Reliable geocasting for random-access underwater acoustic sensor networks

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ABSTRACT

Reliable data delivery for underwater acoustic sensor networks is a major concern in applications such as surveillance, data collection, navigation, and ocean monitoring. *Geocasting* is a crucial communication primitive needed to support these applications, which consists in transmitting one or multiple consecutive data packets – all carrying an atomic message – to nodes located in a certain geographic region. In this article, two versions of a distributed, reliable, and efficient underwater geocasting solution (based on different degrees of neighbor information) are proposed for underwater networks whose acoustic modems use random-access Medium Access Control (MAC) protocols. By *jointly* considering the position uncertainty of nodes as well as the MAC and routing functionalities, packet transmissions are prioritized and scheduled so to maximize link reliability while limiting the end-to-end geocasting delay. Moreover, a simple yet effective timer-based mechanism is designed to limit the number of transmissions by selecting only a subset of neighbors for packet forwarding. Performance is evaluated and compared via thorough simulations against existing geocasting solutions tuned for the underwater environment that were originally designed for terrestrial wireless networks.

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1. Introduction

UnderWater Acoustic Sensor Networks (UW-ASNs) [2] can carry out tactical surveillance missions such as littoral battle space sensing, submarine detection, mine sweeping, and disaster prevention. In many of these applications, sensor nodes are deployed in a pre-defined 3D region: for example, static sensors may stretch along a directional coastal area, whereas mobile Autonomous Underwater Vehicles (AUVs) may move as a team along a pre-specified direction and perform adaptive sampling. *"Geocasting" is a crucial communication primitive needed to support these applications*, which consists in transmitting one or multiple consecutive data packets – all carrying an atomic message – to nodes located in a certain geographic region; as opposed to *"broadcasting,"* in which all the nodes in the network are meant to receive a certain message; and *"multicasting,"* in which the subset of nodes meant to receive the message are not geographically proximal. In UW-ASNs, geocasting may be required to assign surveillance tasks to AUVs or to query sensor nodes in a region. This communication primitive can also be used to notify the nodes within a 3D area of a tactical event (e.g., for detection of enemy vessels); furthermore, it can be used to facilitate location-based services by announcing them in a certain region or by sending an emergency warning to (some of) the nodes.

Existing geocasting solutions such as [3–6] are designed for terrestrial wireless networks, and do not consider the underlying underwater acoustic communication link-layer

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constraints such as large access delay, low bit rate, and high packet loss ratio. Many of these solutions (e.g., [5,6]) are based on theoretical graph models, such as the Unit Disk Graph (UDG) model that only considers link connectivity; also, in these solutions the impact of imperfect link layer is not considered. As a result, these solutions do not perform well in UW-ASNs where non-idealities in the communication channel cannot be neglected. Compared to terrestrial wireless communications, underwater acoustic communications are in fact more challenging as the underwater channel is characterized by high and variable propagation delay – up to five orders of magnitude higher than in Radio Frequency (RF) terrestrial communications – limited bandwidth, frequency-dependent attenuation, ambient noise, fading, Doppler spread, and time-varying multipath especially in the shallow-water environment (i.e., when the depth is less than a hundred meters). Moreover, due to *sound bending*, caused by the sound speed varying with depth, and *bottom/surface reflections*, the existence of *convergence (or shadow) zones* [7] makes underwater acoustic communications highly unreliable (e.g., nodes located in shadow zones may not receive packets from transmitters even if closely located). These phenomena can be modeled accurately using the Bellhop model [7], which is based on ray/beam tracing. According to this model, which requires as input the sound-speed profile, the transmission loss is calculated by solving differential ray equations, as done numerically by HLS Research [8]. Last, but not least, due to the inaccessibility of Global Positioning System (GPS) underwater, node mobility, and the influence of ocean currents, it is difficult for underwater nodes to estimate their positions accurately. Such location uncertainty makes geocasting underwater more difficult than in terrestrial wireless networks. To support geocasting, in fact, location information is required at each node.

Due to these challenges, it is crucial to ensure communication end-to-end (e2e) reliability between nodes with inaccurate position information. Since e2e error-recovery mechanisms generally incur high delay and energy consumption, we choose an approach to guarantee e2e reliability by *maximizing link reliability* although this may not guarantee e2e reliability (as a node may become disconnected due to energy depletion or movement). Given the 3D geocasting region, under the condition of node position uncertainty, the geocasting protocol needs to: (i) select a path that can forward packets to the highest number of nodes along the specified direction in a given time and (ii) maximize the link reliability so that minimal number of retransmissions is required.

In this work, based on different degrees of neighbor information, we propose two versions of an underwater geocasting solution whose objective is to reach the highest number of nodes within a pre-defined directional 3D region in a given amount of time when the positions of the nodes are uncertain. We first adopt the position uncertainty model that we introduced in [9] to estimate node position. Then, based on these position estimates, packets are forwarded along the path that can reach the nodes in the region along the specified direction in minimal time while maximizing link reliability. Moreover, packet

transmissions are scheduled in an optimal manner in order to avoid collisions and thus reduce retransmissions.

To the best of our knowledge, ours is the first geocasting solution for UW-ASNs that accounts for position uncertainty. Specifically, our contribution includes the design and implementation of:

1. A prioritization and scheduling mechanism to maximize link reliability while minimizing the time for geocasting;
2. A mechanism to limit the number of transmissions by partitioning neighboring nodes into two sets, *forwarding nodes* and *non-forwarding nodes*, so that retransmissions can be minimized;
3. A distributed solution that can be used for the existing underwater acoustic modems that use random-access Medium Access Control (MAC) protocols (e.g., Benthos, WHOI).

Note that (i) our solution relies only on the use of timers (without requiring synchronization among nodes) and that (ii) only local neighbor information is used for packet scheduling and forwarding. While more sophisticated MAC protocols have been proposed for UW-ASNs in the past recent years [2], random-access solutions are very robust and simple, and for this reason widely adopted in state-of-the-art underwater acoustic modems used in both static as well as mobile configurations, which makes our geocasting solution relevant and timely.

The remainder of this article is organized as follows. We first review the existing geocasting solutions in Section 2. Then, in Section 3, we introduce the network model and state the assumptions our solution is based on. We propose two versions of our geocasting solution in Section 4, followed by performance evaluation and analysis in Section 5. Finally, conclusions and future work are discussed in Section 6.

2. Related work

Differently than for terrestrial wireless networks, where a number of geocasting protocols have been proposed, geocasting for underwater sensor networks is an almost unexplored area. The underwater channel is characterized by high and variable propagation delay, limited bandwidth, frequency-dependent attenuation, noise, fading, and Doppler spread. Due to these characteristics, geocasting algorithms designed for terrestrial networks do not work well in the underwater environment. In this section, we review the solutions for terrestrial networks and discuss why they would fall short in the underwater environment.

Ko and Vaidya proposed two location-based multicast algorithms in [3], where only nodes within the so-called *forwarding zone* are allowed to relay the packets to the geocasting region. In this way, the number of nodes for forwarding packets is reduced, resulting in reduced delivery overhead. Moreover, the authors proposed GeoTORA [4], which is based on the Temporally-Ordered Routing Algorithm (TORA) unicast routing protocol [10]. Flooding

is incorporated into TORA, but it is limited to nodes within a small region. This integration significantly reduces the overhead of geocasting delivery, while maintaining high accuracy. These two solutions focus mainly on limiting the traffic in a region and on selecting appropriate routes for geocasting without considering the communication link properties. Hence, due to the communication impairments of the underwater acoustic channel, they may not be able to achieve minimum geocasting delay in UW-ASNs.

Two geocasting algorithms are presented in [11], whose aim is to forward packets to the neighbors that may be closer to the possible location of the destination. These neighbors are determined using Voronoi diagrams, where the closest pair of points corresponds to two adjacent cells; the algorithm is further modified to ensure that the routes are loop free. Simulations are performed for two basic scenarios, one for geocasting and reactive routing, and the other for proactive routing; both showed to have high success and low flooding rates compared to other similar methods. Both algorithms rely on the simplifying UDG model and are designed using graph theory; such an idealistic assumption for node connectivity is inadequate in UW-ASNs where the acoustic channel plays a major role to determine the link reliability.

A delivery-guaranteed solution is proposed in [12], which finds a connected planar subgraph of the network and then applies routing algorithms that are designed for planar graphs on this subgraph. While the solution requires no duplication of packets or memory at the nodes, a packet is always guaranteed to be delivered to its destinations, as confirmed through simulations. Like in [11], however, this solution too is designed based on graph theory where communication connectivity between two nodes is assumed if their distance is below a pre-specified fixed distance (i.e., independently on the acoustic channel state).

An Obstacle-Free Single-destination Geocasting Protocol (OFSGP) is proposed for mobile ad hoc networks in [13] to keep messages away from obstacles by creating a very small flooding region; an Obstacle-Free Multi-destination Geocasting Protocol (OFMGP) is also proposed for relaying messages from the source to all hosts located in multiple disconnected geographical regions, where a shared path for different destinations is created so that the number of flooding packets can be limited. Simulation results show that the proposed protocols transmit the message from source host to one or more destination regions with low flooding overhead and with a high success rate.

In [5], a Virtual Surrounding Face Geocasting (VSFG) algorithm is proposed to guarantee message delivery while keeping the flooding overhead low. The network area is partitioned into a set of faces, where a face is a continuous area enclosed by a sequence of edges. In VSFG, all the faces intersecting with a geocasting region are merged into a unique Virtual Surrounding Face (VSF) containing the geocasting region itself. By traversing all the boundary nodes of VSF and performing restricted flooding within the geocasting region, all nodes are guaranteed to receive the message. The proposed VSFG is evaluated through theoretical analysis and comprehensive simulations, which show up to 40% reduction in the number of transmissions.

Geographic Multicast Routing (GMR) [6] is proposed to construct trees with minimal bandwidth for wireless sensor networks. GMR selects the set of next hop neighbors that minimizes the so-called *cost-over-progress ratio*, i.e., the ratio of the number of neighbors selected for relaying to the overall reduction of the remaining distances to destinations. In this way the tradeoff between the bandwidth of the multicast tree and the effectiveness of the data distribution is better handled. The simulation results show that GMR achieves a lower cost of the trees and computation time in a number of networking scenarios than the position-based multicast protocol.

To conclude, we want to reiterate that all these geocasting protocols, which were designed for terrestrial wireless networks, rely on theoretical graph models and only consider link connectivity based on idealistic assumptions. Link characteristics such as bandwidth, delay, and packet loss rate are not considered and, hence, the impact of link level constraints, which is not negligible in underwater acoustic communications, is ignored. Consequently, their performance may not be optimal in the underwater environment. In this work, we attempt to fill this gap by proposing a geocasting solution that takes the large propagation delay, low bandwidth, and high packet-loss rate constraints into account.

3. Network model and assumptions

Positions of underwater nodes, especially AUVs, are highly uncertain. Inaccuracies in models for position estimation, self-localization errors, and drifting due to ocean currents significantly increase the uncertainty in position of an underwater node. Hence, using a "deterministic point" is not sufficient to characterize the position of a node (or – in a broader sense – the region where a node might be with high probability). Furthermore, applying such a deterministic approach underwater may lead to problems such as routing errors in inter-vehicle communications, vehicle collisions, lose of synchronization, and mission failures.

In order to address the problems caused by position uncertainty, in [9] we proposed a probability model to characterize a node's position, where two novel notions of position uncertainty were introduced to facilitate the estimation of a node's own position and positions of other nodes. Depending on the network point of view, we defined two forms of position uncertainty, *internal* and *external uncertainty*: the former refers to the position uncertainty associated with a particular entity/node (such as an AUV) *as seen by itself*, while the latter refers to the position uncertainty associated with a particular entity/node *as seen by others*. As shown in [9], using statistical methods, given a confidence level parameter, a node can first estimate its own internal uncertainty, including the region in which it is possibly distributed and the corresponding probability distribution function (pdf). This internal uncertainty will then be broadcast and used by other nodes to estimate this node's position, i.e., the external uncertainty. Note that the estimation of internal uncertainty does not assume a particular localization technique, e.g., dead-reckoning or long-baseline localization, although

different internal uncertainty regions and pdfs may result depending on the specific technique used (e.g., [14]).

In this work, we propose a solution to geocast packets reliably to nodes that are located within a "directional" 3D region. As shown in Fig. 1, our geocasting region is a *cylinder* specified by a tuple $(\mathbf{c}, \vec{\mathbf{v}}, r)$, where $\mathbf{c} = (x_c, y_c, z_c)$ is the center coordinates, $\vec{\mathbf{v}} = (v_x, v_y, v_z)$ is the vector specifying geocasting distance and direction, and r is the scalar radius of the region in the plane perpendicular to the specified direction. These *seven* parameters are the fewer pieces of information needed to characterize an "elongated" 3D region. Note that $\|\vec{\mathbf{v}}\|/r$, where $\|\vec{\mathbf{v}}\| = \left(v_x^2 + v_y^2 + v_z^2\right)^{1/2}$, gives the "degree of elongation" of the region. The reason for not assuming a (simpler) spherical region (which would be characterized by only four parameters, i.e., $\mathbf{c}$ and r) is that for many underwater applications the three dimensions of a region of interest in the ocean may be very different (especially in shallow water). Hence, a sphere would not represent accurately such an elongated 3D region.

Furthermore, as done in other works, we assume that all the nodes have the same *statistical transmission range R* when geocasting packets, which is defined as the average distance to receive a specified percentage of the transmitted packets (e.g., 50%). In reality, nodes may have different transmission ranges due to the use of different transmit output power levels. Relaxing this assumption may bring in some new problems: for example, the potential asymmetry in the forward and backward directions of a link makes the acknowledgement of packet reception less robust as well as the design of routing algorithms for packet forwarding more complicated. In this article, we focus on the geocoding problem without neighbor or with one-hop neighbor knowledge assuming that all nodes involved in geocasting packets are homogeneous, i.e., use a similar (maximum) output power, and leave the case of heterogeneous transmitters as future work. Let us point out that this is not an unrealistic assumption as many of the existing underwater modems can only use one transmit power (10 W for WHOI Micro-Modem); and even if they could perform power control to save energy when transmitting data, in order to guarantee robustness they should not use this functionality when performing crucial communication primitives such as broadcasting or geocasting.

To perform geocasting, a node (such as a sink) issues a geocasting packet, which contains the geocasting region information, i.e., the tuple $(\mathbf{c}, \vec{\mathbf{v}}, r)$. If this node is inside this region, the packet will then be forwarded using the geocasting algorithm. Otherwise, the problem can be decomposed into *two parts*: first the packet will be unicast to a destination node on the boundary of the destination region and then be forwarded using the geocasting algorithm. In the rest of this article, we focus on the second part of the problem, i.e., geocasting a packet from a node inside the geocasting region. Note that *any* unicasting algorithm tailored for UW-ASNs can be used to reach the boundary of the destination region (first part of the problem).

4. Our geocasting solution: no neighbor vs. one-hop knowledge

As shown in Fig. 2, based on different degrees of neighbor information, two different versions of the geocasting solution are designed for the following cases:
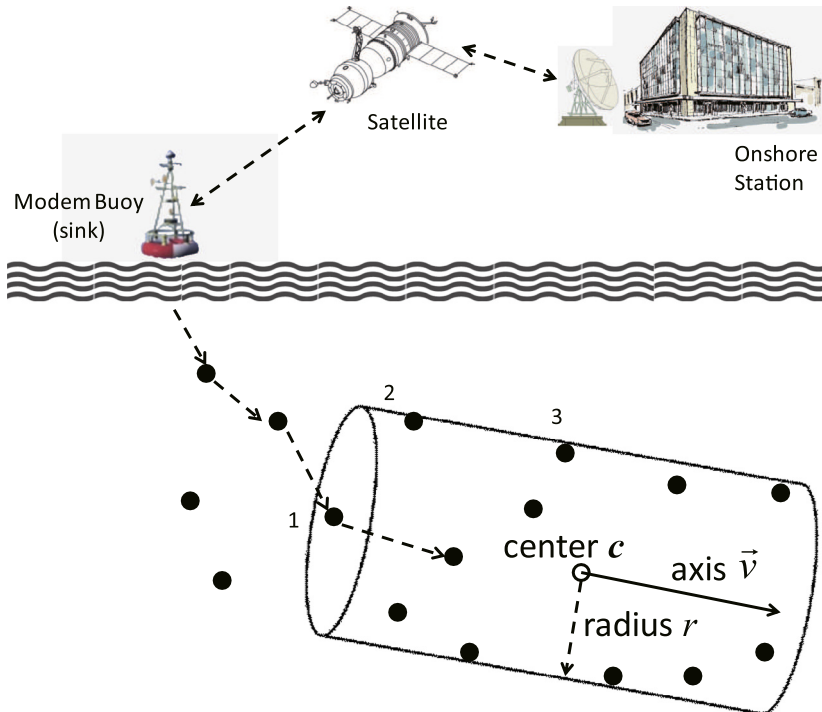

Fig. 1. Geocasting scenario and representative directional 3D region.
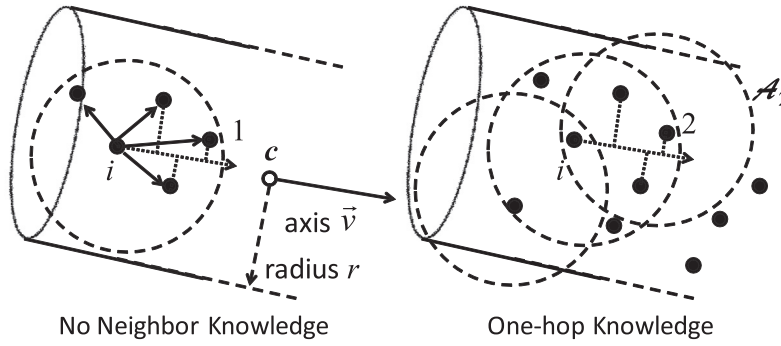
Fig. 2. Two versions of our geocasting solution, no neighbor and one-hop knowledge.

<u>Case (A)</u> – *No neighbor knowledge*, which means that each node in the geocasting region has only its own location information (i.e., internal uncertainty) but not that of other nodes. <u>Case (B)</u> – *One-hop neighbor knowledge*, where each node has the location information of itself (internal uncertainty) and of its neighbors (external uncertainty). Although different, *the underline idea in both versions is to give priority in terms of transmissions to nodes (i) that are close to the central axis of the (elongated) region* <u>and</u> *(ii) that are farther along the $\vec{\mathbf{v}}$ direction.* This idea is intuitive yet powerful as generally nodes that are close to the central axis have more neighbors; and by forwarding packets to nodes that are farther along the $\vec{\mathbf{v}}$ direction, packets can quickly penetrate the geocast region in this direction around the central axis. To prioritize transmissions, we choose to use timers due to their simplicity, robustness, and wide availability on existing underwater modems. Different times are used to hold off the transmissions until the time expires. These times are carefully chosen to avoid packet collisions while trying to maximize the coverage of the transmissions. Moreover, in order to reduce the number of transmissions, we propose a mechanism to select a subset of neighbors for packet forwarding.

Case (A): Each node estimates its own internal uncertainty and decides when to forward the packet by itself. As nodes do not know the external uncertainty of their neighbors, an opportunistic approach is followed. Furthermore, in order to improve the geocasting reliability, an advertising mechanism is adopted to notify the receiver before the transmission of geocasting packets, i.e., a *short packet* with higher packet success rate is used to notify the receivers of an incoming packet. In this way, neighbors that did not receive the geocasting packet – but that *did* receive the short packet – will be able to know that the geocasting packet is lost. An acknowledgement mechanism is also devised to allow neighbors of these nodes to forward the geocasting packet to them without the need for retransmissions from the original sender.

Case (B): Instead of forwarding packets opportunistically, priority of packet forwarding is decided by the positions of the neighbors. A scheduling scheme is designed to prioritize packet transmissions among neighbors. More-over, a subset of neighbors is selected to maximize the coverage region without introducing packet collisions at the original sender. In Case A, obviously, no overhead is incurred for the exchange of location information. On the other hand, in Case B (which relies on one-hop neighbor knowledge), nodes need to periodically broadcast information about their uncertainty region. This could be done in different ways, e.g., by periodically embedding this information in the packet that needs to be geocast. In the rest of this section, we present the details of our solution for both cases.

Case (A) – No neighbor knowledge: To geocast a packet, immediately before broadcasting the packet, node i first transmits a short packet, called NOTICE packet, which is sent to cater for the nodes that may have received it but did not receive the geocasting packet. The reason to send the NOTICE packet is that short packets have lower packet error rates than normal geocasting packets and therefore are correctly received with higher probability. Moreover, this NOTICE packet may be sent using a more reliable modulation and coding scheme. For example, as shown in [15], Packet Error Rates (PERs) of WHOI Micro-Modems for type 0 (using FSK modulation) packet with 32-byte payload is much lower than that of type 5 (using PSK modulation and 9/17 rate block code) packet with 2048-byte payload.

On receiving the geocasting packet for the first time, node j, the neighbor of i, starts a hold-off timer, T_{hold}, which is a uniformly distributed random variable in $[0, 2T_{hold}^{mean}]$. Here,

$$T_{hold}^{mean} = \left(1 - \frac{d_{ij}^{(\vec{v})}}{R}\right)\tau + \frac{d_j}{R}\tau + \frac{\phi_{ij}}{\psi}, \tag{1}$$

where $d_{ij}^{(\vec{v})}$ [m] is the expected projection distance of the vector $\overrightarrow{\mathbf{p}_i\mathbf{p}_j}$ (position vector from i to j, when i and j are at positions $\mathbf{p}_i$ and $\mathbf{p}_j$, respectively) along the vector $\vec{\mathbf{v}}, R$[m] is the statistical transmission range (radius), τ[s] is the estimated transmission time for the current packet, d_j[m] is the expected distance of j to the central vector $\vec{\mathbf{v}}, \psi = 1500$m/s is the expected propagation speed of acoustic waves in "normal" underwater conditions [2], and $\phi_{ij} = \max\{0, R - \mathbb{E}[\|\overrightarrow{\mathbf{p}_i\mathbf{p}_j}\|]\}$[m]. Here

$$d_{ij}^{(\vec{v})} = \int_{\mathbf{p}_j \in \mathcal{U}_{ij}} \left(\overrightarrow{\mathbf{p_i}\mathbf{p_j}} \odot \frac{\vec{\mathbf{v}}}{\|\vec{\mathbf{v}}\|} \right) f_j(\mathbf{p}_j) d\mathbf{p}_j, \tag{2}$$

$$d_j = \int_{\mathbf{p}_j \in \mathcal{U}_{ij}} \left\| \overrightarrow{\mathbf{c}\mathbf{p_j}} \otimes \frac{\vec{\mathbf{v}}}{\|\vec{\mathbf{v}}\|} \right\| \cdot f_j(\mathbf{p}_j) d\mathbf{p}_j, \tag{3}$$

$$\mathbb{E}[\|\overrightarrow{\mathbf{p_i}\mathbf{p_j}}\|] = \int_{\mathbf{p}_j \in \mathcal{U}_{ij}} \|\overrightarrow{\mathbf{p_i}\mathbf{p_j}}\| f_j(\mathbf{p}_j) d\mathbf{p}_j, \tag{4}$$

where $f_j(\mathbf{p}_j)$ is j's pdf at position $\mathbf{p}_j$ in the internal-uncertain region $\mathcal{U}_{ij}$, $\overrightarrow{\mathbf{c}\mathbf{p_j}}$ is the position vector from the geocasting region center $\mathbf{c}$ to $\mathbf{p}_j$, and $\odot$ and $\otimes$ are the inner- and cross-product operators, respectively.

The first and second terms in (1) give less time to the neighbor that goes farther in the $\vec{\mathbf{v}}$ direction and that is closer to the central axis, respectively, while the third term offsets the non-negligible propagation delay so that all the nodes receive the packet at the same time, irrespective of their distance from transmitter i. This term provides fairness by guaranteeing "distributed implicit synchronization" in starting the hold-off timers of the nodes receiving the data packet. Note that this third term is essential as underwater the acoustic speed is five orders of magnitude lower than the speed of light in terrestrial settings. Once the hold-off timer expires, the node broadcasts the packet if the channel is not busy. Otherwise, it just backs off. For the example in Fig. 2, *on average*, node 1 is the first node to forward packets as it has the greatest $d_{ij}^{(\vec{v})}$ and smallest d_j.

A node that does not receive the geocasting packet – but that receives the NOTICE packet – will inform the neighboring nodes by sending a NACK packet. Before transmitting a NACK, the node waits for a duration of $T_{NACK-hold-off} = T_{hold} + \frac{R}{\psi} + T_{TX}^Q$, where $T_{TX}^Q[s]$ is the transmission time of the geocasting packet. This ensures that a node waits long enough to overhear the transmission from a forwarding node in the neighborhood, if any. A node receiving the NACK will respond with probability $\Pr(n)$, where n is the number of NACK packets received and $\Pr(n)$ is an increasing function with respect to (w.r.t.) n. A node that receives a higher number of NACKs will have a higher probability to respond. If a node does not get the packet during the NACK timeout period, it will retransmit the NACK.

In (1), we need to find an appropriate (optimal) τ^* to avoid packet collisions. A small τ cannot space out consecutive transmissions to avoid packet collisions. On the other hand, a large τ may not only introduce a large end-to-end (e2e) delay but also impair the mechanism by altering the priority of transmissions. If the time difference between i's receiving the geocasting packet from j and that from k is greater than T_{TX}^Q, collisions at i can be avoided. That is, if the probability of reception time (the hold-off time plus the propagation delay) difference being less than T_{TX}^Q is kept very low, collisions can be reduced to a great extent at i. Assuming no significant change in ψ spatially (i.e., the spatial gradients of salinity and temperature are small), we derive the following constraint,

$$\Pr\left(|T_{hold}^j + \mathbb{E}[\|\overrightarrow{\mathbf{p_i}\mathbf{p_j}}\|]/\psi - T_{hold}^k - \mathbb{E}[\|\overrightarrow{\mathbf{p_i}\mathbf{p_k}}\|]/\psi | \leqslant T_{TX}^Q \right) < \gamma,$$

where T_{hold}^j and T_{hold}^k are the hold-off times of j and k, respectively, and γ is the threshold collision probability.

Because at i there is no information of the neighbors, we assume that j and k are uniformly distributed in the transmission region of i, i.e., the pdf of $\mathbb{E}[\|\overrightarrow{\mathbf{p_i}\mathbf{p_j}}\|]$ is $f_{\mathbb{E}[\|\overrightarrow{\mathbf{p_i}\mathbf{p_j}}\|]}(r) = \frac{r}{2\pi R}$ (and so for $\mathbb{E}[\|\overrightarrow{\mathbf{p_i}\mathbf{p_k}}\|]$). Since T_{hold}^j and T_{hold}^k are uniformly distributed in their respective intervals, let $\Delta T_{j,k}^i = \left(T_{hold}^j + \mathbb{E}[\|\overrightarrow{\mathbf{p_i}\mathbf{p_j}}\|]/\psi \right) - \left(T_{hold}^k + \mathbb{E}[\|\overrightarrow{\mathbf{p_i}\mathbf{p_k}}\|]/\psi \right)$, the pdf of $\Delta T_{j,k}^i$ can then be derived as,

$$f_{\Delta T_{j,k}^i}(s) = \iiint f_{\mathbb{E}[\|\overrightarrow{\mathbf{p_i}\mathbf{p_j}}\|]}(r_i) f_{\mathbb{E}[\|\overrightarrow{\mathbf{p_i}\mathbf{p_k}}\|]}(r_k) f_{T_{hold}^k}(s_k) \cdot f_{T_{hold}^j}(s + s_k + r_k - r_i) dr_i dr_k ds_k. \tag{5}$$

Therefore, $\Pr\left(|T_{hold}^j + \mathbb{E}[\|\overrightarrow{\mathbf{p_i}\mathbf{p_j}}\|]/\psi - T_{hold}^k - \mathbb{E}[\|\overrightarrow{\mathbf{p_i}\mathbf{p_k}}\|]/\psi | \leqslant T_{TX}^Q \right) = \int_{-T_{TX}^Q}^{T_{TX}^Q} f_{\Delta T_{j,k}^i}(s) ds$. Consequently, the optimal τ^* is found by solving the following optimization problem.

$\mathbf{P}_{desync}^{nohop}$: **No hop desynchronization optimization problem**

Given: $R, \gamma, f_j(\mathbf{p}_j), f_k(\mathbf{p}_k)$; **Find**: τ^*; **Minimize**: τ;
Subject to:

$$\Pr\left(|T_{hold}^j + \mathbb{E}[\|\overrightarrow{\mathbf{p_i}\mathbf{p_j}}\|]/\psi - T_{hold}^k - \mathbb{E}[\|\overrightarrow{\mathbf{p_i}\mathbf{p_k}}\|]/\psi | \leqslant T_{TX}^Q \right) < \gamma.$$

Case (B) – One-hop neighbor knowledge: With one-hope information, transmitter i can now decide which node is the best next hop by using the following metric (the one with minimum value is scheduled to transmit first) – similarly to (1) – as,

$$T_{hold} = \left(1 - \frac{d_{ij}^{(\vec{v})}}{R} + \frac{d_j}{R} \right) \cdot \tau \cdot \frac{1}{\overline{N}_{\mathcal{A}_j}(j)}. \tag{6}$$

Here, $\overline{N}_{\mathcal{A}_j}(j)$ represents the expected number of nodes within the 3D region $\mathcal{A}_j$ near j, which is the region inside the sphere of radius R centered at j. That is, $\overline{N}_{\mathcal{A}_j}(j) = \sum_{k \in \mathcal{N}_i} \int_{\mathcal{U}_{ik} \cap \mathcal{A}_j} f_k(\mathbf{p}_k) d\mathbf{p}_k$, where $\mathcal{N}_i$ is the set of i's neighbors. We use the external-uncertainty region $\mathcal{U}_{ik}$ to take into account neighbors with predictable trajectories such as underwater gliders [9].

W.r.t. (1), the third term is now removed as the calculation at i does not need to offset for the propagation delay. In addition, $\overline{N}_{\mathcal{A}_j}(j)$, the number of nodes near j, is used as a factor to prioritize transmissions: the more neighbors a node has, the earlier it should transmit in order to reduce the e2e delay (note that this can be achieved with an appropriate scheduling of transmissions, which is the approach we use here; in general, this may not be necessarily true as more packet collisions may be introduced). The pdf of $d_{ij}^{(\vec{v})}$ is $f_{d_{ij}^{(\vec{v})}}(d) = \int_{\|\overrightarrow{\mathbf{p_i}\mathbf{p_j}}\| = d, \mathbf{p}_i \in \mathcal{U}_{ii}, \mathbf{p}_j \in \mathcal{U}_{ij}} f_{\mathcal{U}_{ii}}(\mathbf{p}_i) f_{\mathcal{U}_{ij}}(\mathbf{p}_j)$, where $f_{\mathcal{U}_{ii}}()$ and $f_{\mathcal{U}_{ij}}()$ are the pdfs of i inside the internal-uncertainty region $\mathcal{U}_{ii}$ and j inside $\mathcal{U}_{ij}$, respectively. The pdf of d_j can also be obtained similarly. The node with the smallest T_{hold} is selected as the neighbor with the highest priority and is denoted as j^*.

In addition to giving j^* the highest priority, we want to allow for *simultaneous* transmissions that will introduce
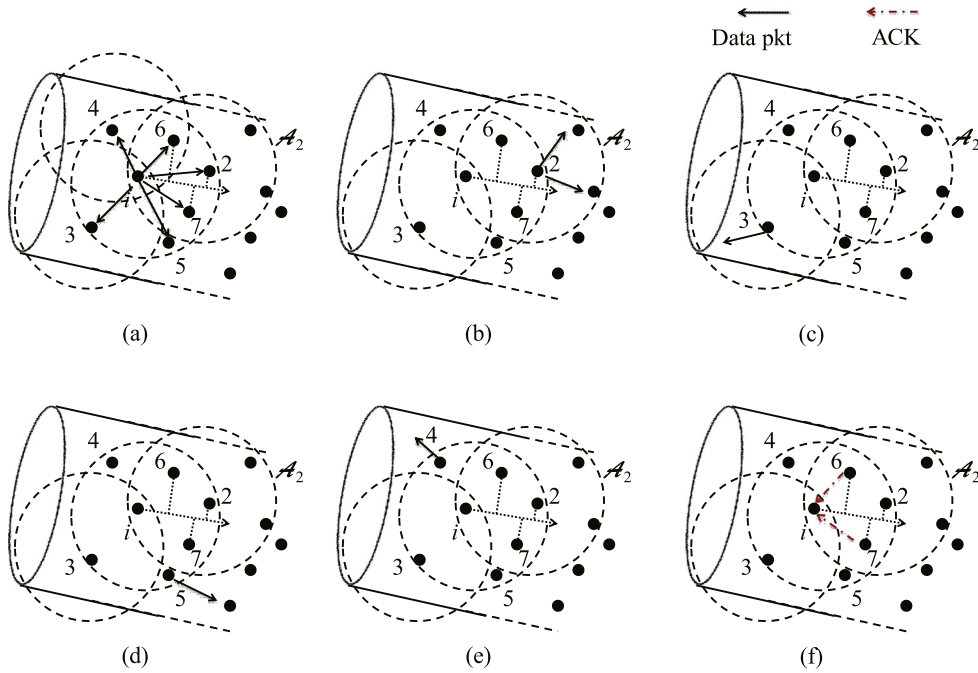
Fig. 3. One-hop neighbor knowledge toy example.

minimal packet collisions so that a larger volume can be covered in a given time interval. The idea is that starting from j^*, i partitions its neighbors into sets $\mathcal{S}_m$ ($m = 0, 1, 2, \ldots, M$) such that simultaneous transmissions for nodes in a set $\mathcal{S}_m$ will incur minimal packet collisions. More precisely, nodes within $\mathcal{S}_m$ can forward packets without colliding at i's neighbors, and nodes in $\mathcal{S}_m$ are scheduled to transmit earlier than nodes in $\mathcal{S}_{m+1}$. As we have assumed the statistical transmission range to be R, collisions will happen with *low probability* at a receiving node if this node is not in the (statistical) transmission ranges of two transmitting nodes. Before introducing the technical details of our geocasting solution for the case of one-hop neighbor knowledge, in Fig. 3 we present a toy example to illustrate the idea of our algorithm (Algorithm 1).

4.1. Toy example

In Fig. 3(a), node i forwards the data packet (which contains scheduling information for neighbors) to its neighbors, where set $\mathcal{S}_0 \equiv \{2, 3\}$ and $\mathcal{S}_1 \equiv \{5, 4\}$ (with the first node in each set selected according to (6) and the rest of the nodes selected according to Algorithm 1). After receiving the data packet, node 2 will be the first to forward the packet to neighbors (Fig. 3(b)), while node 3 will follow (Fig. 3(c)). The reason for not scheduling them (nodes 2 and 3) to transmit at the same time is to avoid packet collisions at i so that i can hear the transmission of 2 and 3 for packet acknowledgement (separate acknowledgement packets are not used here as transmission times for underwater acoustic communications are large due to the low data rate). Then, it is the transmission time of set $\mathcal{S}_1$, i.e., node 5 and then node 4, as shown in Fig. 3(d) and (e). After

the transmissions of the *forwarding sets*, the *non-forwarding nodes* (those not forwarding data packets) will acknowledge the data packet by sending an ACK packet according to node i's schedule, as in Fig. 3(f).

Algorithm 1. Compute Ordered Set $\mathcal{OS}$ using $\mathcal{N}_i$ and $\mathcal{U}_{ij}$'s

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1 $\mathcal{N}_{remain} \equiv \mathcal{N}_i$; Calculate T_{hold}'s, and $\mathbb{E}[\|\overrightarrow{\mathbf{p}_j \mathbf{p}_k}\|]$'s;
2 **while** $\mathcal{N}_{remain} \not\equiv \emptyset$ **do**
3   $j^* = \arg\min_{j \in \mathcal{N}_{remain}} T_{hold}$; $\quad \mathcal{S} \equiv \{j^*\}$;
4   **for** $k \in \mathcal{N}_{remain} - \mathcal{S}$ **do**
5     $\mathcal{S} \equiv \mathcal{S} \cup \{k\}$ where k has no common neighbor (except for i) with nodes in S;
6   **end**
7   Add $\mathcal{S}$ to the end of $\mathcal{OS}$ if $\mathcal{S} \not\equiv \emptyset$; Break if $\mathcal{S} \equiv \emptyset$;
8   $\mathcal{N}_{remain} \equiv \mathcal{N}_{remain} - \{l \mid \mathbb{E}[\|\overrightarrow{\mathbf{p}_q \mathbf{p}_l}\|] \leqslant R, q \in \mathcal{S}\}$;
9 **end**

In the rest of this section, we present the details of our proposed algorithm and derive its complexity. To calculate these sets, i starts from $\mathcal{S}_0$, which includes j^*, and then calculates $\mathcal{S}_{m+1}$ using $\mathcal{S}_0, \ldots, \mathcal{S}_m$ recursively, as illustrated in Algorithm 1. Node j^* is first put in $\mathcal{S}_0$ and then i searches for a node k in $\mathcal{N}_i$ such that there is no node in the transmission ranges of both k and any node in $\mathcal{S}_0$ (except for i itself). The remaining set of nodes not covered by the transmission of nodes in $\mathcal{S}_0$ can be calculated as $\mathcal{N}_{remain} \equiv \mathcal{N}_i - \{k \mid \mathbb{E}[\|\overrightarrow{\mathbf{p}_j \mathbf{p}_k}\|] \leqslant R, j \in \mathcal{S}_0\}$. Similarly, we can find the set $\mathcal{S}_1 \subset \mathcal{N}_{remain}$ such that nodes in $\mathcal{S}_1$ can transmit at the same time without causing collisions except at i. This
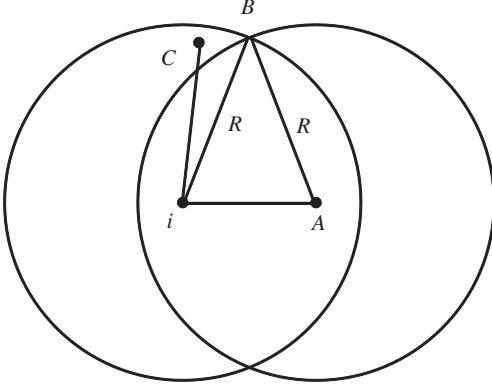
Fig. 4. Complexity analysis of Algorithm 1.

process can be repeated to find $\mathcal{S}_M$ ($M \in \mathbb{N}$) such that $\mathcal{S}_{M+1} \equiv \emptyset$ (i.e., no further sets can be found). $\mathcal{S}_m$ ($m = 0, 1, 2, \ldots, M$) are put sequentially into an ordered set $\mathcal{OS}$ of sets and the transmissions are scheduled accordingly: nodes in $\mathcal{S}_0$ transmit first, followed by nodes in $\mathcal{S}_1, \mathcal{S}_2, \ldots, \mathcal{S}_M$.

4.2. Complexity analysis

The complexity of Algorithm 1 is $\mathcal{O}(N)$ (where N is the number of nodes). This is because M, i.e., the number of iterations in the inner loop of the algorithm, is bounded by a constant. To understand this statement, assume A is a node selected in $\mathcal{S}$ according to the algorithm, as in Fig. 4: for node C to be selected as another node in $\mathcal{S}, C$ must not fall in the area overlapped by the circular transmission area of node i and A. Therefore, $\angle AiC \geqslant \angle AiB$, where B is the intersection point of the circles centered at i and A (for sake of clarity, we only consider here the case where C and B are on the same side of iA as it is not hard to extend to the other case). Since $|AB| = |iB| \geqslant |iA|$, it is not hard to show that $\angle AiB \geqslant 60°$, which implies that $\angle AiC \geqslant 60°$. This means that the nodes in $\mathcal{S}$ should be at least $60°$ apart. Consequently, $|\mathcal{S}| \leqslant 6$ and the number of iterations in the inner loop of Algorithm 1 can be bounded by a constant (which can be achieved by pre-calculating the angles and considering only nodes that satisfy this angle constraint). Finally, as the number of iterations in the outer loop is proportional to N, the complexity of the algorithm is then $\mathcal{O}(N)$.

Nodes in $\mathcal{S}_m$ ($m = 0, 1, 2, \ldots, M$) are tasked as *forwarding nodes* and will forward the geocasting packets to their neighbors. As transmitting a packet (short or not) takes a relative long time for current (low data rate) underwater acoustic modems (e.g., WHOI Micro-Modem highest data rate is 5Kbps), it is better for i to use the overheard transmissions of the forwarding nodes as acknowledgements for these nodes in order to save time. Hence, it is paramount to avoid collisions at i. So, i needs to schedule the transmissions of these nodes by putting the scheduling information in the geocasting packet itself. On the other hand, nodes in $\mathcal{N}_i - \cup_{m=0}^{M} \mathcal{S}_m$ will be set as *non-forwarding nodes*, which will only acknowledge the received geocasting packets but will not forward them. To geocast quickly

the packets to the whole region, the transmission of these ACK packets is scheduled *after* the transmission of the forwarding nodes. Finally, as collisions may still happen at the two-hop neighbors, we randomize the transmissions of the neighbors for collision avoidance.

Scheduling of forwarding nodes: As the transmission time is T_{TX}^Q, collision among packets can be avoided if the time difference between reception of two packets at i is greater than T_{TX}^Q. Packets will arrive sequentially if the transmission time is delayed by some integer multiple of T_{TX}^Q. First, i does not delay the transmission of the node with the highest priority. It then chooses a random permutation of the numbers from 1 to $|\mathcal{S}_m|$ and uses this permutation as the transmission order of the rest of the nodes in $\mathcal{S}_m$ so that their transmissions arrive at i one by one. The timeout for forwarding nodes should be set to $2T_P^{j^*} + |\mathcal{OS}| \cdot T_{TX}^Q$, where $T_p^{j^*}$ is the propagation delay required to reach j^* and $|\mathcal{OS}|$ denotes the number of forwarding nodes, i.e., $|\mathcal{OS}| = \sum_{m=0}^{M} |\mathcal{S}_m|$.

Scheduling of non-forwarding nodes: An explicit ACK is sent by a non-forwarding node to the sender after waiting for an ACK-hold-off period, $T_{hold-off}^{ACK}$. To avoid collisions with the geocasting packet, $T_{hold-off}^{ACK}$ should be greater than the timeout for forwarding nodes. We require it to be uniformly distributed in $\left[2T_P^{j^*} + |\mathcal{OS}| \cdot T_{TX}^Q, 2T_P^{j^*} + |\mathcal{OS}| \cdot T_{TX}^Q + (|\mathcal{N}_i| - |\mathcal{OS}|) \cdot T_{TX}^{ACK} \right]$. The sender will keep track of all the ACKs it receives as well as the packets it overhears, and will retransmit the packet if there is *even a single* neighbor that does not reply (implicitly or explicitly). The retransmission timeout is chosen to be $R/\psi + 2T_P^{j^*} + |\mathcal{OS}| \cdot T_{TX}^Q + (|\mathcal{N}_i| - |\mathcal{OS}| + 1) \cdot T_{TX}^{ACK}$, which is long enough to hear from all its neighbors before it retransmits. Note that R/ψ and the extra T_{TX}^{ACK} are needed to offset the propagation and the transmission delays, respectively.

To de-synchronize the transmissions, an appropriate τ^* needs to be selected. We can formulate an optimization problem similarly to $\mathbf{P_{desync}^{nohop}}$ for Case A (No Neighbor Knowledge). Differently from the previous case, however, the pdfs of T_{hold}^j and T_{hold}^k are now derived from $\mathcal{U}_{ij}$ and $\mathcal{U}_{ik}$, respectively. For example, T_{hold}^j is distributed in $\left[d_{min}^{i,j}/\psi, d_{max}^{i,j}/\psi \right]$ with pdf,

$$f_{T_{hold}^j}(t) = \int_{\|\overrightarrow{\mathbf{p}_i \mathbf{p}_j}\| = \psi t, \mathbf{p}_i \in \mathcal{U}_{ii}, \mathbf{p}_j \in \mathcal{U}_{ij}} f_{\mathcal{U}_{ii}}(\mathbf{p}_i) f_{\mathcal{U}_{ij}}(\mathbf{p}_j), \qquad (7)$$

where $d_{min}^{i,j}$ and $d_{max}^{i,j}$ are the minimal and maximal distances between i (in $\mathcal{U}_{ii}$) and j (in $\mathcal{U}_{ij}$), respectively. Finally, note that rather than pre-computing τ^* *offline*, as in Case A, the optimization can now be done *online* so to adjust it dynamically based on how the network topology changes.

5. Performance evaluation

Both versions of our proposed geocasting solution are implemented and tested via simulations. We are interested in evaluating the performance of our solution to see if it achieves our goal – *maximizing the number of nodes receiving the geocasting packet in a given time*. Our simulation is
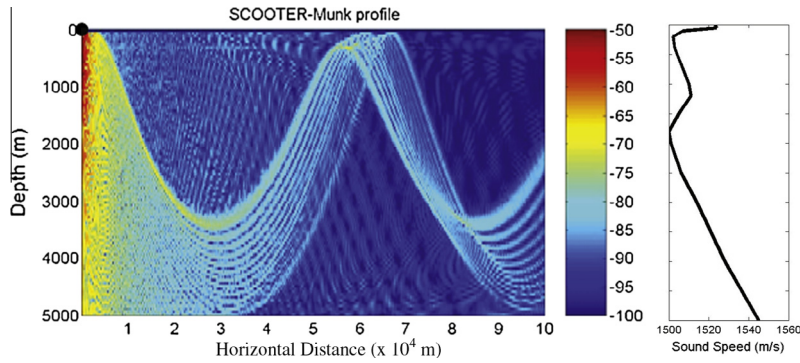
Fig. 5. Bellhop model: the left subfigure represents the transmission loss of a node located at the origin, while the right subfigure depicts the sound speed profile used to derive the transmission loss (the *y*-axis is the depth, which has the same range used in the left; the blue, yellow, and red areas denote large, medium, and small path losses in dB, respectively). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

based on the Bellhop model, where an example is illustrated in Fig. 5. Simulation parameters are set as: number of nodes = 100, $\vec{\mathbf{v}} = (10, 0, 0)$ Km, $\mathbf{c} = (20, 0, 10)$ Km, $r = 5$ Km, $R = 2$ Km (denoted as "Setting I"). Nodes are uniformly distributed in the specified geocasting region with drifting model as in [9]. The communication parameters are based on the specifications and measurements of the WHOI acoustic modem. The transmission radius 2 Km is the typical transmission distance in both shallow- and deep-water horizontal channels, which is measured by WHOI. We use type 0 packets (FSK modulation), which has a measured transmission delay of about 7.8 s. In order to obtain statistical relevance, simulations are run for 100 times and the average is taken as result.

As there are no existing geocasting solutions designed for UW-ASNs, we compare the performance of our solution with two well-known geocasting solutions – both tuned for the underwater environment – that were originally designed for terrestrial wireless networks, i.e., the Location-Based Multicast (LBM) algorithm [3] and GeoTORA [4]. In LBM, a node forwards packets to the geocasting region if it is within the *forwarding zone*, which is generally a region containing the geocasting region. If a node is in the geocasting region, it simply forwards the packets to all the neighbors. Outside of the forwarding zone, packets are discarded. Here we use the second scheme of LBM, where packets are forwarded when nodes are closer to the center of the geocasting region. GeoTORA is a geocasting solution based on the Temporally Ordered Routing Algorithm (TORA) [10], which is a unicasting algorithm designed for ad hoc networks. It maintains a single directed acyclic graph, where the directions are defined by assigning a height (the distance to the destination region) to each node. A packet is always forwarded to a neighbor with lower height. Nodes in the geocasting region are assigned height 0. Neither LBM nor GeoTORA considers the propagation delay (negligible in terrestrial radio-frequency communication links but not in acoustic underwater links).

5.1. Impact of source location, node density, and cylinder size

We compare the performance of the two versions of our solution with LBM and GeoTORA in the following

scenarios: (i) source node located at the base of the cylinder, (ii) different node densities, and (iii) different radii of the geocasting cylinder (i.e., different cylinder sizes). In order to study the pros and cons, we are interested in the percentage of nodes that receive the geocasting packet at a given time. Simulation results for these metrics are plotted in Fig. 6. The following is observed.

As shown in Figs. 6 and 8, our one-hop version solution performs the best, i.e., it takes the least time to geocast to all nodes within the region. Our no-hop version solution uses the second least time to finish geocasting the region. GeoTORA ranks the third among these four algorithms (Figs. 6 and 8). As it needs to use the TORA protocol to *discover* geocasting routes, it waits the longest time before initiating geocasting. As GeoTORA does not rely on simple flooding, it leads to fewer collisions. Hence, its e2e geocasting delay is less than that for LBM. However, as the propagation delay is not considered, it has more packet collisions than the two versions of our solution. LBM algorithm performs the worst – needing the largest amount of time to finish geocasting. This is because it simply floods the packet without coordination, leading to a large number of collisions. Therefore, retransmissions are needed, thus resulting in increased e2e delay.
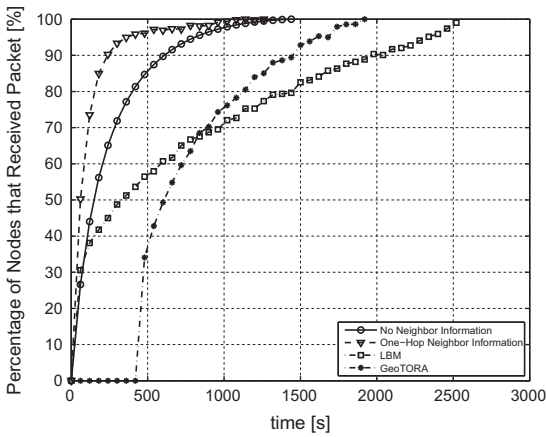
By doubling the node density, the number of neighbors also double. Hence, the probability of packet collisions increases, leading to longer geocasting finishing times, as confirmed by the simulation results (Figs. 6(c) and 7(c)). Similar results can be observed by halving the cylinder radius (Figs. 6(b) and 7(b)). Interesting enough, the increase of geocasting finishing times for both versions of our solution is much less than for LBM and GeoTORA. This is due to the selection of appropriate τ^*'s so to de-synchronize the transmissions. The increase of geocasting finish time for the one-hop version is less than for the no-hop version since τ^* is now computed online in this case, given the additional information available.
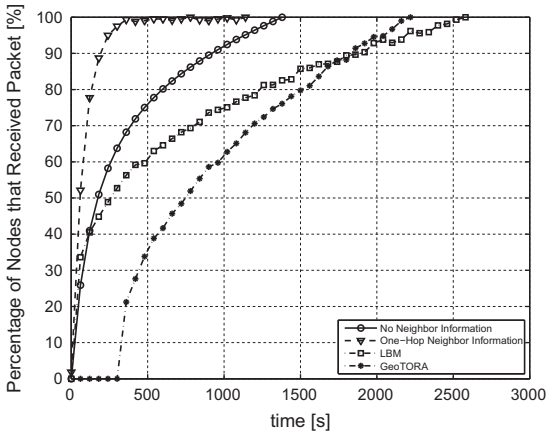
5.2. Overhead

We also want to measure the control overhead of each algorithm. Simulation results are plotted in Figs. 7 and 9. From these figures, we can see that the one-hop version
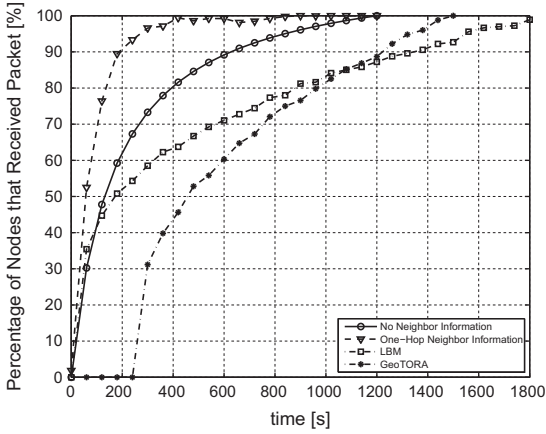
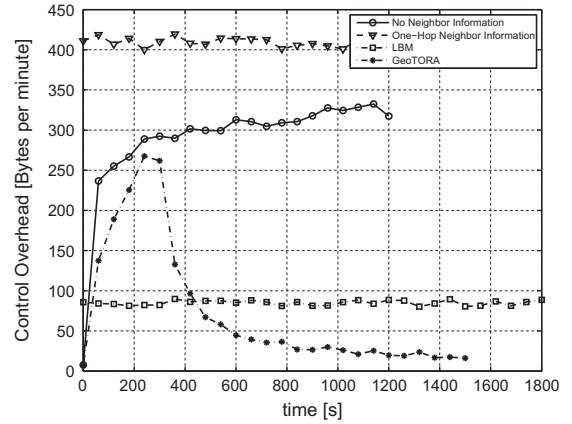(a) Results using parameters in Setting I.

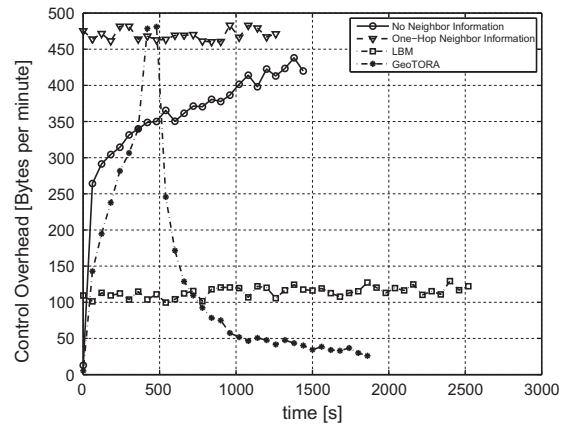(b) Results using parameters in Setting I (except for halving the cylinder radius).

(c) Results using parameters in Setting I (except for doubling the node density by doubling the number of nodes).
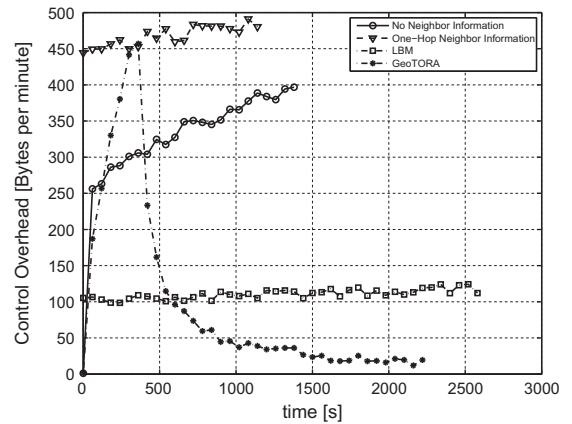
Fig. 6. Comparison of *reliability* for Setting I.

(a) Results using parameters in Setting I.

(b) Results using parameters in Setting I (except for halving the cylinder radius).

(c) Results using parameters in Setting I (except for doubling the node density by doubling the number of nodes).

Fig. 7. Comparison of *control overhead* for Setting I.

has the largest overhead due to the need to exchange location information between neighbors (Fig. 7). The no-hop version ranks the second among these four algorithms

thanks to the use of NOTICE packets. GeoTORA ranks the third as it needs to use the TORA protocol to discover the geocasting routes, which adds delays before initiating
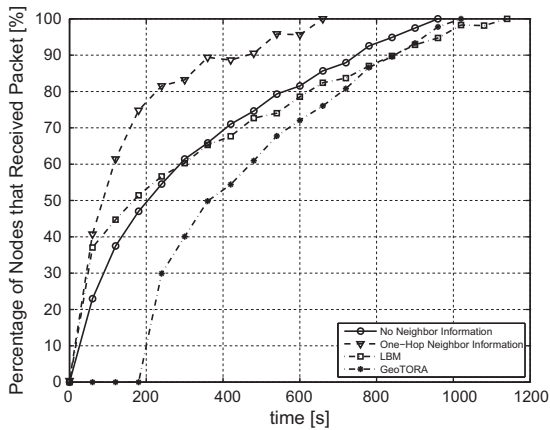
Fig. 8. Percentage of reached nodes (geocasting from the middle of the cylinder surface).
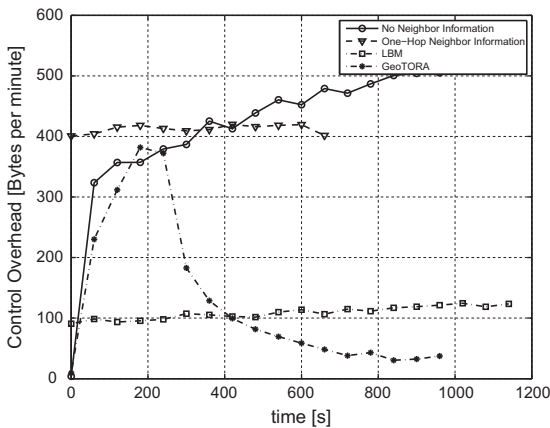

Fig. 9. Control overhead (geocasting from the middle of the cylinder surface).

the geocasting. Once the routes are discovered, the control overhead of GeoTORA decreases as "discovery" is only needed when a route breaks (i.e., to perform route maintenance). LBM has the least overhead as no control at all is needed to coordinate the nodes.

Also, the control overhead for the one-hop version is relatively constant as nodes only need to broadcast location information periodically. Even though location information may be lost when the wireless acoustic link is bad, nodes can use past information to predict the trajectory of a neighbor so the estimation of propagation delay is accurate. On the other hand, the no-hop version needs more retransmissions due to the lack of neighbor information, leading to an increase in control overhead. Such situation is, however, more severe in LBM and GeoTORA.

5.3. Geocasting from the middle of the cylinder surface

As shown in Fig. 8, it takes less time to finish geocasting from the middle of the cylinder region than from the base of the cylinder region, which was expected as in that case

geocasting can be done in both directions along the cylinder (thus "parallelizing" the propagation of the message). This confirms the intuition that it is better that geocasting begins from the middle of the region. It also gives a guideline for unicasting the geocasting packet from the surface station to the geocasting region.

5.4. Traffic performance

We compare the performance of our solution against LBM and GeoTORA for three traffic models – the Poisson, Constant Rate, and a mix of the two – in terms of the geocasting completed time, as shown in Fig. 10. Here, the mix traffic consists of 50% of Poisson and 50% of constant traffic in the probability sense. For both versions, we can see that the completed time increases as the average traffic rate increases. Moreover, the proposed solutions have better performance (i.e., less completed time) for Poisson traffic than for traffic with constant rate. This is because the randomness in the neighbor's position makes it difficult to avoid collisions with constant rate traffic. On the other hand, the randomness in Poisson traffic introduces more randomness in packet forwarding so fewer collisions occur, leading to a lower geocasting time. As expected, the completed time of the mix traffic lies in between for each version. Interesting enough, we see that the mix traffic is closer to the constant traffic in the 'No Hop' version, while it is closer to the Poisson traffic in the 'One Hop' version. This shows that the 'No Hop' version is affected more by the constant traffic due to the lack of neighbor information while the 'One Hop' version is affected more by the randomness introduced by Poisson traffic. We also tried different mixes of traffic (i.e., different transmission probability of Poisson traffic) and similar performance results were observed.

5.5. Ratio of cylinder height over radius

We are also interested in evaluating the performance of our solutions for different ratios of cylinder height over cylinder radius (denoted by 'H/R'). As shown in Fig. 11, for 'No Hop,' 'One Hop,' and LBM, the time to finish
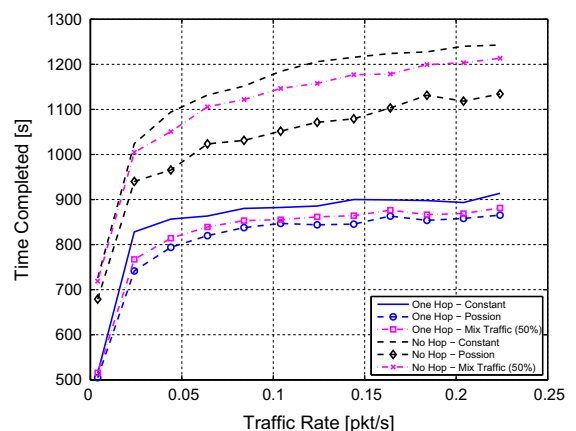

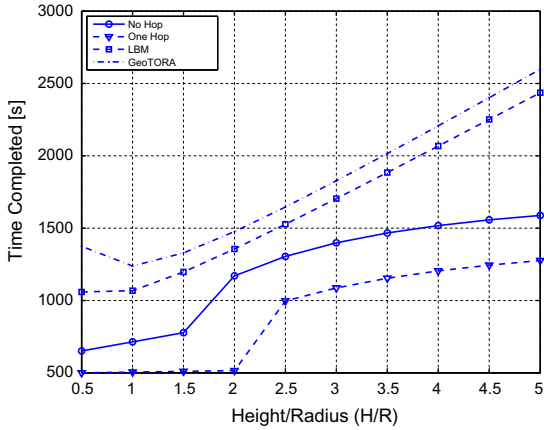**Fig. 10.** Geocasting time: Poisson vs. constant rate traffic.

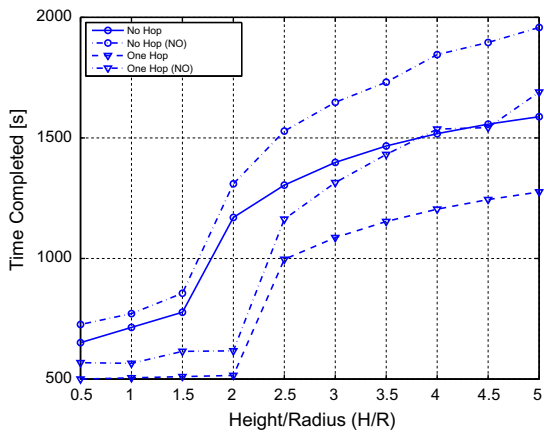**Fig. 11.** Performance for ratio of cylinder height over radius.

Fig. 12. Performance for ratio of cylinder height over radius (geocasting from the middle of cylinder surface).
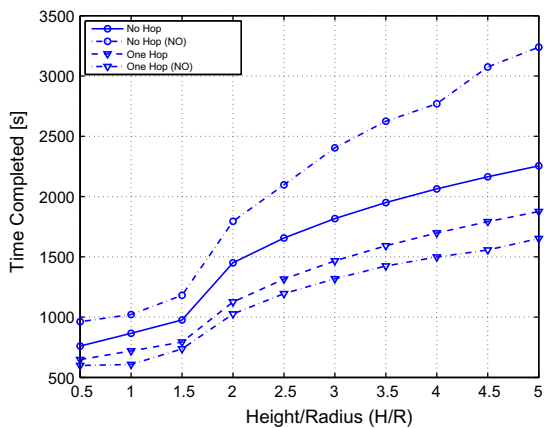

Fig. 13. Performance for ratio of cylinder height over radius (geocasting from cylinder base center).

geocasting increases with the ratio H/R – as this ration increases, the region size also increases, leading to more time to finish geocasting. For GeoTORA, the time completed first decreases (as it takes less time to finish

route discovery), then it increases as the region size increases. When H/R is small (< 2), 'One Hop' has the least slope of the curve (i.e., the rate of change), followed by 'No Hop,' LBM, and GeoTORA. This is because our one-hop version can quickly geocast to the region with the least delay due to its ability to allow for simultaneous forwarding while limiting packet collisions.

5.6. Performance of scheduling optimization

Last, but nor least, we are interested in quantifying how much improvement the scheduling optimization algorithms provide in both versions of our solution. Therefore, we compare the performance of our proposed solutions against the solutions without using scheduling optimization (i.e., no optimal τ^* for both versions, which are denoted by 'No Hop (No)' and 'One Hop (No)'). From Fig. 12, we can see that there is about 11% improvement at $H/R = 0.5$ and 27% improvement at $H/R = 5$ for the one-hop version; and 13% improvement at $H/R = 0.5$ and 24% improvement at $H/R = 5$ for the no-hop version, when geocasting from the middle of cylinder surface. From Fig. 13, we can see that there is about 15% improvement at $H/R = 0.5$ and 14% improvement at $H/R = 5$ for the one-hop version; and 20% improvement at $H/R = 0.5$ and 44% improvement at $H/R = 5$ for the no-hop version, when geocasting from the cylinder base center. These results show that our scheduling optimization algorithms are effective in improving the geocasting performance. The improvement percentage for geocasting from cylinder base center is greater than that from the middle of cylinder surface: this is because the latter incurs more packet collisions while allowing for more simultaneous packet forwarding.

5.7. Summary

To sum up, using more information from the neighborhood, nodes are able to schedule their packet transmissions in a better way so that collisions can be reduced or avoided, which leads to a higher e2e geocasting reliability. Moreover, our solution performs better than LBM and GeoTORA, two solutions that were originally designed for terrestrial wireless networks but that we tuned to work underwater.

6. Conclusion and future work

Geocasting, which consists in transmitting one or multiple consecutive data packets to nodes located in a certain 3D geographic region, is a crucial communication primitive needed to support underwater acoustic sensor network applications such as surveillance, data collection, navigation, and ocean monitoring. Reliable data delivery for these applications is a major concern. We proposed two versions of a reliable geocasting solution for such networks based on different degrees of neighbor information. Both versions were implemented and tested via simulations. The results show that higher reliability can be achieved when more neighbor information is available, and that our solution outperforms both LBM and GeoTORA – two well-known

geocasting solutions originally designed for terrestrial networks and tuned to work underwater. Future work will focus on implementing these solutions on WHOI underwater acoustic modems, and on evaluating the performance in field experiments involving underwater gliders conducting adaptive-sampling missions for ocean exploration.

Acknowledgement

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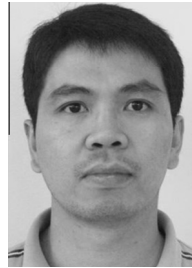
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