A ROBUST UNDERWATER NETWORKING STACK FOR SENSING APPLICATIONS IN SINGAPORE WATERS

Hwee-Pink Tan[a], Xiaoping Ma[a], Roee Diamant[b] and Alvin Valera[a]

[a]Networking Protocols Department, Institute for Infocomm Research, Singapore
[b]Department of Electrical and Computer Engineering, The University of British Columbia, Canada

Corresponding author: Hwee Pink Tan, Institute for Infocomm Research,
1 Fusionopolis Way, #21-01, Singapore 128632
Email address: hptan@i2r.a-star.edu.sg
Fax: +65 6776 1378

Abstract: *Various novel applications of underwater acoustic sensor networks have emerged or been proposed in recent years. As such networks are expected to remain in situ for long durations, multi-hop networking schemes are required for robust and energy-efficient data dissemination. These can be particularly challenging in the warm and shallow waters around Singapore.*

In addition, for meaningful interpretation of sensed data and to assist with network scheduling and data dissemination, accurate underwater localization, typically achieved through range-based methods, is needed. However, signal reflections from the sea surface or bottom, or from objects such as ship hulls and docks, can give rise to localization inaccuracies if falsely identified as the line-of-sight (LOS) and must therefore be identified.

In this paper, we present our experiences in the design and testing of (i) a robust multi-hop underwater network for long-range sensing and (ii) a classification of time-of-arrival measurements to LOS and non-LOS to improve the accuracy of range-based underwater localization in Singapore waters.

Keywords: *Underwater Acoustic Sensor Networks, Multi-hop Networking, Underwater Localization*

1. INTRODUCTION

During the last couple of years, we could observe a growing interest in Underwater Wireless Sensor Networks (UWSNs). One important reason is that they can improve ocean exploration and fulfil the needs of a multitude of underwater applications, including: oceanographic data collection, warning systems for natural disasters (e.g., seismic and tsunami monitoring), ecological applications (e.g., pollution, water quality and biological monitoring), military underwater surveillance, assisted navigation, industrial applications (offshore exploration), etc. To fulfil the objectives of different underwater applications, the sensed data must be disseminated in a robust manner (e.g., in terms of reliability, energy efficiency, latency etc). To make sense of the data, it is typically interpreted with reference to a node's location, e.g., reporting an event occurrence, tracking a moving object or monitoring a region's physical conditions. Since RF communications are significantly attenuated underwater [1], the use of the well-known Global Positioning System (GPS) is restricted to surface nodes. Hence, message exchanges between submerged UWSN nodes and surface nodes (or other reference nodes with known locations) needed for localization must be carried out.

Acoustic waves have been the physical layer technology of choice for communications underwater as RF as well as optical waves are not feasible due to severe attenuation [1]. However, the characteristics of underwater acoustic channel present its own unique challenges in communication protocol design. These characteristics include long propagation delays, limited bandwidth, motion-induced Doppler shift, phase and amplitude fluctuations, multipath interference, etc. [2]. In particular, in Singapore waters, which are shallow and warm, the acoustic channel is subject to noise stemming from snapping shrimps, sea traffic and turbulence [3].

Although the conventional approach of data dissemination via direct transmission (single-hop) from a source to a sink is simple, it suffers from several disadvantages such as high energy consumption, high bit error rates (BER) and low achievable data rates [4], and is not suitable for certain applications that require in-situ deployment over long periods of time. As such, multi-hop data transmission has become attractive as it can provide higher achievable data rates and lower BER over multiple links of shorter distances [4].

Scheduling and data forwarding in underwater acoustic networks can greatly benefit if the location of each node, and thus its propagation delay, with respect to neighbouring nodes is known. However, location discovery for underwater nodes is non-trivial as its accuracy is impacted by propagation speed uncertainties, constant node motions, time-synchronization ambiguities, multipath interference etc. [5]. Moreover, due to the low bandwidth of underwater acoustic signals, line-of-sight (LOS) and non-LOS (NLOS) links may not be separable. As a result, negative superposition of signals often renders mistaking NLOS links as LOS when measuring the time-of-arrival (ToA) in the channel. As the delay spread in the underwater acoustic channel is often of the order of 10msec [6], falsely identifying NLOS links as LOS severely impact the accuracy of underwater localization. This problem becomes acute in near-shore environments where strong reflections from obstacles introduce large bias in TOA measurements.

In this paper, we present a complete system implementation of an underwater network stack that incorporates two key features (i) a two-stage LOS/NLOS classifier of ToA measurements to enhance localization accuracy; and (ii) a bidirectional overhearing scheme for robust multi-hop underwater networking for a linear network. In addition to extensive simulations, we validate this implementation with actual field tests using hydroacoustic modems from two different vendors in shallow underwater environments.

2. DESIGN OF UNDERWATER NETWORK STACK

Figure 1 shows the software architecture and underwater network stack in our implementation. The core of our contribution comprises three major components: (i) network layer; (ii) data link layer; and (iii) cross-layer functions.

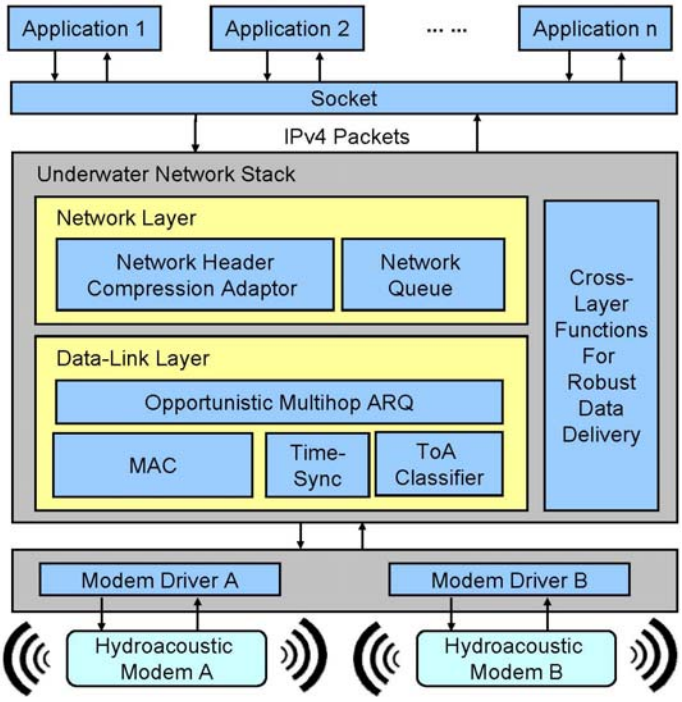

Fig.1: Software architecture and underwater network stack.

The software architecture is designed with modularity, compatibility, customization and ease of porting across different hardware platforms in mind.

- The network stack is implemented entirely in user-space as a monolithic application. This avoids kernel programming which might introduce limitations and potentially constrain the usage of our implementation to a particular software platform and/or version.
- Applications communicate with the network stack through the use of sockets, inter-exchanging standard IPv4 packets. This allows a wide-

range of applications to use the proposed network stack with minimal modifications.

- All functional blocks of the network stack except for the Modem Driver sub-layer are independent of the type of hydroacoustic modem used. The Modem Driver module can thus be easily replaced, allowing the network stack to be ported onto different modems without considerable effort.

Details of the design and implementation can be found in [7]. In the following, we focus on two key functional blocks, namely the ToA classifier and the opportunistic multi-hop ARQ.

2.1. A Two-Stage ToA Classifier to enhance localization accuracy

Existing range-based underwater acoustic localization schemes implicitly assume that propagation delay (PD) measurements reflect the delay in the LOS between the transmitter and receiver in performing ranging. However, while it is expected that power attenuation in the LOS link is smaller than in NLOS links, often due to negative superposition in the channel, the LOS link in the channel impulse response is not the strongest, and NLOS links may be mistaken as LOS when measuring ToA of received signals [2,6]. We identify two types of NLOS links as illustrated in Figure 2 below. For the pair of nodes (u, a_3), a sea surface or bottom reflections link (referred to as sea-related NLOS (*SNLOS*)) exists, in addition to a LOS link. For (u, a_2), both LOS and SNLOS links exist and signals also arrive from reflection off a rock (referred to as object-related NLOS (*ONLOS*)). Lastly, between nodes (u, a_1), there is no LOS link due to an obstacle and only an ONLOS link exists. If PD measurements of NLOS links are mistakenly identified as delay in the LOS link, and the difference in path length is large, localization accuracy can be significantly degraded.

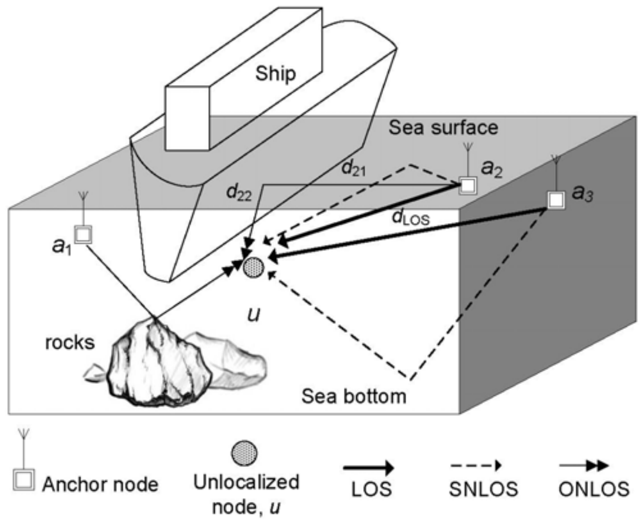

Fig.2: Illustration of LOS and NLOS links in the underwater acoustic channel

In [8,9], we proposed a two-step algorithm to classify a set of PD measurements for a fixed transmitter-receiver distance into classes of **LOS** and

NLOS links, which is a problem that has not been treated in previous literature. We first identify ONLOS related PD-measurements by comparing PD-based range estimations with range obtained from received-signal-strength (RSS) measurements. After excluding PD measurements related to ONLOS, using a constrained expectation maximization (EM) algorithm, we further classify the remaining PD measurements into LOS and SNLOS, and estimate the statistical parameters of both classes to improve localization accuracy.

2.2. Opportunistic ARQ with Bidirectional Overhearing (BiDO)

To achieve reliable end-to-end multi-hop data delivery, automatic repeat request (ARQ) schemes can be employed to improve the reliability of transmissions at every hop. While hop-by-hop ARQ achieves better performance than its end-to-end counterpart [10 it does not fully exploit the broadcast property nor consider the spatial/temporal variations of underwater acoustic channels.

In [11, we proposed a multi-hop data delivery scheme using an opportunistic ARQ with bidirectional overhearing: opportunistic overhearing of DATA or ACK frames, from any nodes in the network (both upstream and downstream: bidirectional), are used for either speeding up DATA delivery to the sink or as implicit acknowledgement for a previous DATA transmission. This increases the robustness of a data delivery scheme by reducing dependency on each link for data transmissions. The single points of failure in strictly hop-by-hop transmissions schemes are thus eliminated.

The proposed scheme relies on accurate underwater localization to provide each node with knowledge of its relative position with respect to its neighbouring nodes as well as the sink node. A detailed description of this scheme and its implementation details can be found in [7,11].

3. EXPERIMENTAL EVALUATION

Next, we present results from experiments conducted off St John’s Island (in the Singapore straits) in September - November 2011, with water depths of 15m.

3.1. ToA classification

The sea trial included two underwater acoustic modems, manufactured by Evologics GmbH [12], and deployed at a depth of 5m from a static platform and from a boat anchored to the sea bottom respectively. Throughout the experiment, the boat changed its location to test results for three different transmitter-receiver distances, which were monitored using GPS measurements. Measurements were obtained at each node using four-way packet exchange in a TDoA fashion, resulting in a set of two-way PD measurements, X. For each transmission distance, the boat remained static for 20 min, allowing around 200 measurements, x_i, at each node. A propagation speed of c=1540 m/sec, as measured throughout the year in the Singapore straits [3], was considered.

For each set X, denoting by d_i the GPS-based transmitter-receiver distance measured at the same instance as x_i, we compute the distance error $\rho^{e}_{2}\ |cx_i-d_i|$ in 3 ways: (i) based on the output of our classifier (denoted by **E(LOS)**), (ii) replacing d_i with E(d) and x_i with E(X) (denoted by **E(X)**) and (iii) replacing d_i with E(d) and x_i with min(X) (denoted by **Min(X)**).

In Figure 3, we plot the normalized positioning error, $\frac{\rho_2^e}{E(d)}$, for the three locations of the boat in the sea trial, averaged for the two nodes. We observe that the minimum value of X usually, but not always, results in better propagation delay estimation than the mean value of X. However, the mean of the measured LOS distance, **E(LOS)**, obtained as the output of our classifier, yields the best results, with average estimation error of 0.7m compared to more than 10m for the other methods.

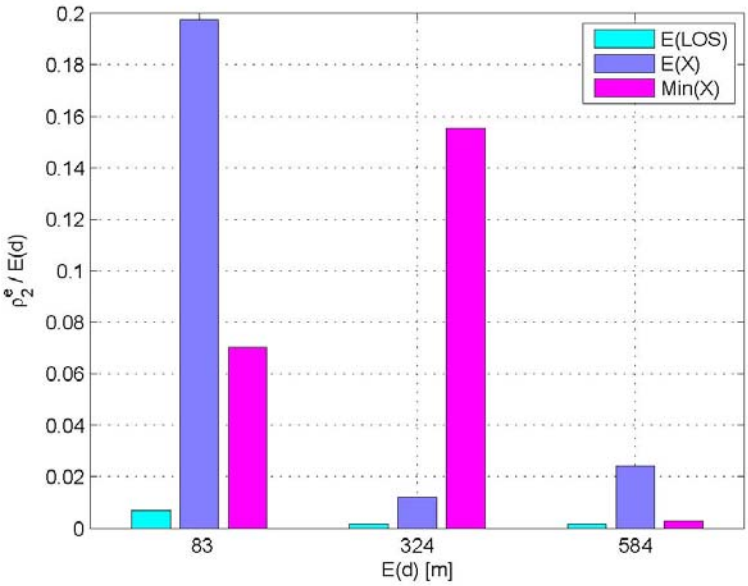

Fig.3: Normalized positioning error obtained for 3 different locations obtained from our estimator (**E(LOS)**) *compared with simple averaging and minimization* (**E(X)** *and* **Min(X)** *respectively*) *of all measurements.*

3.2. Multihop Data Delivery over Linear Underwater Network

The topology for these sea trials comprised four modems from Acoustic Research Lab (ARL), National University of Singapore (NUS), arranged approximately linearly, at a depth of 10-13m below the sea surface. The end-to-end distance of the linear network is about 340 meters, with inter-node distances between 100m to 130m.

The nodes are setup one at a time: Node 1 is deployed to the water from a static platform and is monitored directly by one of the researchers on the platform. Node 2 is then put to water from a boat and is anchored two meters above the sea bottom. Node 2 operates autonomously. When it is ready, Node 1 sends some test packets to Node 2 and checks if it receives ACKs from Node 2 to make sure Node 2 works properly. The same procedures are carried out with Node 3. The boat finally stays beside Node 4 which, like Node 1, can be monitored and controlled directly by researchers on the boat. Before commencing the tests, the four nodes are time-synchronized using the implemented Piggyback-on-ACKs time synchronization scheme [13]. During the tests, the time synchronization scheme is always in active mode, which synchronizes the whole network continuously. Throughout all tests, the MAC-layer packet size (for both DATA packet and ACK packet) is 27 bytes, and 100 packets are sent per test.

In this paper, we focus on the performance comparison of proposed BiDO routing and static hop-by-hop routing scheme, as summarized in Table 1; other detailed results can be found in [13].

Scheme	Retransmission limit	Packet Delivery Ratio	Throughput (bps)	Energy consumed per received packet
Hop-by-hop	0	0.99	21.4	14.3
	2	1.00	20.4	14.2
BiDO	0	0.92	19.9	12.9
	2	1.00	21.4	14.5

Table 1: Summary of experimental results obtained from Sea Trials on 19 Sep 2011 and 03 Oct 2011

When retransmissions are permitted, the performance of both schemes is almost identical in term of packet delivery ratio (PDR), throughput and energy consumption per received packet. One observation based on our raw data is that due to the overhearing feature that can reduce unnecessary transmissions and retransmissions, BiDO actually results in fewer total packet transmissions, which means that it spends less energy in transmitting packets. However, the energy consumption per received packet is still slightly higher for BiDO because it has a higher rate of overhearing during the test[1].

When retransmissions are not permitted, the hop-by-hop data delivery scheme is more reliable than the BiDO scheme, although the latter is intended to be at least as good. This is most likely due to the difference in channel conditions between the two tests. During the BiDO test, five of the total eight lost packets are consecutive (Packet 73 to Packet 77), which indicates a deterioration in the channel during that period.

The hop-by-hop data delivery scheme enjoys a slightly higher throughput than the BiDO scheme as the former has a higher PDR but a similar total delay. Despite a lower PDR, BiDO consumes less energy per successfully delivered packet. This is because compared to the lower PDR, the BiDO scheme has an even lower rate of overhearing and fewer packet transmissions than the hop-by-hop test.

[1] Each time a node transmits a DATA or ACK frame (receives or overhears an uncorrupted frame), it consumes 1 unit (0.5 units) of energy; Energy consumed per received packet = (Total energy consumed by all nodes during a test) / (Number of received packets).

4. ACKNOWLEDGEMENTS

We would like to acknowledge Evologics GmbH and ARL, NUS, for providing access to their respective acoustic modems for implementation and testing, as well as the grant support from ARL for Roee Diamant's internship attachment from October to December 2011.

REFERENCES

[1] **M. Chitre, S. Shahabodeen and M. Stojanovic,** Underwater acoustic communications and networking: Recent advances and future challenges, Marine Technology Society Journal, Vol. 42, Garmish-Partenkirchen, Germany, 2008, pp. 103-116.

[2] **M. Stojanovic, J. G. Proakis**, Acoustic (underwater) Communications, Encyclopedia of Telecommunications, John Wiley and Sons, Hoboken, NJ, USA, 2003.

[3] **M. A. Chitre**, A high-frequency warm shallow water acoustic communications channel model and measurements, Acoustical Society of America, 122 (2007), pp. 2580-2586.

[4] **M. Stojanovic**, On the relationship between capacity and distance in an underwater acoustic communication channel, ACM Sigmobile Mobile Computing and Communications Review, vol 11 (4), Oct 2007, pp 34-43.

[5] **H. P. Tan, R. Diamant, W. Seah and M. Waldmeyer**, A survey of techniques and challenges in underwater localization, Elsevier Journal of Ocean Engineering, Vol. 38, 2011, pp. 1663-1676.

[6] **R. Diamant and L. Chorev**, Emulation system for underwater acoustic channel, International Undersea Defence Technology Europe conference (UDT), Amsterdam, The Netherlands, 2005.

[7] **H. Zhuang, Z. Bai, A. Valera, H. P. Tan and M. Chitre**, A Robust Multihop Underwater Network for Sensing Applications – Implementation and Experimental Evaluation, Proc. of the IEEE ICCS (2010), pp. 376-380.

[8] **R. Diamant, H. P. Tan and L. Lampe**, LOS and NLOS Classification for Underwater Acoustic Localization, To be submitted.

[9] **R. Diamant, H. P. Tan and L. Lampe,** Hybrid ToA-Signal Strength Algorithm for Underwater Acoustic Localization, IEEE/MTS Oceans 2010.

[10] **D. Lucani, M. Medard and M. Stojanovic**, Network coding schemes for underwater networks: The benefits of implicit acknowledgement, Proc. of ACM WUWNet 2007.

[11] **H. Zhuang, H. P. Tan, A. Valera and Z. Bai**, Opportunistic ARQ with Bidirectional Overhearing for Reliable Multihop Underwater Networking, Proc. of IEEE Oceans 2010.

[12] **Evologics GmbH**, Evologics S2C R Series Hydroacoustic Modems.

[13] **X. Ma, A. Valera, H. P. Tan, H. Zhuang and Z. Bai,** Robust Multihop Underwater to support long-range sensing applications, To be submitted.