A Reliable Geocasting Solution for Underwater Acoustic Sensor Networks

Baozhi Chen and Dario Pompili
Department of Electrical and Computer Engineering, Rutgers University, New Brunswick, NJ
Emails: baozhi_chen@cac.rutgers.edu, pompili@ece.rutgers.edu

***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 – which is the transmission of data packet(s) to nodes located in a certain geographic region – is becoming a crucial communication primitive. In this work, two versions of a distributed, reliable, and efficient underwater geocasting protocol, which are 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, MAC, and routing functionalities, packet transmissions are prioritized and scheduled in order to maximize link reliability while limiting end-to-end geocasting delay. Moreover, a mechanism is designed to save the number of transmissions by selecting only a subset of neighbors for packet forwarding. Performance of the proposed protocol is evaluated and compared via simulations against existing geocasting solutions tailored for terrestrial wireless networks.**

I. INTRODUCTION

UnderWater Acoustic Sensor Networks (UW-ASNs) [1] can be deployed to 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 region (e.g., sensors along a directional coastal area and Autonomous Underwater Vehicles (AUVs) moving along a direction). *Geocasting* – which is the transmission of data packet(s) to nodes located in a certain geographic region – is becoming a crucial communication primitive. In UW-ASNs, geocasting may be required to assign surveillance tasks to AUVs or to query sensor nodes in a region. It can also be used to notify the nodes within an area of a tactical event (e.g., for detection of enemy vessels). Furthermore, geocasting can be used to facilitate location-based services by announcing a service in a certain region or by sending an emergency warning to a subset of network elements.

Existing geocasting solutions such as [2]–[5] are designed for terrestrial wireless networks that do not consider underlying link-layer constraints such as large access delay, low bit rate, and high packet loss ratio. Many of these solutions (e.g., [4], [5]) are based on graph theory, which relies on the unrealistic Unit Disk Graph (UDG) model; also, the impact of imperfect link layer is not considered. As a result, these solutions do not perform well in UW-ASNs. Compared to terrestrial wireless communications, underwater acoustic communications are 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, and Doppler spread. Moreover, due to sound bending and bottom/surface reflection, the existence of convergence (or shadow) zones [6] makes underwater acoustic communications highly unreliable (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 [6]. According to this model, which is based on ray/beam tracing, transmission loss is calculated by solving differential ray equations, as done numerically by HLS Research [7].

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 compared with that 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 the 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 maximal 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 in [8] 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 save the number of transmissions.

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

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implementation of: 1) prioritization and scheduling mechanisms to maximize the link reliability while minimizing the time for geocasting; 2) a mechanism to save the number of transmissions by partitioning neighbor nodes into two sets – *forwarding nodes* and *non-forwarding nodes* – so that retransmissions can be minimized; and 3) a distributed solution that can be used for existing underwater acoustic modems using random-access MAC protocols (e.g., Benthos, WHOI). Note that our solution relies only on the use of timers (without requiring synchronization among nodes), and only local neighbor information is used for packet scheduling and forwarding.

The remainder of this paper is organized as follows. In Sect. II, we introduce the network model and assumptions that our solution is based on. We propose two versions of a geocasting solution in Sect. III, followed by performance evaluation and analysis in Sect. IV. Finally, conclusions and future work are discussed in Sect. V.

II. 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 enough to characterize the position of a node. Furthermore, 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 due to position uncertainty, in [8] we proposed a probability model to characterize a node's position, where two novel notions of position uncertainty are 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 [8], 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.

We aim at providing a solution to geocast packets 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 $(\mathbf{c}, \overrightarrow{\mathbf{v}}, r)$, where $\mathbf{c} = (x_c, y_c, z_c)$ is the center coordinates, $\overrightarrow{\mathbf{v}} = (v_x, v_y, v_z)$ is the vector specifying geocasting distance and direction, and r is the radius of the region in the plane perpendicular to the specified direction. These seven parameters are the minimum number to characterize a prolonged 3D region. The reason for not assuming a (simpler) spherical region is that the three dimensions of a region in the ocean are generally very different (especially in shallow water). Hence, a sphere would not represent accurately such a region.

We further assume that all the nodes have the same *statistical transmission range* R, which is defined as the average distance to receive a specified percentage of the transmitted packets (e.g., 50%). The case where nodes have different transmission ranges is left as future work.

To perform geocasting, a node (such as a sink) issues a geocasting packet, which contains the geocasting region information, i.e., $(\mathbf{c}, \overrightarrow{\mathbf{v}}, r)$. If this node is in the geocasting region, the packet will then be forwarded using the geocasting algorithms. Otherwise, the packet will be unicast to a destination node on the boundary of the destination region and then be forwarded using the geocasting algorithms. In the rest of this paper, we focus on the problem of geocasting a packet from a node in the geocasting region.

III. PROPOSED GEOCASTING SOLUTION

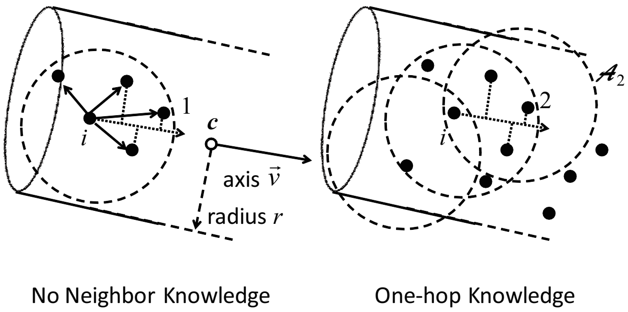

Fig. 1. Two versions of our proposed solution.

As shown in Fig. 1, based on different degrees of neighbor information, two different versions of the geocasting algorithm are designed for the following cases: 1) *No neighbor knowledge*, which means that each node in the geocasting region has only its own location information (i.e., internal uncertainty) but not those of other nodes; 2) *One-hop neighbor knowledge*, where each node has the location information of itself (internal uncertainty) and of its neighbors (external uncertainty). Although different, the overall idea of both versions is to give priority to nodes that are close to the central axis of the region and that are farther along the $\overrightarrow{\mathbf{v}}$ direction. This is intuitive as generally nodes that are close to the central axis have more neighbors; and by forwarding packets to nodes that are farther along the $\overrightarrow{\mathbf{v}}$ 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 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, to reduce the number of transmissions, a mechanism is proposed to select a subset of neighbors for packet forwarding.

In case 1, each node estimates its own internal uncertainty and decides when to forward the packet itself. As nodes do not know the external uncertainty of their neighbors, an opportunistic approach is adopted. 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 devised to allow neighbors of these nodes to forward the geocasting packet to them without the need for retransmissions from the original sender.

In case 2, instead of forwarding packets opportunistically, priority of packet forwarding is decided by the positions of neighbors. A scheduling scheme is designed to prioritize packet transmissions among neighbors. Moreover, a subset of neighbors is selected to maximize the coverage region without introducing packet collisions at the original sender. In case 1, obviously, no overhead is incurred for the exchange of location information. On the other hand, in case 2 (which relies on one-hop neighbor knowledge), nodes need to periodically broadcast information on 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.

No Neighbor Knowledge: To geocast a packet, immediately before broadcasting the packet, 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. Moreover, this NOTICE packet may be sent using a more reliable modulation and coding scheme. For example, as shown in [9], 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}. T_{hold} is a uniformly distributed random variable in $[0, 2T_{hold}^{mean}]$, where

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

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

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

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

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

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

The first and second term in (1) give less time to the neighbor that goes farther in the $\overrightarrow{\mathbf{v}}$ direction and that is closer to the central axis respectively, while the third term offsets the propagation delay so that all the nodes receive the packet. This provides fairness by guaranteeing synchronization in starting the hold-off timers of the nodes receiving the data packet. 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. 1, on average, node 1 is the first node to forward packets as it has the greatest $d_{ij}^{(\overrightarrow{\mathbf{v}})}$ 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} 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 NACKs received and $\Pr(n)$ is an increasing function with respect to (w.r.t.) n. A node that receives 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 τ to avoid packet collisions. A small τ cannot space out consecutive transmissions to avoid packet collisions. On the other hand, large τ may not only introduce big e2e delay but also impair 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}, collision 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, we have the following constraint:

$$\Pr\left(|T_{hold}^{j} + \mathbb{E}[\|\overrightarrow{\mathbf{p}_i\mathbf{p}_j}\|]/\psi - T_{hold}^{k} - \mathbb{E}[\|\overrightarrow{\mathbf{p}_i\mathbf{p}_k}\|]/\psi| \leq T_{TX}^{Q}\right) < \gamma,$$

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. Since there is no information for neighbors, we assume that j and k are uniformly distributed in the transmission region of i, the pdf function of $\mathbb{E}[\|\overrightarrow{\mathbf{p}_i\mathbf{p}_j}\|]$ is $f_{\mathbb{E}[\|\overrightarrow{\mathbf{p}_i\mathbf{p}_j}\|]}(r) = \frac{r}{2\pi R}$ (the same 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

$$\begin{aligned} f_{\Delta T_{j,k}^{i}}(s) = \int\int\int & f_{\mathbb{E}[\|\overrightarrow{\mathbf{p}_i\mathbf{p}_j}\|]}(r_i) f_{\mathbb{E}[\|\overrightarrow{\mathbf{p}_i\mathbf{p}_k}\|]}(r_k) f_{T_{hold}^{k}}(s_k) \cdot \\ & f_{T_{hold}^{j}}(s + s_k + r_k - r_i) dr_i dr_k ds_k. \end{aligned} \tag{5}$$

Therefore $\Pr(|T_{hold}^{j} + \mathbb{E}[\|\overrightarrow{\mathbf{p}_i\mathbf{p}_j}\|]/\psi - T_{hold}^{k} - \mathbb{E}[\|\overrightarrow{\mathbf{p}_i\mathbf{p}_k}\|]/\psi| \leq T_{TX}^{Q}) = \int_{-T_{TX}^{Q}}^{T_{TX}^{Q}} f_{\Delta T_{j,k}^{i}}(s) ds$.

The optimal τ is found by solving an optimization problem.

$\mathbf{P}_{\mathbf{desync}}^{\mathbf{nohop}}$: **No Hop Desyncrhonization Optimization Problem**

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

Subject to:

$$\Pr\left(|T_{hold}^{j} + \mathbb{E}[\|\overrightarrow{\mathbf{p}_i\mathbf{p}_j}\|]/\psi - T_{hold}^{k} - \mathbb{E}[\|\overrightarrow{\mathbf{p}_i\mathbf{p}_k}\|]/\psi| \leq T_{TX}^{Q}\right) < \gamma.$$

One-Hop Neighbor Knowledge: With one-hope information, transmitter i can decide which node is the best next hop by calculating the hold-off timer – similarly to (1) – as,

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

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 external-uncertainty region $\mathcal{U}_{ik}$ to take into account neighbors with predictable trajectories such as underwater gliders [8].

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. The pdf of $d_{ij}^{(\overrightarrow{\mathbf{v}})}$ is $f_{d_{ij}^{(\overrightarrow{\mathbf{v}})}}(d) = \int_{\|\overrightarrow{\mathbf{p}_i\mathbf{p}_j}\| = d, \mathbf{p}_i \in \mathcal{U}_{ii}, \mathbf{p}_j \in \mathcal{U}_{ij}} f_{\mathcal{U}_{ii}}(\mathbf{p}_i) f_{\mathcal{U}_{ij}}(\mathbf{p}_j)$, where $f_{\mathcal{U}_{ii}}()$ and $f_{\mathcal{U}_{ij}}()$ are the pdfs of i in internal-uncertainty region $\mathcal{U}_{ii}$, and j in $\mathcal{U}_{ij}$, 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 more simultaneous transmissions so that more area can be covered. The idea is that starting from j^*, i partitions its neighbors into sets $\mathcal{S}_m$ ($m = 0, 1, 2, \ldots, M$). Nodes within $\mathcal{S}_m$ can forward packets without colliding at i's neighbors. Moreover, nodes in $\mathcal{S}_m$ are scheduled to transmit earlier than nodes in $\mathcal{S}_{m+1}$. To avoid collisions, we require that there be no node that is within the statistical transmission range R of nodes in $\mathcal{S}_m$. 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 i itself). The remaining set of nodes not covered by the transmission of nodes in $\mathcal{S}_0$ can be calculated by $\mathcal{N}_{remain} = \mathcal{N}_i - \{k \mid \mathbb{E}[\|\overrightarrow{\mathbf{p}_j\mathbf{p}_k}\|] \leq R, j \in \mathcal{S}_0\}$. 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 process can be repeated to find $\mathcal{S}_M$ ($M \in \mathbb{N}$) such that $\mathcal{S}_{M+1} = \emptyset$ (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 $\mathcal{S}_1$, $\mathcal{S}_2, \ldots$.

Nodes in $\mathcal{S}_m$ ($m = 0, 1, 2, \ldots, M$) are set as forwarding nodes that will forward the geocasting packets to their neighbors. As transmitting a packet (short or not) takes a relative long time for existing underwater modems, 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 necessary to avoid the collision at i. So, i needs to schedule the transmissions of these nodes by putting the scheduling information in the geocasting packet. On the other hand, nodes in $\mathcal{N}_i - \sum_{m=0}^{M} \mathcal{S}_m$ will be set as non-forwarding nodes, which will only acknowledge the received geocasting packets but not forward. To geocast quickly the packets to the whole region, transmission of these acknowledgement packets is scheduled after the transmission of the forwarding nodes. As collisions may still happen at two-hop neighbors, we randomize the transmissions of the neighbors for collision avoidance.

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

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N_remain = N_i; Calculate T_hold's, and $\mathbb{E}[\|\overrightarrow{\mathbf{p}_j\mathbf{p}_k}\|]$'s;
while $\mathcal{N}_{remain} \neq \emptyset$ do
    $j^* = \arg\min_{j \in \mathcal{N}_{remain}} T_{hold}$; $\mathcal{S} = \{j^*\}$;
    for $k \in \mathcal{N}_{remain} - \mathcal{S}$ do
        $\mathcal{S} = \mathcal{S} \cup \{k\}$ where $k$ have no common neighbor
        except $i$ with nodes in $S$;
    end
    Add $\mathcal{S}$ to the end of $\mathcal{OS}$ if $\mathcal{S} \neq \emptyset$; Break if $\mathcal{S} = \emptyset$;
    $\mathcal{N}_{remain} = \mathcal{N}_{remain} - \{l \mid \mathbb{E}[\|\overrightarrow{\mathbf{p}_q\mathbf{p}_l}\|] \leq R, q \in \mathcal{S}\}$;
end
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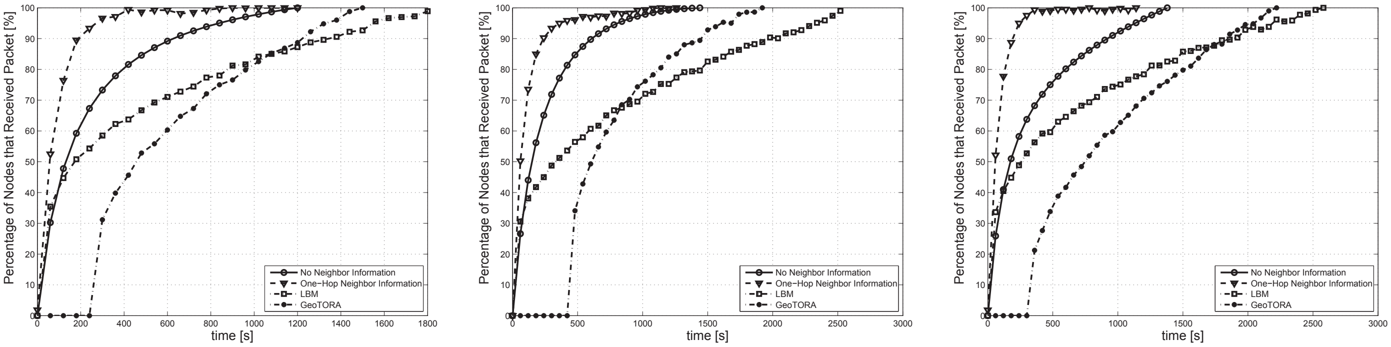
Scheduling of forwarding nodes: As the transmission time is T_{TX}^{Q}, collision between packets can be avoided if the time difference between reception of two packets at i is greater than T_{TX}^{Q}. Packets will arrive sequentially if the transmission time is delayed for some integer multiple of T_{TX}^{Q}. 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 be uniformly distributed in $[2T_P^{j^*} + |\mathcal{OS}| \cdot T_{TX}^{Q}, 2T_P^{j^*} + |\mathcal{OS}| \cdot T_{TX}^{Q} + (|\mathcal{N}_i| - |\mathcal{OS}|) \cdot T_{TX}^{ACK}]$. The sender will keep track of all the ACKs and overhearings it receives, 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 $R/\psi + 2T_P^{j^*} + |\mathcal{OS}| \cdot T_{TX}^{Q} + (|\mathcal{N}_i| - |\mathcal{OS}| + 1) \cdot T_{TX}^{ACK}$ so that it is long enough to hear from all its neighbors before it retransmits. Note that R/ψ and the extra T_{TX}^{ACK} are to offset the propagation delay and the transmission delay, respectively.

To de-synchronize the transmissions, an appropriate τ needs to be selected. We can formulate an optimization problem similarly to case 1. 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 $[d_{\min}^{i,j}/\psi, d_{\max}^{i,j}/\psi]$ with pdf $f_{T_{hold}^{j}}(t) = \int_{\|\overrightarrow{\mathbf{p}_i\mathbf{p}_j}\| = \psi t, \mathbf{p}_i \in \mathcal{U}_{ii}, \mathbf{p}_j \in \mathcal{U}_{ij}} f_{\mathcal{U}_{ii}}(\mathbf{p}_i) f_{\mathcal{U}_{ij}}(\mathbf{p}_j)$, 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. Rather than pre-computing τ as in case 1, calculation of τ can now be done *online* so to adjust dynamically as the network topology changes.

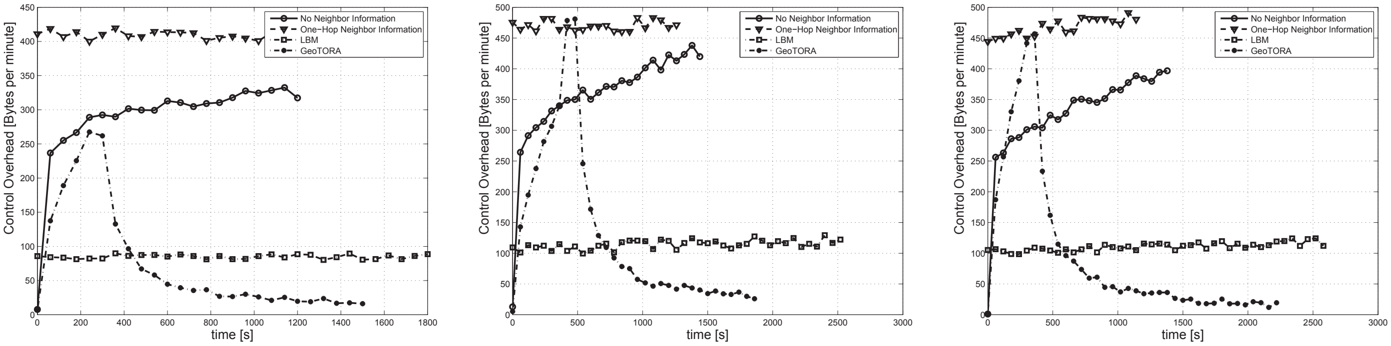


(a) Results using parameters in Setting I

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

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

Fig. 2. Comparison of reliability.



(a) Results using parameters in Setting I

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

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

Fig. 3. Comparison of control overhead.

IV. PERFORMANCE EVALUATION

Both versions of our proposed 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 based on the Bellhop model. Simulation parameters are set as: number of nodes = 100, $\overrightarrow{\mathbf{v}} = (10, 0, 0)$ 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 [8]. The communication parameters are based on the specifications and measurements of the WHOI acoustic modem.

We compare the performance of our solution with two well-known geocasting solutions that were originally designed for terrestrial wireless networks, i.e., the Location-Based Multicast (LBM) [2] algorithm and GeoTORA [3]. 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 the forwarding zone packets are discarded. Here we use the second scheme of LBM [2], 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], a unicasting algorithm 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 consider the propagation delay.

We compare the performance of the two versions of our solution with LBM and GeoTORA in the following scenarios: i) source node located in the base of the cylinder region; ii) different radius sizes of the geocasting cylinder; iii) different node densities; and iv) source node located in the middle of the cylinder region surface. In order to study the pros and cons, we are interested in the percentage of nodes that received the geocasting packet at a given time. At the same time, we also want to measure the control overhead of each algorithm. Simulation results for these metrics are plotted in Figs. 2, 3, 4, and 5. The following is observed:

1) As shown in Figs. 2 and 4, our one-hop version solution performs the best, i.e., it takes the least time to geocast to all nodes within the region. However, this comes at the price of the largest overhead due to the need to exchange location information between neighbors (Figs. 3 and 5). Our no-hop version solution uses the second least time to finish geocasting the region. Due to the use of the NOTICE packet, the overhead it uses ranks the second among these four algorithms.

2) LBM algorithm performs the worst – using 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. In this case, no control is needed to coordinate the nodes so the overhead is the lowest.

3) GeoTORA ranks the third among these four algorithms (Figs. 2 and 4). As it needs to use the TORA protocol to discover the geocasting routes, it waits the longest time before geocasting. Once the routes are discovered, the control overhead decreases as it is only needed when a route breaks (route maintenance). As GeoTORA does not rely on simple flooding, it has less collisions. Hence, its e2e geocasting delay is less than that for LBM. However, as propagation delay is not considered, it has more packet collisions than the two versions of our solution.

4) As shown in Fig. 4, it takes less time to finish geocasting from the middle of the cylinder region than from the base of the cylinder region, which is obvious since geocasting can be done in both directions along the cylinder. This confirms the intuition that it is better that the geocasting begins from the middle of the geocasting region. It also gives a guideline for unicasting the geocasting packet from the surface station to the geocasting region.

5) By doubling the node density, the number of neighbors also double. Hence, the probability of packet collisions may increase, leading to longer geocasting finish time, as confirmed by the simulation results (Figs. 2(c) and 3(c)). Similar results can be observed by halving the cylinder radius (Figs. 2(b) and 3(b)). Interesting enough, the increase of geocasting finish time for both versions of our solution is much less than for LBM and GeoTORA. This is due to the selection of appropriate τs to de-synchronize transmissions. The increase of geocasting finish time for the one-hop version is less than for the no-hop version since τ is computed online for the one-hop version. 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 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 increase in control overhead. Such situation is more severe in LBM and GeoTORA.

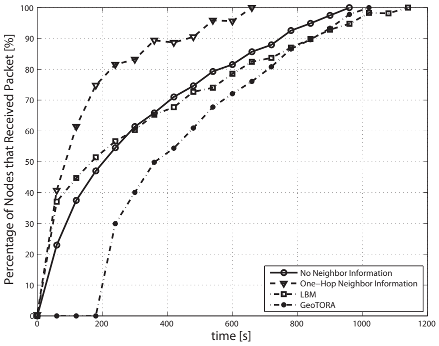


Fig. 4. Geocasting from the middle of the cylinder surface.

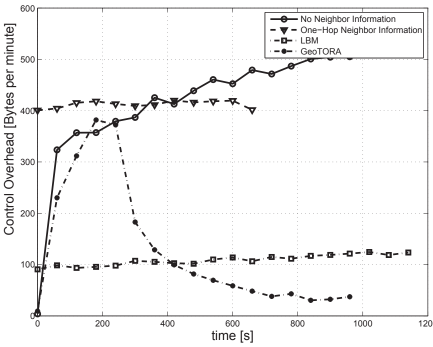


Fig. 5. Control overhead (geocasting from the middle of the cylinder surface).

In sum, 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 originally designed for terrestrial wireless networks.

V. CONCLUSION AND FUTURE WORK

We proposed two versions of geocasting solution for underwater acoustic sensor networks based on different degrees of neighbor information. Both versions of the proposed solution are implemented and tested via simulations, whose results show that higher reliability can be achieved when more neighbor information is available and that our solution performs better than LBM and GeoTORA, two well-known geocasting solutions originally designed for terrestrial networks. Future work will focus on implementing these solutions on the WHOI underwater acoustic modems, and on evaluating the performance in field experiments involving underwater gliders.

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