\,\mathrm{pkts/min}$ to very low traffic load; $\lambda = \{0.1, 0.15\}\,\mathrm{pkts/min}$ to low traffic load; and, $\lambda = \{0.2, 0.25\}\,\mathrm{pkts/min}$ to medium traffic load. We adopt an extended 3 D version of the meandering current mobility (MCM) [34], to simulate a mobile network scenario, considers the effect of meandering sub-surface currents (or jet streams) and vortices. We set the main jet speed to $0.3\,\mathrm{m/s}$. Due to the mobility, nodes would move beyond the deployment region.

In all experiments, the nodes have a transmission range (r_c) of 250 m and a data rate of 50 kbps. They use the CSMA protocol at the MAC layer. The size of the packet is determined by the size of the data payload and by the space required to include the information of the next-hop forwarder set. We consider that data packets have a payload of 150 bytes. As in [8] and [9], we use a Bloom filter to reduce the space required by the forwarding set in the data packet. Thus, a filter size of 19 bytes can be used to represent 15 items with a false positive rate smaller than 1 percent [8], [9]. The energy consumption at each sensor node is a combination of the communication and depth adjustment energy consumption. The values of the energy consumption were $P_t = 2\,W$, $P_r = 0.1\,W$, $P_i = 10\,\mathrm{mW}$ and $E_m = 1500\,\mathrm{mJ/m}$ for the respective sensor operations of transmission, reception, idle and depth adjustment per meter. In our simulation, each run lasted 1 hour. The above mentioned parameters are similar to those ones explored in [7], [8], [9], [17], [40]. The results correspond with an average value of 50 runs with a 95 percent confidence interval.

6.1 Topology-Related Results

In this section, we analyze the results relative to the network topology when the network density is varied. Our objective is to investigate how the greedy forwarding strategy behaves as the network density ranges from low to high densities. The results concern the greedy upward (GUF) strategy, greedy opportunistic (GOR) strategy, and GOR strategy with depth-adjustment based topology control (GEDAR). In the GUF strategy, used by DBR and VAPR, the neighbor closest to the surface is selected as the next-hop forwarder. In the GOR strategy, the neighbor closest to some sonobuoys in terms of the euclidean distance is selected as the next-hop forwarder. GEDAR works as GOR but moves void nodes to new depths to resume the greedy forwarding.

Fig. 3a shows the fraction of void nodes after 1 hour of simulation. As shown in the plot, the fraction of void nodes decreases when the network density increases for all greedy strategies. On the other hand, GEDAR and GOR achieve the best results as compared with the GUF. This happens because nodes deployed closest to the surface that are not in the communication range of any sonobuoy fail to maintain the greedy routing process when the GUF strategy is used. When GEDAR is used, the proposed depth-adjustment

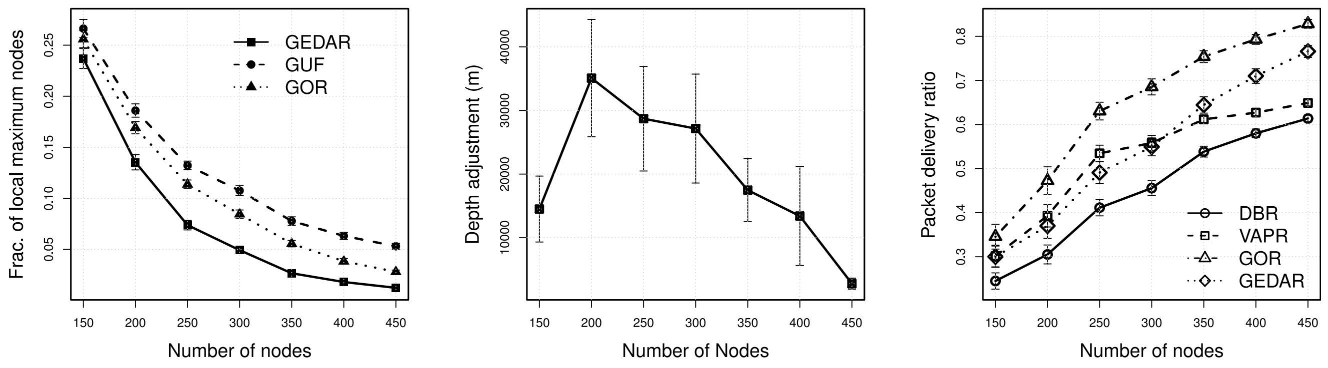


Fig. 3. Simulation results.

based topology control mechanism reduces 58 percent the fraction of void nodes for medium density scenarios in comparison to GUF and approximately 44 percent as compared to GOR.

Fig. 3b depicts simulation results for the average displacement of void nodes in GEDAR. When the network density is low, the displacement of void nodes is high. For instance, when the network has 200 sensor nodes where approximately 15 percent is in a communication void region (Fig. 3a), each void node moves 133 meters on average. As the network density increases, the total displacement decreases. This happens because the fraction of nodes located in communication void regions decreases, as corroborated by the results of GOR in Fig. 3a.

6.2 Network Density-Related Results

In this section, we evaluate the DBR, VAPR, GOR and GEDAR for different network densities. To do this, the number of nodes was varied and the traffic load was maintained in $\lambda = 0.15$ pkts/min. We focused on the network performance mainly for the hard scenarios of low and high densities. In these scenarios, we have a high incidence of void nodes and high congestion occasioned by the concurrent transmissions of a large number of sensor nodes.

Fig. 3c shows the results concerning the packet delivery ratio. This result is quite consistent with the topological results presented in Fig. 3a. The overall trend is an increment in the packet delivery ratio when the network density increases. GEDAR has the best packet delivery ratio performance because of its void node recovery procedure. VAPR outperforms DBR and GOR mainly in low density scenarios. The reason is that packets generated and forwarded by void nodes are routed through directional trails to circumvent communication void regions instead of being discarded as in DBR and GOR.

Fig. 4a shows the results concerning the average number of redundant copies by received packet. As shown in Fig. 4a, the number of redundant copies increases in DBR and VAPR when the network density increases. In DBR, this happens due to both multipath packet delivery and failures in the suppression of data transmission. For some low priority nodes, the transmission is not suppressed given that the DBR next-hop set selection heuristic does not guarantee that the selected nodes will hear the transmission of each other. The increment in redundant packets in VAPR occurs because low priority nodes cannot hear the transmission of high priority ones as we have more interferences. The redundant data packet copies in GEDAR and GOR result from the broadcast nature of the transmission of some nodes closest to the surface that are within the communication range of more than one sonobuoy.

Fig. 4b shows the results concerning the average number of packet transmissions needed to deliver a data packet, including the recovery process. This plot suggests that the average number of packet transmissions needed to deliver a packet is closely related to the redundant packets shown in Fig. 4a. As the overall trend, when the network density increases, more transmissions are necessary for delivery. This increment is significant in DBR and VAPR. In GEDAR and GOR this cost is amortized given the better performance of packet delivery ratio, as corroborated by Fig. 3c.

Fig. 4c shows the results concerning the average end-to-end delay. As expected, the average delay experienced by a packet in GEDAR, VAPR and GOR is higher than in DBR. The cause of this is that these protocols use opportunistic routing paradigm to improve the data delivery. Besides the time needed to move void nodes to new depths in GEDAR, its end-to-end delay is lower than VAPR. This is due to the fact that during the depth adjustment, the generated data packets are discarded. DBR presented the lowest delay which corresponds to the time needed to receive, process and send the data packets until they reach any sonobuoy. VAPR has the worst performance mainly due to the increment in the number of transmissions.

Fig. 4d shows the results concerning the energy consumption per received packet per node. Notice that GEDAR has a high energy consumption for low density scenarios. This cost is relative to the depth adjustment of the void nodes. As we can see in Fig. 3b, the average displacement per node is high in low density scenarios. However, as the network density increases, the energy consumption decreases; it becomes approximately the same as that in DBR and VAPR. This happens because the average displacement per node decreases, as shown in Fig. 3b; and, the high packet delivery ratio (Fig. 3c) amortizes the energy cost relative to node movement.

6.3 Traffic Load-Related Results

In this section, the routing protocols are evaluated when the network traffic load is varied. The motivation for this

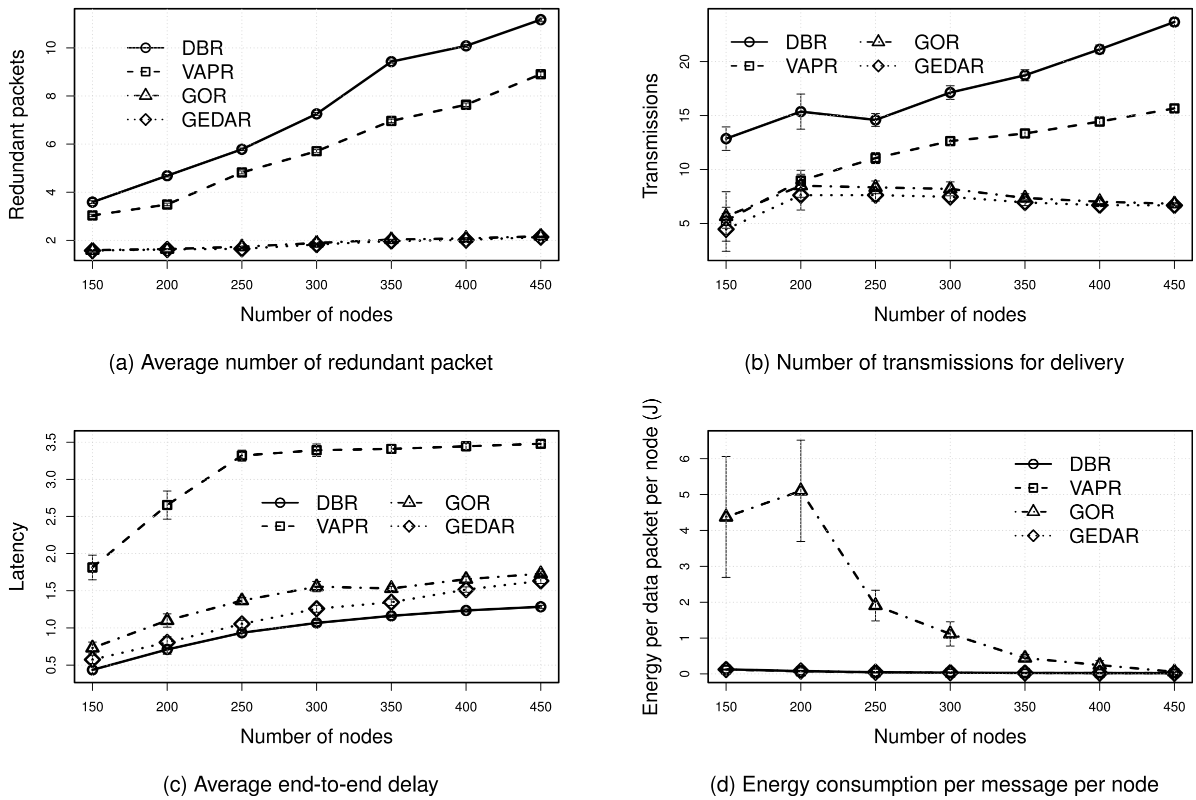


Fig. 4. Simulation results.

analysis is that GOR, VAPR and GEDAR use beacon messages as an important part of the next-hop forwarding selection that can be affected by collisions when the traffic load is high. Furthermore, the multipath packet delivery of DBR can degrade the network performance when we have diverse network traffic loads.

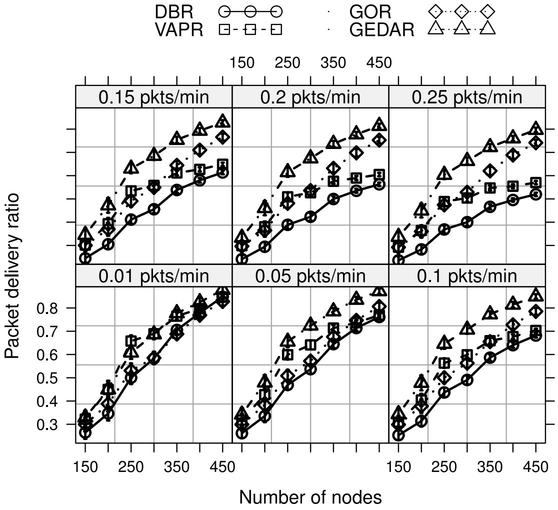
Fig. 5a shows the packet delivery ratio for different traffic load. As shown in the plot, the packet delivery ratio decreases when the network traffic load increases. For high traffic loads, more transmissions will compete for access to the shared acoustic medium and more transmissions will suffer from collisions, reducing the packet delivery ratio. For instance, the packet delivery ratio in DBR is reduced to 38 percent when we compare its performance in high density scenarios when the traffic load goes from the minimum to the maximum. The decrement of packet delivery ratio in GOR, VAPR and GEDAR is less than in DBR because they use opportunistic routing to mitigate the effects of the underwater acoustic channel more expressively experienced during high traffic load.

Fig. 5b shows the average number of redundant copies for delivered packet. Notice that the received redundant copies in DBR decreases significantly when the traffic load increases. For the scenario of 450 nodes, this reduction is of 50 percent when we compare its performance with the traffic load of 0.01 and 0.25 pkts/min. The reason for this behavior is that with the network traffic load increment, more packets are lost along the routing path and less redundant copies are then generated (please refer to Fig. 5a). Quite a trend can be observed for VAPR. The Fig. 5b shows that the redundant copies of delivered packets are low for GOR and GEDAR. This happens thanks to the proposed low priority node transmission suppression algorithm.

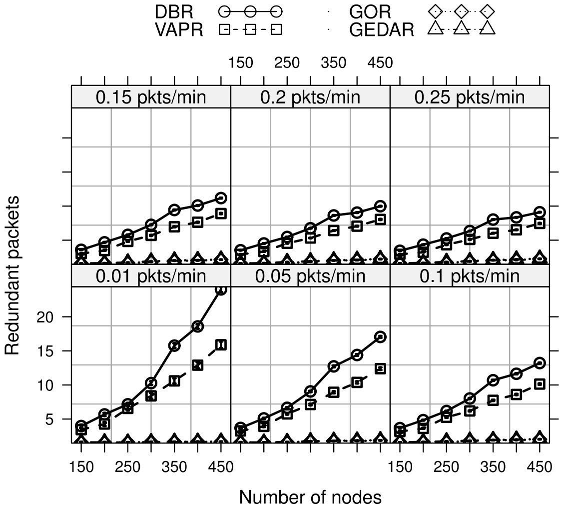
Fig. 5d shows the average end-to-end latency. As a general trend, the latency increases when the network traffic load increases. This is expected given that the increment in the traffic load results in more transmissions competing to access the shared medium. This leads to nodes staying in the back-off collision avoidance mechanism of the CSMA protocol before attempting to sense the carrier again. VAPR, GOR and GEDAR have high delay when compared to DBR mainly in high traffic scenarios because of the opportunistic forwarding.

Fig. 6 shows the average energy consumption per received packet per node. For low density and traffic load, GEDAR has a high energy cost incurred by received packets per node. However, when the traffic load increases, the energy cost per packet significantly decreases. This is because the initial energy consumption needed to move void nodes is diluted along the network lifetime. The energy cost per received packet per node for DBR, GOR and VAPR is almost constant.

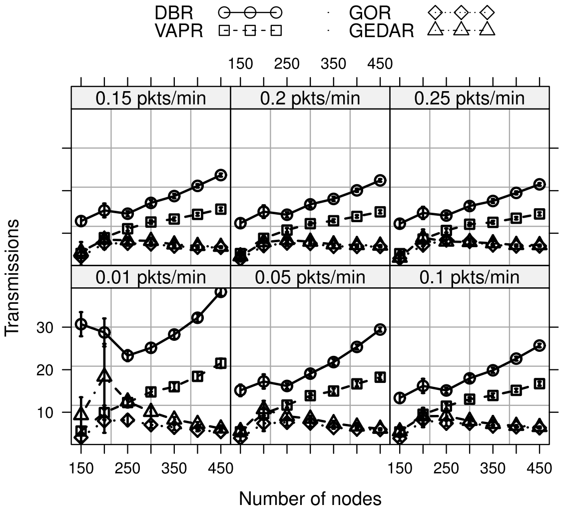
Figs. 7a and 7b show the show the percentage of the network energy consumption relative to the acoustic communication and physical actuation (nodes' depth adjustment), for a low and medium network traffic load, respectively. As depicted in the plot, the nodes depth adjustment is responsible for most of the energy expenditure of the network. For low density network scenario, the depth adjustment task is responsible by more than 80 percent of the network energy consumption. This is because the high energy cost required by the depth adjustment technology to vertically move the node, as the designed in [17]. Moreover, the impact of the



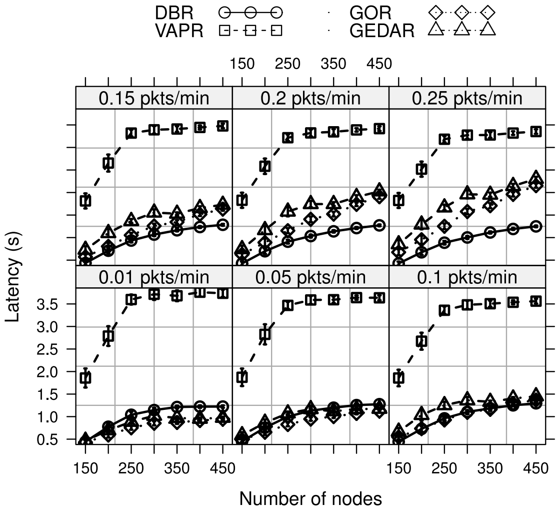
(a) Packet delivery ratio



(b) Average number of redundant packet



(c) Number of transmissions for delivery



(d) Average end-to-end delay

Fig. 5. Simulation results.

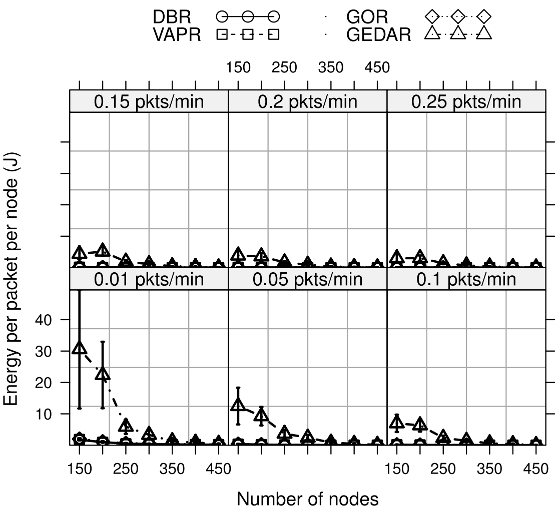
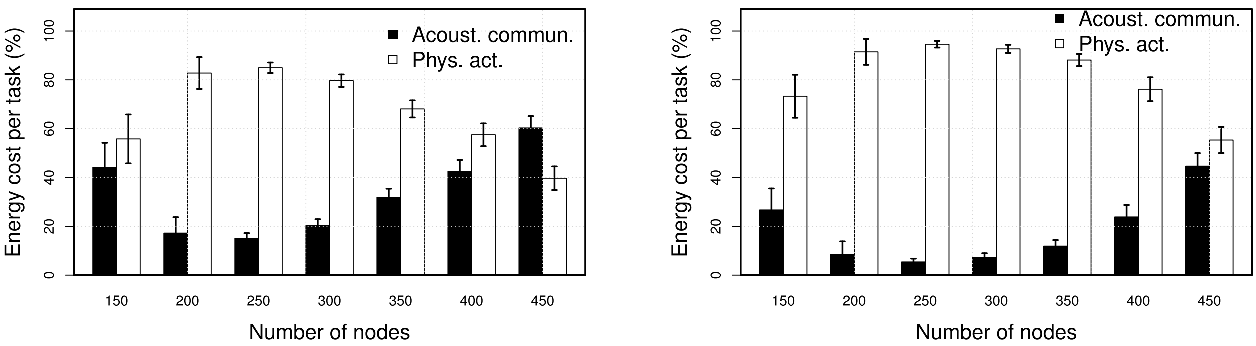


Fig. 6. Energy consumption per message per node.

nodes movement operation on the network energy consumption is high on scenarios of high traffic load (please refer to Fig. 7b). The increment of the network traffic load increases the energy consumption's percentage of the node movement task because the highly dynamic network topology and the reactive nature of the communication void region recovery algorithm proposed in this paper. Thus, as more nodes have packet to be sent, more decisions of depth adjustment will take place.

Discussion. From the simulation results, the proposed GEDAR routing protocol with the depth adjustment based communication void region recovery procedure showed great potential to improve the routing task in the harsh underwater acoustic communication environment. This strategy appears more useful, in terms of the energy consumption, on moderate to high network density scenarios, despite this approach improves the network performance even in harsh low density scenarios when compared against existing related solutions. This is because the energy cost to vertically move the nodes on the current technology that



(a) Packet generation rate of 0.01 pkts/min

(b) Packet generation rate of 0.15 pkts/min

Fig. 7. Energy consumption per task.

was considered in this work. However, as the buoyancy based nodes depth adjustment technology advances in reducing the energy cost to vertically move the nodes, the main drawback of our proposed methodology which is the energy cost of nodes movement, will be overcome.

7 Conclusion

In this paper, we proposed and evaluated the GEDAR routing protocol to improve the data routing in underwater sensor networks. GEDAR is a simple and scalable geographic routing protocol that uses the position information of the nodes and takes advantage of the broadcast communication medium to greedily and opportunistically forward data packets towards the sea surface sonobuoys. Furthermore, GEDAR provides a novel depth adjustment based topology control mechanism used to move void nodes to new depths to overcome the communication void regions. Our simulation results showed that geographic routing protocols based on the position location of the nodes are more efficient than pressure routing protocols. Moreover, opportunistic routing proved crucial for the performance of the network besides the number of transmissions required to deliver the packet. The use of node depth adjustment to cope with communication void regions improved significantly the network performance. GEDAR efficiently reduces the percentage of nodes in communication void regions to 58 percent for medium density scenarios as compared with GUF and reduces these nodes to approximately 44 percent as compared with GOR. Consequently, GEDAR improves the network performance when compared with existing underwater routing protocols for different scenarios of network density and traffic load.

As future work, we plan to apply this topology control of depth adjustment principles to the design of opportunistic routing protocols for UWSNs, considering different QoS requirements for data delivery, the cost for reaches a neighbor node, and the lifetime of the network.

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References

[1] I. F. Akyildiz, D. Pompili, and T. Melodia, “Underwater acoustic sensor networks: Research challenges,” *Ad Hoc Netw.*, vol. 3, no. 3, pp. 257–279, 2005.

[2] I. Vasilescu, K. Kotay, D. Rus, M. Dunbabin, and P. Corke, “Data collection, storage, and retrieval with an underwater sensor network,” in *Proc. 3rd ACM Int. Conf. Embedded Netw. Sensor Syst.*, 2005, pp. 154–165.

[3] J. Partan, J. Kurose, and B. N. Levine, “A survey of practical issues in underwater networks,” in *Proc. 1st ACM Int. Workshop Underwater Netw.*, 2006, pp. 17–24.

[4] J. Heidemann, M. Stojanovic, and M. Zorzi, “Underwater sensor networks: Applications, advances and challenges,” *Philos. Trans. Roy. Soc. A: Math., Phys. Eng. Sci.*, vol. 370, no. 1958, pp. 158–175, 2012.

[5] M. Stojanovic and J. Preisig, “Underwater acoustic communication channels: Propagation models and statistical characterization,” *IEEE Commun. Mag.*, vol. 47, no. 1, pp. 84–89, Jan. 2009.

[6] P. Xie, J.-H. Cui, and L. Lao, “VBF: Vector-based forwarding protocol for underwater sensor networks,” in *Proc. 5th Int. IFIP-TC6 Conf. Netw. Technol., Services, Protocols*, 2006, pp. 1216–1221.

[7] H. Yan, Z. J. Shi, and J.-H. Cui, “DBR: Depth-based routing for underwater sensor networks,” in *Proc. 7th Int. IFIP-TC6 Netw. Conf. Ad Hoc Sensor Netw., Wireless Netw., Next Generation Internet*, 2008, pp. 72–86.

[8] U. Lee, P. Wang, Y. Noh, L. F. M. Vieira, M. Gerla, and J.-H. Cui, “Pressure routing for underwater sensor networks,” in *Proc. IEEE INFOCOM*, 2010, pp. 1–9.

[9] Y. Noh, U. Lee, P. Wang, B. S. C. Choi, and M. Gerla, “VAPR: Void-aware pressure routing for underwater sensor networks,” *IEEE Trans. Mobile Comput.*, vol. 12, no. 5, pp. 895–908, May 2013.

[10] D. Chen and P. Varshney, “A survey of void handling techniques for geographic routing in wireless networks,” *IEEE Commun. Surveys Tuts.*, vol. 9, no. 1, pp. 50–67, First Quarter 2007.

[11] F. Kuhn, R. Wattenhofer, and A. Zollinger, “Worst-case optimal and average-case efficient geometric ad-hoc routing,” in *Proc. 4th ACM Int. Symp. Mobile Ad Hoc Netw. Comput.*, 2003, pp. 267–278.

[12] R. W. L. Coutinho, L. F. M. Vieira, and A. A. F. Loureiro, “DCR: Depth-controlled routing protocol for underwater sensor networks,” in *Proc. IEEE Symp. Comput. Commun.*, 2013, pp. 453–458.

[13] R. W. Coutinho, L. F. Vieira, and A. A. Loureiro, “Movement assisted-topology control and geographic routing protocol for underwater sensor networks,” in *Proc. 6th ACM Int. Conf. Model., Anal. Simul. Wireless Mobile Syst.*, 2013, pp. 189–196.

[14] R. W. L. Coutinho, A. Boukerche, L. F. M. Vieira, and A. A. Loureiro, “GEDAR: Geographic and opportunistic routing protocol with depth adjustment for mobile underwater sensor networks,” in *Proc. IEEE Int. Conf. Commun.*, 2014, pp. 251–256.

[15] Z. S. M. Zuba, M. Fagan, and J. Cui, “A resilient pressure routing scheme for underwater acoustic networks,” in *Proc. 57th IEEE Global Telecommun. Conf.*, 2014, pp. 637–642.

[16] P. Xie, Z. Zhou, Z. Peng, J.-H. Cui, and Z. Shi, “Void avoidance in three-dimensional mobile underwater sensor networks,” in *Proc. 4th Int. Conf. Wireless Algorithms, Syst., Appl.*, 2009, vol. 5682, pp. 305–314.

[17] M. O'Rourke, E. Basha, and C. Detweiler, "Multi-modal communications in underwater sensor networks using depth adjustment," in *Proc. 7th ACM Int. Conf. Underwater Netw. Syst.*, 2012, pp. 31:1–31:5.
[18] M. Erol, F. Vieira, and M. Gerla, "AUV-Aided localization for underwater sensor networks," in *Proc. Int. Conf. Wireless Algorithms, Syst. Appl.*, 2007, pp. 44–54.
[19] M. Erol-Kantarci, H. Mouftah, and S. Oktug, "A survey of architectures and localization techniques for underwater acoustic sensor networks," *IEEE Commun. Surveys Tuts.*, vol. 13, no. 3, pp. 487–502, Third Quarter 2011.
[20] Z. Yu, C. Xiao, and G. Zhou, "Multi-objectivization-based localization of underwater sensors using magnetometers," *IEEE Sens. J.*, vol. 14, no. 4, pp. 1099–1106, Apr. 2014.
[21] J. Jaffe and C. Schurgers, "Sensor networks of freely drifting autonomous underwater explorers," in *Proc. 1st ACM Int. Workshop Underwater Netw.*, 2006, pp. 93–96.
[22] Z. Zhou, Z. Peng, J.-H. Cui, Z. Shi, and A. C. Bagtzoglou, "Scalable localization with mobility prediction for underwater sensor networks," *IEEE Trans. Mobile Comput.*, vol. 10, no. 3, pp. 335–348, Mar. 2011.
[23] E. Cayirci, H. Tezcan, Y. Dogan, and V. Coskun, "Wireless sensor networks for underwater survelliance systems," *Ad Hoc Netw.*, vol. 4, no. 4, pp. 431–446, 2006.
[24] M. Erol, L. F. M. Vieira, and M. Gerla, "Localization with dive'n'-rise (DNR) beacons for underwater acoustic sensor networks," in *Proc. 2nd Workshop Underwater Netw.*, 2007, pp. 97–100.
[25] L. F. M. Vieira, "Performance and trade-offs of opportunistic routing in underwater networks," in *Proc. IEEE Wireless Commun. Netw. Conf.*, 2012, pp. 2911–2915.
[26] L. M. Brekhovskikh and Y. Lysanov, *Fundamentals of Ocean Acoustics*. New York, NY, USA: Springer, 2003.
[27] M. Stojanovic, "On the relationship between capacity and distance in an underwater acoustic communication channel," in *Proc. 1st ACM Int. Workshop Underwater Netw.*, 2006, pp. 41–47.
[28] M. Stojanovic, "Recent advances in high-speed underwater acoustic communications," *IEEE J. Oceanic Eng.*, vol. 21, no. 2, pp. 125–136, Apr. 1996.
[29] C. Carbonelli and U. Mitra, "Cooperative multihop communication for underwater acoustic networks," in *Proc. 1st ACM Int. Workshop Underwater Netw.*, 2006, pp. 97–100.
[30] L. Freitag, M. Grund, S. Singh, J. Partan, P. Koski, and K. Ball, "The WHOI micro-modem: An acoustic communcations and navigation system for multiple platforms," in *Proc. MTS/IEEE Oceans*, 2005, pp. 1086–1092.
[31] H. Yang, B. Liu, F. Ren, H. Wen, and C. Lin, "Optimization of energy efficient transmission in underwater sensor networks," in *Proc. IEEE Global Telecommun. Conf.*, 2009, pp. 1–6.
[32] T. Rappaport, *Wireless Communications: Principles and Practice*. Englewood Cliffs, NJ, USA: Prentice-Hall, 2002.
[33] D. Pompili, T. Melodia, and I. F. Akyildiz, "Routing algorithms for delay-insensitive and delay-sensitive applications in underwater sensor networks," in *Proc. 12th Annu. Int. Conf. Mobile Comput. Netw.*, 2006, pp. 298–309.
[34] A. Caruso, F. Paparella, L. F. M. Vieira, M. Erol, and M. Gerla, "The meandering current mobility model and its impact on underwater mobile sensor networks," presented at the IEEE INFOCOM, Phoenix, AZ, USA, 2008.
[35] J. M. Jornet, M. Stojanovic, and M. Zorzi, "Focused beam routing protocol for underwater acoustic networks," in *Proc. 3rd ACM Int. Workshop Underwater Netw.*, 2008, pp. 75–82.
[36] T. Melodia, D. Pompili, and I. Akyildiz, "Optimal local topology knowledge for energy efficient geographical routing in sensor networks," in *Proc. IEEE INFOCOM*, 2004, vol. 3, pp. 1705–1716.
[37] S. Lee, B. Bhattacharjee, and S. Banerjee, "Efficient geographic routing in multihop wireless networks," in *Proc. 6th ACM Int. Symp. Mobile Ad Hoc Netw. Comput.*, 2005, pp. 230–241.
[38] K. Zeng, W. Lou, J. Yang, and D. Brown, "On geographic collaborative forwarding in wireless ad hoc and sensor networks," in *Proc. Int. Conf. Wireless Algorithms, Syst. Appl.*, 2007, pp. 11–18.
[39] P. Xie, Z. Zhou, Z. Peng, H. Yan, T. Hu, J.-H. Cui, Z. Shi, Y. Fei, and S. Zhou, "Aqua-sim: An ns2 based simulator for underwater sensor networks," in *Proc. IEEE OCEANS Conf.*, 2009, pp. 1–7.
[40] Y. Ren, W. K. G. Seah, and P. D. Teal, "Performance of pressure routing in drifting 3d underwater sensor networks for deep water monitoring," in *Proc. 7th ACM Int. Conf. Underwater Netw. Syst.*, 2012, pp. 28:1–28:8.

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