Clock Synchronization and Ranging Estimation for Control and Cooperation of Multiple UUVs

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***Abstract*—This paper presents the initial implementation of an acoustic synchronization and ranging system to enable the control and cooperation of multiple Unmanned Underwater Vehicles (UUVs). Our solution is based on acoustic clock synchronization and one-way ranging. It requires minimum overhead while providing accurate and quick estimation of the relative distances among underwater nodes. The use of one-way ranging allows to scale up to large teams of UUVs and reduces the energy consumption of localization techniques. Our solution has been implemented in SUNSET, leveraging on the accurate timing information and scheduled transmissions provided by SeaModem acoustic modems. Chip Scale Atomic Clocks have been integrated in the SeaModem to overcome the typical drift of real-time clocks thus enabling accurate one-way ranging estimation during long term missions. The performance of the proposed system have been extensively evaluated in two at-sea campaigns considering different testing scenarios. We have shown that our scheme is able to maintain high ranging accuracy over time without requiring the high overhead and energy consumption of two way ranging techniques. We have also shown that the proposed scheme for acoustic synchronization is very effective in synchronizing real-time and atomic clocks of underwater nodes, whenever needed. Our results confirm that the proposed solution for synchronization and one-way ranging allows to enable the control of multiple UUVs keeping at the bay the overhead in the network and the time needed to estimate relative distances.**

***Index Terms*—UUV cooperation, Acoustic positioning, CSAC, Underwater networking, SUNSET, SeaModem.**

I. Introduction

Distributed control of multiple vehicles systems have been studied extensively in the past two decades. One particular technology that has matured rapidly and could offer significant merit is that of Unmanned Underwater Vehicles (UUVs) communicating through an Underwater Wireless Sensor Networks (UWSNs). The advancements in UUVs and underwater communications technologies have allowed the researchers to move from single vehicle to networked multiple-vehicles deployments by defining algorithms which leverage teams of cooperating UUVs (and possibly other, fixed, underwater assets) to accomplish more challenging tasks. Although the UUVs technology has been widely studied in literature there is still a lack of algorithms and technologies to enable autonomous cooperation among surface and underwater vehicles (UUVs) in operational and commercial in-field scenarios [1], [2], [3].

When designing a cooperative network composed of a heterogeneous set of robots, several aspects have to be considered. Among many, those related to the perception of the underwater robots to assess their positions and those of the other robots are the most challenging since the quality of the underwater acoustic communication is limited and subject to time-delay and packet losses. In particular, it requires a strong and robust communication links, interaction and collaboration among the different assets and also the design of novel algorithms to efficiently and quickly estimate the positions of all the underwater nodes, both mobile and static [4].

The relative distances among UUVs (or static nodes) can be estimated either measuring the two-way travel time (TWTT) or one-way travel time (OWTT) of the acoustic signal. Even if the advantage of the first method is that no absolute precision clock is required for the time travel measurement, TWTT does not scale well as the number of vehicles involved in the ranging process increases. Instead, the OWTT approach scales perfectly with any number of vehicles as all UUVs can get ranging updates at the same time. In fact, all the vehicles measuring the OWTT are able to estimate their relative distances with respect to the sender without replying with any acoustic signal thus reducing the overhead in the network. The main drawback of this approach is that the clocks of the involved nodes have to be synchronized for the whole duration of the mission. Various time synchronization algorithms have been proposed in literature, such as for e.g., TSHL [5], MU-Sync [6], D-Sync [7], Mobi-Synch [8] and ROCS [9]. These algorithms effectively address the peculiarities of underwater domain such as long propagation delays, mobility issues and energy efficiency. However all the proposed solutions introduce a high overhead in the network due to the exchange of several acoustic messages to estimate the drift of the clocks. This makes them unfeasible for the coordination and

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cooperation of multiple vehicles with timing requirements.

High precision clocks can be used to estimate the OWTT and so to reduce the network overhead, as shown in [10]. However, periodic clock synchronization with GPS has to be performed depending on the accuracy of the clocks and on the duration of the mission. The frequency of clock synchronization can be highly reduced by using Chip Scale Atomic Clocks (CSACs) [11] that have a negligible drift over long periods of time. Therefore they can be used to accurately estimate relative distances with one-way messages without losing in accuracy.

In this paper we investigate the performance of acoustic clock synchronization and distance estimation between underwater nodes equipped with heterogeneous clocks (real-time and atomic clocks). We have integrated the CSACs in the SeaModem low-power acoustic modem [12] developed by the University of Calabria. The modem firmware has also been enhanced and extended to support on-line synchronization and to schedule acoustic transmissions with accurate timing information. The SUNSET framework [13], developed by University of Rome "La Sapienza" and WSENSE s.r.l., has been enhanced to provide remote acoustic clock synchronization and one-way/two-way ranging estimation. This has allowed us to implement a prototypal system for acoustic node synchronization and localization through one-way ranging estimation that has been evaluated in field in different scenarios in two at sea campaigns. In all the considered experiments we initially synchronized the clocks of the underwater nodes either through cabled synchronization or acoustically using SUNSET protocols. Once the clocks have been synchronized, we compared the performance of our one-way ranging solution with those of two-way ranging protocols. The results confirm that:

- The use of CSACs allows to overcome the typical clock drifts of the standard real-time clocks integrated in the DSP and embedded platforms thus making feasible one-way range estimation for long term missions.
- Acoustic transmissions can be used to synchronize the clocks when the vehicles are underwater without the need of surfacing for GPS fixing.
- The one-way ranging estimation implemented in our system is highly accurate, low overhead and energy consuming, fast and scalable and thus suitable for supporting cooperation and coordination of multiple UUVs where high accuracy and reduced overhead are required.

The rest of the paper is organized as follows. Previous work on underwater synchronization and one-way/two-way ranging estimation are summarized in Section II. In Section III we describe the new features implemented in the SeaModem acoustic modem and SUNSET, including the acoustic synchronization and ranging estimation protocols. The following Section IV illustrates the results of the in-field experiments. Finally, Section V concludes the paper.

II. Related Work

In this section we summarize the main solutions available in the literature for underwater clock synchronization. We also discuss existing systems integrating high precision clocks suitable for OWTT ranging estimation.

Several clock synchronization protocols have been proposed for underwater acoustic sensors networks taking into account the peculiarities of such domain. Time Synchronization for High Latency, TSHL [5], is one of the first approaches which effectively address the high propagation delay in UWSNs. In the proposed solution, the authors first correct the clock skew and then use this information to calculate its offset. In this way, they are able to precisely synchronize the local clock of a node taking into account the high delays of the underwater communication. MU-Synch [6] presents a master-slave hierarchical approach to perform synchronization. The network is divided into a number of clusters, each containing one master and several slaves. The master node transmits beacons and collects the responses from each slave node. In order to estimate the clock skew and related offset linear regression is applied. Then this information are disseminated to all the slave nodes for the actual synchronization. Mobi-Sync [8], is an energy efficient synchronization protocol which takes into account node mobility. A three phase scheme is proposed. In the first phase, authors use spatial correlation of underwater mobile sensor nodes to estimate the long dynamic propagation delays. In the second and third phase the clock skew and offset are calculated by using an advanced regression method and a calibration process. The solution presented in [7], named D-Sync, addresses clock synchronization of mobile nodes without any assumption about their motions. It presents a cluster based approach and relies on Doppler measurements to estimate the dynamic propagation delays between cluster-head and the cluster nodes. ROCS [9] is a recent opportunistic clock synchronization protocol for UWSNs. It follows a similar approach of D-Sync for clock offset and skew estimation by making use of Doppler measurements and transmission/reception timing information provided by the acoustics modems. In ROCS, the network nodes collect and periodically broadcast information about packet reception and transmission thus allowing the estimation of the clock skew and offset by means of an online algorithm. ROCS has been experimentally validated in a sea trial using the Evologics modems and their capability to provide accurate timing information, as described in [14]. In order to accurately account for the clock drift, all the presented synchronization protocols incur in a high overhead which results unacceptable for coordination of multiple UUVs with severe timing constraints.

The high overhead of synchronization protocols can be avoided by using high precision clocks for OWTT estimation, as presented in [10]. In such paper the authors investigate the performance of using synchronized modems to enable the underwater vehicles navigation. In particular, the use of an external pulse per second (PPS) reference clock with the transmission capabilities of WHOI Micro-Modem [15] allows to directly measure the time of flight of the signal with an error on the accuracy of maximum 120μs. Even if the measured clock drift is very low (about 4μs in one hour), the underwater

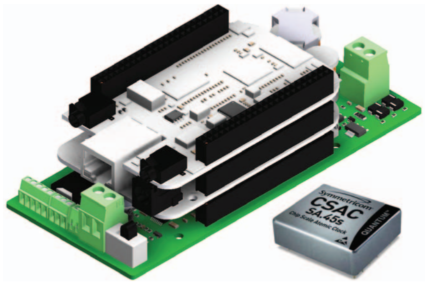

Figure 1: SeaModem stacked with BeagleBone and CSAC.

vehicles need to periodically re-synchronize their clocks to that of a GPS emerging at the surface. Since in some scenarios this is not feasible, the solution presented in this paper proposes to perform periodic acoustic clock synchronization. We show that the frequency of the periodic resynchronization can be extremely reduced using atomic clocks.

III. Implementation of acoustic synchronization and ranging estimation

Accurate acoustic synchronization and OWTT/TWTT ranging estimation can be achieved by precisely knowing the transmission and reception times of the underwater acoustic packets. Furthermore, the estimation of the distance using one-way messages demands for synchronized clocks that have a negligible drift, such as the CSACs [11]. In what follows we first describe the enhanced features of Seamodem [12] to provide timing information to the upper layers of the protocols stack and its integration with the CSACs. Then we describe the acoustic synchronization and the OWTT/TWTT ranging estimation protocols implemented in SUNSET [13].

A. Modem

SeaModem [12] is a MFSK underwater acoustic modem developed by AppliCon s.r.l. for shallow water communications, currently working in the $25 - 40$ KHz frequency band. Two-, four- and eight-tone MFSK modulation protocols can be selected achieving a transmission data rate of 750, 1500 and 2250 bits per second, respectively. A 16 bit CRC error detection mechanism is implemented. The modem also implements an optional error correction scheme based on the Viterbi algorithm. Four different transmission power levels are supported by the modem, from 5W up to 40W, that are selectable on-line. An Automatic Gain Control (AGC) device is present in the input channel.

Two header connectors which are part of the SeaModem allow the stacking of expansion board(s) on top of it (Figure 1). The header pin-out is compatible with the Linux embedded platform "BeagleBone" and with its plug-in boards called "capes". BeagleBone [16] is a low-cost, open source, community-supported development platform for ARM Cortex-A8 processor. It runs Debian GNU/Linux with the support for many other Linux distributions and operating systems (i.e., Ubuntu, Android, Fedora). In this way, new high-level functionalities that use the modem as a communication device can be easily developed by exploiting the power and flexibility provided by a stand-alone system with a Linux OS. This approach has been used to integrate in the SeaModem the SUNSET networking framework and the JANUS modulation scheme [17].

The Real Time Clock (RTC) integrated in the modem board has a low accuracy, around one millisecond, and an estimated drift of about $\pm$20ppm at $25\,^{\circ}$C. In order to increase its accuracy beyond the millisecond the internal Digital Signal Processing (DSP) timer counters are used. The resolution of such timers achieves a precision up to 40ns. They are also used by the SeaModem to implement the two-way ranging protocol which allows to accurately estimate the distance between any two modems. When a requesting modem sends a two-way ranging packet via the acoustic link, a timer counter is started and it counts the time elapsed between the time of transmission and the time of reception of the corresponding response packet transmitted by the destination modem. In this way, subtracting the fixed waiting time of the destination modem and the CPU processing time required to decode the response packet, SeaModem can accurately calculate the Time of Flight.

In what follows, we describe the novel functionalities provided by the modem's firmware and its integration with the atomic clock CSACs.

Firmware enhancements. To enable the upper layers of the protocol stack to perform acoustic synchronization and two-way/one-way ranging protocols, novel functionalities have been added to the modem firmware:

- *transmission scheduling*: the actual start of a packet transmission can be scheduled by setting the specific time;
- *timing information about packet reception*: the reception time refers to the exact time when the first acoustic data is received by the modem transducer;
- *timing information about packet transmission*: the transmission time refers to the exact time when the first acoustic data is transmitted by the modem transducer.

CSAC Integration. To provide a negligible drift in system clocks, the Microsemi Quantum$^{\text{TM}}$ SA.45s CSAC [11] has been integrated in SeaModem (Figure 1). The SA.45s CSAC is the world's first commercially available chip scale atomic clock, providing the accuracy and stability of atomic clock technology while achieving true breakthroughs in reduced size, weight and power consumption lower than 120mW. The CSAC produces two outputs, a 10MHz square wave and 1 Pulse Per Second (PPS), both at standard CMOS levels, with short-term stability (Allan Deviation) of $2.5e^{-10}$ at TAU $=$ 1s, long term aging lower than $9e^{-10}$ per month, and maximum frequency change of $5e^{-10}$ over an operating temperature range of $10\,^{\circ}$C to $35\,^{\circ}$C. It also accepts a 1 PPS input that may be used to synchronize the unit's 1 PPS output to an external reference clock up to 10ns of accuracy (cabled synchronization), like a GPS or another CSAC, and provides an RS-232 interface for monitoring and control. To allow the CSAC SA.45s integration, the SeaModem hardware/firmware has been enhanced by adding a 1 PPS input. The CSAC 1

PPS rising edge enables an edge-triggered hardware interrupt on a modem's GPIO and increases the internal counter of seconds. As in the RTC case, the sub-seconds time intervals are measured by the internal DSP timers. Furthermore, the CSAC RS-232 interface has been connected to Beaglebone to monitor CSAC status, temperature, alarms and lock condition in case of cable synchronization.

B. SUNSET

The Sapienza University Networking framework for underwater Simulation Emulation and real-life Testing framework [13] (SUNSET) is a partially open-source framework that provides networking and communication capabilities to underwater nodes. Using SUNSET, novel protocols and new algorithms can be easily implemented and tested first in a controlled simulative environment, where various scenarios and settings (much more than actually possible in field) can be explored. These new algorithms can then be easily tested without any code rewriting through in lab emulation using real hardware and finally evaluated at sea, investigating the performance of a complete underwater system. The architecture of SUNSET, shown in Figure 2, has recently been extended to support the innovative concept of Software Defined Communication Stack (SDCS) [18], where different network protocol stacks, or different parameters of a protocol stacks, can be dynamically and adaptively selected according to the network conditions, and applications requirements. Several security solutions [19] and network protocols, such as CARP [20], CSMA [21], T-Lhoi [22], Flooding-based solutions [23], etc., have already been implemented and tested in field. SUNSET

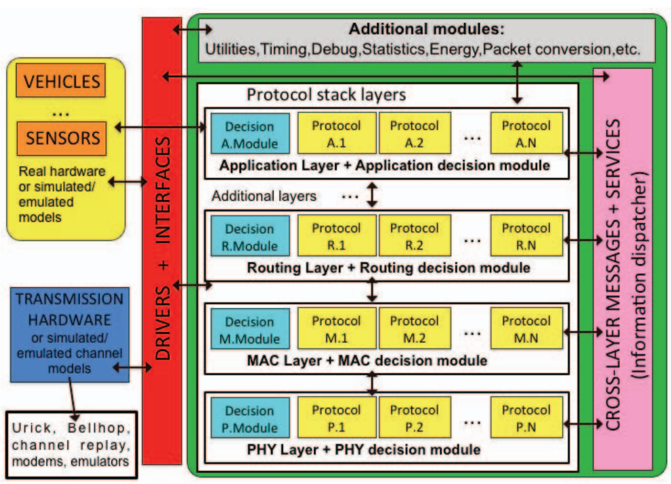

Figure 2: SUNSET architecture.

has been used to remotely and acoustically control different underwater vehicles [3], [4] by supporting several acoustic modems, including those produced by WHOI, Evologics, Kongsberg, Teledyne Benthos and Applicon.

The driver for the Applicon SeaModem has been extended to fully support the new functionalities provided by the modem, such as transmission scheduling and the timing information regarding the reception and transmission of acoustic packets. In addition, three new network protocols have been designed and implemented in SUNSET. They transparently provide distance estimation using TWTT and OWTT information and one-way acoustic synchronization. The protocols require that acoustic modems implement scheduled transmissions and provide timing information about packet transmission/reception. All the protocols are briefly described in what follows.

One-way ranging protocol. One-way ranging estimation can be successfully performed only if the clocks of the involved nodes are synchronized and the receiving nodes know exactly the actual starting (or ending) transmission time of the received packet. This information is contained in the header of the one-way ranging packets. When the transmitting node wants to send such a packet, it first requests to the modem to schedule the start of the transmission at a given time and then writes this information (named transmission time in the following) in the header of the packet. All the nodes that receive the one-way ranging packet are therefore able to estimate the relative distance with the sender by using the time of packet reception provided by the modem, the transmission time contained in the packet and the value of the sound speed. The one-way ranging can be performed on single or multiple destination nodes, simultaneously. Only one broadcast packet is needed for all neighbors nodes to be able to estimate the distance to the sender.

Two-way ranging protocol. Two-way ranging, unlike one-way, does not need the clocks to be synchronized. Once the two-way ranging request has been transmitted by a node x, the related transmission time is stored for the subsequent TWTT estimation. If the request is transmitted in unicast, the destination node replies immediately after receiving the packet with a response packet. Otherwise, if the request is sent to multiple nodes, each of them schedules the transmission of the response packet after a random time offset to reduce the probability of collision in the network. In both cases, the elapsed time between the reception of the request and the transmission of the response, namely the processing time, is added to the header of the response packet. For each response packet received, the node x is able to estimate the TWTT as the time of the response reception minus the processing time contained in the response packet and the previously stored request transmission time. The distance is estimated as half the product of the TWTT and the sound speed.

One way synchronization protocol. The one-way synchronization protocol aims to acoustically synchronize the clock of each node in the network to that of a particular node, named the reference node. Assuming that the clocks do not drift, each node in the network needs to calculate its relative time offset with respect to the clock of a reference node x. The node x needs to know in advance the Time of Flights (ToFs) to each destination node: They can be estimated for instance using the two-way ranging protocol. Then this information is broadcasted in a single one-way synchronization request packet, which is also timestamped with the actual transmission time, to allow multiple nodes to be synchronized. Each destination node receiving the one-way synchronization request can therefore set its clock offset by using the information contained in the packet header (time of transmission and its ToF) and the packet reception time provided by the modem.

IV. Experimental Evaluation

The performance of the proposed system have been evaluated through two at-sea campaigns. The first one has been carried out during October 2015 in waters at south of Cartagena, Spain, during the TJMEX'15 campaign (Trident Juncture MCM EXperiment 2015 organized by the NATO STO CMRE) to check the feasibility of the proposed approach. The second one has been performed in the port of Amantea, Italy, in February 2016. The main objective of these experiments was to prove the feasibility of acoustic synchronization and one-way ranging estimation for multiple underwater nodes equipped with CSACs.

A. *TJMEX'15 experiment*

In this experiment, three nodes with IDs 1, 2 and 3 have been deployed at the same depths, as shown in Figure 3. Each node has been anchored to the bottom of the sea and connected to a floating buoy through a rope. All the nodes were free to move around the anchoring point according to the currents of the sea. The nodes with IDs 2 and 3 have been equipped with the CSACs, while the node with ID 1 used the standard real-clock provided by the SeaModem. We set the sound speed velocity to a default value of 1500m/s to estimate the distance.

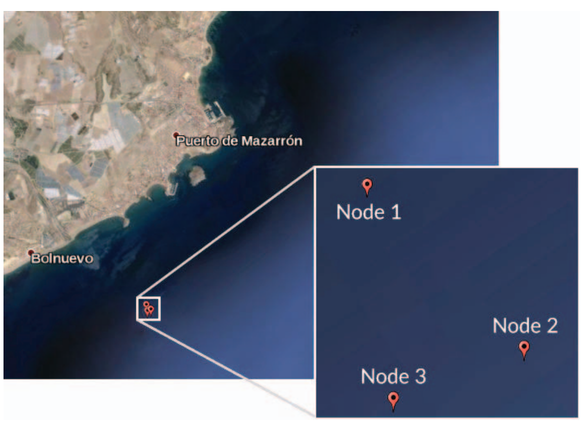

Figure 3: Topology used in TJMEX'15 campaign.

Figure 4 shows the results related to the estimation of the distance between nodes 3 and 1 using two-way and one-way ranging when the receiving node is not equipped with atomic clock. The distance between these nodes was about 260 meters. The first step of the experiment was to measure ToF with TWTT messages (blue triangles). Using this information, the clock of node 1 has been acoustically synchronized to that of node 3 using the synchronization protocol (red crosses).[1] Then one-way ranging measurements have been performed (green dots). As expected, the clock drift of node 1 reduces the accuracy of the OWTT ranging estimation. In particular, the clock of node 1 starts to drift after few seconds from the clock synchronization. As the experiment time increases, the difference between the clocks of nodes 3 and 1 increases as well, leading to a maximum error on distance estimation of about 49.7 meters. Such error corresponds to a clock drift of about ±27ppm that is slightly higher than that of the SeaModem's RTC at 25 °C due to the lack of temperature compensatation. Since the clock drift is not predictable at fine granularity, periodic clock synchronization is needed to allow one-way distance estimation by using information provided by the two-way ranging. Due to the clock drift and the high overhead introduced in the network when using two-way messages, this approach is usually not feasible for real-time control and cooperation of mobile platforms.

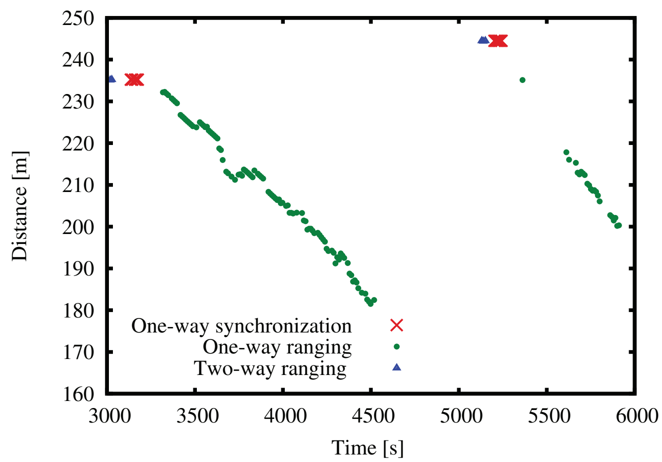

Figure 4: One-way ranging estimation from node 3 to node 1.

Figure 5 shows instead the results of running OWTT and TWTT ranging estimation between two nodes (IDs 3 and 2) both equipped with CSACs. Before the actual experiments, the atomic clocks have been cabled and accurately synchronized. In this way, the nodes 2 and 3 were able to compute their distances through OWTT estimation without the need to perform acoustic synchronization. The estimated distance between nodes 2 and 3 was 150.69 meters. In Table I we report the real distance and the average distances (μ) with the related standard deviations (σ) computed through TWTT and OWTT ranging estimation between nodes 2 and 3. It is easy to see that both ranging techniques achieve very good results, with a standard deviation of about 0.26 and 0.32 meters when running one-way (green dots) and two-way (blue triangles) ranging estimation, respectively. These results show also that the one-way ranging is more accurate than the two-way one since it is less prone to errors related to wrong transmission/reception times estimated by the modem. In particular, the average distance estimated with the OWTT presents an average error of 0.26 meters. In addition, the value of the distance is steady for the whole experiment meaning that the drift of the CSACs is negligible. It is interesting also

[1] Running this protocol allows the receiving node to estimate also the distance.

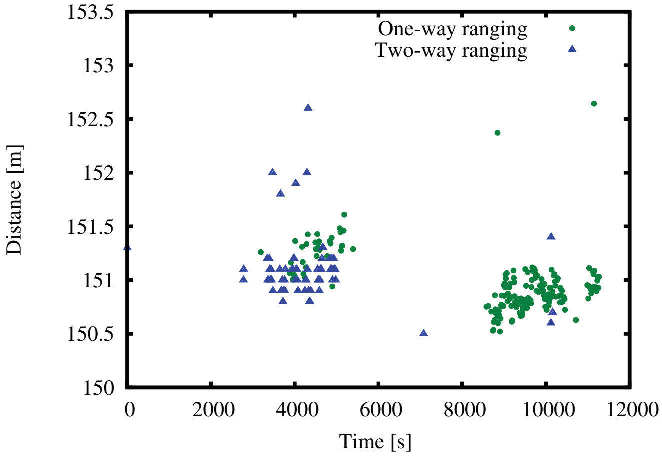

Figure 5: One-way and two-way ranging estimation from node 3 to node 2.

to notice that the distance computed with both the methods is slightly different as the experiment time increases. That is, the average distance estimated in the first and in the second part of the experiment is 151.10 and 150.88 meters, respectively. The reason is that the positions of the nodes change due to the currents of the sea that move the position of the buoys and therefore the nodes. (The movement of the nodes affected also the results shown in Figure 4.)

Distance [m]	Range Type	μ [m]	σ [m]
150.69	OWTT	150.95	0.26
150.69	TWTT	151.10	0.32

Table I: Distance estimation using OWTT and TWTT ranging from node 3 to node 2.

B. Amantea experiments

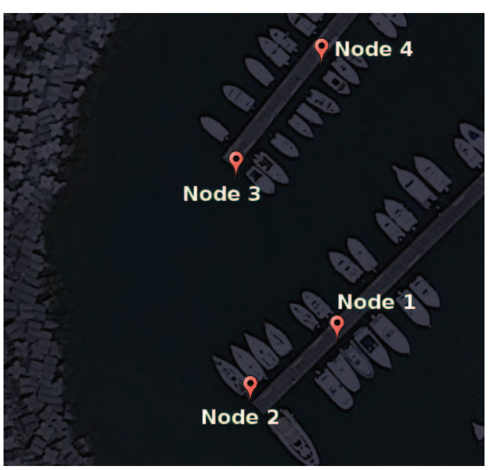

Figure 6: Topology used in Amantea's experiments.

In this set of experiments, we have performed acoustic synchronization and one-way/two-way ranging estimation in a more challenging very shallow water scenario (Amantea port, Italy) that is more subject to interferences and multi-path signal reflections. The topology, shown in Figure 6, consists of 4 nodes deployed and fixed to the port piers to prevent movements caused by sea currents. Node 1 acts as a reference node and is synchronized with the clock of a surface GPS. We use the Piksi GPS receiver produced by Swift Navigation, equipped with Real Time Kinematics (RTK) functionality for centimeter level relative positioning accuracy [24] providing a free drifting PPS signal. Nodes with IDs 2 and 4 use the real-time clocks provided by the modem (RTC), while node 3 is equipped with the CSAC clock, as in the previous experiment.

Our objective is to mimick a typical application scenario where a reference node, such as an Autonomous Surface Vehicle, is equipped with a stable GPS clock and can serve as a moving beacon that broadcasts one-way messages to allow the underwater nodes to estimate their relative distances. In order to enable OWTT ranging estimation, all the nodes have to be synchronized. Since the nodes are not initially synchronized, the reference node needs to estimate the Time of Flight of the signal using a two-way approach. To such purpose, the reference node can estimate the signal travel time for each node using one of the two-way ranging protocols provided by either SeaModem or SUNSET. Once the signal travel time has been estimated, the acoustic clock synchronization can be performed by broadcasting such information through the one-way synchronization protocol implemented in SUNSET. To account for clock drifts, the TWTT estimation and acoustic synchronization can be periodically repeated to keep synchronized the clocks of the underwater nodes.

The results of this experiment are shown in Figure 7. The acoustic synchronization and two-way/one-way ranging protocols have been performed by the reference node with ID 1. In particular, the blue triangles, the orange diamonds and the turned triangles represent the distance estimated from node 1 to node 2, 3 and 4, respectively, using the two-way ranging functionality provided by the SeaModem. The black squares instead represent the distance estimated through the broadcasting requests of the two-way ranging protocol developed in SUNSET. As in the previous experiment, the red crosses indicate when the acoustic synchronization has been performed, while the green dots show the distance estimated using the one-way ranging protocol of SUNSET. The sound speed has been set to a default value of 1500 m/s when converting from ToF to distance. The performance results are briefly shown in Table II. In particular, we report the real distances and the average distances μ (and the related standard deviations σ) between nodes equipped with different clocks that have been estimated using the two-way and one-way ranging protocols. We remark that node 1 estimated the distance to nodes 2, 3 and 4 using the two-way protocols, while the nodes 2, 3 and 4 computed their relative distance to node 1 when receiving its one-way message.

Looking at both Figure 8, where the details of the two-way ranging results are shown, and Table II, we can see that both SeaModem and SUNSET achieve almost the same per-

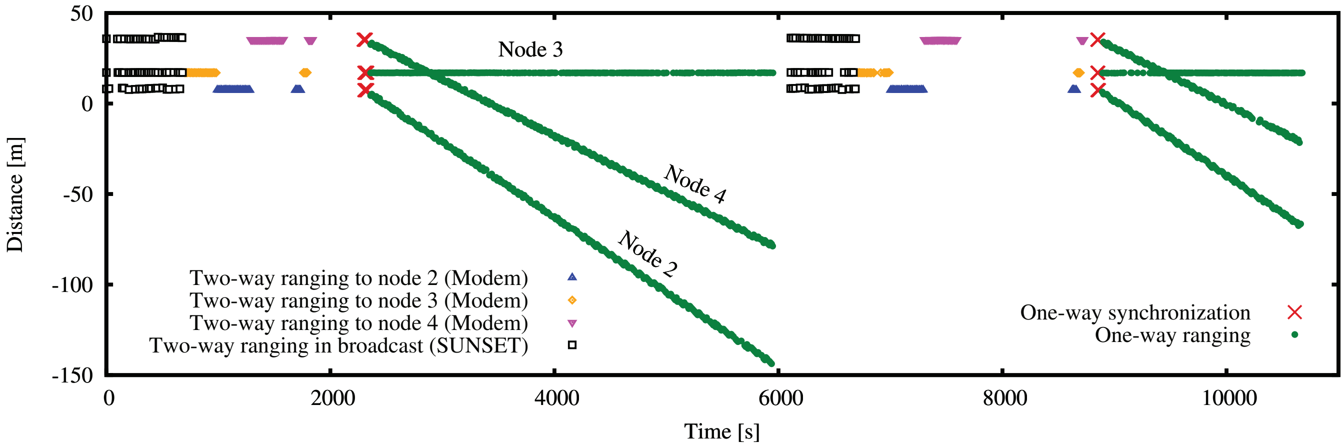

Figure 7: Results of the Amantea's experiments: Two-way/one-way ranging and acoustic synchronization.

ID	Distance [m]	Range Type	μ [m]	σ [m]	Clock
2	7.30	TWTT Modem	7.42	0.044	RTC
		TWTT SUNSET	8.24	0.28	
3	16.98	TWTT Modem	17.01	0.043	CSAC
		TWTT SUNSET	17.16	0.039	
4	35.3	TWTT Modem	35.31	0.040	RTC
		TWTT SUNSET	36.00	0.31	
3	16.98	OWTT SUNSET	16.99	0.045	CSAC

Table II: Distance estimation using TWTT and OWTT.

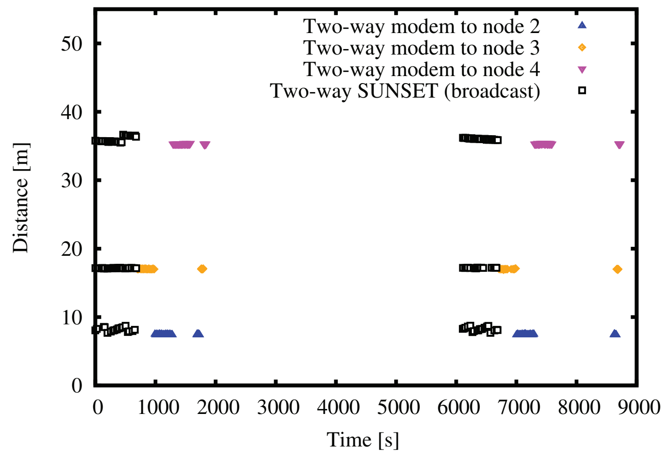

Figure 8: Two-way ranging estimation.

formance. The distances estimated by the SeaModem to nodes equipped with real-time clocks are more accurate than those of SUNSET. The reason is that the SUNSET protocol suffers from the clock drift that occurs during the waiting time needed to de-synchronize the response messages when multiple nodes are involved in the same ranging request. In particular, each node waits for a random time before transmitting the response message to reduce the probability of packet collisions. During this time the clock drifts, thus affecting the actual distance estimation. The SeaModem protocol instead does not suffer from the clock drift since it can be performed only in unicast and the response messages are immediately transmitted after the request reception. However this approach has two main drawbacks. The first one is that it leads to higher network overhead since one request has to be transmitted for each network node. The second one is that more time is needed to estimate the distance with multiple destination nodes. When using them with drift-less clocks (i.e., CSAC and GPS) both the SeaModem and the SUNSET protocols have the same accuracy in range estimation but the SUNSET solution allows us to reduce time and overhead.

Once the ToFs between the reference node 1 and the other underwater nodes has been estimated, we perform acoustic synchronization (red crosses in Figure 7). In order to accurately calculate the offset and to take into account possible packet losses, 5 synchronization requests are transmitted. The offset on each node has been calculated as the average of all received requests. After the synchronization step we perform one-way ranging estimation using the protocol implemented in SUNSET. As in the previous experiment, the performance of one-way ranging estimation quickly degrades when using low precision clocks due to their drifts. In particular, the distances estimated by nodes 2 and 4 decrease in about 1 hour up to 148 and 111 meters, respectively, which corresponds to a negative drift of about 27.57 and 20.67ppm. Since the clock drift strictly depends on the temperature and the real-time clocks are not compensated in temperature, the drift is up to 7ppm higher that the one reported by the modem clock datasheet, i.e., $\pm$20ppm at 25 °C. Note that the difference on the drift rate between the two clocks is reflected also in degradation of ranging accuracy. The two-way measurements presented in Table II show that the average distance error when using the less drifting node 4 is 25% lower than that of node 2.

In Figure 9 we report in detail the experiment results of the one-way ranging protocol between nodes equipped with GPS and CSAC clocks. In the same figure we show also the

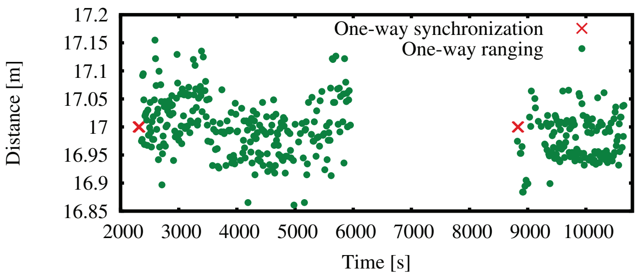

Figure 9: Acoustic synchronization and one-way ranging estimation from node 1 to node 3.

time when acoustic synchronization has been performed by the reference node (red crosses). Looking also at Table II, it can been seen that the distance estimated by node 3 (i.e., the one equipped with CSAC) is very stable and very precise for the whole duration of the experiment thus making unnecessary the second acoustic synchronization. In particular, in the first and second part of the experiment, node 3 estimated an average distance of 17.00 and 16.98 meters with a standard deviation of 0.05 and 0.04 meters, respectively, resulting in an average error of 0.02 meters.

V. Conclusions

In this paper we have investigated the performance of an acoustic system which provides accurate clock synchronization and distance estimation in order to enable the cooperation and coordination of multiple Unmanned Underwater Vehicles for long term missions. One-way ranging measurements have been used to estimate the relative distances between underwater nodes, while acoustic synchronization has been performed to synchronize their clocks when needed. To such purpose, the SeaModem has been enhanced to provide accurate timing information about packet transmission and reception times and has also been integrated with a Chip Scale Atomic Clock to mitigate the effect of clock drifting during long term missions. Finally, three different protocols have been designed and implemented in SUNSET to provide efficient acoustic clock synchronization and accurate one-way/two-way distance estimation to multiple underwater nodes. Results from two at-sea campaigns have been reported confirming that the proposed scheme is lightweight and results in high ranging and synchronization accuracy.

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