PRACTICAL STATELESS GEOGRAPHICAL ROUTING (PSGR) - 3-D STATELESS GEOGRAPHIC ROUTING FOR UNDERWATER ACOUSTIC SENSOR NETWORKS

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Sang Joon Lee

Certificate of Approval:

Saad Biaz
Associate Professor
Computer Science and
Software Engineering

Min-Te Sun, Chair
Assistant Professor
Computer Science and
Software Engineering

Yu Wang
Assistant Professor
Computer Science and
Software Engineering

George T. Flowers
Interim Dean
Graduate School

PRACTICAL STATELESS GEOGRAPHICAL ROUTING (PSGR) - 3-D STATELESS GEOGRAPHIC ROUTING FOR UNDERWATER ACOUSTIC SENSOR NETWORKS

Sang Joon Lee

A Thesis

Submitted to

the Graduate Faculty of

Auburn University

in Partial Fulfillment of the

Requirements for the

Degree of

Master of Science

Auburn, Alabama
May 10, 2008

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Sang Joon Lee

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Signature of Author

____
Date of Graduation

Thesis Abstract

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Sang Joon Lee

Master of Science, May 10, 2008
(M.E., Chung Buk National University, 2002)
(B.S., Chung Buk National University, 1999)

53 Typed Pages

Directed by Min-Te Sun

Underwater acoustic sensor networks have recently gained increasing research attentions due to their vast potential applications. Although the limited bandwidth and power resources in such networks have made stateless geographic routing a favorable choice, the existing detouring strategies in geographic routing are either inefficient or simply fail in 3-D underwater environments. In this thesis, we propose the first stateless geographic routing protocol for 3-D networks, namely Practical Stateless Geographic Routing. The proposed routing protocol not only performs effectively in underwater environments but also degrades smoothly when the location information is either inaccurate or simply unavailable for a portion of nodes in the network. In addition, we propose a light-weight path pruning algorithm, namely Departed Tree-Branch Pruning, that can be combined with the proposed routing protocol to enhance the routing performance with very little overhead. The extensive simulation results have shown that the proposed routing protocol as well as the path pruning technique perform significantly better than the existing routing protocols for underwater acoustic sensor networks in terms of delivery rate, delay, hop stretch, and energy consumption.

Style manual or journal used Journal of Approximation Theory (together with the style known as "aums"). Bibliograpy follows van Leunen's *A Handbook for Scholars*.

Computer software used The document preparation package TEX (specifically LATEX) together with the departmental style-file `aums.sty`.

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Chapter 1

Introduction

Underwater acoustic sensor networks (UWSNs) [1,2] are a special type of wireless sensor networks arising from various applications such as ocean environment monitoring, tactical military surveillance, target tracking, and undersea navigation [3]. As an example, Fig. 1.1 illustrates a 3-D UWSN that monitors the condition of sub sea equipment for a floating oil production platform. Due to the limitation of each node's transmission range and the possibility of nodal failure in the erosive underwater environment, data collected by individual sensor node are usually forwarded to a control center through a network of nodes [4]. Thus, proper routing algorithms are needed to direct data packets from their source to the destination.

Traditional routing algorithms in wireless sensor networks can be classified into two categories: proactive protocols and reactive protocols. In proactive protocols [5,6], each node maintains a routing table by exchanging link state or distance vector control packets with neighboring nodes. The advantage of proactive routing is that the routing table allows each node to quickly identify the next hop of a packet. In addition, different metrics, including hop count, available bandwidth, and congestion status, can be taken into consideration in the construction of the routing table [6]. The major disadvantage of proactive routing, however, is that the communication and storage overheads of routing table maintenance grow quickly as the size of the network increases or network topology changes. In reactive protocols [7,8], when a

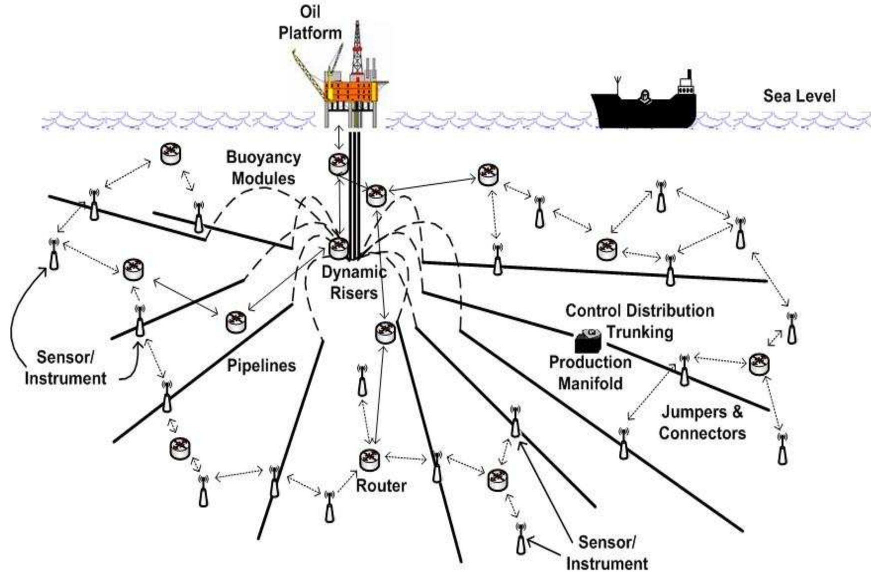

Figure 1.1: A 3-D underwater acoustic sensor network for floating oil production platform.

node has a packet to send, it floods the network with queries to discover a route to the destination. The primary difference among various reactive protocols is how the responded path information is cached at intermediate nodes and reused. While reactive routing avoids the overhead incurred in routing table maintenance, the network-wide query flooding of path discovery is an extremely expensive operation and may create additional problems, such as the infamous broadcast storm problem [9]. Therefore, while proactive and reactive routing protocols do not rely on assumptions of network topology and link characteristics, they incur heavy communication and storage overhead, which becomes a serious issue in resource-constrained UWSNs.

In recent years, a new class of routing protocols – namely geographic routing protocols [10–13] – have been proposed. Under the assumptions that each node knows the geographic locations of itself and its neighbors as well as the source knows and encodes the geographic location of the destination in the packet, geographic routing can determine where to forward the packet without maintaining the routing table or flooding the network, an important property known as *stateless*. While GPS signal is not available under the surface of the ocean, the relative location of each underwater sensor node can be pinpointed via triangulation [14]. The stateless property of geographic routing is especially useful for UWSNs. It helps the routing overhead to be better decoupled with the size of the network, allows additional sensor nodes to be deployed transparently, and permits some nodes to be turned off for power saving so long as the network remains connected. As a result, geographic routing has been suggested for UWSNs in [1, 4].

In general, for the existing geographic routing algorithms to function correctly, three assumptions are commonly required. First, the location information at each node needs to be accurate. Second, the link model is assumed to be the unit disk model i.e., nodes within a predefined transmission radius can always exchange packets with each other. Last, the network topology needs to be on a 2-D plane. In practice, it is difficult to obtain accurate location information at each node regardless what localization algorithm is used. The unit disk link model does not apply to underwater acoustic links, which have highly dynamic physical characteristics due to time-varying multipath intersymbol interferences and Doppler shifts and spreads [15]. In addition, nodes in UWSNs are mostly deployed over 3-D space at different depths and on the bottom of the ocean that is normally not flat. As a result, these assumptions render the existing geographic routing protocols unusable for UWSNs. While there are some attempts [13,16,17] recently to do away with some of these assumptions for geographic routing, they either introduce heavy communications overhead or require each node to proactively maintain routing information.

In this thesis, we propose a novel geographic routing protocol, namely Practical Stateless Geographic Routing (PSGR). Unlike the existing geographic routing protocols, PSGR does not rely on the aforementioned impractical assumptions and is able to route the traffic efficiently and statelessly in 3-D UWSNs. The performance of PSGR degrades gracefully when the location information becomes less accurate. To further optimize the route obtained by PSGR, we propose a light-weight algorithm, namely Departed Tree-Branch Pruning (DTBP), which effectively removes the loops in the path. The extensive simulation results validate that the proposed routing algorithms significantly outperform Delay Sensitive Distributive Routing (DSDR) [32] and Dynamic Source Routing (DSR) [7], the routing protocol adopted by the well-known underwater AUSNET project [47].

The rest of the thesis is structured as follows. Chapter 2 surveys the related work of geographic routing. The Practical Stateless Geographic Routing protocol as well as the Departed Tree-Branch Pruning algorithm are illustrated in Chapter 3 and the experimental results are presented in Chapter 4. Finally, Chapter 5 concludes the thesis and outlines future research directions.

Chapter 2

Literature Review

Geographic routing is a powerful routing scheme which is able to identify a route from source to destination statelessly with the help of the location information (see e.g., [11]). In general, geographic routing consists of two parts – greedy forwarding and a detouring strategy. If a node holding a packet finds some neighbors that are "better" than itself for a given destination, the node forwards the packet to the best neighbor. This is called *greedy forwarding*. Note that greedy forwarding alone has low delivery rate even in a connected network. When a local minimum is reached (i.e., no "better" neighbor can be found), the geographic routing protocol falls back to its *detouring strategy* to find a detour to leave the local minimum and then move toward the destination. To design a complete geographic routing protocol, two fundamental issues need to be addressed: How to define the better neighbors and what strategy should be used to find a detour? Different geographic routing protocols propose different means to address these two issues.

Assume that the node currently holding the packet is denoted as n and the destination as d. For a pair of nodes a and b, the distance between them is denoted as $dist(a, b)$. In [11,12,19–21], a better neighbor a for node n is defined as one such that $dist(a, d) < dist(n, d)$. In [22], a better neighbor a is defined as the one with a smaller angle span from $\overrightarrow{nd}$ to $\overrightarrow{na}$. In [24], a better neighbor a is the one whose projection on $\overline{nd}$ yields the most advancement toward d. In [25], a better neighbor is the one whose cell in Voronoi diagram intersects $\overline{nd}$. In [26], an analytical model is given to show that to achieve more reliable packet delivery, the criteria of the better neighbor in geographic routing protocols should base on the product of the expected reception power and the forwarding distance. In [32], a non-linear optimization technique is used to find the greedy criteria for delay-sensitive and delay-insensitive data in UWSNs. Note that, if only the forwarding mode of the skeleton is involved in the routing process, it has been shown in [20] that any definition of the better neighbor in [11,12,19–22,24,25,32] leads to a sub-optimal path. However, greedy forwarding alone achieves low delivery rate even when the networks are connected.

When there is no better neighbor i.e., a local minimum is present, several detouring strategies were proposed [10–12, 19, 21, 23] that find a detour to a node closer to the destination than the current local minimum. In [19, 23], flooding, the simplest recovery plan, was proposed when the greedy forwarding does not yield a path to the destination. This strategy, however, is expensive and not preferred. In [10–12, 21], several non-flooding detouring strategies were proposed. The basic idea of these strategies is to forward the packet in the network according to certain rules so that no loop will be repeated. Obviously, if the network remains connected and network is explored this way, eventually the destination will be reached. Although it is difficult to guarantee the traverse contains no repeated loop for an arbitrary network topology distributively, there exist several heuristics to achieve this guarantee if the underlying topology is a planar graph. Hence, these strategies employ a similar two-step process:

- They first reduce the network topology to a planar graph distributively. After the reduction, the topology contains no cross edges and the network is most likely still connected. The remaining edges divide the two-dimensional space into faces.

- Each strategy picks a certain set of faces in the resulting planar graph. The boundaries of these faces are then explored until the destination is reached or the packet is switched back to the greedy forwarding mode.

For a given network topology, several distributed algorithms [27–30] are available to planarize a network topology. In these algorithms, each node autonomously eliminates its connections (i.e., edges) to its neighbors from the consideration of the routing based on the locations of the neighbors so that the network topology contains no cross edges. In the Relative Neighborhood Graph (RNG) [29], a node u eliminates a link to a neighbor v if there exists at least one node in the intersection of radio coverages of u and v. In the Gabriel Graph (GG) [27], a node u eliminates a link to a neighbor v if there exists at least one node in the circle with diameter $\overline{uv}$. The Planar Spanner in [28] and the Morelia test in [30] employ more complicated algorithms to compute the planar graph so that a smaller number of edges are deleted from the original topology. In the computation of any of these distributed planarization algorithms, it is crucial that the location information of nodes to be accurate or some edges will be incorrectly dropped. In addition, these algorithms implicitly assume that the network is on a 2-D plane and a node is always connected to all nodes within a fixed radio transmission range (i.e., ideal unit disk link model). In [16], a planarization algorithm is proposed that relaxes the assumptions of the accurate location information and unit disk link model, but it introduces a large amount of signaling [13] among neighboring nodes and still relies on the 2-D assumption.

After the network topology is planarized, the resulting graph is composed of a set of faces. Each non-flooding based geographic routing protocol picks a subset of faces and explores the boundaries of the faces to find a detour to the destination. The GPSR [11] algorithm and the face routing family (e.g., AFR, GOAFR$^+$) [12,20,21] are among the most popular geographic routing protocols. For instance, in the perimeter mode of GPSR, the packet is forwarded successively on closer faces of the planar graph (i.e., faces toward the perimeter of all faces) until it reaches the destination or a node closer to the destination than the previous local minimum, where the packet is switched back to the greedy forwarding mode. GOAFR$^+$ uses a dynamically adjustable bound in its face exploration and falls back to the greedy forwarding mode if one has visited (up to a constant factor) more nodes on the face boundary closer to the destination than nodes not closer to the destination. In any of these face-traversal algorithms, it is crucial to identify the "left" or "right" side of a face. This, unfortunately, can not be well-defined in a 3-D network topology.

Although the criteria and performance analysis of greedy forwarding for UWSNs have been well-studied in [32], the flooding-based detouring strategy is too expensive for the resource-constraint UWSNs and non-flooding detouring strategies require assumptions that are not available in the 3-D UWSNs. How to route the traffic statelessly and efficiently in 3-D UWSNs is still an issue at large.

Chapter 3

Practical Stateless Geographic Routing

In Chapter 2, we have identified three assumptions commonly shared by the existing geographic routing protocols but unavailable in 3-D UWSNs. These assumptions are primarily stemmed from non-flooding detouring strategies and have made the existing geographic routing protocols inappropriate for 3-D UWSNs. This has motivated us to design a new detouring strategy for geographic routing. In the following sections, we intend to answer the question: Is it possible to find a detour *directly* (i.e., without the planarization process) from a given network topology?

3.1 Practical Stateless Geographic Routing

Notice that finding a detour means locating a node that is closer to the destination than the previous local minimum. Without planarization and subsequent face routing, any node in the network can lead to a detour. This implies that the detouring strategy which works directly for a given network topology will need to visit all nodes in the network in the worst case. Given a connected graph, two well-known approaches to visit all nodes in the graph are breath-first search (BFS) and depth-first search (DFS) [45]. If the information of the visited nodes is kept in the packet, both approaches have the potential to find a detour statelessly after a local minimum is encountered.

To ensure BFS or DFS to function properly as a detouring strategy, there are also three required assumptions: i) the link needs to be bi-directional so that a packet can traverse back as needed, ii) source and destination are connected, and iii) the network topology remains static during the routing process. The bi-directional link assumption can be had by using a three-way handshaking localized link-layer protocol. As for the source-destination connectivity assumption, since any pair of nodes can be selected as source and destination, this assumption implicitly requires that the network is connected. The connectivity of a sensor network can be verified at the time of network deployment or be checked by one of localized topology control algorithms [41–44], regardless of the network dimension 2-D or 3-D. The last assumption is commonly assumed by most of the routing protocols. In fact, no routing protocol can guarantee the delivery of the packet if the network topology changes fast during the routing process. In other words, these assumptions can be fulfilled much more easily than the aforementioned impractical assumptions required by the existing geographic routing protocols.

In BFS, a packet will traverse back and forth among nodes that are near the node initiating the BFS (i.e., the local minimum), an undesirable property when it is used for routing. On the other hand, DFS does not go back until a branch is fully explored. If a node has some information to estimate which neighbor is better to explore the next, DFS seems to be a better choice than BFS counterpart. The remaining design issues are i) what partial topology information that has been explored should be kept in the packet, and ii) what data structure should be used to keep the partial explored topology. Theoretically the more partial explored topology information is recorded in the packet, the more efficient the routing is likely to be. On the other hand, if more information is recorded in the packet, it will likely to take up more space in the packet and increase the communication overhead of packet forwarding. As for the type of data structure, intuitively it seems that the partial explored topology should be kept as a graph. However, keeping the partial explored topology by means of a graph data structure, regardless adjacency lists or adjacency matrix is used, will increase the data processing complexity and thus the time to process each packet. To solve these issues, we develop an algorithm that seamlessly integrates DFS and the greedy forwarding. Our algorithm strategically records the partial explored topology by using a simple list of visited nodes. In Table 3.1, we present the first stateless geographic routing protocol that works without those impractical assumptions, namely Practical Stateless Geographic Routing (PSGR).

Table 3.1: The Practical Stateless Geographic Routing Protocol

```
A node n holding packet m with destination d
append n at the end of the partial path list of m
if n appears on the list twice
    color nodes in between blue (i.e., the “tried branch”)
    delete the previous n on the list
if n has neighbors not on the lis
    forward m to the one nearest to d
else
    forward m back to where it originally came from
```

PSGR is a prioritized DFS that gives the visit (i.e., packet forwarding) priority to the neighbor closer to the destination. When a node n receives a packet m destined for d, it first appends itself to the partial path list of m and checks if it appears on the list more than once. If n appears on the list twice, the nodes in between two entries are one of the branches m has just visited. There is no need to keep both n's entries in the list, so in the algorithm the earlier duplicated entry is removed. At this moment, if n still has unvisited neighbors, n forwards m to the one closest to d among them. Otherwise, n will just forward m back to where it originally came from, which will appear as the first neighbor of n on the list.

Because PSGR is basically a variation of DFS, it goes without saying that a packet will definitely reach the destination as long as the network topology remains stable during the time of routing process and source and destination are connected, regardless how accurate the location information at each node is. In case if some nodes in the network do not have the location information at all, the order of exploration among neighbors can be assigned so that the priority is given to those that lead the packet closer to the destination, then to those without the location information, and finally to those that lead the packet away from the destination.

The communication overhead is bounded by the size of the list, which is the number of nodes a packet traverses. When a node receives a packet, it also needs to scan through the list to check if it is on the list or not. Hence, the time complexity of data processing is also bounded by the number of nodes a packet traverses.

3.2 Illustration of Practical Stateless Geographic Routing

In Fig. 3.1, a 2-D example is provided to illustrate how PSGR routes a packet. In the figure, the source and destination are S and D, respectively. The neighborhood relationship of the network is denoted by the dotted lines. According to the PSGR algorithm, S appends itself to the list ($< S >$) and forwards it to N_1 since N_1 is closer to D than N_2. N_1 again appends itself to the list ($< S, N_1 >$) and then forwards it to N_3 as N_3 is closer to D than N_2. N_3 appends itself to the list ($< S, N_1, N_3 >$) and forwards the packet to N_4, the neighbor closest to D. N_4 is a dead-end, so it appends itself to the list ($< S, N_1, N_3, N_4 >$) and send it back to N_3, which it originally received the packet from. Afterwards, N_3 appends itself to the list and finds that there are duplicated entry of N_3 on the list, so it deletes the previous entry on the list ($< S, N_1, N_4, N_3 >$) and forwards the packet to N_5, the last neighbor not on the list. N_5 is also a dead-end, so it appends itself to the list ($< S, N_1, N_4, N_3, N_5 >$) and forwards the packet back to N_3. At this moment, all of N_3's neighbors have been visited and on the list, so it appends itself to the list again, deletes the previous duplicated entry ($< S, N_1, N_4, N_5, N_3 >$), and then forwards the packet to N_1, the first neighbor of N_3 on the list. Similarly, after N_1 receives the packet, it again appends itself to the list, deletes the duplicated entry ($< S, N_4, N_5, N_3, N_1 >$), and forwards the packet to N_2, the only neighbor of N_1 not on the list. Consequently, N_2, N_6, N_7, N_9, N_{12}, and N_{13} will append themselves to the list as the packet travels through them before the packet eventually reaches D.

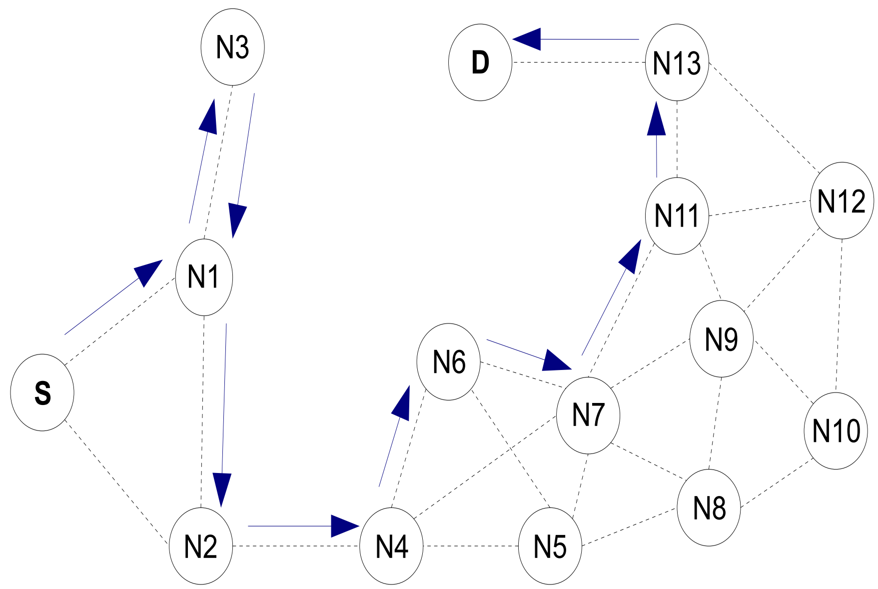

Figure 3.1: PSGR routes a packet from S to D.

As shown in Fig. 3.1, PSGR will pay dearly if some branch explored earlier (e.g., N_1 to N_3) fails to reach the destination. However, as we will show in our performance studies in Chapter 4 that even with very inaccurate location information PSGR will give us very satisfactory routing performance on average. Notice that all of the non-flooding detouring strategies, including perimeter routing [11] and face routing [12], perform poorly at critical network density regions [12, 18].

3.3 Departed Tree-Branch Pruning

In [18], a post optimization technique, namely Path Pruning (PP), is introduced that can be applied to improve the performance of geographic routing protocols. We have found that the similar technique works even better with PSGR. The basic idea of PP is that a node listens to the wireless radio channel after it transmits a packet. If after a short period of time the node finds that the same packet is transmitted by one of its neighbors different from the one it previously forwarded the packet to, it identifies this neighbor as the next hop of the destination of the packet and forwards the subsequent packets for the same destination directly to this neighbor. PP helps identify the shortcuts that are not utilized by the non-flooding detouring strategies in the existing geographic routing.

Although PP keeps next hop entries at a subset of nodes on the path, this information is passively acquired by listening to the wireless radio channel. There is no communication cost to maintain the next hop entry for terrestrial wireless networks. In addition, the state information is kept only for active connections. If a node with a next hop entry for a destination does not receive subsequent packets for the destination, the next hop entry will time out and be deleted. With the help of PP, the routing performance of geographic routing protocols improves dramatically at critical network densities.

Unfortunately, the path pruning algorithm, if directly applies to UWSNs, may have some issues. First, it takes much higher energy level for an underwater sensor node to even passively listen to acoustic signals. Second, the inferior physical characteristics of underwater acoustic links have tendency to produce higher bit error rates, which may prevent a node from identify a neighbor sending the same packet. Third, in order to find shortcuts, each node will have to keep the information of each packet it transmits for a period of time in the path pruning algorithm. In resource-constraint underwater environment, this storage requirement may not be feasible.

Table 3.2: The Practical Stateless Geographic Routing Protocol with Departed Tree-Branch Pruning

```
A node n holding packet m with destination d
if m is the first packet from source to destination d
    append n at the end of the partial path list of m
    if n appear on the list twice
        color nodes in between blue (i.e., the "tried branch")
        delete the previous n on the list
    if n has neighbors not on the list
        forward m to the one nearest to d
    else
        forward m back to where it originally came from
    if m is forwarded to a neighbor different from n's greedy choice
        record the neighbor as the next hop for destination d
    else
        remove the next hop entry for d if there is one
else
    if n has no next hop entry for d
        forward m to the neighbor of greedy choice
    else
        forward m to the neighbor indicated in the next hop entry
```

To minimize the overhead of path pruning, we propose a light-weight path pruning, namely Departed Tree-Branch Pruning (DTBP) that goes with PSGR. In DTBP, if a node forwards a packet to a neighbor different from its greedy choice, it keeps a next hop entry for the destination of that packet. When a packet comes back from one neighbor and gets forwarded to another one, the next hop entry is updated accordingly. If a node receives subsequent packets for a destination and it has a next hop entry for the destination, it forwards the packets directly to the one indicated in the next hop entry. Otherwise, it forwards subsequent packets to its greedy choice. Table 3.2 illustrates the protocol of Practical Stateless Geographic Routing with Departed Tree-Branch Pruning. As an example, in Fig. 3.1, when N_1 first forwards a packet destined for D to N_3, N_1 will not record the next hop entry for D as N_3 is the greedy choice for destination D. However, when N_1 later forwards the packet to N_2, N_1 will keep a next hop entry $< D, N_2 >$ and N_1 will then forward the subsequent packets for D directly to N_2.

Since there is no planarization process involved in PSGR, all edges, including different types of shortcuts, will be considered for packet routing. In addition, DTBP helps PSGR to identify and remove loops. As a result, although PSGR with DTBP does not require a node to passively listen to the acoustic signals looking for the same packet it transmitted earlier nor an underwater sensor node to keep the information of every packet it transmits, it shows excellent routing performance. The only type of shortcuts PSGR with DTBP fails to identify is those that lead the packet away from the destination, such as the link between N_6 and N_9 in Fig. 3.1. In the original path pruning algorithm, N_6 will overhear the transmission of the same packet from N_9, so N_6 is able to identify a shortcut to N_9. However, we have found that such shortcuts appear rather infrequently in our performance studies.

Chapter 4

Performance Evaluation

To evaluate the performance of the proposed PSGR and DTBP algorithms, we compared our protocols with other two well-known underwater routing protocols – DSR [7] and DSDR [32] by using ns-2 [33]. In this section, the simulation configurations, metrics, and results of different routing protocols are presented.

4.1 Simulation Configurations

In our simulations, the network topology is randomly generated by placing nodes in a 4000 m x 4000 m x 1000 m volume field. The transmission power is set to be 97 dB which approximately corresponds to 500 m of transmission range. the total number of nodes ranges from 100 to 500, which corresponds to network density ranging from 3.27 to 16.35 neighbors per node. For a given network density, 200 realizations of network topology are generated. For each realization, three pairs of source and destination, which are connected through the network, are randomly selected. Each source node generates constant bit-rate (CBR) traffic flows to its destination simultaneously. Each CBR flow sends 5 consecutive packets of 100 $bytes$ at the transmission rate of 10 $Kbps$. The inter arrival time of packets is set to be 30 seconds.

To simulate the characteristics of the underwater environment, the ns-2 underwater module [34] is used. For MAC protocol, CSMA/CA [35] with stop-n-wait ARQ (i.e., ACK) is implemented. The following sections elaborate on physical and MAC layer configurations.

4.2 Physical Layer Configurations

In [34], the physical characteristics of UWSN are realized by the creation of propagation, channel, and physical layer models. The propagation model calculates the signal-to-noise ratio (SNR) at each receiver node after attenuation, ambient noise, and the interference range of a signal. The attenuation is based on the spreading loss [37] and on Thorp's approximation [38] for the absorption loss. In addition, the orientation of the link (i.e., whether it is horizontal or vertical) affects the signal attenuation through acoustic fading channels. The ambient noise in the underwater environment is obtained from turbulence, shipping, wind, and thermal.

The channel model is used for the calculation of neighbor sets, collision, and so on. In addition, it calculates propagation delay, which is formulated by the speed of the sound, the depth of the water, and the temperature of the water [39].

The physical layer model is responsible for packet reception including transmission error, transmission time, and propagation delay by calling the function in the propagation and channel models. In addition, it calculates the energy consumption for transmission. The hardware related parameters of the physical interface, such as the receiving signal strength threshold and the maximum transmission power, are set according to the WHOI micro modem [40].

Although the underwater model in [34] does not provide the bit error rate (BER), it is able to calculate the receiving power, which can be used to infer the BER from the experiment results presented in [36]. Without loss of generality, we adopt the error model in [36] as an exponential equation, $0.4 \times exp(-0.323 \times Pr)$, where Pr is the receiving power. In this equation, BER increases quickly as the receiving power decreases. For instance, when Pr is 30 dB, BER is 2×10^{-5}, and when Pr is 40 dB, BER is 10^{-6}.

4.3 MAC Layer Configurations

As suggested in [48], the CSMA/CA with ARQ is adopted as the medium access control mechanism for our underwater simulations. The RTS/CTS handshaking is removed because it causes serious delays in a low rate and high delay underwater environment. To battle with high BER, the stop-n-wait ARQ (i.e., link layer ACK [46]) is used in our underwater simulations. If a node does not receive ACK within the period of the ACK timeout after it transmits a packet, it assumes the packet is lost and retransmits the packet. A packet can be retransmitted as needed up to a prefixed number of times. To simplify the simulation design, the forward error correction [46] is not implemented and the packet error rate (PER) is approximated as the product of BER and packet size. In other words, if any bit in a packet is lost, the whole packet will be discarded.

Due to the special physical characteristics of underwater acoustic links, the MAC parameters are adjusted accordingly. For instance, the value of the slot time in the CSMA/CA backoff mechanism has to account for the propagation delay of the physical layer. Since the speed of sound in water is approximately 1500 m/s, the slot time should be much longer than that in wireless media. The MAC parameters in our simulations are set similar to what are used in [32]. The inter frame spacing and the slot time are both set to be 0.18 second. The minimum and maximum contention window size are set to be 4 and 32, respectively. To accommodate the high propagation delay of acoustic signals, the duration of the ACK timeout is set to be 5 seconds and the number of maximum link retransmissions is set to be 10.

4.4 Evaluation Metrics

To evaluate routing protocols, five different metrics, including delivery rate, end-to-end delay, hop stretch, energy consumption, and communication overhead, are used. Their definitions are provided as follows.

1. Delivery rate – The delivery rate is defined as the ratio of the total number of received packets and the total number of generated packets.

2. End-to-end delay – The end-to-end delay is defined as the duration from the time a packet is generated to the time the packet is received by its destination without collision. It is affected by many factors, but the dominating one in the underwater environment is the propagation delay.

3. Hop stretch – The hop stretch, as defined in [21], is calculated by the following formula.

$$P_A(i) = \frac{h_A(N_i, n_{si}, n_{di})}{h_D(N_i, n_{si}, n_{di})}. \tag{4.1}$$

In Eq. 1, $h_A(N_i, n_{si}, n_{di})$ denotes the number of hops of the route obtained by routing algorithm A on network N_i with source n_{si} and destination n_{di}, and $h_D(N_i, n_{si}, n_{di})$ is the number of hops of the shortest path between n_{si} and n_{di} on network N_i computed by Dijkstra's algorithm [45] assuming the transmission range of each node to be 500 m. In the case of unit disk link model, the number of hops obtained by Dijkstra's algorithm is guaranteed to be the smallest. However, in our ns-2 simulations depending on the orientation of a link the transmission range can be slightly more than 500 m at times. Thus, hop stretch of some routing algorithms can be less than one. Similar to end-to-end delay, hop stretch only accounts for successfully delivered packets.

4. Energy consumption – Energy consumption is calculated by the ns-2 underwater module [34]. The unit of energy consumption is Joule.

5. Communication overhead – For PSGR, the extra information (i.e., source node ID, destination node ID, location of the destination, and partial path list) stored in the packet header is considered as its communication overhead. The size of the partial path list increases by 4 bytes (to store the ID of the node currently holding the packet) for each hop. For DSDR source node ID, destination node ID, and the location of the destination are considered as its communication

overhead. For DSR, the communication traffic in the path discovery phase is calculated as its communication overhead.

In addition, to evaluate DTBP, the storage overhead is used and is defined as the number of nodes that keep the next hop entry in the DTBP algorithm. A next hop entry consists of destination ID, next hop ID, and a time stamp of the entry.

In the following sections, the simulation results of three types of scenarios are presented. The first scenario is that all nodes possess accurate location information; the second scenario is that some nodes do not have their location information; the third scenario is that there is location error at each node.

4.5 Accurate Location Information Scenario

In this section, the simulation results in the scenario that all nodes have accurate location information are presented.

Fig. 4.1 illustrates the delivery rate of different routing protocol with respect to the network density. As can be seen in Fig. 4.1, the critical density region in 3-D networks that results in lower greedy success rate ranges from 5 to 7, which is slightly higher than the critical region (3 to 7) in 2-D networks found in [12,18]. As observed, PSGR achieves much higher delivery rate compared with DSDR and DSR, regardless whether DTBP is adopted or not. The delivery rate of DSDR reaches the lowest in the critical density region because DSDR does not have a detouring strategy and in the critical density region many packets will likely be forwarded to the local minimum. The delivery rate of DSDR is slight lower than the greedy success rate in the ideal

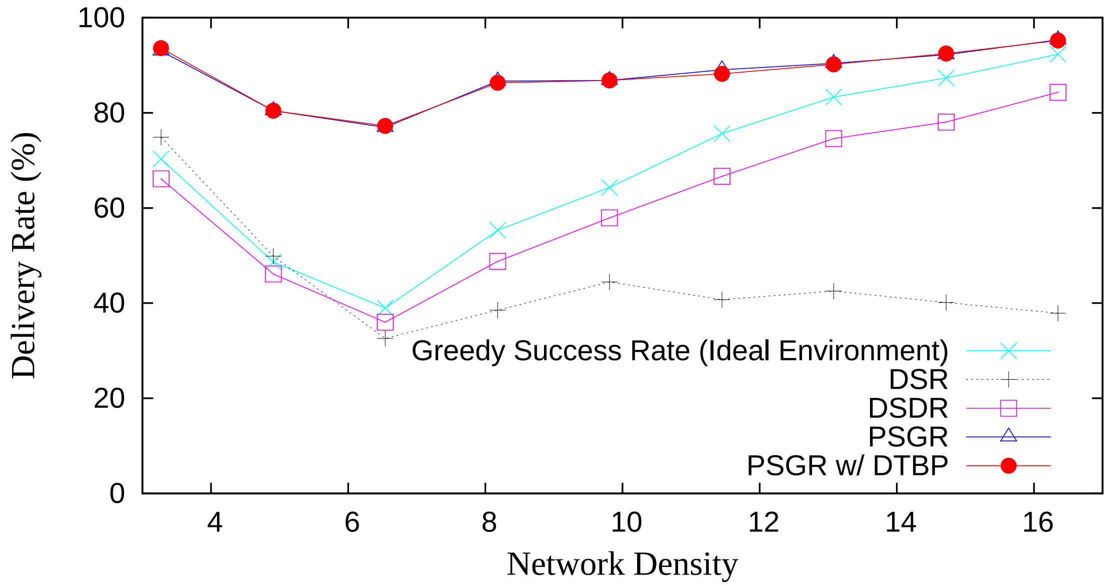

Figure 4.1: Delivery rate

environment where the effects of MAC and physical layer are completely ignored. The delivery rate of DSR decreases as the network density increases. This is due to the fact that DSR uses flooding in its path discovery phase, which incurs a large number of packet collisions and severe channel contention when the number of neighbors increases. This confirms that in the resource-constraint underwater environment, the flooding operation is not effective.

Fig. 4.2 shows the end-to-end delay of different routing protocol with respect to the network density. DSDR has the shortest delay among all routing protocols. However, note that this delay only accounts for packets successfully delivered and the number of successfully delivered packets for DSDR is the lowest as depicted in Fig. 4.1. The end-to-end delay of PSGR reaches the highest point in the critical

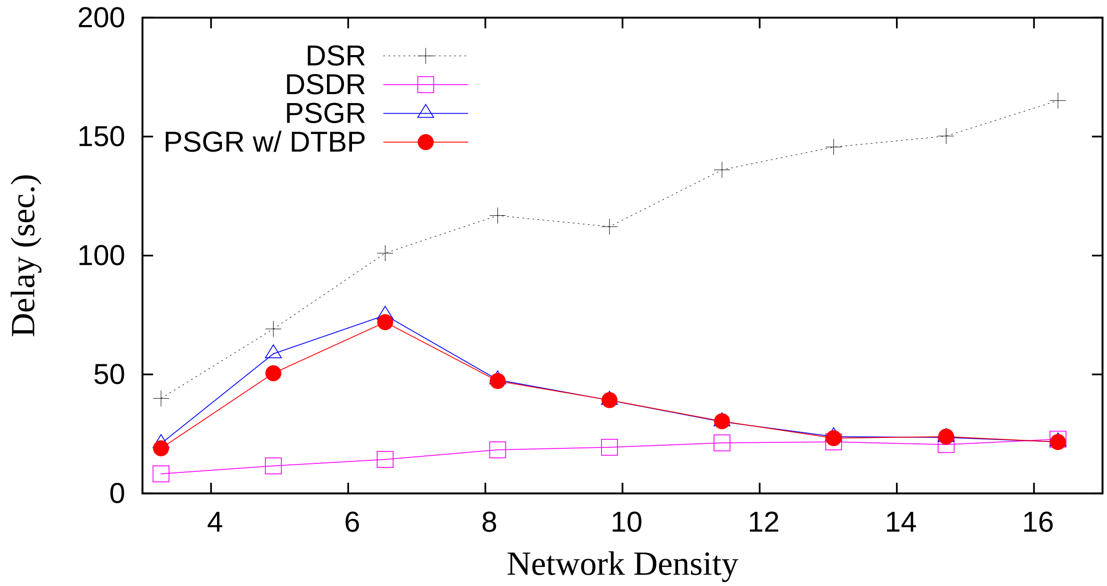

Figure 4.2: End to end delay

density region. This is because that packets are likely to traverse a longer route in case of the critical density region. PSGR with DTBP leads to slightly shorter delay than PSGR because after the delivery of the first packet subsequence packets can go through a pruned shorter route. DSR results in the longest end-to-end delay because the delay includes the time of path discovery phase in DSR.

Fig. 4.3 demonstrates the average hop stretch of different routing protocol with respect to the network density. Similar to the end-to-end delay, DSDR has the smallest hop stretch among all routing protocols, but that is because DSDR only deliver a small number of packets that do not lead to any local minimum. Since only the greedy forwarding is involved, the paths these packets traverse are guaranteed to be sub-optimal [25]. DSR produces small hop stretch at low network density, but the

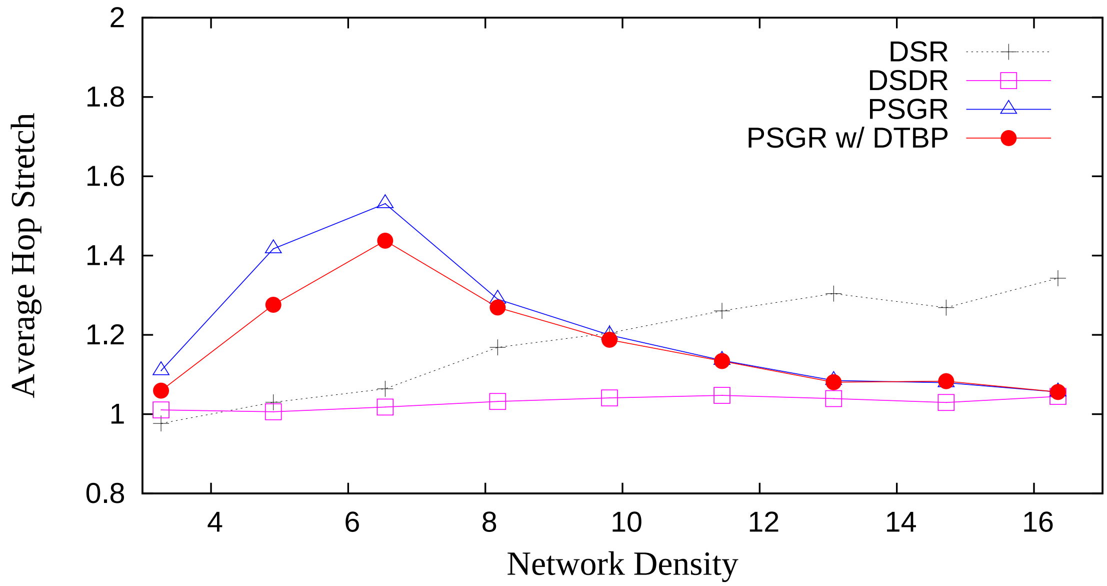

Figure 4.3: Average Hop Stretch

hop stretch increases along with the network density. This is because flooding done in networks with higher density will suffer from the broadcast storm problem [9]. As a result, the path discovery phase of DSR fails to produce short paths at high network density. Both PSGR and PSGR with DTBP produce longer hop stretch in the critical network density region, and the hop stretch of PSGR with DTBP is slightly lower than PSGR. Note that even the largest hop stretch produced by PSGR (approximately 1.6) is much smaller than that produced by GPSR [11] and GOAFR$^+$ [12] in 2-D networks (approximately 6 to 8) [18].

Fig. 4.4 shows the energy consumption of different routing protocol with respect to the network density. PSGR and PSGR with DTBP consume almost the same low amount of energy. DSDR consumes even less energy, but it is because it delivers fewer

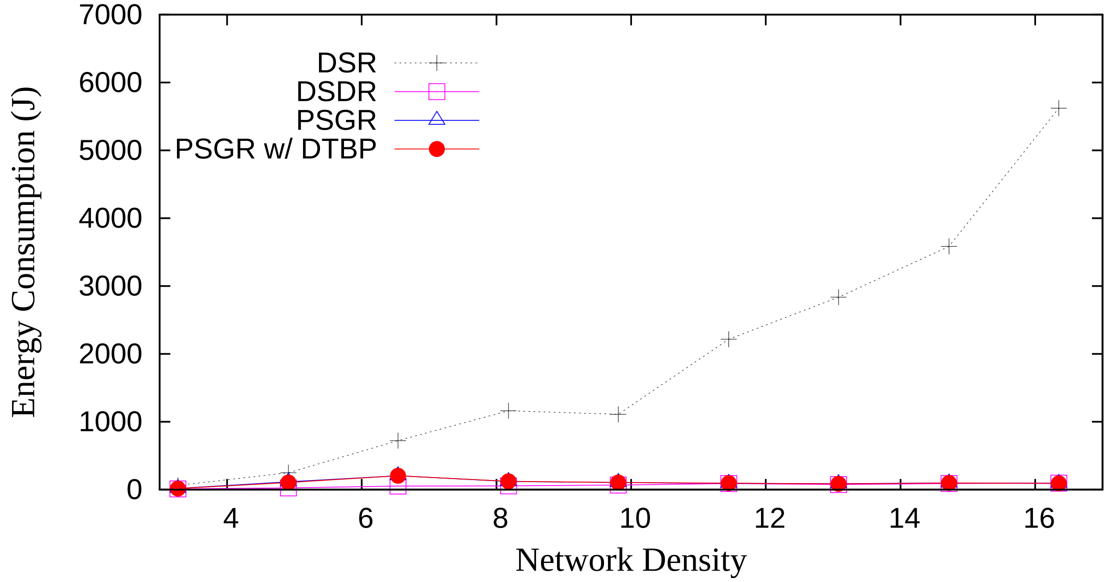

Figure 4.4: Energy Consumption

packets. DSR consumes the most energy among all routing protocols. Since the hop stretch of DSR is not higher than that of PSGR in most of the density region, the reason of more energy consumption of DSR can only be the flooding operations in the path discovery phase.

Fig. 4.5 illustrates the communication overhead of different routing protocol with respect to the network density. As can be seen in Fig. 4.5, all the geographic routing protocols, including DSDR, PSGR, and PSGR with DTBP, have low communication overhead and their communication overhead is insensitive to the network density. On the other hand, DSR introduces much more communication overhead due to flooding in the path discovery phase and the overhead grows quickly as the network density increases.

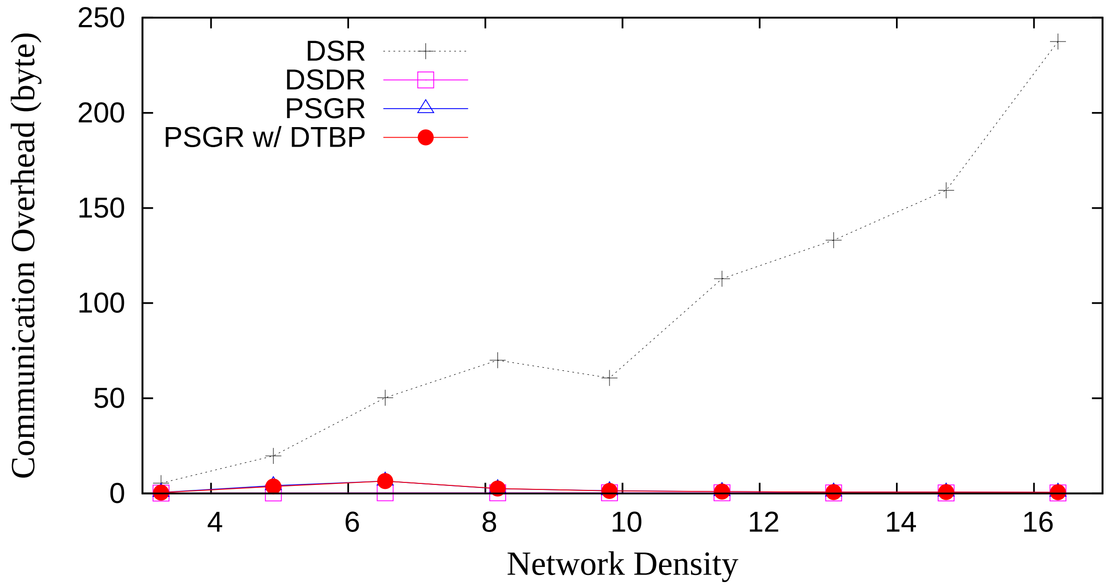

Figure 4.5: Communication Overhead

Fig. 4.6 demonstrates the storage overhead of the DTBP. On average there are only few (< 3) nodes on the path that need to keep the next hop entry. Interestingly, when the network density increases, more nodes in the network will not cause more nodes to keep the next hop entry. This is because the probability of greedy forwarding increases along with the network density.

4.6 Partial Accurate Location Information

To validate the robustness of PSGR and PSGR with DTBP, in this section the simulation results of them in the scenario that a portion of nodes in the network do not have the location information are presented. The percentage of nodes with the

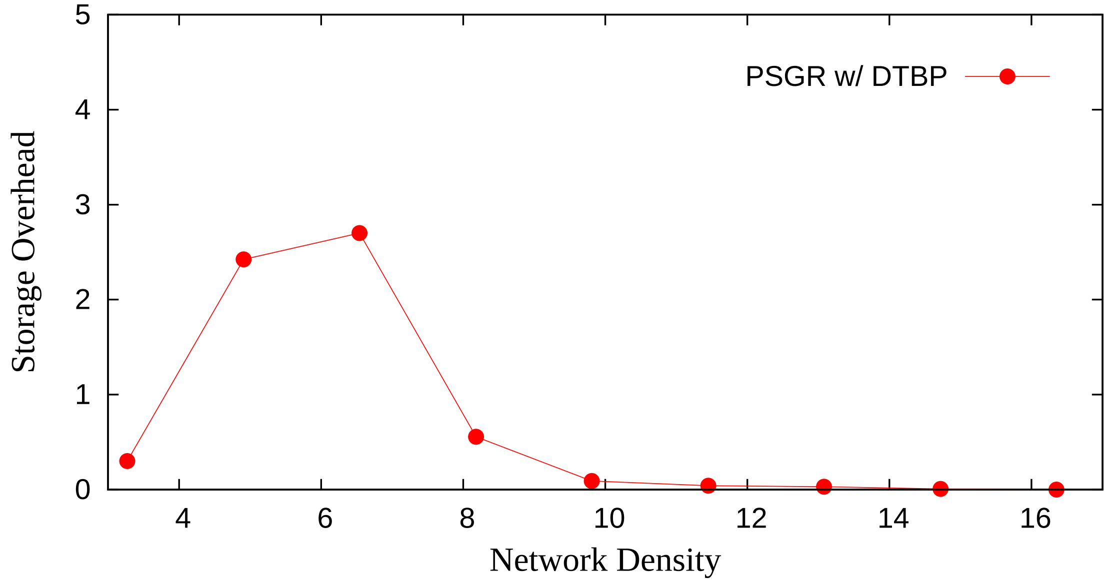

Figure 4.6: Storage Overhead

location information is set to be 50%, 75%, and 100%. Note that the rest of nodes in the network is assumed to have no location information at all.

Fig. 4.7 shows the hop stretch of PSGR and PSGR with DTBP with respect to the network density in the scenario where only a percentage of nodes have the location information. As expected, the fewer nodes possess the location information, the larger the hop stretch is. This is because the probability for a node to forward a packet to a neighbor away from the destination increases as more and more neighbors have no location information. The hop stretch goes above 4 in the critical network density region when only 75% nodes have the location information. The hop stretch is doubled (approximately 8) in the critical network density region when only half of nodes in the network have the location information. However, it is worth noting that

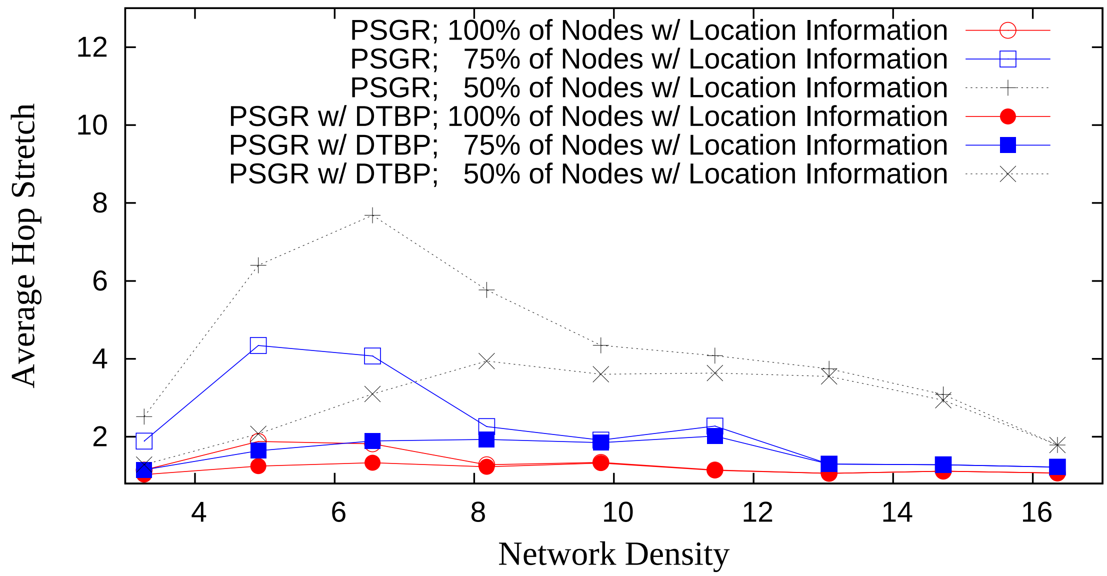

Figure 4.7: Average Hop Stretch

in the critical density region DTBP helps reduce the hop stretch by more than 50% regardless of the percentage of nodes that possess the location information.

Fig. 4.8 illustrates the storage overhead of PSGR with DTBP with respect to the network density in the scenario where only a percentage of nodes have the location information. The lack of location information at some nodes increases the probability for PSGR with DTBP to produce longer path, which in turn results in more nodes to keep the next hop entry. However, by keeping few extra next hop entries, DTBP is able to prune the path by more than 50% as depicted in Fig. 4.7 in critical density region. In addition, the storage overhead decreases quickly when network density increases.

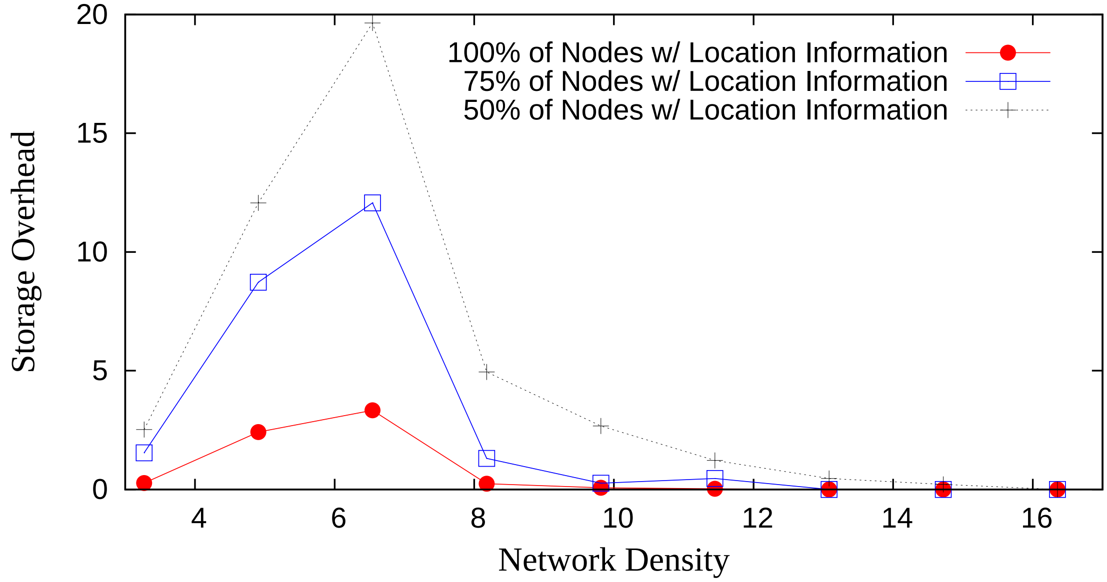

Figure 4.8: Storage Overhead

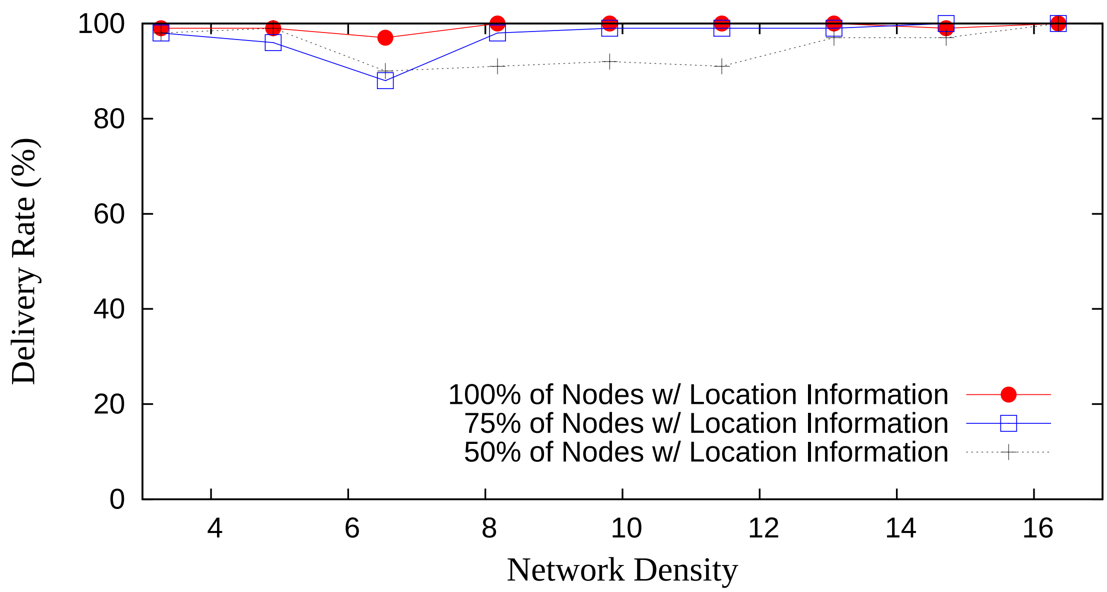

Figure 4.9: Delivery Rate

Fig. 4.9 demonstrates the delivery rate of PSGR with respect to the network density in the scenario where only a percentage of nodes have the location information. In case when 75% of nodes have location information, the delivery rate of PSGR is almost 100% except at the critical density, where the delivery rate of PSGR is reduced to around 90%. In case when only half of nodes have the location information, the delivery rate is still more than 90%. Recall in Fig. 4.1 DSR and DSDR can never achieve the delivery rate higher than 90%, it shows that PSGR is very robust even when a large portion of nodes in the network do not have location information.

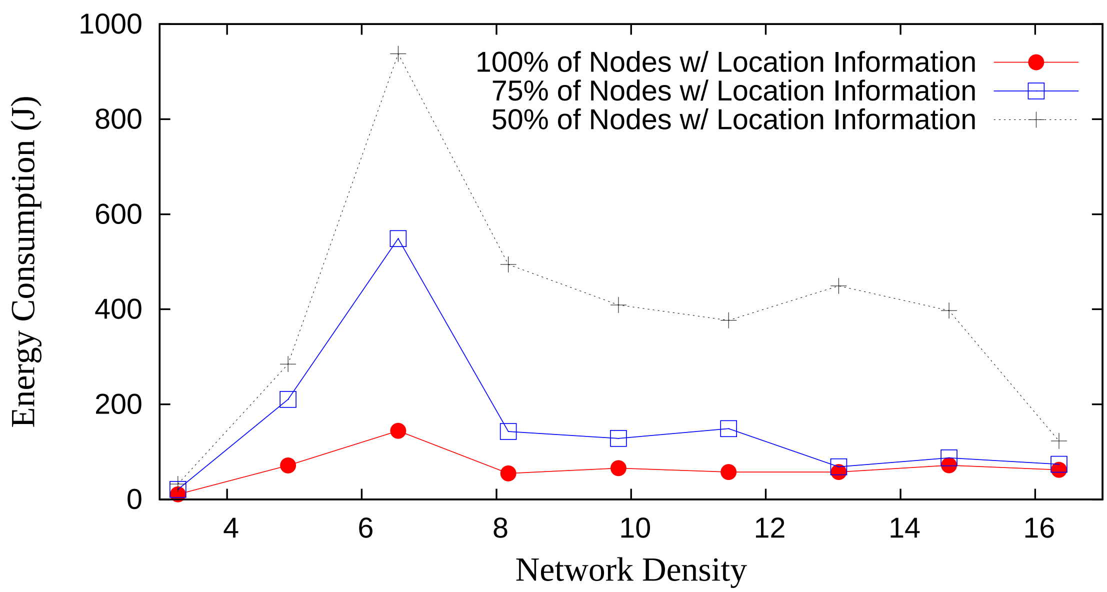

Figure 4.10: Energy Consumption

Fig. 4.10 shows the energy consumption of PSGR with respect to the network density in the scenario where only a percentage of nodes have the location information. As can be seen in Fig. 4.10, more energy is consumed by PSGR if more nodes have no location information. However, if we compare the energy consumption between PSGR and DSR in Fig. 4.10 and Fig. 4.4, it is clear that PSGR consumes much less energy than DSR even when 50% of nodes do not have the location information.

4.7 Inaccurate Location Information

In this section, we further validate the robustness of PSGR and PSGR with DTBP on location information errors. Suppose that a node has transmission range r. The location error is modeled as a uniform random value between $[-e\% \times r, e\% \times r]$ on each dimension. That means if a nodes true location is $[x, y, z]$, then the location information is generated as any 3-tuple value within the cube bounded by $[x - e\% \times r, x + e\% \times r]$, $[y - e\% \times r, y + e\% \times r]$ and $[z - e\% \times r, z + e\% \times r]$. The location error is set to be either 0%, 50%, or 100%.

Fig. 4.11, 4.12, 4.13, and 4.14 illustrate the hop stretch, storage overhead, delivery rate, and energy consumption of PSGR and PSGR with DTBP with respect to the network density in the scenario where there is location error at each node. It is not difficult to see that the trend in these figures is very similar to that in Fig. 4.7, 4.8, 4.9, and 4.10, respectively. In general, the routing performance of PSGR and PSGR with DTBP in the scenario where there is location error at each node is better (i.e., lower hop stretch, lower storage overhead, higher delivery rate, and lower energy consumption) than that in the scenario where only a portion of nodes have the location information, regardless which metric is used. For instance, the peak of the hop stretch of PSGR in the scenario of the huge 100% of location error at each

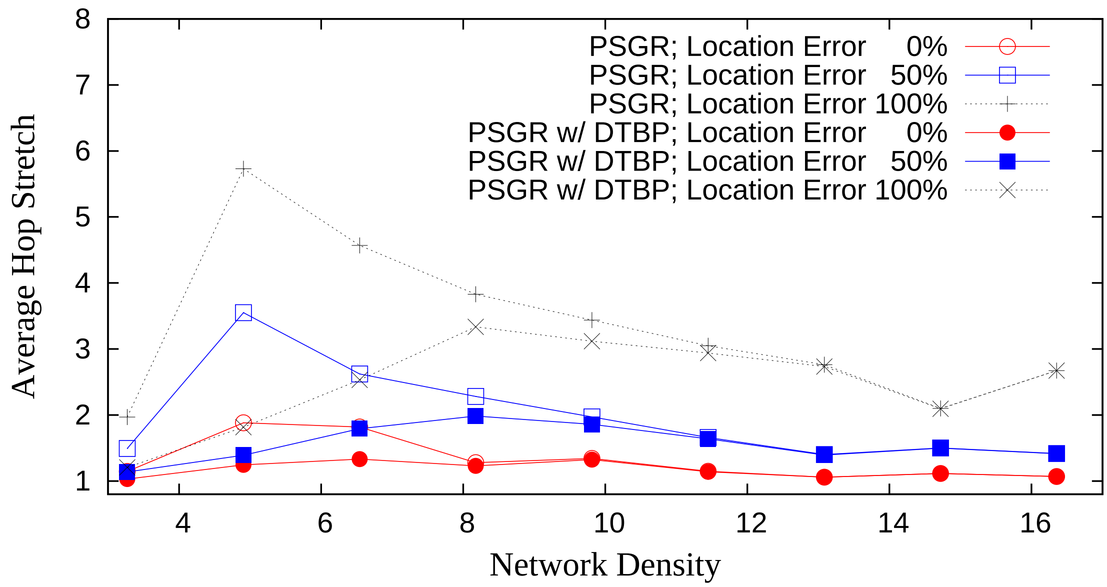

Figure 4.11: Average Hop Stretch

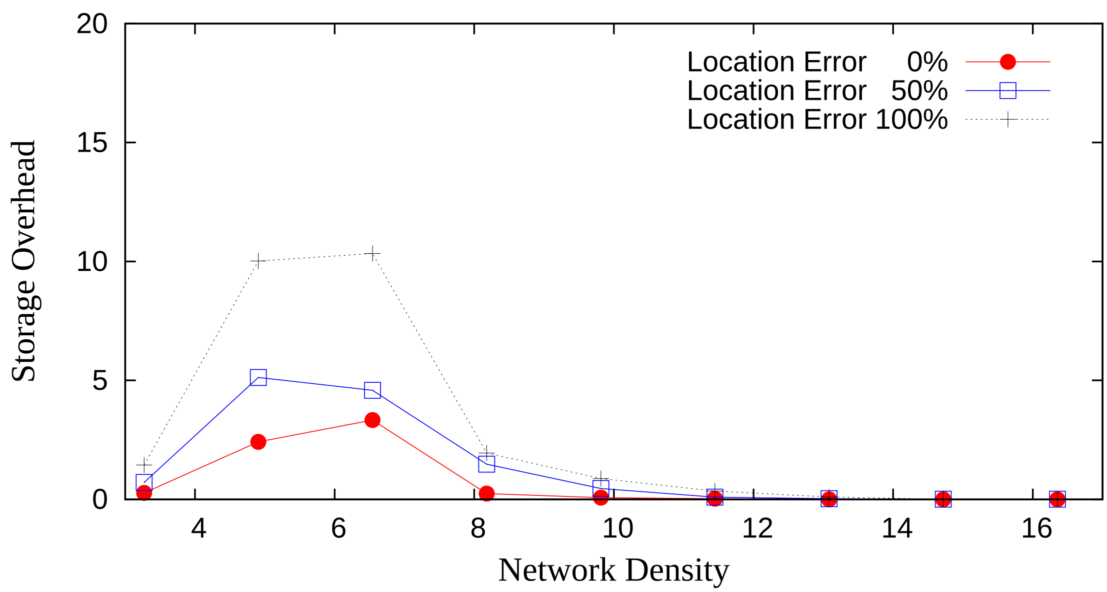

Figure 4.12: Storage Overhead

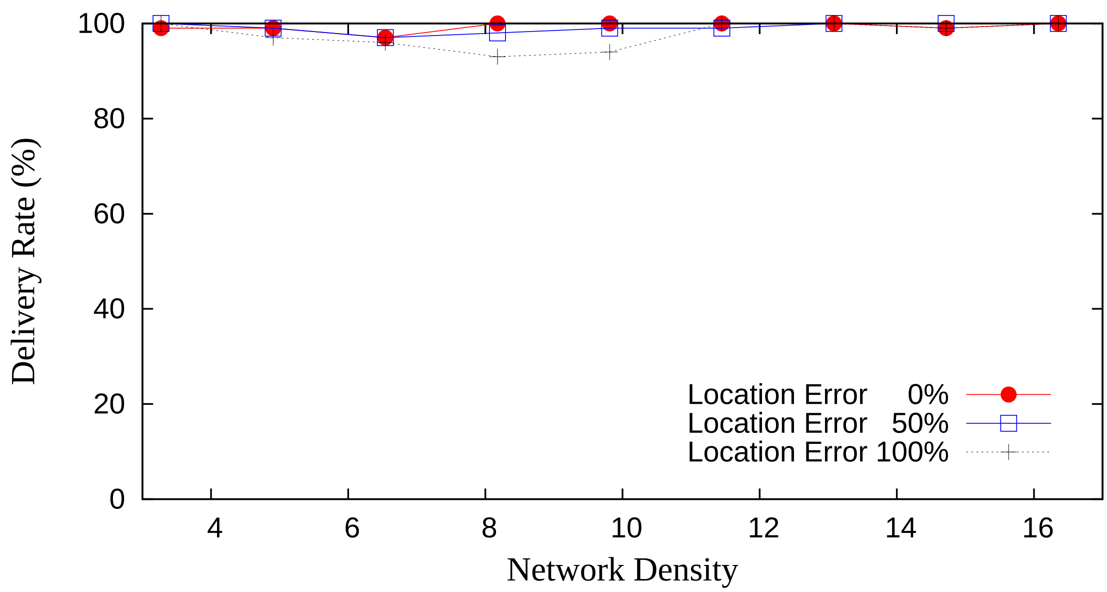

Figure 4.13: Delivery Rate

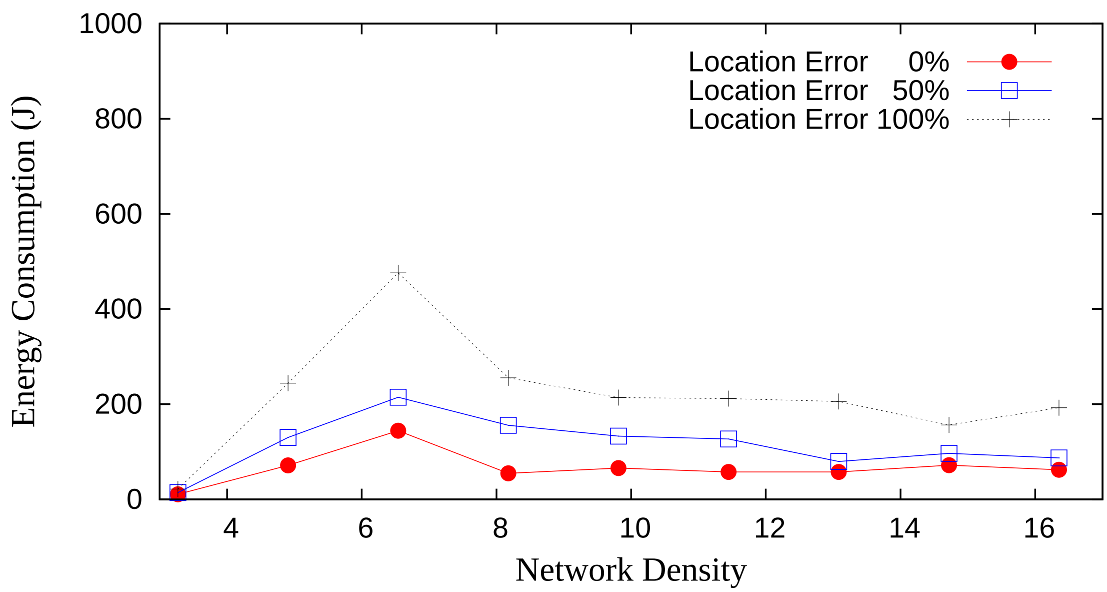

Figure 4.14: Energy Consumption

node (approximately 5.8) is much smaller than the peak of hop stretch of PSGR in the scenario that 50% of nodes have location information (approximately 7.5).

From these simulation results, we conclude the following two observations: First, PSGR as well as PSGR with DTBP is robust no matter the location information is missing or there is error in the location information at each node. Second, a little location information, even a very inaccurate one, can improve the routing performance significantly.

Chapter 5

Conclusions and Future Work

Routing in 3-D underwater acoustic sensor networks is challenging due to the resource constraints in underwater environment and inferior physical characteristics of acoustic links. Although geographic routing has been suggested for such networks, the existing detouring strategies are not appropriate for the 3-D underwater environment. In this thesis, we propose the first stateless geographic routing protocol for 3-D underwater acoustic sensor networks, namely Practical Stateless Geographic Routing. Our routing protocol is based on the concept of depth-first search and is robust in the sense that it functions well even when the location information is not available. In addition, we propose a light-weight algorithm, namely Departed Tree-Branch Pruning, to effectively optimize the path obtained from the proposed routing protocol. The extensive simulation results have validated that the proposed routing algorithms achieve much better routing performance than the existing routing protocols for underwater networks in terms of different metrics.

As we have pointed out in Chapter 4, our proposed protocol performs better when all nodes have huge errors than when a large portion of nodes have accurate location information but the rest have none. This observation teaches us that even a very rudimental and light-weight localization algorithm (e.g., a node sets its location as the average of neighbor's) may help the routing performance significantly. In the future, we would like to investigate different localization algorithms and study which one provides the best trade-off between the routing performance gains and the communication/computational overheads for localization.

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