Ad-Hoc Multi-hop Underwater Optical Network for Deep Ocean Monitoring

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***Abstract*—We present a fully ad-hoc, optical multi-hop underwater optical sensor network. All network nodes are identical, uncabled and battery operated with the exception of the master node which represents the terminal link to land for real-time monitoring capability. Multi-hop functionality allows for high-bandwidth underwater communication without sacrificing range. Ad-hoc capability allows for nodes to dynamically enter and exit the network, forming arbitrary topologies. Onboard sensors imbue every network node with monitoring capability. Redundant onboard data storage and automatic rerouting of communication paths create a mesh sensing network ideal for high-density, large-area sensor networks deployed to regions with high-risk of node loss and intermittent connectivity. Multi-hop and dynamic ad-hoc capabilities were tested in salt-water pools. The communications algorithm and high-level node design are presented.**

Keywords—Ad-hoc, multi-hop, underwater, optical network, mesh network, ocean sensing,

I. Introduction

An environmental Wireless Sensor Network (WSN) is a spatially distributed array of communicating nodes, in which each node collects and transmits data that is temporally and geographically referenced to a broader environmental context. Simultaneous distributed sensing is required to monitor large-scale dynamic changes of rapidly changing environmental conditions [1, 2]. Underwater Sensor Networks (USNs) are a subset of WSNs that are best used to answer those biogeochemical questions that cannot be addressed from the surface using remote sensing techniques, or by any other method that might observe a too limited region of space and time. For example, individual Remotely Operated Vehicles (ROVs) and Autonomous Underwater Vehicles (AUVs) can only serially measure points against the immense backdrop of an evolving ocean environment [3-5].

Underwater optical systems can provide higher communication bandwidth, faster signal propagation speed, better energy efficiency and have greater potential for miniaturization as compared to acoustic counterparts [6-9]. The fundamental challenges for optical methods in water are that attenuation and multiple scattering of electromagnetic waves strongly limit signal propagation range. Practically as well, opaque biofilm growth hampers optical systems more easily than acoustic systems. Were it not for these physical and practical limits, optical technologies would be the method of choice for a great many underwater communications applications by virtue of their extremely high bandwidth utilization and signal propagation speed. Furthermore, the energy efficiency and scale of optical technologies are highly commercially developed for ready integration into robust, miniaturized, and low-cost devices.

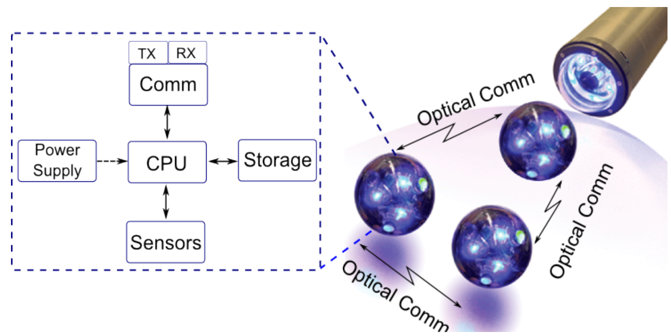

Figure 1. The Sensorbot optical communications network and subsystems diagram.

Optical multi-hop networking strategies can overcome range and scattering limitations of light underwater. Incorporating ad-hoc capability in the optical network is important to meet the needs of ocean engineering operations where it may be difficult and costly to position, orient, repair or replace network nodes.

To our knowledge, the work presented here is the first implemented example of an ad-hoc, point-to-multipoint underwater optical communications network as shown in Figure 1. We call this approach a Sensorbot-UON.

II. Related Work

A. Underwater Network Monitoring Systems

Existing network communication systems in the ocean monitor events from biological behavior to industrial underwater oil leaks. For example, radio-frequency tags are regularly used to wirelessly monitor the activities of marine animals, collecting and storing data locally for manual extraction or surface transmission at periodic intervals [10]. Cabled observation networks, from single-camera systems to national shoreline networks, transport both information and power through underwater cables to designated areas on-shore [11, 12]. Network communication between groups of underwater robots and sensors is becoming increasingly common [13, 14].

B. Underwater Optical Communication Systems

Underwater optical communications systems have been explored less extensively than underwater acoustic systems. Examples include theoretical studies on underwater

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observatories and development of underwater optical point-to-point communications [15, 16]. One notable example of an existing underwater optical modem is the BlueComm modem developed at Woods Hole Oceanographic Institute and commercially available from Sonardyne [17]. Another example is Massachusetts Institute of Technology's CSAIL and CSIRO's ICT Amour, Starbug system, composed of mobile AUVs and many more fixed sensor nodes [18-20]. These previously reported optical communication systems utilize point-to-point signal transfer methods. Our multi-hop network eliminates the need for data muling and directional alignment and instead intrinsically transmits and receives data uniformly around each node and is thus propagated through entirely optical means.

III. SENSORBOT-UON OVERVIEW

The presented Sensorbot-UON is comprised of three main components: 1) The Sensorbot nodes which house the power, optical transceivers, memory and sensors, 2) A cabled photomultiplier tube (PMT) master node which provides the high-bandwidth network connection to shore for real-time operations, 3) The communications algorithm, which in this case is a time division multiple access (TDMA) based ad-hoc, multi-hop communication protocol. These components are shown together in Figure 1.

Each node, or Sensorbot, maintains a dynamic role in the network using a TDMA-based multi-hop communication protocol that is meant to preclude cross-channel interference. Sensorbots act as data sources and repeaters, transmitting information via optical signals to neighboring nodes until the data reaches the PMT and is transferred to shore. As a result of the ad-hoc design, node failures or node additions automatically result in re-routing signal pathways. All network data is redundantly stored on individual nodes. This approach is well suited for realistic ocean operations where, in event of catastrophic loss of the PMT connection, data from the whole deployment can be recovered from even a single Sensorbot.

IV. DESIGN CONSIDERATIONS

A. Optical Channel Properties

How far can light go underwater? This is the first question that comes to mind when discussing underwater optical communications. Many oceanographic engineering papers have dealt with the question based on the extinction coefficient of water and the geometric relationship of the emitter and detector. These approaches have resulted in large claims for theoretical distances. In an early paper, Farr et al. calculated 100-meters range for a collimated 25 mW blue source, transmitting at 1 Mbits/s [9]. These methods can only account for the signal-to-noise ratio on the communication channel and cannot predict the Bit Error Rate (BER) which is what specifies the actual communication range [21]. Any accurate communications range prediction needs to account for emitter and detector geometry, instrument noise, and the impulse response of the intervening medium to fully describe the point-to-point range of an underwater communication channel. Using such approaches, it has been calculated that channel capacities of optical communication in deep (clear) and coastal (lightly turbid) ocean are both on the order of several hundreds of MHz and on the order of several tens of MHz in harbor (highly turbid) water. For exceptionally clear water, GHz communication for distances within 100 m is theoretically possible [21,22].

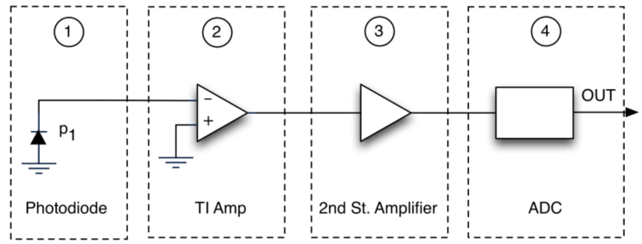

Figure 2: Block diagram of Rx/Tx design

This all seems very promising, with reports of high channel capacities driving interest in underwater optical communications. However, in reality the situation is certainly worse for networking schemes as neighboring interference should be accounted for. Also, the necessity of low-power systems for long-term, high node density deployments require the use of diffuse, non-lambertian light sources like LEDs which have limited collimation potential as compared to laser sources. In real ocean water, the turbidity based scattering used in the models described above is only part of the story. Large flocculent (marine snow), biofilm growth, and intermittent animals are common and can completely eclipse an optical path. Neighboring interference, diffuse sources, and stochastic interruptions are best accounted for by Monte Carlo network modelling techniques and not solely with analytical equations [21].

Limitations on node-to-node communication range are imposed by the dynamic scattering and absorption characteristics of the environment, desired communication bandwidth, power utilization, as well as background and cross-channel optical interference. The nodes in this project were designed for deep ocean operations and so no effort was made to exclude background light sources other than physical filtering by means of short-pass absorption filters. Blue light is chosen because deep ocean water typically exhibits a minimum of absorption at this wavelength [23]. The nodes presented here are half-duplex, sending and receiving at separate times, and the protocol is TDMA so no account is taken for internal or cross-channel interference. The multi-hop ad-hoc communications algorithm used herein was developed by iterative design improvements based on simulation testing with ns-2 [24].

B. Mechanical Stress

In the current configuration, each node housing is a transparent polycarbonate spherical shell designed and pressure rated to operate at 2 kilometers depth. Polycarbonate was used because it is cost effectively injection molded, exhibits high strength, low gas diffusion, and is optically transparent. Using polycarbonate also allows the nodes to be deployed in areas where manned submersibles visit and evacuated glass spheres are prohibited. The theoretical collapse depth of each spherical node was determined using standard design curves for pressure-resistant housings to determine the ratio of the wall thickness to its outer diameter based on the Poisson ratio, Young's modulus and yield strength of Polycarbonate [25]. The spheres were then tested according to Alvin Dive Certification standards for 2 km depth rating [26].

C. Power

Energy consumption plays a pivotal role in the Sensorbot design, especially to ensure lengthy missions. The current on-board microcontroller consumes less than 90 µA/MHz when active and has a typical quiescent current of 0.32 µA. Each of the light emitting diodes on the Sensorbots uses 165mW when transmitting, which lasts for only on the order of microseconds. The photodiodes operate in zero bias and therefore consume no power. The sum total of all discrete components use less than 20mW continuous while in operation. Using a 7 Ah primary lithium battery it is estimated that the system is able to sense, store and communicate every few minutes for extended periods on the order of months.

V. Sensorbot Node Architecture

Sensorbot architecture follows recognized mote design principles [27] and is composed of five elements: a central control processor, a sensor processor, a data storage manager, a communication system, and a power supply unit.

A. Hardware Design of Sensorbot UON Nodes

The central control is designed around an ultra-low-power microcontroller. The sensor processor is capable of supporting or simulating multiple sensors. For this first test of network communications capability only a temperature sensor was included on each node. Other "sensor values" in the data stream were simulated by random number generation. The frequency at which data are gathered depends on the transmission and processing cycle time, as determined by the power limitations of the node. The data storage manager redundantly stores all network data received to improve network stability. The memory manager uses an external module to store data onto a non-volatile µSD storage card at regular intervals. The transmitter component of the communication system consists of a light emitting diode (LED) driving circuit and the LEDs themselves, operating at 470 nm peak wavelength. The receiver is a set of optically filtered and electronically filtered photodiodes placed around the perimeter of each spherical node. Multi-stage amplified photodiode signals are routed to the central microcontroller via the onboard Universal Asynchronous Receiver/Transmitter (UART).

MacArtney Underwater Technology Group (MacArtney) built and tested the master node. The master node consists of a PMT instead of the standard photodiodes on the child nodes, a ring of LEDs of the same type used on the child nodes, a cylindrical pressure housing and the underwater cable connection that supports RS-232. The master node is the terminal transceiver link in the system, connecting the most proximal nodes (and thus the entire mesh network) to shore. Using a high-speed PMT with nanosecond response times allows flexibility for future network bandwidth improvements if desired.

1) Power Management

Many applications for underwater sensor networks will not have access to a cabled source of constant power, so low power consumption is an important consideration. The microcontroller's ultra-low-power design consumes less than a microwatt of power in its sleep mode. All components are chosen to fit the low power and extended lifetime that nodes would require in the deep sea.

Each LED must carry enough current to transmit over long distances underwater. The current system uses 50 mA of current at system voltage for each of its 8 transmitting LEDs at the system voltage of 3.3V. To reduce the power usage at this level, short bursts of transmission are used to extend the lifetime of each node in the network.

Because of space constraints, higher density batteries such as lithium primary batteries are used along with a system voltage DC regulation circuit, providing an operation time in the range of days to years depending on operation cycles. Biofouling and other physical node loss is expected to occur sooner than battery depletion.

2) Rx/Tx Design and Characterization

Transmitter design utilizes a fast switch array to power on each LED triggered by the microcontroller. The receiver design is shown in Figure 2, where the photodiode (1) is chosen as a large-area sensor to increase the signal received. A transimpedance amplifier (2) is used to convert current to voltage, and second stage amplifier (3) is used to control the gain on the resulting voltage signal. This voltage is passed through an ADC (4) with a threshold decision to output a binary high or low value, and the result is then routed through digital logic before finally arriving at the UART of the microcontroller.

3) Physical Layout

Manipulating individual Sensorbot nodes underwater would be difficult and expensive. To relax the need for orienting each node, all nodes transmit and receive uniformly in a plane, communicating with nodes at any angle. To achieve this, transmitting LEDs and receiving photodiodes are arranged in a circle on each Sensorbot node. The current iteration has 8 LEDs and 4 photodiodes spaced equally, arranged in a circle.

B. Software Design

We have implemented algorithms to test the data transmission and reception among the nodes of the network during the multiple development phases of this research. This process led to the ad-hoc, multi-hop wireless communication protocol presented.

Algorithm 1 Underwater Communication Protocol for node n_i

```
n_i.t ← 0
n_i.sendFirstTime ← −1
if n_i == masterNode|| successfully received a packet P then
    while n_i.t < 2n^2 or n_i.parent == null do
        while interval % 10!=0 do
            hold
        end while
        if n_i.t%n ≠ i or n_i.parent == null then
            if n_i successfully received a packet P then
                if n_i.parent == null then
                    n_i.parent ← P.src
                    n_i.t ← P.t
                else if P.src == n_i.botId then
                    n_i.child ← P.botId
                end if
                n_i.t = P.t
            end if
        else
            if n_i.parent ≠ null then
                n_i sends a packet P(=P.n_i, P.src, n_i.t, timeStamp(hh, mm, ss),
                "I'm alive") containing the information of the n_i:{ID,
                timestamp, level, "I'm alive"}
                if n_i.sendFirstTime == −1 then
                    n_i.sendFirstTime ← n_i.t
                end if
            end if
        end if
        if n_i.t == n_i.sendFirstTime + n and n_i.child == ∅ then
            n_i.isLeaf ← true
        end if
        {Entering data transmission phase.}
        if (n_i.isLeaf == true or n_i.hasReceivedFromAllChildren =
        true) and n_i.t%n == i then
            n_i sends a DATA packet P containing all the data gathered by
            n_i and its children, i.e., n_i.DATA[j] for all n_i' child n_j.
        else
            if n_i successfully received a packet P then
                n_i.DATA[P.src] ← P.DATA
                if n_i has successfully received all packets from all children
                then
                    n_i.hasReceivedFromAllChildren ← true.
                end if
            end if
        end if
        n_i.t ← n_i.t + 1
    end while
end if
```

1) Overview

We have implemented a TDMA-based MAC protocol capable of ad-hoc multi-hop operations. Our algorithm provides a novel cross-layer local protocol design that uses a TDMA (Time Division Multiple Access) approach for lightwave contention resolution (MAC layer) directly integrated with an ad-hoc spanning tree building mechanism on a set of n Sensorbots. The spanning tree is used for coordinating the flow of environmental data collected by the Sensorbots to the master node. It is also through the spanning tree that the Sensorbots are woken up at the start of each data collection cycle. Each Sensorbot will go to sleep after it has transmitted its data to its parent node on the tree.

2) Opt-AdHoc Algorithm

There are n nodes in the network, denoted as $N = \{n_i | \, i = 0 \dots n-1$, where *i* represents the *i*th node n . We assume n_0 is the *master* node. The remaining nodes are wireless nodes, and use light waves to communicate with each other. Pseudo code is illustrated in Algorithm 1 and is summarized as follows:

a) Construct a tree with n_0 as the root in a level by level, as well as TDMA fashion. Each node acquires its parent and children information.

b) Starting from the leaf nodes, the data is propagated back up to the root node, so that the \emph{master} node has the entire information about the network.

c) To make the network more robust, each node has a copy of entire network data. To achieve this, the algorithm does an additional pass top-down propagating all the data from the root node.

This approach maintains individual identification and the *level* information ($n_i.level$), which is defined with respect to its distance from the master node, i.e., how many communication hops one needed from n_0 to the node itself (Initially, $n_i.level = n_0.level = 0$). Also, each node keeps track of its parent and children nodes, such as $n_i.parent$ and $n_i.child$, where $n_i.child$ is a linked list of n_i's children. We assume nodes are well synchronized and the protocol proceeds in unit time slots. Since the protocol is TDMA-based, it means that each time frame is divided into n time slots, and in each time slot i, only n_i can transmit. This assumption guarantees that there will never be a collision because of concurrent transmissions.

Our protocol has two of the main characteristics that are crucial for the eventual deployment of a high-density wide area Sensorbot network over very long periods of time: robustness and energy efficiency. In particular, our spanning tree construction and data collection procedure does not require global clock synchronization: As each node is awakened at the start of each data collection cycle and establishes a link to its parent node, it also receives the current time according to its parent node in the tree, which it adopts as its own. In this protocol, we account for any drifts introduced by the link traversal times by setting the TDMA slot to be long enough to ensure that, even if the receiver and transmitter clocks differ slightly, they will both have a long enough overlap of their respective TDMA slots to ensure successful communication. Note that a worsening drift over time of the clocks is not an issue, since local clock synchronization occurs at the start of every data collection cycle.

VI. Future Work and Conclusions

The work presented here is the first implemented example of an ad-hoc, point-to-multipoint underwater optical communications network. The Sensorbot-UON was displayed live in the test tank at Ocean Business 2013 at the National Oceanography Centre, Southampton, UK on April 9-11, 2013.

Future modifications to the Sensorbots include incorporating ambient light filtering, omni-directionality for 4π steradian data transfer, and re-chargeable battery systems. The Sensorbots will be deployed for oceanographic data gathering with a suite of sensors incorporated on each node to provide monitoring capability.

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