Advanced Underwater Acoustic Networking and Cooperation of Multiple Marine Robots

Vladimir Djapic*, Wenjie Dong†, Anthony Jones*, Gianni Cario§‖, Alessandro Casavola §‖, Marco Lupia§‖, Claudio Rosace§, Petrika Gjanci‡¶, Roberto Petroccia‡¶, Chiara Petrioli‡¶, Daniele Spaccini‡¶, and Domenico Tommaselli‡¶

* SPAWAR Systems Center Pacific, San Diego, CA, USA
† Department of Electrical Engineering, The University of Texas-Pan American, Edinburg, TX, USA
‡ Computer Science Department, University of Rome, “La Sapienza,” Italy
§ Department of Informatics, Modelling, Electronics and Systems, University of Calabria, Rende, Italy
¶ WSENSE s.r.l., Rome, Italy
‖ Applicon s.r.l., Rende, Italy

***Abstract*—In this paper we present the initial implementation of an advanced communication and networking solution that can enable the coordination and cooperation of autonomous mobile marine robots. To enable such a heterogeneous network three main research areas have been blended: 1) communications, 2) networking, and 3) decentralized cooperative localization and control. This paper focuses on the first two components and addresses the integration of the third one. Due to the challenges of the underwater environment, novel communication software and hardware have to be investigated to provide the level of flexibility and features that are required for efficient networking and robots cooperation. Robust and reliable distributed networking protocols have to be developed and implemented to enable an efficient sharing of data and control messages among heterogeneous surface and underwater platforms. Moreover, the combination of communications, networking and cooperative navigation has to be addressed in order to develop more capable, distributed and efficient underwater systems.**

I. Introduction

Until recent developments made in technology, the combinations of Autonomous Surface Vehicles (ASVs) and Autonomous Underwater Vehicles (AUVs), maritime autonomous systems (MAS), had only been visions for the future. The distributed cooperative estimation algorithms presented in Section IV enable a system that will be capable of coordinating a group of aerial and maritime autonomous systems (MAS), gathering data from the ocean over several months, significantly enhancing current capabilities to track and sample dynamic features. Distributed estimation and formation control of ASVs and AUVs has many practical applications. Groups or teams of autonomous robots can trace a target and enclose it; they can search a target in a large water area cooperatively; they can coordinate to monitor a large area for security, etc. Cooperation of multiple vehicles has received increasing attention as group performance often lead to higher efficiency and robustness. Formation control of heterogeneous surface and underwater robots has also been recognized as an important topic to address. In [1] the cooperation and coordination of different underwater assets has been addressed. More specifically, the authors present a mission to precisely guide an inexpensive underwater vehicle to an underwater target using the navigation suite and control system of a more capable underwater vehicle.

In order to cooperate, however, devices have to communicate and share information. Acoustic is currently the main technology used for communications in water. Acoustic underwater communication channels, however, provide probably the harshest conditions encountered in the communications world. Several challenges have to be faced, including long propagation delays, low data rates, shadow zones, high variable link qualities over time, etc. Severe time-varying multipath propagation may heavily distort the received signals and result into inter-symbol-interference. Also the achievable bandwidths are usually small due to the limitations of the piezoelectric transducers and because of frequency-dependent propagation characteristics of sea water. Use of high frequencies suffers from the increase in the attenuation levels that strongly limits the achievable communication ranges. This in turn significantly limits the bandwdith available in typical operation scenarios. Moreover, sound speed gradients in shallow waters bend the acoustic waves away from their designated propagation paths. There is therefore the need for novel software and hardware solutions that are able to provide robust and reliable underwater acoustic communications even if the single link quality varies over time, and that are able to support the cooperation and coordination of heterogeneous assets. Each underwater device has to be part of a larger network

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where assigned tasks are solved in a distributed way through the use of multi-hop communications. The final goal is to have an entire network of assets working as a single more capable system rather than having multiple more limited devices.

This paper covers current progress within the AUANC (Advanced Underwater Acoustic Networking & Cooperation) project supported by ONRG (Office of Naval Research Global) on the implementation of communication and networking solutions for joint ASV and AUV operations. In particular, the Control Engineering Group of the Autonomous Systems Laboratory at the DIMES Department of the University of Calabria have developed a compact low-power underwater acoustic modem for underwater vehicle guidance and communication applications [2]. It has the capability to be configured to transmit with frequency shift keying (FSK) modulation in three different rates in the $20-40$ kHz band. It supports multiple transmission powers and data rates up to 2250 bits/sec. The modem is also capable to calculate the distance between any two nodes via either one- and two-way protocols.

In order to provide the networking capability to the described system, the modem has been interfaced with the SUNSET networking system [3], [4] developed by University of Rome "La Sapienza" and WSENSE s.r.l. SUNSET provides a tool to implement a complete protocol stack for underwater acoustic sensor networks. It includes several MAC, routing and cross-layer solutions that have already been extensively implemented and tested in field showing very good performance. Additionally, SUNSET supports an easy interaction with multiple external hardware and software (acoustic modems, radio transceivers, sensors, navigation solutions, etc.). A module to support interconnection of heterogeneous mobile platforms has been developed. A specific interface has been designed to enable the interaction with the SPAWAR Systems Center Pacific mobile assets and provide to the system operator the possibility to control remotely and in real time these assets, even when submerged.

Since the AUANC project aims at the creation of a heterogeneous network where devices with different capabilities can cooperate and communicate, one of the project objective is the support for emerging standards in the underwater digital communication domain. Currently underwater digital modems produced by different manufacturers are not able to communicate with each other, and this poses a very strong barrier for interoperability. A first initiative to overcome this limitation has been carried out by the NATO Centre for Maritime Research and Experimentation (CMRE), in collaboration with Academia and Industry. A simple and robust physical coding scheme has been created with the intention to allow multi-vendor underwater acoustic modems to transmit information using a common physical coding scheme that can be decoded by compliant devices [5]–[8]. This coding scheme, named JANUS, is currently in process to become a NATO standard. To support the JANUS initiative, both the SeaModem and SUNSET have been extended to make use of the JANUS capabilities and to make possible the integration and cooperation of various assets in the network [9].

In-lab experiments and in-field tests have been conducted to validate and evaluate the proposed system. The in-field tests have been carried out in December 2014 at SPAWAR premises in San Diego, CA, USA, where a network of 4 nodes was deployed. Various experiments were performed to test the integration of the different components (hardware and software) and the implemented networking, ranging and JANUS capabilities. Positive results were collected during all the tests, thus validating the considered system.

The rest of the paper is organized as follows.

Section II describes the used acoustic modem and its integration with JANUS. The SUNSET networking software is presented in Section III describing also the integration with the modem and the mobile assets. Section IV explains our Distributed Kalman Filtering cooperative estimation scheme. The experimental activities are detailed in Section V. Finally, Section VI concludes the paper.

II. MODEM

SeaModem [2] is a FSK underwater acoustic modem developed by AppliCon s.r.l. for shallow water communications. The working frequency band is $25-40$ KHz, with selectable data-rates of 750 bits/sec, 1500 bits/sec and 2250 bits/sec. A Universal Asynchronous Receiver-Transmitter (UART) interface is used to interact with the modem. SeaModem also uses a 16 bit CRC error detection and a selectable error correction functionality based on the Viterbi algorithm. The use of the Viterbi code halves the communication data rate. Four different transmission power levels are supported by the modem, from 5W up to 40W.

SeaModem supports a built-in mechanism to calculate the distance between any two modems via both one-way and two-way message exchange. The two-way protocol uses the internal Digital Signal Processing (DSP) timer counters to measure the round-trip delay. Using the timer counters, SeaModem can measure round-trip time intervals with a precision up to 10 microseconds, that in principle leads to ranging precision up to $0,015$ meters. The one-way protocol requires instead an accurate synchronization of the clocks of all the intended modems. The Real Time Clock (RTC) integrated on the modem board is quite cheap (low cost was one of the main

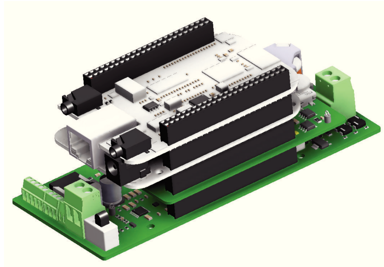


Figure 1: SeaModem stacked with BeagleBone

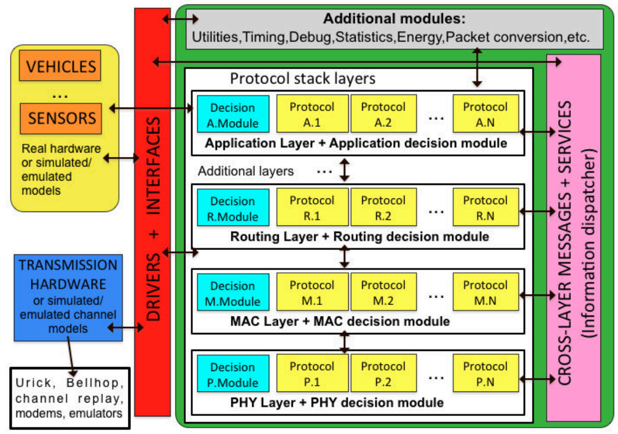


Figure 2: SUNSET architecture.

objective of SeaModem) and it has a precision over one millisecond. Such limited precision results in a ranging error of ~ 1.5 meters. Additionally, the embedded RTC suffers from a high drift. It is therefore difficult to maintain modems synchronized for a long time. For more accurate one-way ranging, however, more accurate and drift-less RTC clocks can be integrated.

SeaModem has two header connectors that allow an expansion board to be stacked on top (Figure 1). The header pinout is compatible with the Linux embedded platform "BeagleBone" and with its plug-in boards called "capes". BeagleBone [10] is a low-cost, open source, community-supported development platform for ARM Cortex-A8 processor. BeagleBone runs Debian GNU/Linux with the support for many other Linux distributions and operating systems (i.e., Ubuntu, Android, Fedora). The BeagleBone is configured to be a host that uses the integrated UART interface to communicate with the modem. An end-user can develop new high-level functionalities that use the modem as a communication device. In this way the power and flexibility provided by a stand-alone system with a Linux OS can be exploited when implementing novel services, without the need to deal with low level programming on the DSP. This solution has been considered to integrate and interface the SeaModem with SUNSET and to support the use of the JANUS modulation scheme.

JANUS code was compiled and ported on the BeagleBone. A plug-in board, named "audio capes", providing an external codec for the BeagleBone was used. This board has been used to modulate and demodulate the JANUS acoustic signals going/coming to/from the acoustic transducer. The JANUS code was, however, customized in order to control the SeaModem power amplifier. Additionally, the JANUS configuration script was changed in order to match the SeaModem transducer characteristics and generate modulated signals around a central frequency of 30 kHz. A useful bandwidth of 10 kHz was selected according to the JANUS guidelines stating that a bandwidth around one third of the central frequency should be used.

III. SUNSET

The Sapienza University Networking framework for underwater Simulation Emulation and real-life Testing framework [3] (SUNSET) has been designed to provide networking and communication capabilities to underwater nodes, both static and mobile. SUNSET provides a tool to implement a complete protocol stack for underwater acoustic sensor networks. Several MAC, routing and cross-layer solutions have already been implemented and tested in field, including: CARP [11], TDMA, CSMA [12], T-Lhoi [13], DACAP [14], Flooding-based solutions, etc. Using SUNSET, the implemented solutions can be first tested by means of simulations to speed up the development and bug fixing process and then ported to work in field. Simulations allow the researchers to deeply investigate the performance of protocols in a variety of settings (e.g., considering different bit rates, delays, payload sizes, underwater channel models, etc.) and scenarios, thus allowing the improvement of the system according to the collected results. The same exact code can be then tested via in lab emulation and in-field experiments without any rewriting, thus reducing at the minimum the efforts needed to work with real-hardware. Several modules and drivers have been implemented in SUNSET enabling the interaction with multiple external real hardware and making transparent to the user the switch between simulation and real-life experiments. Currently SUNSET supports: Six different acoustic modems (SeaModem, WHOI FSK and PSK Micro-modems, Evologics modems, Kongsberg modems, and Teledyne Benthos modems); different sensing and mobile platform, such as environmental underwater sensor and autonomous underwater vehicles. Several in field tests and experiments have been conducted in the past years to prove SUNSET efficiency and flexibility to work with different devices and hardware in a variety of scenarios and conditions (sea, ocean, lake, river, fjord). All the conducted experiments have shown that SUNSET is a really powerful, reliable and easy to use solution for implementing and managing underwater sensor networks.

A. *SeaModem integration*

SUNSET has been extended to fully support the Applicon SeaModem operations by developing a new driver to control and reconfigure the modem, locally or via acoustic links. This driver allows developers to set the transmission gain, the FSK modulation, the Viterbi algorithm for forward error correction, the guard period and the chirp threshold, etc. Additionally, SUNSET has been ported on the BeagleBone ARM embedded platform used by the acoustic modems in order to avoid the use of any extra hardware and to reduce the energy consumption, size and weight of the overall system. All the code has been optimized, fixed and cross-compiled to run on such a board and it has been successfully tested during the at-sea experiments. Moreover, this embedded platform has also been integrated into the SPAWAR surface vehicle and into the static nodes used during the first at-sea experiments. To support the use of the JANUS physical coding scheme, novel SUNSET modules have been developed. In particular, a first implementation of a new policy module that allows to switch between different communication schemes has been implemented and tested by means of in-lab experiments and in-field tests.

B. *Vehicle integration*

A new module has been developed to interface the vehicle on-board control software with SUNSET. This SUNSET module allows the vehicle software to easily interact with both the acoustic modem and SUNSET communication stack. Parameters can be set and configured according to the operations that the vehicle has to perform. Additionally, the implemented module makes possible for the control software to interact with the other mobile nodes in the network over both single link and multi-hop paths. This feature is key to support the implementation of cooperative algorithms and offers to the system operator the possibility to interact with the nodes in the network remotely and in real time while they are submerged (sending requests, receiving data or feedback about the status of the node, etc.) This module has been tested during the first at-sea experiments with very positive results.

IV. DISTRIBUTED KALMAN FILTERING

Cooperation of groups of vehicles has received significant attention in recent years as group operation often leads to higher efficiency, robustness, and greater aperture. As opposed to centralized formation tracking control, distributed formation tracking control utilizes information of vehicle's own states and of those of the vehicle's neighbors. We will consider delayed communication for the proposed distributed controllers, estimate parameter uncertainties by adaptive control methods, and design a dynamics-based controller with the aid of kinematic-based controller and backstepping methods. For a COTS glider/AUV there are less control inputs than the numbers of degrees of freedom, and control is challenging due to its underactuated nature and disturbances such as currents. In [15] the algorithms were presented that will be used for formation control of multiple glider/AUVs with uncertainty. It is assumed that there is parametric uncertainty and non-parametric uncertainty in the model of each glider/AUVs and the information of the leader glider/AUVs is available only to a portion of the follower glider/AUVs.

Distributed estimation with the aid of local information is challenging as information is not available for each agent. For multiple underwater vehicles with communication among vehicles, state estimation is more challenging because of limited communication bandwidth. We propose a new distributed estimation algorithms with the aid of Kalman filtering theory and distributed control theory to be then integrated with the rest of the system (i.e., the communication and networking components).

A. *Distributed Estimation for Static System*

For a static system with state x, there are m agents which can measure an output of the system by the equipped sensors. For agent j, the measured output of the system is

$$y_j(k) = H_j x + v_j(k) \tag{1}$$

where H_j is the output matrix and v_j is the measurement noise. It is reasonable to assume that the measurement noise v_j is independent for different times and the measurement noise for different agents are independent, i.e.,

$$E[v_j(k)v_j^\top(l)] = R_j\delta_{kl} \tag{2}$$

$$E[v_j(k)v_i^\top(l)] = 0 \tag{3}$$

for any time k and l and for any $1 \leq j \neq i \leq m$, where R_j is a positive definite matrix.

Each agent is considered as a node. The communication at time k can be defined by a directed graph $\mathcal{G}_k = \{\mathcal{A}, \mathcal{E}_k\}$ where $\mathcal{A}$ denotes the node set and $\mathcal{E}_k$ denotes the directed edges between nodes at time k. For agent j, its neighbors are in a set denoted by $\mathcal{N}_j$. The agent j and its neighbors are in a set denoted by $\bar{\mathcal{N}}_j$. It is obvious that $\bar{\mathcal{N}}_j = \mathcal{N}_j \cup \{j\}$.

For the communication graph, the following assumption is made.

Assumption 1:

There exists a positive integer N such that the graph $(\mathcal{V}, \cup_{l=1}^{N}\mathcal{E}_{k+l})$ is strongly connected for all k.

For agent j, the cost function is defined as

$$\begin{aligned} J_j(k) &= v_j^\top(k) R_j^{-1} v_j(k) & (4)\\ &= (y_j(k) - H_j x)^\top R_j^{-1}(y_j(k) - H_j x) & (5)\end{aligned}$$

The cost function at time k for all agents is defined as

$$J(k) = \sum_{j=1}^{m} J_j(k). \tag{6}$$

The distributed optimization problem of (6) with the aid of neighbors' information is solved.

With the aid of the results in [16], the estimate of x for agent j is

$$\begin{aligned} x_j(k+1) = &\sum_{i\in\bar{\mathcal{N}}_j} a_{ji}(k+1)x_i(k) \\ &- \alpha(k+1)H_j^\top R_j^{-1}(y_j(k+1) - H_j x_j(k)) \end{aligned} \tag{7}$$

where $a_{ji}(k+1)$ are positive weights and $\alpha(k+1)$ is the stepsize.

B. Distributed Estimation of Dynamic System

For a linear dynamic system

$$x(k+1) = A(k)x(k) + w(k) \tag{8}$$

where $x(k)$ is the state and $w(k)$ is the noise. It is assumed that

$$E(w(k)) = 0, \quad E(w(k)w(l)^\top) = Q\delta_{kl}$$

where Q is a positive definite matrix.

There are m agents which can measure an output of the system by the equipped sensors. For agent j, the measured output of the system is (1), where H_j is the output matrix and v_j is the measurement noise. It is reasonable to assume that the measurement noise v_j is independent for different times and the measurement noise for different agents are independent, i.e., (2)-(3) are satisfied for positive definite matrix R_j. The communication digraph at time k is defined by a digraph $\mathcal{G}(k) = \{\mathcal{A}, \mathcal{E}(k)\}$.

An estimate $x(k)$ for agent j is found such that the cost function in (6) is minimized in two steps.

Step 1: At time $k+1$, if there is no measurement available the estimate of $x(k+1)$ is denoted as $x_j^-(k+1)$. Taking the expectation of both sides of (8) results in

$$E(x(k+1)) = A(k)E(x(k))$$

Therefore, the unbiased state estimate at time $k+1$ prior to incorporating the measurement is

$$x_j^-(k+1) = A(k)x_j^+(k) = x(k+1) - x_j^-(k+1) \tag{9}$$

The variance of this estimate is

$$\begin{aligned} P_j^-(k+1) &= Var(\tilde{x}_j^-(k+1)) \\ &= Var((x(k+1) - x_j^-(k+1)) \\ &= A(k)P_j^+(k)A^\top(k) + Q_k \end{aligned}$$

Step 2: At time $k+1$, there is measurement y_{k+1} and $x(k+1)$ is estimated based on the following two sets of information

$$\begin{aligned} x_j^-(k+1) &= x(k+1) - \tilde{x}_j^-(k+1) & (10)\\ y_j(k+1) &= H_j x(k+1) + v_j(k+1) & (11)\end{aligned}$$

where $Var(\tilde{x}_j^-(k+1)) = P_j^-(k+1)$, $Var(v_j(k+1)) = R_j$, $\tilde{x}_j^-(k+1)$ and $v_j(k+1)$ are linearly independent.

For agent j, the cost function is defined as

$$\begin{aligned} J_j(k+1) = v_j(k+1)^\top R_j^{-1} v_j(k+1) \\ +(\tilde{x}_j^-(k+1))^\top (P_j^-(k+1))^{-1}\tilde{x}_j^-(k+1) \end{aligned} \tag{12}$$

For all agents, the cost function is defined as

$$J(k+1) = \sum_{j=1}^{m} J_j(k+1) \tag{13}$$

The minimization problem of (13) is solved and the following estimate algorithm is proposed as

$$\begin{aligned} x_j^+(k+1) = &\sum_{i\in\bar{\mathcal{N}}_j(k+1)} a_{ji}(k+1)x_i^+(k) \\ &-\alpha(k+1)H_j^\top R_j^{-1}(y_j(k+1) - H_j x_j^-(k+1)). \end{aligned} \tag{14}$$

C. Applications of the Proposed Algorithms

We consider multiple vehicles where each vehicle is equipped with different sensors. The dynamics of vehicle j is

$$\dot{z}_j = f_j(z_j, v_j) \tag{15}$$

where z_j is the state and the noise of the vehicle.

Figure 3: Network topology.

The state of each vehicle with the aid of its own sensors and its neighbors' information should be estimated. To this end, (15) is converted to discrete time. Its discrete-time model can be written as

$$z_j((k+1)T) = \Phi_j(kT)z_j(kT) + B_j(kT)v_j(kT)$$

Let $x(k) = [z_1^\top(kT), \ldots, z_m^\top(kT)]^\top$ and $w(k) = [(B_1(kT)v_1(kT))^\top, \ldots, (B_m(kT)v_m(kT))^\top]^\top$, the dynamics of the m systems can be written as (8), where $A(k) = \mathrm{diag}[\Phi_1(kT), \ldots, \Phi_m(kT)]$. The sensor's measurement of vehicle j can be written as (11) by linearization.

The algorithm is applied in the subsection IV-B to estimate $x(k)$ for each vehicle. Therefore, each vehicle can estimate its own state.

V. Performance Evaluation

To validate the presented system combining communication and networking capabilities on board of SPAWAR assets, in-lab experiments and in-field tests have been conducted. The in-field activities have been carried out in December 2014 at SPAWAR premises in San Diego, CA, USA. During these experiments 4 nodes have been deployed in the network (Figure 3): 3 static nodes (nodes with IDs 1, 2 and 4) and one autonomous surface vehicle (node with ID 3). Node 1 was connected to the control station and used by the system operator to instruct the other nodes and collect the requested data. Node 2 and 4 were used as relays. The surface vehicle was used as mobile platform. In what follows we describe the experiments performed addressing networking, ranging, and JANUS capabilities.

A. *Networking experiments*

During these experiments, the Autonomous Surface Vehicle (ASV) was moving according to different paths, as shown in Figure 4. We performed acoustic communications from the control station to the vehicle and vice versa to mimic the control of the vehicle operations. Different packet sizes have been used according to different control messages. These instructions have been sent using both the networking capabilities provided by SUNSET and regular modem transmission with no networking support.

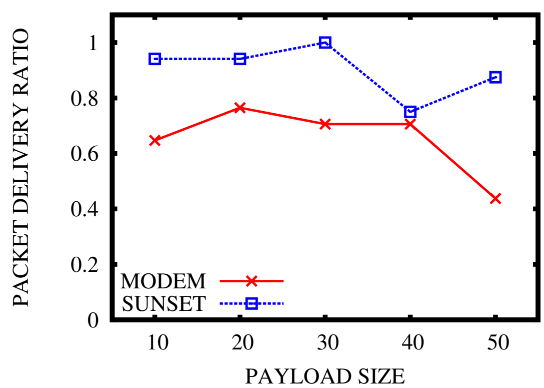


Figure 5: Packet Deliver ratio.

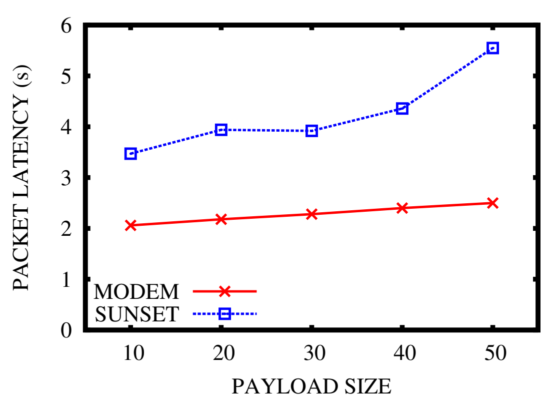
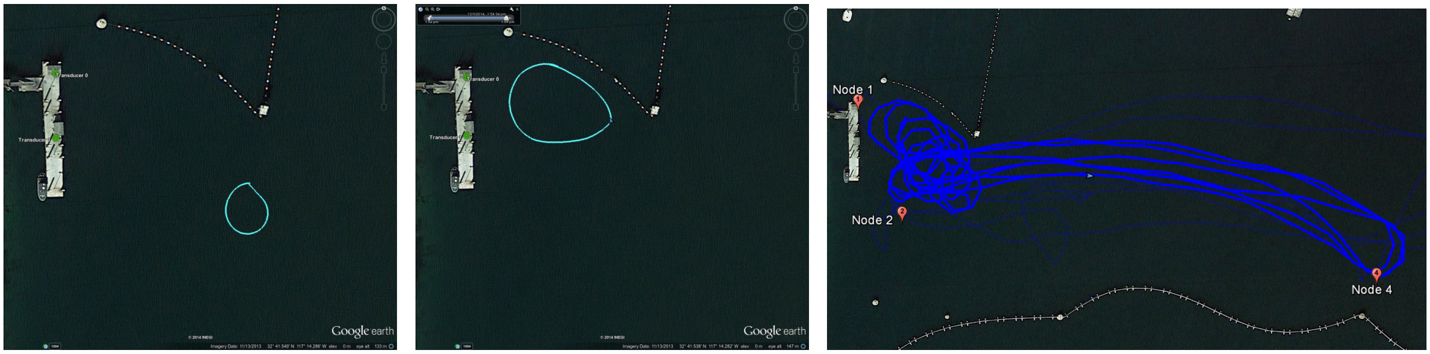


Figure 6: Latency.

As shown in Figure 5, using SUNSET a higher packet delivery ratio (up to the 72% higher) has been obtained.



(a) Circular search away from Node 1.

(b) Circular search close to Node 1.

(c) Linear motion from Node 2 to Node 4.

Figure 4: Path trajectories of the ASV.

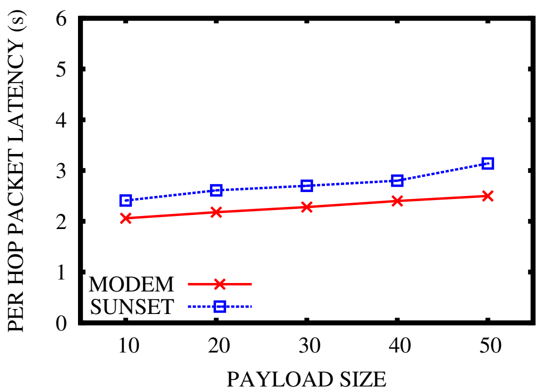


Figure 7: Latency per hop.

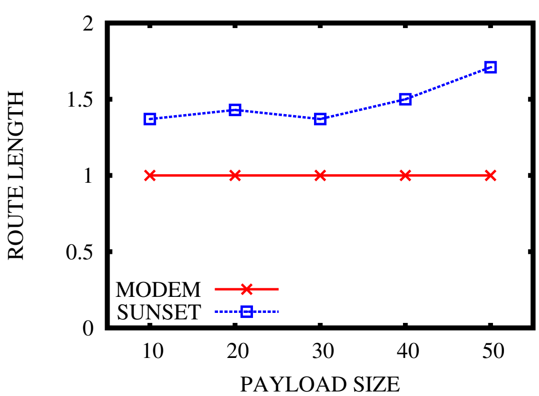


Figure 8: Route length in hops.

[1] Thanks to SUNSET routing capabilities, packets were traveling over more reliable multi-hop routes (Figure 8) when no direct links from the sources were available or when these links were poorly performing. Routes were dynamically adapted according to the changes in the network topology and link quality. The significant increase in reliability, however, comes with an increase in terms of overall end-to-end latency, as shown in Figure 6, even if the offered SUNSET packet latency over each traversed link is quite similar to the one obtained using just the regular modem (Figure 7).

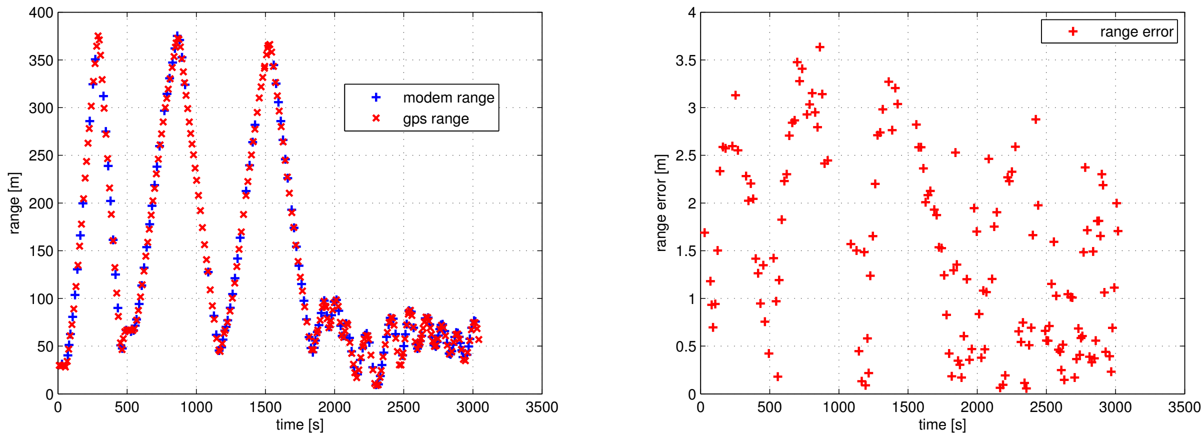
[1] SUNSET's PDR drop for the 40 byte packet size is mostly due to hardware problems experienced by node 2 during the specific tests.

B. Ranging experiments

During the same in-field trial we have also tested the built-in ranging capabilities of the Applicon SeaModem. In particular, we have estimated the distance between the ASV (node 3) and both the control station (node 1) and one static node (node 4). The ASV was moving following the paths shown in Figure 4c. The ranges estimated by the acoustic modem have then been compared with the ones collected by the GPS on board of the ASV, equipped with a Wide Area Augmentation System (WAAS). The results are shown in Figure 9 and in Figure 10. In Figure 9a and 10a, we show the distance between the two considered nodes using both the acoustic modems (+ in blue) and the commercial GPS (x in red). The error introduced by the acoustic estimation is quite limited, as it can be seen in Figure 9b and 10b: It ranges from 0 to 3.3 meters.

C. JANUS experiments

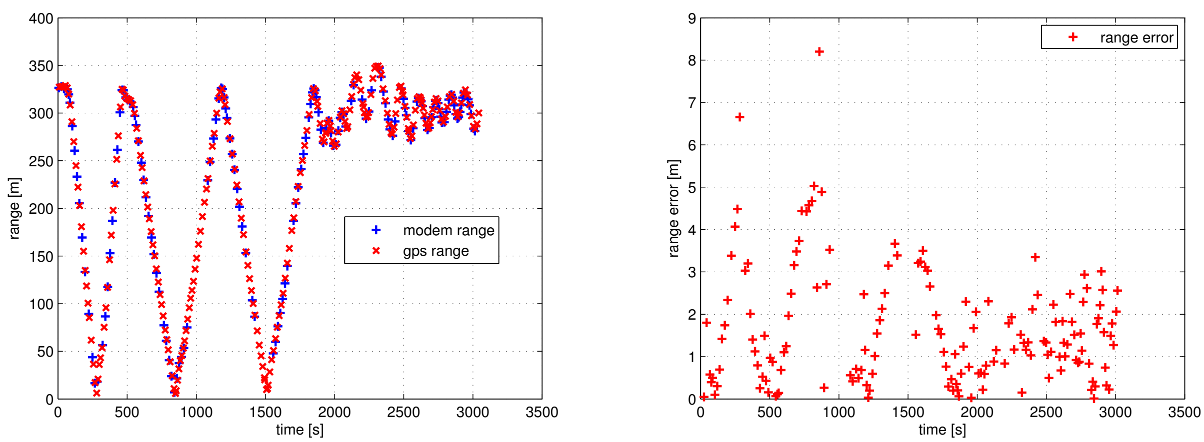
During the in-field exercises conducted at SSC Pacific, the integration of the JANUS scheme in the Applicon SeaModem and SUNSET has been tested. Again, a network of 4 nodes consisting of 3 static nodes and one surface vehicle has been considered. One static node (connected to the control station) and the surface vehicle were able to support both JANUS and the proprietary SeaModem modulation scheme, while the other two static nodes were running only the SeaModem modulation scheme. The surface vehicle was using JANUS to



(a) Ranging estimation.

(b) Ranging error.

Figure 9: Ranging estimation between node 1 and node 3.



(a) Ranging estimation.

(b) Ranging error.

Figure 10: Ranging estimation between node 3 and node 4.

announce its presence and to negotiate the communication parameters with the control station in order to then switch to a different and more performing modulation scheme. A policy module was implemented in SUNSET to handle this switching. After the in filed tests in San Diego, an enhanced integration of the overall system and an advanced policy module have been implemented and will be tested in future trials. Additional details about the conducted JANUS experiments can be found in [9]

VI. Conclusions

A significant work has been performed to implement new capabilities and to enhance current hardware and software, as required by the initial specifications for the AUANC system. The system modules and features have then been tested during a first set of in-field experiments performed at SPAWAR. The results, briefly described in this paper, show that all the different components of the system have been successfully integrated and that the developed system was able to support the formation and operation of heterogeneous and multi-hop underwater networks. In the next months new system components will be developed while some of the ones tested in field will be improved. In particular, the ranging estimation provided the Applicon SeaModem will be enhanced to make possible full integration of this feature in SUNSET. Therefore a new version of the modem firmware and of the SUNSET driver will be developed. In this way the nodes of the network will be able to exchange and use this information according to their needs. The SUNSET policy module that allows to choose the best physical coding scheme to be used at the physical layer will be completed and then tested in field. Additional tests will be performed to further validate the findings and assess different schemes performance. The distributed cooperative localization and control algorithms will be tested onboard of SPAWAR ASV and AUV assets. SUNSET networking solutions will be customized for underwater vehicle networking and integrated with the distributed cooperative localization algorithms.

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