PAPER

Ray-model-based Routing for Underwater Acoustic Sensor Networks Accounting For Anisotropic Sound Propagation

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SUMMARY In classical routing protocols, geographical distances/locations are typically used as the metric to select the best route, under the assumption that shorter distances exhibit lower energy consumption and nodes within the communication range of the sender can receive packets with a certain success probability. However, in underwater acoustic sensor networks (UASNs), sound propagation in the ocean medium is more complex than that in the air due to many factors, including sound speed variations and the interaction of sound waves with the sea surface and floor, causing the sound rays to bend. Therefore, propagation of sound is anisotropic in water, and may cause a phenomenon called shadow zone where nodes in the communication range of the sender cannot hear any signal. This renders conventional routing protocols no longer energy-efficient. In this paper, we make use of the ray-model to account for the environment-dependent behavior of the underwater channel, re-define nodes' one-hop neighbors based on signal attenuation rather than geographical distance, and design a distributed energy-efficient routing protocol for UASNs. Results show that our ray-model-based routing policy consistently outperforms the shortest path policy, and performs very close to the optimal one in several scenarios.

key words: *Energy-Efficient Routing, Underwater Acoustic Sensor Networks, Geographical Distance, Ray Model, Anisotropic Propagation.*

1. Introduction

In the early 1970s, earth geology studies, oceanic life studies and studies on how to defend against seaborne invasion spawned much research on underwater acoustic sensor networks (UASNs). Routing is an indispensable part of such networks. Moreover, since UASNs are always powered by batteries, which are costly to recharge or replace, a critical consideration for the routing protocol design is the energy consumption. Energy-efficient routing in terrestrial networks has been studied intensively and many algorithms have been proposed. However, the peculiar properties of the underwater medium make existing routing protocols inappropriate for UASNs, and it is necessary to design and develop new routing algorithms.

Given the similarity of the broadcasting channel in wireless networks and UASNs, many pioneering work of UASN routing protocol borrowed ideas from wireless networks, including geographical routing, energy-efficient routing, and reactive routing. Some even considered the special characteristics of the water medium. Xie et al. [1] propose a location-based routing protocol for UASNs, namely, Vector-Based Forwarding Protocol (VBF). In VBF, a "routing pipe" is established between the source and the destination nodes and the packet delivery is along this pipe. All nodes that receive a packet compute their positions recursively. If a node determines that it is close to the routing vector according to a predefined distance threshold value, it places its own position into the packet and continues forwarding; otherwise it discards the packet. Yan et al. [2] propose a Depth-Based Routing (DBR). DBR assumes all nodes to be equipped with a pressure gauge from which the current depth can be estimated: routing is then performed by looking for relays at progressively shallower depths, so as to advance the packet towards the sea surface. Gopi et al. [3] propose a layering-based routing protocol for UASNs. It has two phases. The first phase corresponds to a layering process in which concentric spheres are formed around a sink and each sphere corresponds to one of the layers. The selection of the intermediate nodes and the data delivery from the source to the target takes place in the second phase. Zorzi et al. [4] are the first to carry out analysis of the bandwidth-distance relationship and distance-and-frequency-based attenuation of underwater acoustic signal propagation on energy-efficient routing design for UASNs. They use a simple empirical channel model to observe an optimal hop distance, and develop routing algorithms where relays are chosen to provide a hop length close to the optimum. In [5], Nguyen et al. propose a shadow zone and delay-aware routing (SZODAR), in which sensor nodes raise or lower their acoustic transceivers to a depth such that shadow zones of the neighboring nodes are avoided. When a node decides to move its transceiver, it starts a stepwise movement. The step length is a critical engineering parameter, and must be selected carefully. If it is too long, the node may move transceivers unnecessarily, and may even move the transceivers from one shadow zone to another. On the other hand, if it is too short, the node has to check frequently whether or not it can communicate with the sender. Both cases cause unnecessary power consumption and delay.

However, the influences of spatial configurations of underwater acoustic communication links on channel quality (see [6] and [7]) have not been incorporated in the previous routing designs. Moreover, since sound refraction varies from day to day and from season to season, keeping the routes fixed is not the best strategy because of time-varying

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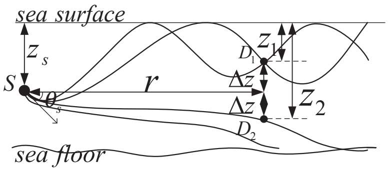

Fig. 1 Sound propagation in inhomogeneous ocean medium

propagation effects, and even infrequent route updates (once every three hours) achieve much better results than static routes [8]. Therefore, routing policies that are fixed and use only the geographical distance to select the next relayer will suffer deteriorated performance when applied in a realistic UASNs.

Our study stems from the idea that the different sound refraction effects observed under different spatial configurations require specific routing approaches. The main contribution of this work is to make use of the transmission losses computed by the ray-model (which stresses all these features of underwater acoustic propagation) instead of traditional geographical distances (such as communication range, or optimal hop-distance [4]), to re-define the neighbor node set, and apply it into energy-efficient routing protocol design for UASNs, thus avoiding the selection of a relay node that lies in the communication range in terms of geographical distance but is unreachable by the sender†. Furthermore, performances of our ray-model-based energy-efficient routing algorithms are tested by a set of simulations in a three-dimensional network under several configurations.

The remainder of this paper is organized as follows. In Section II, the anisotropic propagation of sound is introduced, and one specific example is used to show the influences of source and receiver locations in the water column on communications performance. The network model, energy consumption model, and neighbor node model are introduced in Section III. In Section IV, we develop the ray-model-based routing algorithms, and compare them with standard geographical distance-based routing approaches such as shortest path and optimal hop-distance based routing, as well as the centrally computed minimum-energy benchmark in Section V. Finally, we conclude with suggestions on future research in Section VI.

2. Anisotropic Propagation of Sound

Propagation of sound is complex due to the varying speed of sound within the water medium and reflections from the sea surface and/or ocean floor, resulting in dramatic differences

†In particular, our work is similar to the routing designed for wireless ad hoc networks in [9], which exploits the expected transmission count metric (ETX) to account for the link loss ratios and interference among the successive links of a path. The main difference is that our work focuses on tackling the anisotropic characteristic of underwater communication by using the transmission loss metric to design energy-efficient routing, while [9] finds paths with the fewest ETX to deliver a packet all the way to its destination to improve throughput.

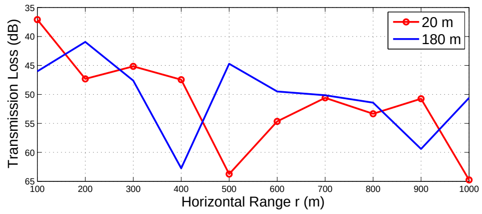

Fig. 2 Transmission Losses under Different Configurations

in acoustic channels with various configurations [10].

As shown in Fig. 1, for a source node S located at a depth of z_s m, there are two receiver nodes D_1 and D_2, located at depths of z_1 and z_2 m, respectively. It is obvious that, although the geographical distances for $S\vec{D}_1$ and $S\vec{D}_2$ are both $\sqrt{r^2 + \triangle z^2}$, the arrival rays at D_1 and D_2 are quite different, generating different received signals at the two receiver nodes. As a result, the sound propagation in the sea is always anisotropic. In this paper, the ray tracing method [11] is used to model the anisotropic propagation of sound. Specifically, the BELLHOP beam tracing program [12] is used to compute the transmission loss, which is the standard quantitative measure in underwater acoustics of the change in signal strength with range, denoted TL. Fig. 2 shows how transmission loss TL varies with horizontal ranges r for two link configurations ($S\vec{D}_1$ and $S\vec{D}_2$ shown in Fig. 1), where the source node is located at a depth of 100 m, and two receivers are located at depths of 20 m and 180 m, respectively. The sound speed profile adopted in this calculation is observed in the ocean near Santa Barbara, California, USA (at a depth of 216 m). The speed varies from 1500 to 1487 m/s [12]. Fig. 2 shows that the transmission loss curves are not monotonically increasing. This is because the summation of multi-path signals at the receiver may exhibit constructive or destructive superposition. Besides, Fig. 2 shows that although the geographic distances for two kinds of link configurations are kept the same, the transmission losses are always different, reflecting sound's anisotropic propagation characteristics in the water medium. Moreover, there is a phenomenon caused by the anisotropic propagation of sound, namely shadow zone, where there is little signal propagation energy due to the refraction of signals by the sound speed fluctuation [13].

Based on the above observations, routing policies that take anisotropic propagation of sound into account will be designed in this paper. We focus on the phenomenon that anisotropic propagation of sound may threaten underwater communication reliability and energy efficiency, and propose distributed adaptive routing schemes that make use of anisotropic propagation of sound and avoid choosing nodes in shadow zone for three-dimensional UASNs.

3. The basic system model

3.1 Network Model

Fig. 3 shows the architecture of an UASN of interest in this

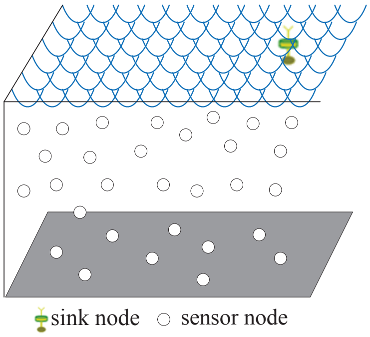

Fig. 3 Architecture of Underwater Acoustic Sensor Network

paper. It is three-dimensional and used to detect phenomena that cannot be adequately observed by a two-dimensional model. One sink is deployed on the water surface, and is equipped with acoustic and radio modems. The acoustic modem is used to communicate with underwater sensor nodes and the radio modem is for onshore communications. Sensor nodes are anchored to the bottom of the ocean and equipped with a floating buoy that can be inflated by a pump. The buoy pushes the sensor towards the ocean surface by means of an electronically controlled engine that resides on the sensor [15].

It is assumed that sensors should be able to relay information to the surface sink hop by hop. Every node knows its own location, the sink node's position and its one-hop neighbor nodes' positions[†].

3.2 Energy Consumption Model

The energy consumed by underwater sensor nodes is the sum of the energy consumed for transmitting, receiving and listening. Specifically, for each specific acoustic modem interface, the received energy is fixed (take the Woods Hole Oceanographic Institution (WHOI) micro-modem as an example [18], which has a few Watts of receive power). Additionally, the difference in energy consumption between receive and idle modes for acoustic modems can be an order of magnitude or more [18], whereas for radio modems they are nearly identical [19]. Therefore, in the following, we will focus on transmit energy consumption of an L-bit packet from a node i located at coordinates (x_i, y_i, z_i) to a receiver node j with coordinates (x_j, y_j, z_j).

Firstly, the passive sonar equation in [10] is used to characterize the signal to noise ratio (SNR) of a transmitted underwater signal from node i at the receiver j, denoted as SNR_{ij}:

$$SNR_{ij} = SL_i - TL_{ij} - NL + DI, \tag{1}$$

where SL_i is the source node i 's acoustic pressure level, TL_{ij} is the transmission loss, NL is the noise level, and DI is the directivity index. All the quantities in Eq. (1) are in dB re μPa. Specifically, SL_i relates to the transmitted signal intensity I at 1 m from the source according to the following expression:

$$SL_i = 10\lg \frac{I}{1\mu Pa}, \tag{2}$$

where I is in μPa. Solving for I yields:

$$I = 10^{SL_i/10} \times 0.67 \times 10^{-18}. \tag{3}$$

in $Watts/m^2$, where the constant 0.67×10^{-18} converts μPa into $Watts/m^2$ [10].

Thus, the transmit power $P_{tr,i}$, which is required to achieve intensity I at a distance of 1 m from the source in the direction of the receiver is

$$P_{tr,i} = 2\pi \times 1m \times H \times I, \tag{4}$$

where $P_{tr,i}$ is in watts, and H is the water depth in m.

In this analysis, we assume omnidirectional hydrophones are used, and DI is 0. The ambient noise in the ocean is primarily from four different sources: turbulence, shipping, waves, and thermal noise, and the overall power spectral density (p.s.d.) of the noise depends on the carrier frequency [10]. Here, as reported in [10], an average value 70 dB for the ambient noise level NL is used, for simplicity of analysis, as a shallow water representative case. Moreover, in this paper, an orthogonal frequency division multiplexing (OFDM) system combined with low density parity check (LDPC) code is used over underwater acoustic channels, and a target SNR of 15 dB at the receiver is required for a given performance objective. Here the bit error rate of 10^{-3} is required [20]. Therefore, based on Eq. (1), Eq. (3), and Eq. (4), the transmit power can be further written as

$$P_{tr,i} = 2\pi \times H \times 10^{(TL_{ij}+85)/10} \times 0.67 \times 10^{-18}, \tag{5}$$

where TL_{ij} is computed based on the BELLHOP beam tracing program [12].

In short, we have presented a method to obtain the required transmitter power $P_{tr,i}$ for signal transmissions through a specific link l_{ij} connecting node i with coordinates (x_i, y_i, z_i) and node j with coordinates (x_j, y_j, z_j). First, we can compute the transmission loss TL_{ij} based on the BELLHOP beam tracing program and subsequently compute the source level SL_i, which yields the source intensity I. Finally, we can compute the corresponding transmit power $P_{tr,i}$ needed to achieve a source intensity of I.

Furthermore, given the received power is distance-independent and is fixed for a particular interface [18], the energy consumption for link e_{ij}, denoted as E_{ij}, (it is the weight for link e_{ij}), can be written as

$$E_{ij} = \frac{(P_{tr,i} + P_r) \times L}{B}, \tag{6}$$

where L is the length for a packet in bits, and B is the available data rate in bps.

3.3 Transmission Loss based Neighbor Node Model

Traditionally, one node is assumed to be another node's

[†]How this information is gained is beyond the scope of this paper. However, there has been recent work on localization for underwater nodes [16], [17].

neighbor if and only if it is within the communication range of that node. The potential area (or volume) covered by the neighbor node set is round (or a sphere). However, as discussed in Section II, due to anisotropic propagation of sound underwater, the distance-based definition of the neighbor node is inadequate for UASNs. The existence of shadow zone may render a node which lies within the communication range of a node unable to communicate with the node.

In our study, we propose a Transmission-Loss-based Neighbor Node Model (TLNNM), where one node is another node's neighbor if the transmission loss between them is less than a threshold TL_{th}. Further, we define sender i's Transmission-Loss-based Neighbor Node Set NS_i^{TL} as $NS_i^{TL} = \{j \mid TL_{ij} \leq TL_{th}\}$, where TL_{ij} is the transmission loss for the link connecting Node i to Node j. In a specific network scenario, TL_{th} is dependent upon the maximal available transmit power, the noise level, and the minimal required SNR. Specifically, based on Equation (5), the maximal value of TL_{th}, denoted as TL_{th}^{max}, can be calculated as

$$TL_{th}^{max} = 10\lg\frac{P_{max}}{2\pi\times H\times 0.67\times 10^{-18}} - 85, \qquad (7)$$

where P_{max} is the available maximal transmit power for a sensor node. It is noted that TL_{th} is a tunable constant which satisfies $TL_{th} \leq TL_{th}^{max}$. We will evaluate its influence on routing protocols in Section V.

4. Ray-model-based Energy-efficient Routing

4.1 Overview

In underwater acoustic sensor networks, two nodes cannot communicate although they are within the transmission range if they are in the shadow zone of each other. In this section, we use the TL-based Neighbor Node Model defined in Section 3.3 to design routing protocols to address this problem. Our proposed ray-model-based routing protocols are distributed and heuristic, and quite easy to implement in practice: local information (i.e., positions of itself, the final destination, and its neighbors, which can be obtained by proper handshaking messages and positioning techniques). With the data collected from the environment and neighboring nodes, each node in our proposed routing protocol chooses the next relayer based on the transmission loss value according to the analysis of Section 3.3. In other words, our routing scheme exploits quantitative information about the behavior of the underwater channel, to choose the next hop toward the destination, thus avoiding selecting a relay which lies in a shadow zone.

4.2 Protocol Details

4.2.1 Neighbor Information Maintenance

Each node periodically broadcasts a *Hello* packet, including its node ID and the coordinate information. Meanwhile, each node keeps listening to the *Hello* packet generated by its neighbors. In principle, for any sensor node i (except from the sink node), upon receiving a *Hello* packet from other nodes, Node i should compute the transmission loss online through performing ray tracing. However, this will impose a high computational burden on sensor nodes. Moreover, considering that the senor nodes may move because of water mass or water current movements, each sender should periodically run BELLHOP program to compute the transmission losses for links connecting itself to its neighbors, based on the newest location information (it can be obtained by information exchanges between neighbors.). In the following, we reduce this computational load by generating a transmission loss table off-line, and storing it at all sensor nodes. We divide the ocean region of interest with volume of $X_{MAX}\times Y_{MAX}\times Z_{MAX}$ into cuboids with size $\triangle x\times\triangle y\times\triangle z$. Then we run BELLHOP program off-line to compute the transmission losses for all the potential source-destination pair in the divided discrete space under a certain given environment, generating a transmission loss table that is fine enough to allow a good evaluation of the channel behavior for nodes placed at any point in the network area. To account for seasonal variations, the transmission loss table obtained above can be refreshed in different seasons. To this end, once Node i receives the *Hello* packet from another node, it can easily get the transmission loss between them by looking up the transmission loss table[†].

For any sensor node i, with known transmission losses between itself and other reachable nodes, based on the definition of neighbor nodes proposed in Section 3.3, it can easily determine its Transmission-Loss-based Neighbor Node Set NS_i^{TL}.

Given that the senor nodes may move because of water mass or water current movements, it is necessary for nodes to broadcast a *Hello* packet every T_b seconds. Generally, the broadcast period T_b is dependent on the network density and speed of mobile sensor nodes. Compared with a data packet, the length of *Hello* is small, and thus the energy spent in Neighbor Information Maintenance is just a small fraction in the total energy consumption.

4.2.2 Data Forwarding

After the neighbor information maintenance phase, given a specific transmission loss threshold TL_{th}, since each node knows its own neighbor node set and their physical distances towards the final destination, the sender of the data packet selects the forwarding node in this phase. Two selection methods for UASNs are proposed in this paper. The first one is the Most Forward Progress within Transmission Loss Threshold (MFPTLT) algorithm. In MFPTLT, the sender i selects the node which is farthest from itself in the direction of the destination (i.e. with the most progress in the direc-

[†] Although the transmission loss may be computed based on the strength of the received signal in some scenarios, it is not applicable in our studies since nodes always use different transmit power under different network densities (also more likely in the realistic networks).

tion of the destination) among the sender i's Transmission-Loss-based Neighbor Node Set NS_i^{TL} as the next relay node. The transmission-loss-based definition of neighbor node set guarantees that nodes in the shadow zone will never be s-elected as the next relay node. The second method is N-earest Neighbor Forward within Transmission Loss Threshold (NNFTLT). NNFTLT chooses the closest neighbor to the sender within the sender i's Transmission-Loss-based Neighbor Node Set NS_i^{TL}. We summarize them in Algorithms 1 and 2, respectively. Specifically, $ForwardPacket()$, a core function in our proposed routing algorithms, is used to find the next relay node and forward the packet to the next relay node. It has four input parameters, which are Current Node ($^*Ni$), Packet waiting to be forwarded (p), TransmissionLoss Threshold (TL_{th}), Sea Depth (H), and has no return value. $ForwardPacket()$ is repeatedly called until the packet is received by the sink node. $TransLoss(N_i, N_j)$ and $Dist(N_i, N_j)$ are used to denote the transmission loss and the phisical distance from node N_i to node N_j, respectively, and both are incorporated in Node $^*N_i$.

Algorithm 1: MFPTLT: the Most Forward Progress within Transmission Loss Threshold

```
ForwardPacket( *N_i, p, TL_th, H)
begin
    if TransLoss(N_i, Sink) ≤ TL_th then
        send the p directly to Sink;
        return;
    end
    // Initialization;
    DistRef=0.0;
    NextHop=N_i;
    for N_j ∈ NS_i^TL do
        if Dist(N_i, N_j) > DistRef &&
        Dist(N_j, Sink) < Dist(N_i, Sink) then // Find the
        farthest from itself in the direction of
        the destination
            DistRef=Dist(N_i, Nj);
            NextHop=N_j;
        end
    end
    if NextHop==N_i then // No neighbor in the
    direction of the destination, and backtrack
        DistRef2=1e10;
        for N_j ∈ NS_i^TL do
            if Dist(N_j, Sink) < DistRef2 then
                DistRef2=Dist(N_j, Sink);
                NextHop=N_j;
            end
        end
    end
    Suppose NextHop=N_k;
    send the packet p to N_k with transmit power
    P_tr,i = 2π × H × 10^((TL_ik+85)/10) × 0.67 × 10^-18;
    ForwardPacket(*N_k, p, TL_th, H);
end
```

4.2.3 Loop Avoidance

To avoid getting stuck in an infinite loop, for each packet, we add a "nodes visited" field in the packet header, which is a vector $VisitedCount$ ($VisitedCount = [VisitedCount_1, VisitedCount_2, ..., VisitedCount_N]$, N is the total number of nodes in the network). For any j, the node-visited-count $VisitedCount_j$ for node j has an initial value of 0. Once node j is selected as a relay node and packet p is forwarded to it by the sender i, the sender i increases $VisitedCount_j$ by 1. Upon receiving a data packet, the router node i executes MFPTLT or NNFTLT only among neighbors with node-visited-count below a certain threshold value (e.g., 3). In this way, infinite routing loops can be avoided. We use an example shown in Fig. 4 to explain how it works. We use an edge that connects two n-odes to indicate they can communicate with each other. It is assumed that node 1 is the source node, and node 8 is the sink node. The dotted lines with arrows constitute the path for the packet from the source node to the sink n-ode, and the numbers on the dotted lines indicate the order of the transmission hop. The values for $VistedCount = [VisitedCount_1, VisitedCount_2, ., VisitedCount_8]$ on each hop is specified on the right in Fig. 4. Because we limit next hop nodes to ones with VisitedCount below a certain

Algorithm 2: NNFTLT: the Nearest Neighbor Forward within Transmission Loss Threshold

```
ForwardPacket(*N_i, p, TL_th, H)
begin
    if TransLoss(N_i, Sink) ≤ TL_th then
        send the p directly to Sink;
        return;
    end
    // Initialization;
    DistRef=1e10;
    NextHop=N_i;
    for N_j ∈ NS_i^TL do
        if Dist(N_i, N_j) < DistRef &&
        Dist(N_j, Sink) < Dist(N_i, Sink) then // Find the
        nearest from itself in the direction of
        the destination
            DistRef=Dist(N_i, Nj);
            NextHop=N_j;
        end
    end
    if NextHop==N_i then // No neighbor in the
    direction of the destination, and backtrack
        DistRef2=1e10;
        for N_j ∈ NS_i^TL do
            if Dist(N_i, N_j) < DistRef2 then
                DistRef2=Dist(N_j, Sink);
                NextHop=N_j;
            end
        end
    end
    Suppose NextHop=N_k;
    send the packet p to N_k with transmit power
    P_tr,i = 2π × H × 10^((TL_ik+85)/10) × 0.67 × 10^-18;
    ForwardPacket(*N_k, p, TL_th, H);
end
```

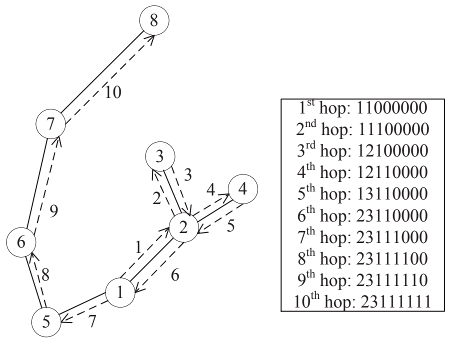

Fig. 4 An example to show how infinite loops are avoided

threshold value (say 3), there will not be any infinite loop between node 1 and node 2. Also, if the threshold value is too small (e.g. 1), the packet will be trapped at node 3 and will never be sent to the sink node 8.

4.3 Optimal Routing

For comparison, the genie-aided centralized optimum approach is used. This optimal routing pursues the minimum total energy consumption path to the sink node through Dijkstra's algorithm [21], where the edge weight input for Dijkstra's algorithm is the energy consumption E_{ij} (computed by Eq. (6)) for one packet to be delivered successfully with a probability under an OFDM combined with LDPC system. When a sensor node has data to send, i.e., data sensed by itself or received from another node to be relayed towards the sink node, the data is forwarded to the uplink node with the minimum energy consumption in its routing table. This policy assumes that the transmitter has complete knowledge of the whole network's links and always chooses the path that ensures the minimum energy consumption for a given scenario.

5. Simulation Results

5.1 Simulation Setup

As in [4], the three-dimensional volume used in the simulations has a constant height H = 216 m, a width W = 2000 m, and a length L of either 30,000 or 50,000 m. This volume may be used to model a network of sensors traversing a long distance (e.g., monitoring a pipeline). The overall network is composed of one fixed source node, one fixed destination node, and 30 to 200 relay nodes (randomly deployed within the network area). This makes it possible to model several network densities. For all the simulations, one group of WHOI modem's parameters is adopted [18]. Specifically, the received power is 2 W, the carrier frequency is 9 kHz, and the available data rates is 4,000 bps. Moreover, as in [4], the packet length used in our simulations is L = 256 bytes. It is assumed that the transmitting node can adaptively choose its transmit power to satisfy communication quality. The WHOI micro-modem has a maximum transmit power of 50

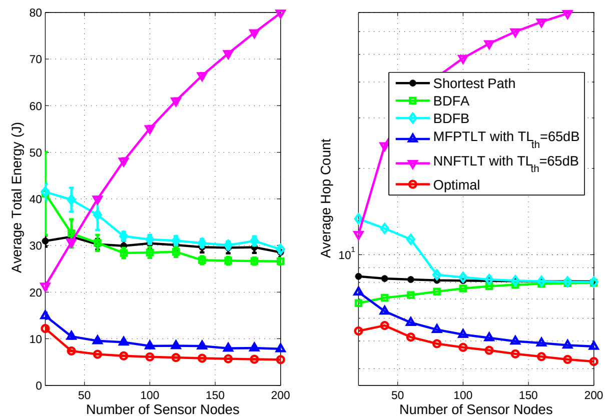

Fig. 5 Total path energy and average hop count vs. number of nodes in the network ($H = 216m$, $W = 2000m$, $L = 30,000m$)

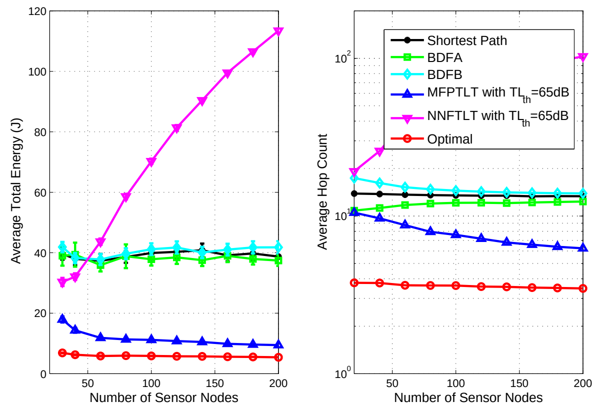

Fig. 6 Total path energy and average hop count vs. number of nodes in the network ($H = 216m$, $W = 2000m$, $L = 50,000m$)

W and a 10 W minimum transmit power level, potentially providing a 40 W dynamic range for power control†. We compare our ray-model-based routing with three other routing protocols. The first is a pure shortest path approach, which builds routes with the least number of hops. It is noted that the shortest path algorithm is completely oblivious of the channel performance. The other two routing policies compared are the optimal hop-distance based routing protocols proposed in [4], namely, Bounded Distance from above (BDFA) and Bounded Distance from below (BDFB), respectively. In BDFA, at any hop, if the sink node is in the communication range of the sender, then transmit to the sink directly; otherwise, pick the next relay node whose distance from the sender is larger than the optimal hop-distance but closest to the sender. In BDFB, the node whose distance from the sender is shorter than the optimal hop-distance but farthest from the sender, will be picked as the next relay.

†Note that power control is not currently implemented in the WHOI micro-modem, but is expected to be considered for future versions [18].

If no such node exists, apply BDFA. BDFA and BDFB are chosen for comparison with our proposed ray-model-based routing because they have been shown to exhibit large energy savings compared to other existing underwater routing algorithms.

For each simulation run, the sender is fixed at the sea bottom with coordinates $(0, 0, 216)$ and the destination is placed at the opposite corner of the network. We run each simulation 1000 times and show the mean and 95% confidence intervals for each statistic. Two evaluation parameters, namely, the total energy consumption (ignoring collisions and other costs caused by multiple traffic flow interactions) and the hop-count, are used to compare performances of our proposed MFPTLT and NNFTLT with the Shortest Path Scheme, BDFA, BDFB, and the Optimal Routing Scheme.

5.2 Results

Firstly, with the Santa Barbara sound-speed profile [12] (water depth is maintained at 216 m, and the sound speed increases with a negative gradient), results for average total energy and hop count required for the sender to send a packet successfully to the destination under network lengths of 30, 000 m and 50, 000 m are presented in Figures 5 and 6. We also tested other sound speed distributions and network lengths[†], but omit those results here due to similarity.

It suffices to say that our proposed distributed Most Forward Progress within Transmission Loss Threshold (MFPTLT) protocol with a proper transmission loss threshold ($TL_{th} = 65dB$ used here) performs very close to the optimum for all node densities under both 30, 000 m and 50, 000 m. However, we find that in our proposed Nearest Neighbor Forward within Transmission Loss Threshold (NNFTLT) protocol, the energy consumed for each successfully received packet increases when the node density increases (whereas it decreases in the other algorithms when the node density increases). The reason is that in NNFTLT, for both network lengths, i.e., 30, 000 m and 50, 000 m, when the node densities are high, more hops are used for the end-to-end transmission between the source and the destination nodes, and the energy consumed for each received packet increases. As for MFPTLT, on the one hand, based on our defined Transmission-Loss-based Neighbor Node Model, nodes that are within the communication range but not reachable by the sender (in other words, nodes in the shadow zone) will never be selected as a relay node, while nodes that are out of geographical communication range but experience small transmission loss can be efficiently utilized to relay packets. On the other hand, as shown in Fig. 5, MFPTLT minimizes the hop-count as much as possible by forwarding packets to the

[†]The other tested sound speed distributions are from the Taiwan Strait. As reported in [22], the speed increases linearly with a positive gradient with depths in January (1510 – 1515 m/s), stays constant across the water volume in May (1527 m/s), and decreases linearly with depths in August (1540 – 1530m/s) of 1998 (water depth 60 m). The other two tested network lengths are 100, 000 m (very long) and 10, 000 m (relatively short).

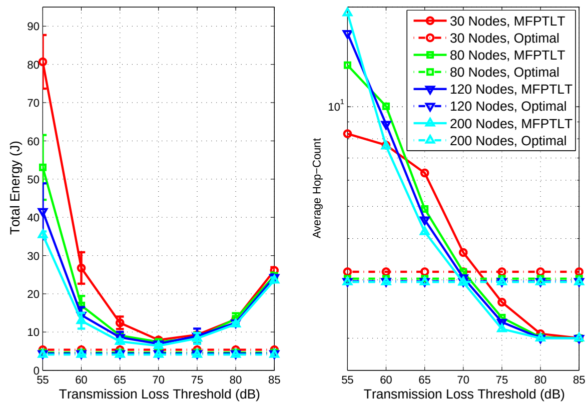

Fig. 7 Total path energy and average hop-count vs. transmission loss threshold ($L = 30, 000m$)

neighbor that is the farthest from the sender i in the direction of the destination within the sender i's Transmission-Loss-based Neighbor Node Set NS_i^{TL}. Therefore, in MFPTLT, the energy per packet decreases when the node density increases when the node density is low, and it remains unchanged when the node density is high. Geographical distance based routing protocols, specifically, optimal hop-distance based routing algorithms [4], namely, BDFA and BDFB, perform similarly to the centralized shortest path algorithm and maintain a nearly constant hop-count given a scenario as shown in Fig. 5. However, because they do not account for anisotropic propagation, they may select relay nodes with large transmission losses. Therefore, as seen in Fig. 5 and 6, they consume much more energy than MFPTLT. Secondly, in Figures 7 and 8, the influences of the transmission loss threshold TL_{th} on the performance of MFPTLT is presented[††]. It is easily seen that, with the WHOI micro-modem, with a received power $P_r = 2W$, the optimal transmission loss threshold is approximately $70dB$ (as shown in Figures 7 and 8) and is weakly dependent on the overall network size, which makes the MFPTLT scheme robust. When TL_{th} is small, nodes near the sender are more likely to be its neighbor node, rendering more hops required given a certain distance as seen in the right sub-figures in Figures 7 and 8. Moreover, according to Eq. (5), the required transmit power is relatively small under small TL_{th}. Besides, since the receive power P_r is fixed, the hop-count plays an important role in total energy consumption. Therefore, as seen in Figures 7 and 8, at the very beginning, when TL_{th} increases from very small values, the total energy is decreasing and the hop-count is also decreasing. When TL_{th} increases beyond a specific value (here it is $70dB$), the total energy begins to increase while the hop-count continues to decrease. This is because the energy consumption for one link is an exponential function of the transmission loss. Therefore, the choice of the transmission loss threshold TL_{th} is critical for the performance of

[††]Here how TL_{th} influences NNFTLT is not shown because of its bad performance shown in Figures 5 and 6.

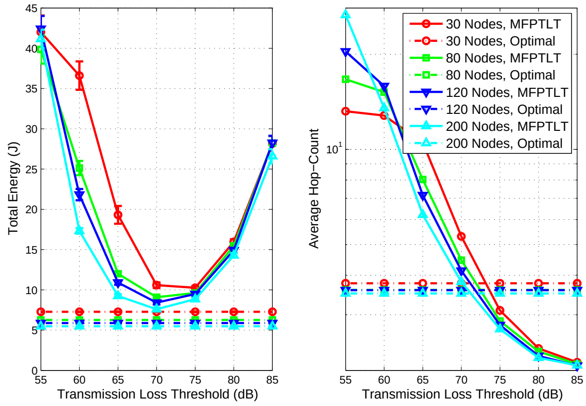

Fig. 8 Total path energy and average hop-count vs. transmission loss threshold ($L = 50,000m$)

MFPTLT. Further optimization and parameter tuning of the MFPTLT protocol will be included in our future research.

6. Conclusion

In this paper we first described the anisotropic propagation of sound in the inhomogeneous ocean medium based on a standard ray-tracing channel model. Second, acoustic signal attenuation computed by the BELLHOP model was utilized to re-define nodes' one-hop neighbors. Finally, we proposed a distributed energy-efficient routing scheme that exploits quantitative information on the behavior of the underwater channel to choose the next hop toward the destination. Simulation results showed that our proposed Most Forward Progress within Transmission Loss Threshold (MFPTLT) algorithm works well in different scenarios. It consistently outperforms channel-oblivious, geographical distance-based shortest-path policies, and yields similar results to the centralized optimal policy which is perfectly aware of the channel and always picks the relays providing the minimum energy. We also find that the transmission loss threshold TL_{th} is critical for the performance of MFPTLT. In future research, we will study further optimization and parameter tuning of the protocol, integrating this work with other MAC layer protocols.

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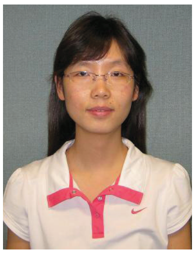
7. Captions for Figures, Tables, and Algorithms

Fig. 1: Sound propagation in inhomogeneous ocean medium

Fig. 2: Transmission losses under different configurations

Fig. 3: Architecture of Underwater Acoustic Sensor Network

Fig. 4: An example to show how infinite loops are avoided



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