Ad Hoc Networks 7 (2009) 837–848

Contents lists available at ScienceDirect

Ad Hoc Networks

journal homepage: www.elsevier.com/locate/adhoc

Software-driven sensor networks for short-range shallow water applications

Raja Jurdak [a,*], Pierre Baldi [b], Cristina Videira Lopes [b]

[a] CSIRO ICT Centre, Pullenvale QLD 4069, Australia
[b] School of Information and Computer Sciences, University of California, Irvine, United States

ARTICLE INFO

Article history:
Received 7 January 2008
Received in revised form 13 May 2008
Accepted 20 July 2008
Available online 15 August 2008

Keywords:
Underwater
Sensor
Network
Software
Modem
Short-range
Shallow
Water
Frequency shift keying

ABSTRACT

Most existing underwater networks target deep and long range oceanic environments, which has led to the design of power hungry and expensive underwater communication hardware. Because of prohibitive monetary and energy cost of currently over-engineered communication hardware, dense deployments of shallow water sensor networks remain an elusive goal. To enable dense shallow water networks, we propose a network architecture that builds on the success of terrestrial sensor motes and that relies on the coupling of software modems and widely available speakers and microphones in sensor motes to establish acoustic communication links. In this paper, we analytically and empirically explore the potential of this acoustic communication system for the underwater environment. Our experimental approach first profiles the hardware in water after waterproofing the components with elastic membranes. The medium profiling results expose the favorable frequencies of operation for the hardware, enabling us to design a software FSK modem. Subsequently, our experiments evaluate the data transfer capability of the underwater channel with 8-frequency FSK software modems. The experiments within a 17×8 m controlled underwater environment yield an error-free channel capacity of 24 bps, and they also demonstrate that the system supports date rates between 6 and 48 bps with adaptive fidelity.

1. Introduction

Water is a crucial resource for most life on earth, covering more than 70% of our planet. Sustainable use and exploitation of our water resources requires a deep understanding of both oceanic and inland aquatic environments through long-term monitoring of these environments. Existing aquatic monitoring platforms have attempted to capture information at high temporal scale (e.g. surface buoys with suspended probes in the water, satellites that observe large geographic regions) or high spatial scale (e.g. research vessels that survey sea floors) from the oceanic environment. Monitoring aquatic environments at both high temporal and spatial scales remains an elusive goal despite its strategic significance to the social and economic development of the global population.

An enabling technology for granular monitoring of aquatic environments is wireless sensor networks, which has been successful in many terrestrial applications. A dense deployment of in situ sensor nodes that communicate wirelessly in the water can meet the scale requirements of aquatic monitoring, as the sensor nodes are relatively cheap (ranging from 10 to 250 US dollars in price depending on purchase volume) compared to conventional platforms, making it cost-feasible to deploy a large number of nodes in a physical area. Because the nodes reside in the aquatic environment, they can supply data at any temporal scale required by the network user. Adapting sensor nodes for wireless underwater communication requires the addition of hardware for acoustic modulation

* Corresponding author. Tel.: +61 7 3327 4581.
E-mail addresses: rjurdak@ieee.org (R. Jurdak), pfbaldi@ics.uci.edu (P. Baldi), lopes@ics.uci.edu (C.V. Lopes).

1570-8705/$ - see front matter © 2008 Elsevier B.V. All rights reserved.
doi:10.1016/j.adhoc.2008.07.012

and communication. While the cost of sensor modules themselves is low, the cost of add-on hardware for acoustic communication, for modulation and demodulation, and for protecting and waterproofing the components is prohibitive, typically running into the thousands of dollars.

Most of the existing work on wireless underwater networking targets oceanic applications, where the communication range and depth are typically in the order of hundreds to thousands of meters, and the data transfer rates go up to few Kbits per second. Design strategies for wireless underwater communication in the oceanic environment must also consider harsh conditions and peculiar characteristics of the underwater channel that distinguish it from the aerial channel [1]. First, the underwater channel has severely limited bandwidth that is highly dependent on communication range, which requires bandwidth-efficient modulation and data compression techniques. Another unique characteristic of the underwater channel is the time-varying multi-path effects, where inter-symbol interference can span several data symbols. The fading and outage behavior of the underwater channel is also not yet understood. This requires dynamic protocols that rely on cross-layer optimization to adapt to unpredictable channel variations. Finally, the speed of sound in water, which is 1500 m/s, is significantly lower than the speed of electro-magnetic signals in air. The relatively slow signal speed in water causes severe doppler distortion and very long propagation delays. This emphasizes the importance of synchronization mechanisms and throughput efficiency of protocols.

The numerous constraints for wireless underwater communications in medium to long range oceanic applications has led companies and researchers to highly engineer specialized hardware for modulating, transmitting, receiving and demodulating acoustic signals. The specialized modulation hardware ranges from expensive commercially available acoustic modems [9,10] to more affordable dedicated integrated circuits [6] and dedicated DSP boards [12,11,13]. The communication hardware ranges from specialized underwater acoustic transducers and hydrophones [7] to generic speakers and microphones [6]. The use of specialized hardware for establishing acoustic communications underwater typically increases the network cost, the design time spent in interfacing node hardware components, and the size and weight of individual network nodes.

While using specialized hardware is a necessity for oceanic applications to establish communication links, it represents an overkill for *short-range shallow water applications*, such as the water quality monitoring of lakes, bays, rivers, estuaries, and reservoirs. Water quality monitoring in a river [2] exemplifies an application that requires monitoring at a high spatial granularity, which is synonymous with short inter-node distances in sensor networks, in order to capture the small scale variations in contamination and to identify pollution sources and causes. Nodes located at close proximity to each other only require short-range wireless communication in the water. Despite the availability of underwater communication hardware, short-range shallow water monitoring applications have not adopted existing technologies specifically because of their prohibitive cost and over-engineering for this class of applications. Shallow water networks refer to depths ranging from 0 to 50 m, where sound propagation is mostly horizontal except for surface and bottom reflections [3]. Section 5 considers the impact of applying our architecture to deep water networks.

In the past, most underwater deployment efforts have focused on hardware acoustic modulation because low processing speeds did not allow the modulation of acoustic signals in software. Software modulation and demodulation [14] is an alternative approach which overcomes most of the drawbacks of hardware modems. Recent advances in miniaturization and circuit integration have yielded smaller and more powerful processors that are capable of efficiently running acoustic modulation and demodulation software. Software modulation also provides a higher level of flexibility for on-the-fly tuning of modulation parameters to suit different environments. The transmission and reception of the software modulated acoustic signal can also avoid using specialized hardware through generic speakers and microphones.

Eliminating the need for specialized hardware for acoustic communication greatly reduces the cost of network nodes, which facilitates the dense deployment of mote-class nodes to form underwater sensor networks. Within this context, this article proposes *software-driven underwater acoustic sensor networks* for dense shallow water quality monitoring in rivers, bays, estuaries, and lakes. The network consists of affordable off-the-shelf sensor modules (motes) that use software modems and generic hardware to communicate acoustically and send the data towards the base station through multi-hop communication. The motes are placed into elastic latex membranes that waterproof the hardware while maintaining acoustic coupling with the water channel. In addition to being cost-feasible and satisfying the temporal and spatial scale requirements, sensor motes, which are originally designed for terrestrial applications, combine processing and storage capabilities that provide an intelligent platform for network self-configuration and self-management. Finally, the speakers on board the mote platform have low output power, which is favorable for both network longevity and for minimizing interference with aquatic ecosystems.

Software-driven underwater sensor networks involve the design and development of the acoustic communication links, communication protocols, and application behavior. This paper investigates the design and development of reliable acoustic communication links for realizing software-driven underwater sensor networks. In particular, the paper first profiles through empirical experiments the unique channel of the proposed software-driven underwater sensor networks that includes the speaker, the microphone, the latex membranes, and the water. Based on the underwater profiling results, we derive the theoretical error-free transfer rate of each hardware set. To validate the transfer rate projections, our second set of experiments evaluates the data transfer capability of the underwater channel with 8-frequency FSK software modems coupled with the mote's acoustic hardware.