Signal Reflection-enabled Geographical Routing for Underwater Sensor Networks

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***Abstract*—The 3-D nature of the underwater environment has made geographical-routing a popular choice in underwater acoustic sensor networks (UW-ASNs). A geographical (geo) routing protocol works by using the position information to find the best route from a source to a destination. These algorithms, often try to minimize the line-of-sight (LOS) Euclidean distance between hops, which is not always possible due to blocked LOS paths resulting in voids (or local minimum). Thus, traditional geo-routing algorithms typically employ a face routing recovery scheme that allows for back-tracking when blocked LOS links are encountered, which adds delay to the data delivery time. To overcome this, we propose a geo-routing scheme that does not depend on the LOS and utilize directional antennas to incorporate surface-reflected non-line-of-sight (NLOS) links in the routing process. Furthermore, the proposed algorithm is configured to optimize the route selection to achieve maximum network throughput. Simulation results are provided to validate the performance of the proposed algorithm.**

Keywords*— geographical routing, Acoustic communication, underwater sensor networks

I. INTRODUCTION

Recent years have witnessed growing interest in the use of underwater acoustic sensor networks (UW-ASNs) in many applications. Examples of these applications include environmental state monitoring, oceanic profile measurements, tactical surveillance and navigation [1]. For these applications, it is envisioned that a set of sensor nodes will be employed to collaboratively monitor an area of interest and track certain events or phenomena. In addition, it is common to find autonomous underwater vehicles (AUVs) acting as mobile sensor nodes in search-and-rescue missions and coastal patrol and working cooperatively to achieve a desired goal [2]. These AUVs will need to corporate in an ad-hoc manner to be able to establish and sustain communication links in order to ensure some desired level of quality of service (QoS) [1][2]. Moreover, communications between nodes rely on acoustic channels instead of radio channels since radio waves quickly get absorbed in the water medium.

Establishing optimized paths for routing data packets is a very popular strategy for achieving the desired QoS, i.e., high throughput, as well as other design objectives, e.g., long lifespan [3]. In addition, the 3-dimensional nature of the underwater environment makes geographical (geo) routing a popular routing option since nodes can leverage the known position information in the routing process [3]. A geo-routing algorithm can either serve unicast, multicast, geocast or anycast. A geocast is a special case of multicast in which the recipients are collocated in specific geographical regions. Geocast is popular in sensors networks where queries can be disseminated to solicit data from nodes in some area or when the data is sent to a mobile sink whose trajectory is not precisely known. Anycast often serves applications in which multiple sinks exist and it is necessary to reach any of them.

Distributed geo-routing protocols often employ greedy forwarding techniques, whereby the packet is forwarded to the next hop closest to the destination node. Although this strategy simplifies the routing process, it is still prone to a local minimum. A local minimum is a node that is closest to the destination than any of its neighbors, but no link exists connecting the node to the destination due to blocked line-of-sight (LOS) paths. Furthermore, most geo-routing algorithms do not take into consideration the physical layer characteristics and antenna model as cross-layer optimizations in the routing process.

To address these concerns, we propose GORRILA, a geographical optimized reflection-enabled routing algorithm that is immune to link ambiguity. GORRILA aims to establish the best stable unicast route from a sender to a group of destination nodes within a specific geocast region as depicted in Figure 1. Unlike traditional Euclidean distance based routing protocols, GORRILA not only relies on the LOS link between one-hop neighbors when establishing routes but considers other reflected paths while routing packets to neighbors. GORRILA factors in two NLOS links (or eigenrays), which are the refracted-surface-reflected (RSR) and refracted-bottom-reflected (RBR) eigenrays. Utilizing

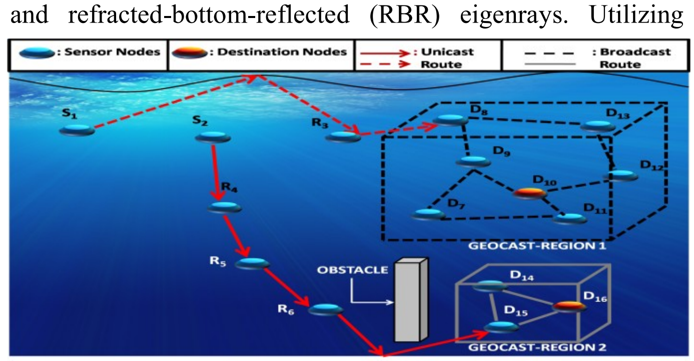

Figure 1: Underwater routing scenario showing the two geocast options from the source S_1 to the mobile destination D_{10} (dashed line), and the source S_2 to the mobile destination D_{16} (solid line). Our algorithm will be focusing on the unicast routes (red lines).

RSR or RBR links enables GORRILA to be robust to LOS link failures due to high network traffic or blocked paths that cause a packet to be trapped in a local minimum (i.e. voids) which has plagued most published geo-routing protocols. The main contribution of this paper can be summarized as follows:

(1) An optimized physical (PHY) and medium access (MAC) cross-layer design, which factors in underwater acoustic transmission loss effects to optimize the route selection for maximum network throughput.

(2) A novel GORRILA algorithm, which incorporates non-line-of-sight (NLOS) links in the routing process and utilizes directional antennas.

The remainder of the paper is organized as follows. In section II, we discuss the related work in the literature. In section III we go over the system model. The throughput optimizer is described in section IV while section V describes the proposed GORRILA protocol in detail. The approach is evaluated in section VI and section VII concludes the paper.

II. Related Work

Prior work on routing in UW-ASNs mainly focus on optimizing for energy consumption [3][4] or route robustness [5][6] with little attention given to optimize the network throughput. In [3], a vector-based forwarding (VBF) was used to compute the next hop of a traveling packet that essentially minimizes the traveling distance. VBF minimizes the number of forwarding nodes by adjusting the threshold of the minimum distance between two consecutive nodes on the route, which ultimately minimizes the network energy. An extension to the VBF algorithm was given in [5], which stores the routing vector on each forwarding node rather than a network-wide routing vector to increase redundancy. This allows each node to adaptively make packet forwarding decisions based on its current location, and thus enhancing data delivery ratio in sparse networks.

A depth-based routing scheme was proposed in [4]. The approach is to use the depth information of each node to route packets to the desired destination node on the water surface. Hence, this approach can only route packets floating sink nodes. In [6], the authors proposed three reliable data delivery mechanisms for UW-ASNs. The first method does not require any position information about the neighbors and uses a limited-flooding technique to get to the destination. The second method assumes that the transmitting node has one-hop neighborhood information. In this case, the sender will insert in the packet the ID of its next hop node that is closest to the destination. The last method assumes that the transmitting node has two-hop neighborhood information which enables the node to avoid collisions within one- and two-hop distances. Our proposed GORRILA algorithm differs from [6] in two aspects; first our approach assumes k-hop neighborhood information, where k is the estimated number of hops to the destination node, and second our routing mechanism optimizes the route to achieve maximum network throughput.

III. SYSTEM MODEL

Utilizing NLOS (e.g., reflected) links would overcome many of the challenges in forming data paths among nodes in UW-ASNs. Basically, the NLOS links will enable robustness by overcoming obstacles and noisy LOS links. Moreover, it will boost the simultaneity of the transmissions and minimizes interferences among the different paths. In this section we highlight the potential of multi-hop routing with directional antennas when utilizing NLOS links. Given the lack of GPS and anchor information in the networking scenario in Figure 1, we have adopted an anchor-free relative localization scheme [8], which we employ to support geographical routing and directional communication.

A. *Multi-hop with Directional Antennas*

As mentioned earlier, utilizing NLOS will allow for simultaneous communication. To illustrate, let us consider Figure 2, where k_{LOS} is the LOS transmission range. With omni-directional antennas, multiple simultaneous transmissions cannot occur when nodes are within each other's transmission range. As shown in Figure 2-(a), while the transmissions $(B \rightarrow C \rightarrow E)$ are taking place, node D cannot send packet to node F since it will interfere with the ongoing packet traffic. With directional antennas, in Figure 2-(b), two simultaneous multi-hop transfers $(A \rightarrow B \rightarrow C \rightarrow E)$ and $(D \rightarrow F)$ can take place, which increases overall network throughput. Figure 2-(c) shows that NLOS links can enable unique simultaneous multi-hop transfer scenarios by bypassing node B, which is the destination on another path. The scenario in Figure 2-(c) is not feasible with omni and LOS-directional transmissions.

IV. PHY/MAC CROSS-LAYER OPTIMIZER

In this section we will go over acoustic transmission loss and present PHY/MAC layer based optimization will be employed by the GORRILA algorithm in selecting data paths that maximize the network throughput.

A. *Acoustic Transmission Loss*

The slow propagation delay in the underwater channel makes PHY/MAC optimization a challenge. According to [7] the sound speed (c) is dependent on the temperature (T) in degrees centigrade, salinity (S) in parts per thousand, and depth (z) in meters. This can be expressed mathematically as:

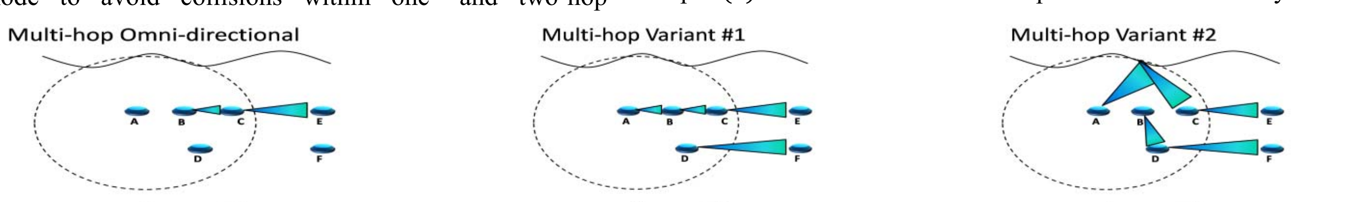

Figure 2: (a) Multi-hop with omni-directional antennas. k_{LOS} is the line-of-sight transmission range, shown for node A. (b) Multi-hop with directional antennas enables multiple simultaneous transmissions (c) Enabling reflections while using directional antennas yields an increase in simultaneous transmissions

$$c = 1449.2 + 4.6T - 0.055T^2 + 0.00029T^3 + (1.34 - 0.01T)(S - 35) + 0.016z \tag{1}$$

In general, there are three main causes of transmission loss in an underwater environment which are transmission loss due to multipath attenuation effects (TL_{MULT}), transmission loss due to spherical geometric spreading(TL_{SGP}) and transmission loss due to plane-wave attenuation, i.e. absorption (TL_{WAVE}). The total transmission loss in decibels can be expressed mathematically as:

$$TL_{TOTAL} = TL_{MULT} + (TL_{SGP} + TL_{WAVE})$$

$$TL_{TOTAL} = TL_{MULT} + TL_{LOS} \quad [dB] \tag{2}$$

where we have now grouped the spherical geometric spreading TL_{SGP} and plane-wave TL_{WAVE} transmission loss to what we define as the line-of-sight (LOS) transmission loss TL_{LOS}. In shallow water most of the transmission loss is due to the attenuation from multipath effects. The LOS transmission TL_{LOS} (in dB) has the following frequency-distance dependent relationship:

$$TL_{LOS} = s \cdot 10\log(d) + \ d \cdot 10\log\alpha(f) \quad [dB] \tag{3}$$

where $s = 2$ is the spherical spreading factor, f is the frequency (in kHz), $\alpha(f)$ is the attenuation due to absorption in units of dB/km and $d = k_{LOS}$ is the LOS transmission range in meters. The multipath transmission loss TL_{MULT} can be determined by modeling the shallow water environment as a homogeneous fluid-fluid media where the top layer is the water layer and the bottom layer is the oceanic bottom in a shallow water environment. In the water layer the parameters $\{c_w, p_w, \theta_w\}$ corresponds to the speed of sound (in m/s), the density (in kg/m^3) and grazing angles (in radians). The same applies for the parameters $\{c_b, p_b, \theta_b\}$ in sea bottom. Hence, using Snell's Law we have:

$$R = \frac{p_b c_b/sin\theta_b - p_w c_w/sin\theta_w}{p_b c_b/sin\theta_b + p_w c_w/sin\theta_w}$$

$$\acute{R}_{bottom}(\theta) = Re^{-0.5\Gamma^2} \tag{4}$$

$$\acute{R}_{water}(\theta) = -e^{-0.5\Gamma^2} \tag{5}$$

$$TL_{MULT}(\theta) = \begin{cases} -10\log\left(\left|\acute{R}_{water}(\theta)\right|^2\right) & RSR \\ -10\log\left(\left|\acute{R}_{bottom}(\theta)\right|^2\right) & RBR \end{cases} \tag{6}$$

where R is the reflection coefficient for a flat bottom such that $\Gamma = 2k\sigma_{RMS}sin\theta$. The Raleigh roughness parameter Γ depends on the wavenumber $k = 2\pi f/c$, for sound speed of $c = c_w$ or c_b. Given the expression (6) for the multipath transmission loss we can now derive the received power as:

$$P_{RX} = P_{TX} \cdot A(d, f, \theta) \cdot G(\theta) \tag{7}$$

For $A(d, f, \theta) = 10^{\frac{TL_{TOTAL}}{10}} = d^2\alpha(f)^d\left(\acute{R}(\theta)^2\right)^{-1}$, where $\acute{R}$ is the reflection coefficient for the rough water bottom or surface in (4) and (5) respectively for an antenna gain of $G(\theta)$ and a transmission power of P_{TX}. We can further define the antenna gain $G(\theta)$ at the beam steering angle $\theta = \theta_s$ and for an array gain of AG as:

$$G(\theta) \cong \begin{cases} AG, & Omnidirectional\ Antenna \\ DI(\theta = \theta_s), & Directional\ Antenna \end{cases} \tag{8}$$

The directivity index of a directional antenna at the beam steering angle θ_s can be expressed as: $DI(\theta_s) = 10 * \log\left(D(\theta_s)\right)$ with directivity $D(\theta_s) = 4\pi/\Omega(\theta_s)$. $\Omega(\theta_s)$ is the beam area depending on the antenna pattern at the beam steering angle $\theta = \theta_s$. In the next subsection, we derive expressions for the network throughput optimizer that will be based on the received power expression in (7).

B. Throughput Optimizer

The network throughput optimizer starts by deriving the saturation throughput for a PHY/MAC cross-layer utilizing the CSMA/CA protocol. According to [9] the CSMA/CA saturation throughput is defined in as the ratio of the average payload transmitted during one slot to the average slot duration as shown:

$$TH = \frac{\text{Average payload transmitted during one slot}}{\text{Average slot duration}}$$

$$TH = \frac{p_{tr}p_s E[P]}{(1 - p_{tr})\sigma + p_{tr}(1 - p_s)T_c + p_{tr}p_s T_s} \tag{9}$$

such that $E[P]$, T_c, T_s and σ correspond to the average payload size, the average collision duration, the average successful transmission duration, and the duration of an empty time slot. p_{tr} and $p_s$correspond to the probability that at least one node is actively transmitting and the probability of a successful transmission, respectively. From [10], the probability of a successful transmission p_s can be calculated from p_{tr} , the outage probability p_o and the capture probability for N contending nodes $p_{CAP}(N)$ as:

$$p_s = \frac{\Pr\{\text{The frame RSS} > threshold\} + \Pr\{\text{The frame is captured}\}}{p_{tr}}$$

$$p_s = \frac{N\tau(1-\tau)^{N-1}(1-p_o) + p_{CAP}(N)\left(1-(1-\tau)^{N-1}\right)}{p_{tr}} \tag{11}$$

If the CSMA/CA MAC implements a constant back-off mechanism with a window size of W for N contending node where $\tau = 2/(W+1)$, p_{tr} can be easily calculated as

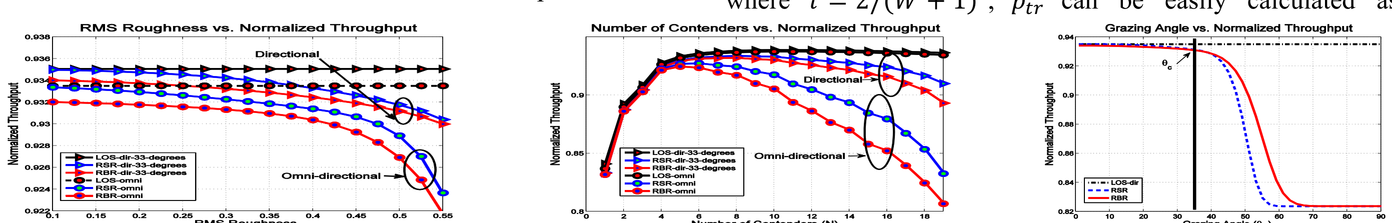

Figure 3: (a) RMS roughness effect on the normalized throughput

(b) Effects of the network density on the normalized throughput for omni and directional antennas

(c) Plot showing that utilizing reflected links will sustain the throughput so long as $\theta_w \leq \theta_c$

$$p_o = \Pr\left\{\frac{\mathrm{P_{RX}}y}{\mathrm{N_T}} < \mathrm{z_T}\right\} = \Pr\left\{\mathrm{y} < \frac{\mathrm{z_T N_T}}{\mathrm{P_{TX}}}\left(A(d,f_c,\theta)\right)^{-1} G(\theta)^{-1}\right\} = \Pr\left\{\mathrm{y} < \frac{\mathrm{z_T N_T}}{\mathrm{P_{TX}}}\left(d^2\alpha(f_c)^d\left(\acute{R}(\theta)^2\right)^{-1}\right)^{-1} G(\theta)^{-1}\right\} \tag{12}$$

$$p_{CAP}(N) = \mathrm{N}\cdot\Pr\left\{\mathrm{y_1} > \mathrm{z_T}\sum_{\mathrm{i}=2}^{\mathrm{N}}\frac{A(d_i,f_c,\theta_i)G(\theta_i)}{A(d_1,f_c,\theta_1)G(\theta_1)}\mathrm{y_i}\right\} = \mathrm{N}\cdot\Pr\left\{\mathrm{y_1} > \mathrm{z_T}\sum_{\mathrm{i}=2}^{\mathrm{N}}\frac{d_i^2\alpha(f_c)^{d_i}\left(\acute{R}(\theta_i)^2\right)^{-1}G(\theta_i)}{d_1^2\alpha(f_c)^{d_1}\left(\acute{R}(\theta_1)^2\right)^{-1}G(\theta_1)}\mathrm{y_i}\right\} \tag{13}$$

$p_{tr} = 1-(1-\tau)^N$. From Equation (11) we see that the probability of a successful transmission will be dependent on two probabilities which are the outage probability and the capture probability. These values are defined for a shallow water environment as depicted in (12) and (13), respectively. The outage probability determines the probability that the received signal strength of a packet is lower than the required threshold due to large propagation attenuation, while the capture probability defines the probability that the received signal power of the data frame exceeds the interference power of the frames from other contending nodes (N-1). Thus, we see that both probabilities are derived by incorporating the received power $\mathrm{P_{TX}}$ for a shallow water environment as defined in (7), where $\mathrm{N_T}$ is the noise level, $\mathrm{z_T}$ is the signal-to-nose (SNR) threshold and f_c is the carrier frequency. y is a random variable with unit power and is modeled after a Raleigh distribution. The normalized network throughput is depicted in Figure 3 for different surface roughness σ_{RMS}, contending nodes N and grazing angles to the water surface θ_w. We see that in all cases, utilizing directional antennas will boost the normalized network throughput. Most importantly, we see that the inclusion of NLOS links, namely RSR and RBR, will sustain the LOS throughput so long as the grazing angle to the surface is less than the critical angle θ_c as depicted in Figure 3–c. Hence, the *Throughput-optimizer* selects the best next-hop neighbor that will maximize the network throughput. Each routing node R_i will start by determining the subset of next-hop candidate nodes $H \subset S$ that advance towards the destination node D_j for $S = (S_1, S_2, \ldots, S_N)$ and $i \neq j$ as:

$$H_j = S_j\big|_{distance(S_j,D_j)<distance(R_j,D_j)} \tag{14}$$

The routing node R_i then selects the next-hop node H_j that maximizes the localized network saturation throughput. Thus, the next-hop node will be obtained from N possible nodes as shown:

$$H_j = max\big(TH(H_1), TH(H_2), \ldots TH(H_N)\big) \tag{15}$$

V. GORRILA ALGORITHM

GORRILA is composed of two stages. In the first stage the algorithm is executed in the source node S_i and in the second stage it is executed by every node along the path to the destination. In stage 1, the source node performs a k-hop node discovery to obtain the positions and movement information of all k-hops neighbors. This is done by incorporating a surface based reflected anchor-free localization (SBR-AL) scheme [8]. After obtaining the position information, the node will then determine the geocast region R (cubic boundary) centered on the destination node D_j, based on the node degree and movement information (speed and direction) of the destination. In stage 2, the packet gets routed to R using an optimized unicast routing mechanism described in the balance of this section. The unicast route will be optimized for maximum network throughput using (15). Once inside the geocast region, the packet is then broadcasted to all nodes within that region until it gets to the destination mode D_j.

Unicast Routing with Localized Delaunay Triangulation: Given that we know the position of nodes k-hops away, one can construct a planar graph from the position information to be used for unicast routing. A planar graph is a graph whereby no two edges intersect each other except at a vertex (or end point). The construction of a planar graph is important, especially when face routing is needed to recover from voids [11]. Periodically, each node will need to construct a planar graph from the k-hop location information to be used in the GORRILA routing protocol. In 3D, the planar graph is constructed through Delaunay tessellation, denoted by $\mathrm{Det(V)}$, which determines the set of tetrahedrons such that none of the points (or vertices) in V are contained in any of the circum-spheres of the tetrahedrons. To simplify the presentation, our analysis focuses on the 2D planar graph representation, namely $\mathrm{Del(V)}$, where we have adopted the divide-and-conquer approach [12] to construct the $\mathrm{Del(V)}$ subgraph in $\mathrm{O(N\,logN)}$ time. Although the $\mathrm{Del(V)}$ triangulation is a planar graph, a major drawback in applying it in an ad hoc network is that it cannot be constructed locally since some edges of the Delaunay triangulation could exceed the transmission range. We overcome this by defining a new graph structure namely a *k-localized Delaunay graph* (LDeL^k) as demonstrated in [11].

When creating the LDel(V) graph from the location information of the nodes k-hops away, the node S_i will also need to know of any obstacles blocking the LOS links and adjust the LDel(V) graph accordingly. We refer to the inclusion of reflection points in the localized Delaunay triangulation as the $\mathrm{LDel_R(V)}$ planar graph. Recall from Figure 1 the LOS links may be blocked due to an obstacle or an unknown node, to account for this the node S_i building the $\mathrm{LDel_R(V)}$ graph will determine which LOS links are blocked from the information obtained from network-discovery (stage 1) and calculate reflection points to the water surface and bottom to be used as temporary reference vertices in the $\mathrm{LDel_R(V)}$ graph by applying the SBR-AL technique [8]. After creating the planar graph, each routing node R_i will apply (15) to select the next-hop that maximizes the network throughput.

VI. GORRILA EVALUATION

In this section we validate the performance of the GORRILA routing algorithm. The simulation experiments were conducted using MATLAB with the underwater and PHY/MAC parameters described in Table 1. The underwater environment is represented as a cube with dimensions of 200m x 200m x 200m, where the water bottom is modeled as a rough surface with a silt-like material (i.e.$p_b/p_w = 1.7$). The water surface is also modeled as a rough surface with σ_{RMS}

approximately 0.5. We then randomly place N nodes in the underwater environment and up to B=40 obstacles that will block the LOS links between some nodes. Thus, some nodes will have LOS links available while other nodes will need to use NLOS links (i.e. RSR or RBR). Results are shown for both omni-directional and directional antennas. We then compare the network the throughput performance to the well-known greedy perimeter stateless routing (GPSR)[13], where we focus on the unicast performance with stationary nodes. Finally, we report the results where we observe that within a 90% confidence level the network saturation throughput stays within 10% of the sample mean. Other metrics, e.g. delay and energy, were considered but could not be included due to space constraints.

Figure 4-(a) shows a plot of the throughput per-hop of the GORRILA algorithm for a network size of N=20, from source S_{12} to destination D_2, where we notice that utilizing directional antennas increases the throughput-per-hop due to an increase in the signal-to-interference-ratio (SIR). More importantly, we see that regardless of the antenna variant, GORRILA maintains a steady throughput at each hop due to its throughput optimization process. Figure 4-(b) shows the performance of the GORRILA algorithm in comparison with the GPSR algorithm. We see that GORRILA maintains a higher network throughput than GPSR, especially when the network density is high (N > 20). At higher network densities the probability of collisions increases, leading to lower network throughput when greedy routing is employed which is not the case with GORRILA. Furthermore, the inclusion of reflected links will provide an optional hop so long as the reflected link (RSR or RBR) will sustain the LOS throughput as pointed out in Figure 3-(c). Lastly, we see that when utilizing directional antennas the GORRILA algorithm far exceeds the greedy algorithm which is expected.

VII. Conclusion

In this paper we have introduced a novel geographical routing algorithm for UW-ASN that is not dependent on the line-of-sight (LOS) but utilizes reflected links in the routing process. The proposed geographical optimized reflection-enabled routing immune to link ambiguity (GORRILA) algorithm aims to establish the best stable route from a source to a destination node. The route is also optimized to achieve the maximum network throughput. Furthermore, GORRILA can also utilize directional antennas, which boost the network throughput. Results show that the GORRILA algorithm outperforms the traditional greedy algorithm since it maintains a high network throughput at each hop during the routing process. Thus, GORRILA can be used to sustain the desired quality-of-service (QoS), i.e. network throughput.

k_{LOS}	θ_s	$c_w\ (m/s)$	$c_b\ (m/s)$
100m	30°	1500	1800
u(bps)	z_T	$p_w\ (kg/m^3)$	$p_b\ (kg/m^3)$
1000	-1dB	1000	1700
P_{TX}	N_T	f_c(kHz)	W
20dB	-90dB	1	100
RTS(bits)	CTS(bits)	P(bits)	ACK(bits)
100	100	5200	100

Table 1: Simulation parameters

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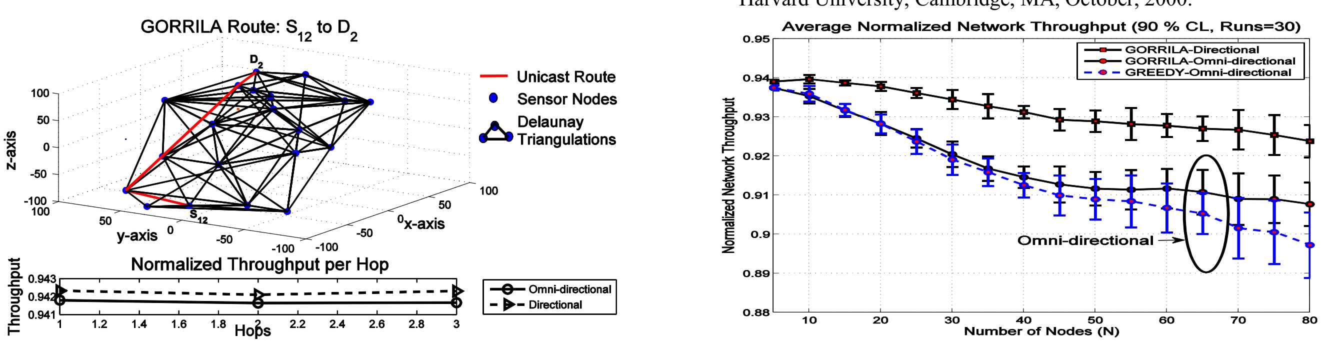

Figure 4: (a) 3D plot of unicast route (red-line) with the throughput-per-hop.

(b) Effect of increasing the network density on the normalized throughput