Ad Hoc Networks 34 (2015) 224–238

Contents lists available at ScienceDirect

Ad Hoc Networks

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

The SUNSET framework for simulation, emulation and at-sea testing of underwater wireless sensor networks

Chiara Petrioli [a,b,*], Roberto Petroccia [a,b], John R. Potter [c], Daniele Spaccini [a]

[a] Dipartimento di Informatica, Università di Roma "La Sapienza", Via Salaria, 113, 00198 Roma, Italy
[b] WSENSE s.r.l., Rome, Italy
[c] NATO STO Centre for Maritime Research and Experimentation, Viale San Bartolomeo 400, 19126 La Spezia, Italy

ARTICLE INFO

Article history:
Received 28 February 2014
Received in revised form 5 August 2014
Accepted 11 August 2014
Available online 27 August 2014

Keywords:
Underwater networks
Simulation
Emulation
In-field
Experiments
Internet of Underwater Things

ABSTRACT

The Sapienza University Networking framework for underwater Simulation Emulation and real-life Testing (SUNSET) is a toolkit for the implementation and testing of protocols for underwater sensor networks. SUNSET enables a radical new way of performing experimental research on underwater communications. It allows protocol designers and implementors to easily realize their solutions and to evaluate their performance through simulation, in-lab emulation and trials at sea in a direct and transparent way, and independently of specific underwater hardware platforms. SUNSET provides a complete toolchain of pre-deployment and deployment time tools able to identify risks, malfunctioning and under-performing solutions before incurring the expense of going to sea. Novel underwater systems can therefore be rapidly and easily investigated. Heterogeneous underwater communication technologies from different vendors can be used, allowing the evaluation of the impact of different combinations of hardware and software on the overall system performance. Using SUNSET, underwater devices can be reconfigured and controlled remotely in real time, using acoustic links. This allows the performance investigation of underwater systems under different settings and configurations and significantly reduces the cost and complexity of at-sea trials. This paper describes the architectural concept of SUNSET and presents some exemplary results of its use in the field. The SUNSET framework has been extensively validated during more than fifteen at-sea experimental campaigns in the past four years. Several of these have been conducted jointly with the NATO STO Centre for Maritime Research and Experimentation (CMRE) under a collaboration between the University of Rome and CMRE.

1. Introduction

Underwater Wireless Sensor Networks (UWSNs) have become an important area of research with many potential applications, including the monitoring and discovery of the marine environment, offshore hydrocarbon surveying and extraction, underwater CO_2 storage, coastal protection, and the prediction of underwater seismic and volcanic events [1,2]. A common feature in all these applications is the increasing need of underwater communications technologies connecting existing static and mobile platforms into cooperative underwater monitoring and control systems. The protocols that will support this underwater communications networking do not yet exist and so must be designed and tested.

Several solutions have been proposed to implement new networking protocols for UWSNs [3–6]. New protocols

* Corresponding author at: Dipartimento di Informatica, Università di Roma "La Sapienza", Via Salaria, 113, 00198 Roma, Italy.

E-mail addresses: petrioli@di.uniroma1.it (C. Petrioli), petroccia@di.uniroma1.it (R. Petroccia), Potter@cmre.nato.int (J.R. Potter), spaccini@di.uniroma1.it (D. Spaccini).

http://dx.doi.org/10.1016/j.adhoc.2014.08.012
1570-8705/

are usually evaluated by means of simulations with only a few being tested at sea [7–11]. Comparisons between simulation and experimental results have clearly shown that existing simulation tools often do not capture important features of the environment or hardware and this reduces confidence in their usefulness for solution validation, evaluation and benchmarking. The shortfalls of simulations arise from two major areas. Firstly, simulations can only capture a subset of the environmental variability, resulting in an approximate and generally simplified model of the acoustic channel and its dynamics [12]. Secondly, simulators also do not generally account for hardware features which can significantly impact system performance [13].

Even if a simulator captures the environment and hardware with sufficient fidelity, moving from simulation to real-life testing usually requires significant changes in the code needed to run on representative hardware embedded platforms. Significant effort is therefore spent in preparing expensive at-sea experiments, much of which is consumed solving problems identified only at the time of test. This results in significant inefficiencies in exploiting the limited at-sea testing opportunities. Research and development of innovative solutions for underwater monitoring systems would therefore greatly benefit from a tool that allows a seamless transition from simulation, where malfunctioning and incorrect code can be effectively detected and corrected, to an at-sea testing environment without code rewriting, avoiding delays and errors in code re-implementation. Such a tool should also enable tuning of the protocol parameters on the fly to efficiently explore the dependence of performance on parameter settings. This would be a key asset to speed up innovation in the field, allowing researchers to easily test, evaluate, and compare the performance of different protocols for UWSNs. To create this tool, we have developed and extensively validated a complete framework for Underwater Acoustic Sensor Networks (UASNs) simulation, emulation and real-life testing that we call SUNSET.

The first framework was originally presented and tested in [14] and it has since been extensively extended and improved [15] leading to the creation of SUNSET, the *Sapienza University Networking framework for underwater Simulation Emulation and real-life Testing*, recently released open source [16]. SUNSET version 1.0 was freely released in May 2012, following which it has been significantly improved and enhanced, adapting to the lessons learned during extensive at-sea experimentation, resulting in SUNSET version 2.0 [17], released in October 2013.[1] SUNSET is based on the well known network simulator ns-2 [18] (and its extension ns2-Miracle [19]). Both these simulation tools have been significantly extended to reduce the gap between simulation and at-sea results. More accurate channel and interference models have been implemented, with the possibility to replay the channel conditions measured at sea and to use real hardware models. Using SUNSET, researchers and developers can first implement, evaluate and improve their solutions in simulation, using ns-2. Developers can then seamlessly use the same code for emulation and at-sea testing, where real modems are used for data transmission and additional external devices can be integrated to the nodes for sensing and navigation. Five different acoustic modems, various sensing platforms, and several surface and underwater robots have been already interfaced and tested at sea.

The framework has been extensively validated and evaluated through several trials at different locations (at sea, in rivers, lakes, fjords) and considering different network configurations (mobile and static nodes placed according to different topologies). In particular we have tested MAC, routing, localization and synchronization solutions in network configurations ranging from small scale single-hop networks (4–5 nodes) to large scale multi-hop scenarios (up to 12 nodes). The collected results have shown that SUNSET is a powerful, reliable and flexible solution for both simulations and at-sea trials, leading to no impairment in terms of protocol performance. Moreover, SUNSET supports fast reconfiguration and fast porting of all the implemented solutions to different hardware assets. One of the main functionalities of the latest SUNSET version is a novel mechanism, called *back-seat driver*, to remotely control and operate the entire underwater network via acoustic links [20]. This module allows researchers to remotely operate the network in real time, reconfiguring the network (activating only the nodes needed for the specific tests), changing protocol and node parameters and test settings. Everything is done 'on the fly', without the need to retrieve the underwater devices. This allows researchers to easily run different experiments without interruptions, thus saving time during at-sea campaigns.

The rest of this paper is organized as follows; Section 2 outlines the state of the art of testbeds and emulation frameworks for underwater networks. A detailed description of the latest version of the proposed SUNSET framework is presented in Section 3. In Section 5 we report the results of tests we have conducted in the past years to validate and evaluate SUNSET during at-sea testing activity. Finally, concluding remarks are given in Section 6.

2. Related works

Several underwater acoustic sensor network frameworks have been proposed to evaluate protocols for UWSNs [21–25].

Aqua-Sim [21] is a simulation tool developed on the ns-2 simulator [18], which however does not support the use of any ray tracing software to more accurately model the underwater acoustic channel. Additionally, it can be used only to run simulations without the possibility to test the implemented solutions on real platforms in at-sea experiments.

The Aqua-Lab testbed [22] consists of a water tank, a set of WHOI Micro-Modems and Application Programming Interfaces (APIs). Using the APIs, users can develop their own applications without knowing the exact mechanisms of the underlying acoustic physical layer. Using Aqua-Lab

[1] The main SUNSET components for simulation, emulation and at-sea testing are released as open source software. Additional modules and solutions, developed in collaboration with industrial partners or covered by a non disclosure agreement, are released in a binary format or are not released.