A Robust Multihop Underwater Network for Sensing Applications - Implementation and Experimental Evaluation

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***Abstract*—Various novel applications of underwater acoustic sensor networks have emerged or been proposed in recent years. In this paper, we present a complete system implementation of a robust multihop underwater network for sensing applications. At the core of the system is a robust data delivery scheme which uses *opportunistic* automatic repeat request (ARQ) with *bidirectional overhearing*. We demonstrate the modular and hardware-independent nature of our implementation by porting and deploying the software architecture and underwater network stack into hydroacoustic modems from different vendors. We integrate off-the-shelf GPS receivers and temperature sensors and evaluate the performance of the data delivery scheme by transmitting actual sensor data over two hops in shallow underwater environments in Singapore. Received sensor data are then visualized using Google Earth as they arrive at the sink node.**

I. Introduction

Acoustic waves have been the physical layer technology of choice for long-range underwater wireless communications. The use of electromagnetic waves (radio frequency and optical) for medium to long range underwater communications is 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 high bit error rates, significant propagation delay, multipath and noise stemming from snapping shrimps, sea traffic and turbulence [1]–[3].

Several automatic repeat request (ARQ) schemes designed for multihop underwater networks have been proposed to mitigate the severely impaired acoustic channel and improve reliability of data transmission over long-range and across multiple relays. Recently, Zhuang *et al.* [4] proposed a data delivery scheme (DDS) using an *opportunistic* ARQ with *bidirectional overhearing*. The scheme leverages on the broadcast nature and spatial and temporal variance of the underwater acoustic channel to improve overall network performance. Using simulations, the DDS has been shown to outperform its non-*opportunistic* and semi-*opportunistic* counterparts in terms of reliability, energy-efficiency and latency.

In this paper, we present a complete system implementation of a robust multihop underwater network stack that incorporates the above-mentioned DDS. A sensing application which uses off-the-shelf temperature sensors is developed and integrated into the network stack. In addition, a server application that uses Google Earth [5] is also developed to graphically display location and sensing information received from the underwater acoustic sensor network. We validate this implementation with actual field tests using hydroacoustic modems from two different vendors in shallow underwater environments.

The rest of this paper is organized as follows: Section II presents implementation design and details of the underwater network stack and software architecture. The experimental setup and results of the field tests are presented in Section III. Finally, we provide some concluding remarks and outline directions for future work in Section IV.

II. Implementation Design

A. Software Architecture & Underwater Network Stack

Figure 1 shows the software architecture and underwater network stack in our implementation. As can be seen from the diagram, the core of the implementation is in the DDS block which contains three major components: (*i*) network layer; (*ii*) data link layer; and (*iii*) cross-layer functions.

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

- The DDS 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 DDS 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 DDS to be ported onto different modems without considerable effort.

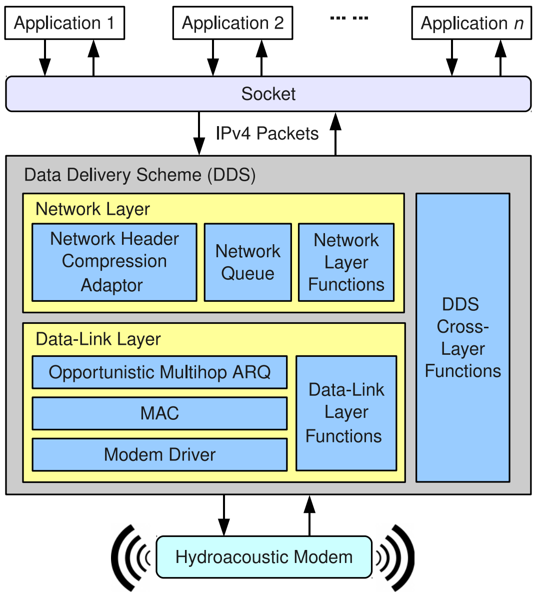

Fig. 1. Software architecture & underwater network stack of the actual implementation.

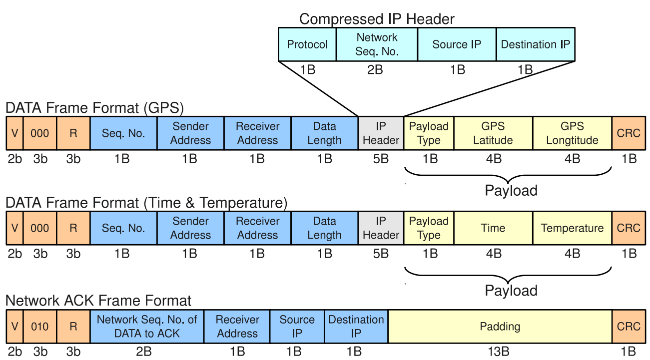

Fig. 2. DATA and ACK frame formats used in our implementation.

2) Underwater Network Stack: The network stack is an adaptation of the design proposed in [4], whereby the authors adopted the application-network layers interface and IP header compression as described in [6]. The IPv4 packets of the well-tested TCP/IP protocol stack is used for data interchange between user applications and our network stack implementation.

The Network Header Compression Adaptor reduces the size of the standard IPv4 header in order to minimize overhead and make full use of the limited bandwidth of the adverse underwater acoustic channel. The compressed IP header is illustrated in Fig. 2

The Opportunistic Multihop ARQ functional block contains the key intelligence of the DDS described in Section II-B. Other important features of the network stack are described in detail in [4].

3) Frame Formats: The DATA and ACK frame formats proposed in [4] are used in our implementation, except for an extra cyclic-redundancy check (CRC) byte for error detection. Depending on the type of applications, the frame lengths

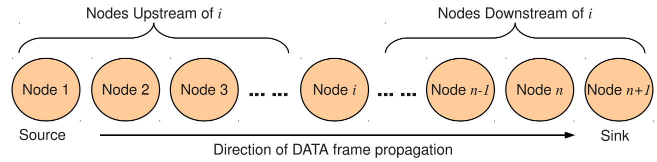

Fig. 3. A n-hop underwater network with single source and sink, arranged in a linear topology.

will vary with the amount of payload from the user application. The frame formats shown in Fig. 2 are specific to the sensing application used in our field tests that will be described in Section II-D1.

B. Opportunistic ARQ with Bidirectional Overhearing

The major component of the DDS that enables efficient multihop data transmission is the *opportunistic* ARQ with *bidirectional overhearing* data delivery scheme (DDS) as proposed by Zhuang *et el* [4]. A major contribution of this paper is the real-world implementation of the said scheme. We briefly describe the distinctive features of this scheme before presenting the implementation details; interested readers are referred to [4] for full details of the scheme.

Consider a linearly arranged underwater acoustic network consisting of n+1 nodes as illustrated in Fig. 3. A node i using a strictly hop-by-hop stop-and-wait (S&W) ARQ transmits a DATA frame p to the immediate downstream node i+1. Node i then proceeds to wait for an acknowledgement (ACK) frame from node i+1, necessarily re-transmitting frame p when no explicit ACK was received upon timeout expiry.

The proposed *opportunistic* ARQ with *bidirectional overhearing* enhances the strictly hop-by-hop S&W ARQ by leveraging on the broadcast nature and spatial and temporal variance of the underwater acoustic channel. Any *opportunistic overhearing* of DATA or ACK frames, from any nodes in the network (both upstream & 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.

C. Protocol States

Fig. 4 shows the protocol's state transition diagram for a node i of an underwater network as illustrated in Fig. 3. The state diagram is generic, applicable to source, relay and sink nodes. The key protocol transitions are as follows:

- When node i receives a DATA frame from the network layer, it is first buffered in the AWAIT TRANSMIT state. This state is controlled by the medium access control (MAC) protocol. Upon transmission, node i transits to AWAIT ACK and waits for an explicit acknowledgement until timeout expiry, retransmitting when no ACK was received up to *max_retry* times. Finally, i transitions

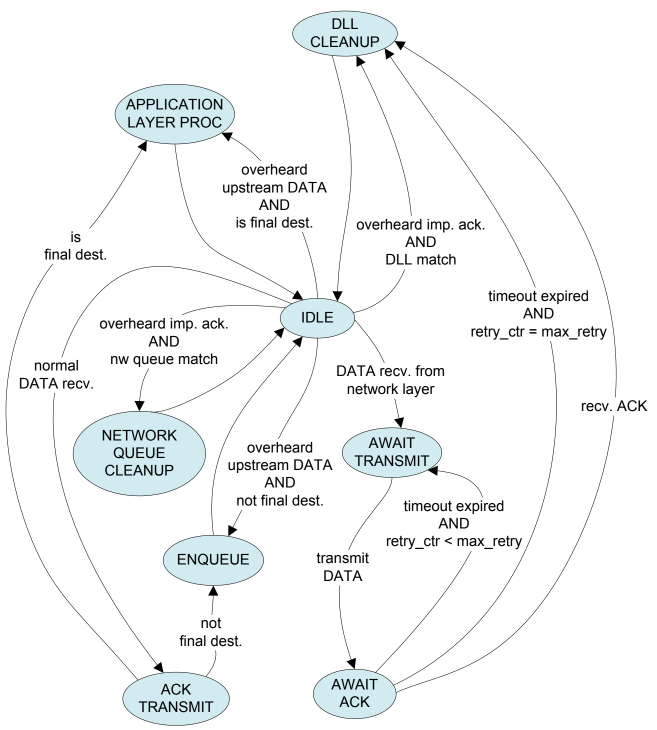

Fig. 4. Protocol state diagram of the *opportunistic* ARQ with *bidirectional overhearing* data delivery scheme.

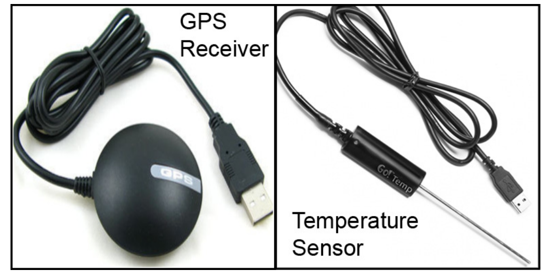

Fig. 5. GlobalSat BU-353 USB GPS Navigation Receiver for obtaining geographical location of sensing nodes. Vernier Go!Temp USB Temperature Sensor for obtaining accurate sea water temperature. Geographical location & temperature information are packed into DATA frames and forwarded along the network to the sink.

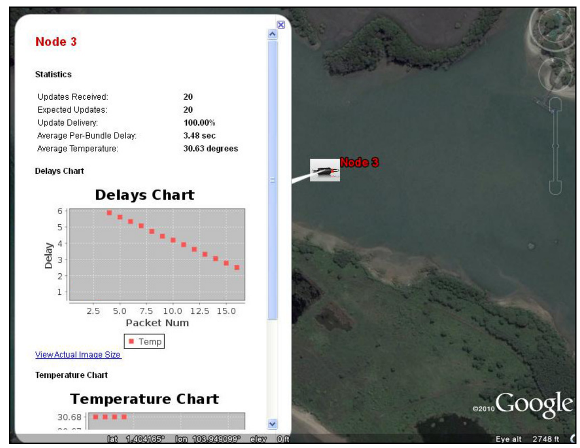

Fig. 6. Screen-shot of the Google Earth mapping software displaying sensing data, packet delays and the geographical location of the node from which the sensing data originated from.

to DLL CLEANUP whereby the data link layer (DLL) buffer is cleared.

- Upon normal receipt of DATA frame p from node i-1, node i will immediately switch to ACK TRANSMIT, sending an explicit ACK back to i-1. If the final destination of p is i, the frame will be passed to the application layer for processing at the APPLICATION LAYER PROC state, else p will be enqueued at the network layer.
- When node i *overhears* a DATA frame p and i is the frame's final destination, p will be passed to the application for processing at the APPLICATION LAYER PROC state, else p will be enqueued at the network layer for relay. No explicit ACK is ever sent for *overheard* DATA frames.
- On *overhearing* an implicit acknowledgement (either downstream DATA or ACK), node i will proceed to check for any matches in the DLL or network layer queue. A match will result in node i transiting to DLL CLEAN UP or NETWORK QUEUE CLEANUP respectively for the removal of the matching DATA frame.

D. Implementation Details

1) Sensing Application: To demonstrate the utility of the multihop underwater network stack, we developed a sensing application which uses a Vernier Go!Temp USB Temperature Sensor [7]. A sensing node is also equipped with a GlobalSat BU-353 USB GPS Navigation Receiver [8]. Figure 5 shows the temperature sensor and GPS receiver.

The application periodically extracts geographical location and seawater temperature information from the GPS receiver and temperature sensor, respectively. It then formats the extracted data accordingly before passing the payload to the DDS's network stack for forwarding along the network to the sink.

A relatively short DATA frame length of 20 bytes was chosen in view of the extremely lossy underwater acoustic channel. As such, the geographical location has to be packed and transmitted separately from the time and temperature information. Furthermore, compression has to be performed on the raw latitude and longitude readings so that each becomes 4-bytes in length, as illustrated in Fig. 2. The Payload Type field indicates the type of data payload the frame carries.

At the sink, a server application parses sensor data received by the hydroacoustic modem and exports it to a Google Earth readable KML file. The Google Earth mapping software then displays the temperature readings and packet latencies on a chart in a cumulative manner, together with the actual location of the sensing nodes on a map. A screen-shot from an actual field test is shown in Fig. 6.

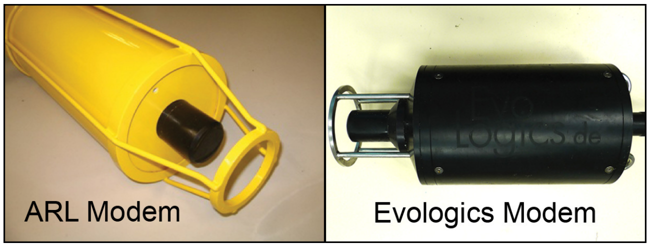

Fig. 7. The data delivery scheme was ported onto hydroacoustic modems from (1) Acoustic Research Laboratory (ARL), National University of Singapore (NUS) and (2) EvoLogics, demonstrating the modular and hardware-independent nature of the implementation design.

TABLE I
SPECIFICATIONS OF THE ACOUSTIC RESEARCH LABORATORY & EVOLOGICS HYDROACOUSTIC MODEMS.

	Acoustic Research Lab (ARL) Modem	Evologics S2C R 48 / 78 Modem
Parameter	**Value**	**Value**
Data rate	15 kilo bits / sec	Nominal bitrate up to 31.2 kilo bits / sec
Operating frequency	50 – 75 KHz	48 – 78 KHz
Range	Up to 1.5 Km	Up to 2 Km
Modulation	Proprietary Doppler Resilient modulation	S2C Sweep-spread carrier modulation
Host interface	Ethernet	Ethernet

2) Hydroacoustic Modems: We tested our implementation design by porting the DDS onto hydroacoustic modems from two vendors: (1) Acoustic Research Laboratory, National University of Singapore (NUS) [9] and (2) Evologics GmbH [10]. The modems are shown in Fig. 7, and their respective specifications listed in Table I.

As the hydroacoustic modems do not support on-the-fly modification of frame lengths, the ACK frame is padded with 13 bytes to match the DATA frame's length of 20 bytes as illustrated in Fig. 2.

3) Underwater Network Stack: We implemented the DDS and its functional blocks on the Linux operating system (using kernel version 2.6). The underwater network stack provides application programming interfaces (APIs) at each of the layers such that the individual components can be easily replaced. In our study, the interweaved time-division-multiple-access (TDMA) proposed in [4] is implemented in the MAC sub-layer.

For the ARL modem, the APIs as described by Chitre *et al* in [11] are used from within the Modem Driver module. The DDS is then cross-compiled for the ARM architecture, and finally transferred to the modem's on-board memory for execution.

In the case of the Evologics modem, AT commands are used for interfacing with the modem via the Ethernet interface, with the compiled DDS program running off a laptop computer.

III. EVALUATION

A. Experimental Setup

The field tests were conducted at two separate locations: (*i*) The Republic of Singapore Yacht Club (RSYC) marina with water depths of approximately 5 metres; and (*ii*) channel between the islands of Pulau Ubin and Ketam, Singapore, with depths of 10-15 metres. The ARL modems were used in the tests at RSYC and the Evologics modems deployed in the tests at Ubin/Ketam.

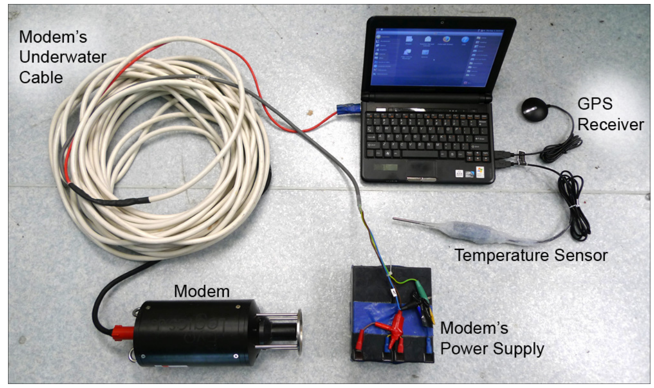

Fig. 8. Experimental setup of a sensing node in the underwater acoustic network. All key components are annoted.

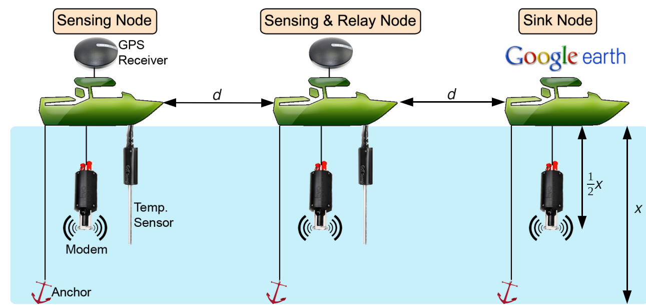

Fig. 9. A 2-hop underwater network with linear topology for a temperature sensing application. The middle node is a pure relay node in our field tests. Inter-nodal distance d fixed at approximately 150 metres for all tests.

The experimental setup of a sensing node is illustrated in Fig. 8. Fig. 9 gives an overview of our 2-hops linearly-arranged underwater network, except that the middle node in our tests is a pure relay node. Fig. 9 illustrates that all nodes can play multiple roles. In fact, all nodes can be a source or relay simultaneously. The inter-nodal distance d is set at approximately 150 metres for both locations, and the modems submerged at approximately half the water depth x.

The application at the source node extracts sensor data and dispatches 100 20-bytes-long DATA frames (alternating between GPS and time & temperature payloads) down to the DDS at an interval of 1 second. All nodes are programmed to retransmit a DATA frame up to a maximum of 5 times before dropping the frame, with the experiment ending once all transmissions at all nodes terminate.

B. Results

Similar to the methodology used in [4] for comparing results between simulations, we run separate experiments for (*i*) fully-*opportunistic* ARQ with *bidirectional overhearing*, (*ii*) semi-*opportunistic* ARQ with *overhearing* for upstream DATA only,

TABLE II
EXPERIMENTAL RESULTS OF THE TESTS CONDUCTED AT THE RSYC MARINA USING ARL HYDROACOUSTIC MODEMS

Field experimental results using ARL modems at the Republic of Singapore Yatch Club (RSYC)'s marina		
Scheme	**PDR**	**Goodput (bps)**
Bidirectional overhearing	0.99	0.16
Overhear upstream DATA only	1.00	0.06
Overheard downstream DATA & ACK only (Implicit ack.)	0.78	0.09
Basic hop-by-hop	0.90	0.09

TABLE III
EXPERIMENTAL RESULTS OF THE TESTS CONDUCTED AT WATER CHANNEL IN BETWEEN PULAU UBIN & PULAU KETAM USING EVOLOGICS HYDROACOUSTIC MODEMS.

Field experimental results using Evologics modems in between Pulau Ubin & Pulau Ketam, Singapore		
Scheme	**PDR**	**Goodput (bps)**
Bidirectional overhearing	1.00	0.74
Overhear upstream DATA only	1.00	0.74
Overheard downstream DATA & ACK only (Implicit ack.)	1.00	0.36
Basic hop-by-hop	1.00	0.49

(*iii*) semi-*opportunistic* ARQ with *overhearing* of downstream DATA & ACK as implicit acknowledgement only, and finally (*iv*) a non-*opportunistic* basic hop-by-hop ARQ.

The results for the experiments conducted at the two locations are presented in Table II and III.

RSYC Results: The RSYC marina was an exceptionally challenging location for underwater acoustic communication due to the extremely shallow depth, abundance of underwater structures reflecting acoustic waves, and frequent marine traffic moving into and out of the marina. Frame corruptions were observed to be more frequent whenever marine traffic increases. This led to frequent retransmissions up to the maximum of 5 times due to lost or corrupted DATA and ACK frames.

However, the *bidirectional overhearing* scheme still outperformed its semi and non-*opportunistic* counterparts with comparable packet delivery ratio (PDR) and a relatively better goodput performance.

Pulau Ubin/Ketam Results: The underwater acoustic channel conditions were observably better at this location than that at the RSYC marina. Water depth was up to 3 times deeper, marine traffic was less frequent and the nearest shore was around 200 metres away. This resulted in a larger number of frames getting received successfully, reducing the need for frequent retransmissions. The favorable underwater acoustic channel conditions experienced also reduced the need for implicit acknowledgments in terminating pending retransmissions and purging the network queue, resulting in similar performance achieved with both *bidirectional overhearing* and *overhearing*.

IV. CONCLUSION AND FUTURE WORK

In this paper, we presented a modular implementation of a robust and fully-*opportunistic* ARQ with *bidirectional overhearing* in a real system. We designed and implemented a customizable, extensible and modular software architecture and underwater network stack that is suitable for sensing applications operating over multihop underwater acoustic networks. We demonstrated the implementation's hardware-independence by porting our network stack onto hydroacoustic modems from ARL,NUS and Evologics. We evaluated the performance of the data delivery scheme in its full, semi and non-*opportunistic* flavors. Real sensing data from off-the-shelf GPS receivers and temperature sensors were transmitted over two-hops in shallow underwater environments and displayed via the Google Earth mapping software at the destination node.

The fully-*opportunistic* DDS is shown to outperform its non-*opportunistic counterpart* in the actual field tests, whereas due to the small size of the network, the improvements are inconclusive for comparison against the semi-*opportunistic* scheme. In the future, we plan to extend our field tests to larger underwater networks to investigate the improvement gains of such a delivery scheme.

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