Topology Control For Depth Adjustment Using Geographic Routing In Underwater Wireless Sensor Networks

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ABSTRACT
In the recent years, Underwater Sensor Network (UWSN) is treated to be the best suited brain storming technology to inspect the oceans using marine wireline communication. The UWSN has limited data gathering process due to the individuality of acoustic communication. Routing protocols are used in UWSN which helps to improve the data collection by its individuality of acoustic communication with its dynamic network topology. In this paper, Geographic and opportunistic routing with Depth Adjustment based topology control for communication Recovery over void region (GEDAR) is proposed. It uses the greedy opportunistic forwarding to broadcast the data packets from each sensor nodes to multiple distinct sinks at the sea level. If the node persists in the communication void region, then this opportunistic protocol advances one step forward to the recovery mode procedure. The utilization of this evolving procedure can automatically manages the depth adjustments of the void nodes rather than using the control messages to discover the routing paths. The experimental result shows that our proposed routing protocol GEDAR outperforms the best amidst other routing protocols by varying network density and traffic load.

KEYWORDS: Underwater sensor network, routing protocol, topology, void region.

INTRODUCTION

OCEANS cover 70% of our planet and along with rivers and lakes are critical to our well-being. Monitoring these environments is difficult and costly for humans. These environments are enormously important for human life. In this context, underwater wireless sensor networks (UWSNs) have achieved the concentration on both scientific and industrial communities to scrutinize and explore aquatic environments [1]. The traditional approach for ocean-bottom monitoring is to deploy underwater sensors nodes that record data during the monitoring mission, and then recover the instruments. There is a need to facilitate underwater communications among underwater devices. Wireless underwater acoustic networking is the enabling technology to monitor and explore the oceans in lieu of traditional instruments. They have large number of applications such as monitoring of marine life, geological process on the ocean floor, tsunamis, climate, and seaquakes; long-term monitoring of coral reefs and fisheries and to monitor [2]. These sensor nodes have various sensing capabilities like cameras, water temperature, and pressure.

Acoustic propagation [3] has low frequencies and bandwidth is extremely limited. An acoustic system may operate in a frequency range between 10 and 15 kHz. Vector-Based Forwarding (VBF) is to address the routing problem in UWSNs [4]. It is also called as position-based routing. In each packet it carries the positions of the sender, the target and the forwarder. The forwarding path is specified by the routing vector from the sender to...
the target. Upon receiving a packet, a node computes its relative position to the forwarder by measuring its distance to the forwarder and the angle of arrival (AOA) of the signal. In order to save energy, VBF adopts a self-adaptation algorithm to allow nodes to evaluate the benefit of forwarding packets.

Depth-based routing (DBR) [5],[6] is the first routing protocol for underwater sensor network that uses the depth information of the node and is to forward data packets greedily towards the water surface. Thus, packets can reach multiple data sinks deployed at the water surface. After receiving the packet, the current sender broadcasts the packet. After receiving it, if the receiver is closer to the water surface, it becomes eligible as a candidate to forward the packet. Otherwise, it will discard the packet. In VAPR [7], the presence of the void nodes is known by means of periodic beacons. The next-hop selection is done according to the match of the forwarding direction (upwards or downwards). The drawback of these recovery mode approaches is that an explicit path must be discovered and maintained.

**Related Work:**
GEDAR is an anycast, geographic and opportunistic protocol that tries to deliver a packet from a source node to some 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[8]. GEDAR is the first routing protocol 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 [9], [10].

Resilient Pressure Routing (RPR) [11], is modeled after DBR by dealing with malicious attackers. The RPR protocol utilize cryptographic mechanisms, implicit acknowledgments, retransmissions, geographic constraints with a sliding window feature and randomization to achieve robust packet delivery service in the presence of attackers. Vector-Based Void Avoidance (VBVA) [12],[13], addresses the routing void problem in mobile underwater sensor networks. VBVA adopts two mechanisms, vector-shift and back-pressure, to handle voids. Vector-shift mechanism is used to route data packets along the boundary of a void. Back-pressure mechanism routes data packets backward to bypass a concave void. Nodes determine if they should surface to communicate by approximating the network energy usage and data latency given the data transmission size.

**Preliminaries:**

**A. System Model:**

Fig. 1: System Architecture

In this architecture, a large number of mobile underwater sensor nodes are placed in the ocean bottom and sink nodes are located at the ocean surface. Meantime, all the nodes are move as a group according to the water current. The surface sonobuoys (sink nodes) are uniformly deployed on the sea surface which has both acoustic and radio transceivers, its acoustic links are used to send commands and to receive data from sensor nodes; and the radio links to forward data packets to the monitoring center. Our model consists of a set $N = N_s \cup N_s$ 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 sonobuoys $N_s = \{s_1, s_2, . . . , s_s\}$ are special nodes and are randomly deployed at the sea surface. Each sonobuoy is equipped with GPS (Global Positioning System) in order to determine its location. The $N = \{n_1, n_2, . . . , n_{|N|}\}$ are evenly deployed in a geographic area of interest $D \in R^3$ to provide 4D (space and time) monitoring and they can control its depth, moving vertically with velocity $v = 0.5m/s$, through a floating buoy mechanism that can be inflated by a pump.

By considering the energy cost $E_m = 15J/m$ the sensor nodes are moved vertically, as in [12]. Each sensor node knows its own location by means of distributed localization system [13]. The system as an undirected graph $G(t) = (V, E(t))$ at time $t$, where $V = \{n_1\}$ is the set of vertices corresponding to the sensor nodes and
sonobuoys, and $E(t) = \{e_{ij}\}$ is the finite set of links between them. An edge $e_{ij}(t) \in E(t)$ exists, if the nodes $n_i$ and $n_j \in V$ can communicate directly with each other at the time $t$. Thus, the nodes $n_i$ and $n_j$ are neighbors at the time $t$ and can send and receive messages directly via an acoustic link. Assume that all nodes transmit using the same transmitting power, resulting in a maximum communication range of $R_c = 250m$.

**B. Underwater Packet Delivery Probability Estimation:**

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. The novice underwater acoustic channel model was illustrated in [8]. The path loss, which 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:

$$A(d,f) = a(f)^d$$  \hspace{1cm} (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 average Signal-to-Noise Ratio (SNR) over distance $d$ is given as

$$\Gamma(d) = \frac{E_b}{N_0 d^k a(f)^d}$$  \hspace{1cm} (2)

Where $E_b$ and $N_0$ are constants that represent the average transmission energy per bit and noise power density in a nonfading additive white Gaussian noise (AWGN) channel. The BPSK (Binary Phase Shift Keying) modulation that is widely used in the state-of-the-art. In BPSK, each symbol carries a bit. In [10], the probability of bit error over distance $d$ is given as

$$p_e(d) = \frac{1}{2} \left( 1 - \frac{\Gamma(d)}{1 + \Gamma(d)} \right)$$  \hspace{1cm} (3)

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

$$P(d,m) = (1 - p_e(d))^m$$  \hspace{1cm} (4)

**Gedar: The Geographic And Opportunistic Proposed Routing Protocol:**

This paper proposes GEDAR (GEographic and opportunistic routing with Depth Adjustment-based topology control for communication Recovery over void regions) routing protocol. GEDAR is a geographic and opportunistic routing protocol for short-time monitoring underwater sensor. It uses the greedy opportunistic forwarding strategy to determine the set of next-hop forwarders and a depth adjustment-based topology control to move void nodes for new depths during recovery mode. 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.

Furthermore, GEDAR is opportunistic routing aiming to mitigate the effects of the acoustic channel. Thus, a subset of the neighbor nodes is determined to forwarding the packet continuously towards some surface sonobuoys (next-hop forwarder set). The research challenge of opportunistic routing (OR) next-hop forwarder set selection determine the 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.

**C. Periodic Beaconing:**

Periodic beaconing plays an important role in GEDAR. In Depth Controlled Routing (DCR) protocol, it adjusts the depth of the nodes in order to organize the network topology for improving the network connectivity and forward data where the greedy geographic routing fails.

**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_s then
6:          for s ∈ S_t (node) do
7:              if ∧(s) = 0 then
8:                  m.addson.(seq_num(s), ID(s), X(s), Y(s))
9:              ∧(s) ← 1
10:         end if
11:      end for
12:  end if
13     Broadcast m
14: end if
15: end procedure
16: end procedure
17: Procedure ReceiveBeacon(node,m)
18: if m is from a sonobuoy then
19:    update ((node), m)
20: else
21:    update_neighbor(m.seq_num, m.id, m.location)
22:     for s ∈ m do
23:       if seq_num(s,m) >seq_num(s, S_t(node)) then
24:           update (S_t (node), s)
25:        end if
26:     end for
27: end if
28: end procedure
29: end procedure

In this Algorithm 1, the beacon message contains a sequence number, its unique ID, and its X, Y location. It is assumed 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. 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. Otherwise, it updates its known sonobuoys Si 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_t.

D. 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 of neighbor is not performing well, a packet may be lost meantime other neighbor may eavesdrop it.

For each transmission, a next-hop forwarder set F is determined. The next-hop forwarder set is composed of the most suitable nodes from the next-hop candidate set C_t 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]. For each next-hop neighbor candidate node n_c ∈ C_t normalized packet advancement is:

\[
\text{NADV}(n_c) = \text{ADV}(n_c) \times p(d_{c \rightarrow m})
\]  

(5)

The expected packet advance (EPA) of the set F_j, which is the normalized sum of advancements is defined by Equation (5). The objective of the greedy opportunistic forwarding strategy is to determine the subset of F such that the (EPA) is maximized.

\[
\text{EPA}(F_j) = \sum_{i=1}^{k} \text{NADV}(n_i) \prod_{j=0}^{l-1}(1 - p(d_{i \rightarrow j}, m))
\]  

(6)

**Algorithm 2 Next-hop forwarder set selection**

1: Procedure GetNextHopForwarders(source node n_i)
2: for n_c ∈ C_t do
3:     NADV(n_c) ← d_c \times p(d_{c \rightarrow m})


Algorithm 2 depicts the pseudocode for next-hop forwarder set selection. First, determine the NADV of each qualified neighbor. Then the neighbor candidate set $C_i$ is ordered according to the priority of the nodes as a result of the NADV. To determine the clusters from the neighbor candidate set $C_i$. Each cluster $F_j$ starts with the greatest priority node from $C_i$ and is expanded by including all nodes in $C_i$ which have a distance less than $\frac{1}{2}r_c$. Fourth each cluster $F_j$ is expanded to include those nodes in $C_i$ (a copy from $F_j$) that have a distance of less than the communication radius $r_c$ for all nodes already in the cluster. 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 $F$ with the highest EPA is selected as the next-hop forwarder set.

After computing the forwarding set, the current forwarder broadcasts the packet for the next-hop forwarder set $F^*$. The nodes that receive the packet set the timer to forward it such that the greater the priority, the shorter the time. The highest priority node becomes a next-hop forwarder and the rest of lower priority nodes transmit the packet only if the highest priority node fails to do so. Otherwise, these nodes suppress their transmissions after listening to the next-hop forwarder’s data.

E. Void Node Recovery Mode:

If a node cannot forward a packet using the greedy forwarding strategy, then the void node recovery procedure is used. At that time, GEDAR switches to the void node recovery mode. Instead of the message-based procedures used in recovery mode, where a path must be discovered and maintained to route data around the communication void region, a depth adjustment-based topology control is proposed. The void node will move to a new depth such that the greedy opportunistic forwarding can resume. When the void node receives these replay messages, it will keep the information of neighbors (x,y,z location) in the set to be used to determine its new depth two tangents is defined as free region of the virtual mapping circle as region $C$. It should be noted that three regions are divided according to the current routing void; and, the division of three regions is different for different destination nodes.

**Algorithm 3 Void node recovery algorithm**

1: procedure RecoveryMode()
2: isVoid_node ← true
3: Stop beaconing
4: $\Omega \leftarrow \emptyset$ Set of neighbors to topology control
5: Send void_node_announcement_message
6: CalculateNewDepth()
The GEDAR recovery mode is described in Algorithm 3. The recovery mode function, lines 1-7, is called when the node is in a communication void region. The node will stop the beaconing, send a void node announcement message, and schedule the call to the function to determine its new depth (line 6). The neighbors that receive the void node announcement message will remove the void node from their routing table and, if it is not a void node, they will replay with a void node replay message, containing the information about their neighbors.

Performance Evaluation:

This section evaluates the performance of our proposed protocol is implemented using Aqua-Sim, that was developed on NS-2. Aqua-sim is one of the most widely used network simulators. They are randomly deployed in a varying number of sensor nodes ranging from 150 to 450 in a 3D region of size 1500m×1500m×1500m, and 45 sonobuoys at the sea surface region of size 1500m×1500m. They move according to an extended 3D version of the Meandering Current Mobility (MCM) which considers the effect of meandering sub-surface currents (or jet streams) and vertices. And then set the main jet speed to 0.3m/s. Due to the mobility, nodes would move beyond of the deployment region.

The proposed GEDAR protocol is comparing it with DBR (Depth-Based Routing) [5] and VAPR (Void-Aware Pressure Routing) [7] protocols. In DBR and VAPR, the packets are forwarded in a greedy manner to the sea surface to be received by any sonobuoy (pressure-based routing). The main difference between them is that the first one does not employ any mechanism to deal with communication void regions, i.e., a packet is discarded when it gets stuck in a void node, and in the second one, communication void regions is known by means of periodic beaconing, and then, routing is performed in this situation. Our objective is to analyze the performance of these protocols in terms of the packet delivery ratio, latency and energy consumption. Fig.2 shows the result of average end to end delay. The average end to end delay gives better results for GEDAR and VPR than DBR which improves the data delivery. Hence, the delay of moving the void nodes to new depth gets reduced.
Fig. 2: Average end-to-end delay

Fig. 3 shows the result of average of number of packet transmission to deliver a data packet. GEDAR gives the better performance for packet delivery ratio compared to others. Fig. 2 implies that the packet delivery of nodes is closely related to the redundant packets.

Fig. 3: Number of transmission for delivery

Fig. 4 shows the result of average number of redundant packet copies by received packet. The number of redundant copies increases in DBR and VAPR when the network density increases.

Fig. 4: Average number of redundant packet

Conclusion:

In this paper, a novel geographic and opportunistic routing protocol (GEDAR), for underwater mobile sensor networks is proposed. GEDAR uses the position information of the nodes to greedily and opportunistically forward data packets to sonobuoy. Instead of message-based procedures to deal with the communication void region problem found in geographic routing for mobile underwater sensor networks. The proposed system is a depth adjustment-based topology control such that void nodes move to new depths to resume the greedy opportunistic forwarding. GEDAR efficiently reduces the percentage of nodes in communication void regions to 58% as compared to other routing protocols by varying different values of
network density and traffic load. Simulation results showed that this new algorithm improves the data packet delivery ratio when compared with the baseline routing protocols.

REFERENCES