Underwater Sensor Networks with Mobile Agents: Experience from the Field

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Abstract. This paper reports the experimental results obtained by two research projects, UAN and Thesaurus, in which two different network communication schemes have been implemented in the context of underwater robots cooperation. UAN implemented a complex layered communication scheme including collision avoidance medium access, node addressing and routing strategies, and mobile nodes as adaptable network components able to sustain the communication. Thesaurus is deploying a Time Division Multiplexing network with the explicit objective of supporting the robotic exploration of deep water archaeological sites. The paper examines the approaches and challenges in the design and implementation of both underwater sensor networks. It discusses how the specific application influenced the design and the operation of the communication protocols at the various network layers. Field results are presented to discuss how the network structure impacts on the underwater robot cooperation and on the overall sensing network performance.

Keywords: Underwater mobile sensor networks, Autonomous systems, Multi-agent systems, Underwater acoustic communication, Autonomous Underwater Vehicles (AUVs).

1 Introduction

The development of underwater sensor networks is the direct consequence of the todays need to sense the underwater environments [1,2]. Their requirements can be very diverse, ranging from short-lived applications for rapid assement, to persistent networks for continuous long-term monitoring; they be can characterized by many autonomous sensing units, either fixed or mobile, by distributed sensing and data processing, by adaptivity (re-configuration, re-deployment, etc.) on the basis of locally sensed data and information available from other nodes through a communication infrastructure. Autonomous underwater vehicles (AUVs) play obviously a central role in this process, since they constitute the ideal sensor carrier for a moving or redeployable autonomous (or even remotely controlled) node. However, while the research on autonomous sensing network is well advanced in the robotics community, including marine robotics [3,4], there is still a wide gap between theoretical or proof of concept experiment to operational application in the underwater domain. Primary reasons rely on the much more

M. Zuniga and G. Dini (Eds): S-Cube 2013, LNICST 122, pp. 79–93, 2013.

demanding resources, both in terms of time and costs, required for the deployment and usage of underwater systems. While the motivations for underwater sensor networks are similar to those for terrestrial networks their in the field deployment usually requires a great deal of preparations and logistics. Moreover, as AUVs have reached a considerable maturity in reliability and performance, the major challenge in underwater application of autonomous cooperating sensing networks is still represented by node communication. The intrinsic limitations in bandwidth, time delay, channel fluctuation, imposed by the physics of acoustic propagation [15], is still constraining the reliable set-up of communication infrastructures for sensor networks.

The aim of this work is to present recent results of underwater sensor networks as obtained within two research projects, UAN [8] and Thesaurus [9], in which two different network communication schemes have been implemented in the context of underwater robot cooperation. In the UAN case, a communication network was set-up and deployed for five days of continuous operation, with the objective of protecting coastal critical infrastructures. The focus of the Thesaurus project is instead much different, the ultimate goal being to survey marine areas of archaeological interest in the Tuscan Archipelago, Italy. As a result, the two projects relies on different network architectures: UAN implemented a communication scheme able to route the information via multi-hops towards the desired recipients; the physical layer of the UAN network was supported by modems able to communicate up to 500bps, by a CSMA/CA (Carrier Sense Multiple Access / Collision Avoidance) medium access control, by node addressing and routing strategies. The upper levels of UAN were composed of the standard implementation of IP and UDP and by a modified version of the MOOS (Mission Oriented Operating Suite) publish/subscribe system as middleware capable of including network security features. In the UAN scenario, the AUVs were used both as movable nodes of the network, able to modify its position and hence the network topology in response to communication variations, and as protection assests of the UAN protection systems. The project Thesaurus pursued a complementary approach, where the objective of the network was functional to the needs of the cooperative exploration. The resulting network is based on broadcast transmissions, sharing the medium access among all nodes through Time Division Multiplexing (TDM). The aim of the communication was in fact that of maximizing the amount of information exchanged between any two nodes, at the price of limiting the communication to shorter communication ranges.

Note that the purpose of the paper is not that of determining the "best" networking scheme by comparison of performance of two different network structures, but to separately report the observed performances. We believe that direct comparison between the two experiments has little sense because of the differences in the applications, in the number of nodes, communication ranges, and environmental conditions between the two experiments: UAN included up to 6 nodes, water depths between 50 and 150 m, changes in the sound speed profile.

Thesaurus has been limited so far to 3 nodes operated in very shallow water (4m) and at much shorter ranges.

It is worth remarking that field examples of underwater acoustic networks are still very scarse. It has been only recently that some examples of acoustic networks have been used in the field [4]. In most of these cases, the communication was based on one-to-many broadcasting with simple networking protocols (no routing, no re-transmissions). The Thesaurus project moves within this line of research as it aims at creating a network with a reduced footprint on the performance of the overall system. In this case, the novel approach of the project relies on including system-wide capabilities as network layers (e.g. node-localization capabilities). To the best of our knowledge, the UAN case still remains the sole example of layered acoustic network, with a structure similar to those currently used in traditional terrestrial networks.

The rest of the paper is organized as follows: Section 2 describes the UAN system, its concept and its objectives. Details of the UAN communication network are reported here. Section 3 describes the deployment of the UAN acoustic network at sea, during the UAN11 sea trial, held in the Trondheim Fjord, Norway, in May 2011. Thesaurus is described from Section 4. Here we give a general overview of the project's objectives and a description of the specific communication network implemented to obtain AUV cooperation. Section 5 describes some preliminary results obtained during an engineering test of the project, held in February 2013, in the Bacino di Roffia lake in Italy. Section 6 is dedicated to a discussion on the main lessons learned from the deployment of the two networks. Section 7 concludes the paper summarizing the results.

2 The UAN Network: Using AUVs to Sustain Communication

In this section, we will describe the UAN sensor network. The network, developed within the EU-funded project Underwater Acoustic Network (UAN), was composed of both fixed and mobile nodes, where the mobile ones were installed on autonomous underwater vehicles. The UAN project explicitely aimed at the development of an integrated system capable of including above water and underwater sensors/nodes/devices, with the final objective of having an operational system for security and protection of coastal and off-shore critical infrastructures. The context for the sensor network was hence that of an integrated security system with a centralized command and control center (C2), from where it must be possible to monitor and operate both aerial, terrestrial and submerged nodes. The UAN communication infrastructure was quite complex. The network was realized in a modular way, through a stack of interacting layers. It included a broad range of services such as addressing and forwarding, routing, and retransmissions. As components of the network, the mobile nodes usage was twofold: they were used as network devices, able to modify the geometry of the network in response to communication variations or to provide multi-hop capabilities guaranteeing the connectivity of the fixed nodes, and as protection assets for long range detection/inspection of possible intruders, acoustically controlled by the C2. The depicted UAN scenario is conceptually represented in Figure 1. The integration of above water and underwater devices is realized through an underwater base station (STU - subsea telemetry unit/gateway) which is capable of offering two diverse interfaces to connect the two worlds. It is cabled to shore with a high bandwidth link, and it is equipped with an acoustic modem for underwater communications. On the above water side, the UAN system includes fixed sensors such as cameras, radars, or mobile nodes such as Unmanned Aerial Vehicles (UAVs) all connected via traditional terrestrial/aerial communication links (e.g. radio or optical) that allows for a continuous control of the devices an operator within the C2. On the underwater side all the fixed and mobile nodes are acoustically connected in an underwater sensor network which includes the STU. Each underwater node is equipped with an acoustic modem for communication and might integrate a sonar for intrusion detection and surveillance. The command and control center hence appears as a master node for the UAN system, which gathers all the information coming from aerial/terrestrial and submerged devices, to make it available to an operator.

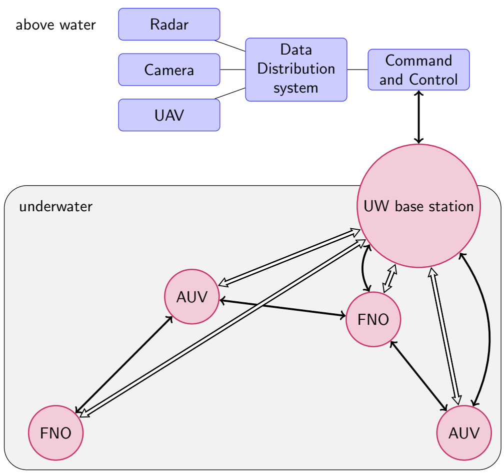

Fig. 1. The UAN concept: integration of above water and underwater sensors/devices into a unique system for critical infrastructure surveillance. Arrows represent flow of information/data. The picture shows both physical links with possible multi-hops (thin black arrows), and the middleware client-server flow of information (thick arrows) with the UW base station acting as a master station (star-shaped).

2.1 Network Architecture

In terms of network architecture, the project UAN implemented a communication scheme able to route the information via multi-hops towards the desired recipients. The physical layer of the UAN network was supported by Kongsberg prototypal acoustic modems [10] which are able to communicate up to 500bps rate, at a central frequency of f=25.6kHz, in a bandwidth of 8kHz. The modems were able to communicate up to a maximum range of 1km setting the source level to 190dB re 1μPa@1m. The Medium Access Control (MAC) and the routing layer were implemented directly on the modem processing board. CSMA/CA (Carrier Sense Multiple Access / Collision Avoidance) was the implemented medium access control, whereas the routing was based on a flooding algorithm, which allowed for network discovery at network start up and whenever there was a change in the network topology (e.g. due to AUV redeployment). Retransmissions, to decrease the probability of packet loss, was supported at physical layer, while the upper layers had the option to direcly interrogate the modems to have delivery reports. The network stack was completed with a standard implementation of IP and UDP, and using MOOS to support network security. More details on the general MOOS framework can be found in [12], whereas information on the specific security features implemented have been reported in [6]. The use of IP had the advantage of providing a standard interface towards the application level of the network. The use of UDP was motivated to reduce the communication overhead, but required moving some services to other network layers (e.g. retransmissions were confined at physical level and at application level through modem delivery reports). It is worth noticing that the IP/MOOS layer created a star-shaped network with the underwater base station at the center (master node). The MOOS system, in fact, is a centralized system which requires a direct connection between the nodes (clients) and the central MOOS database (server), which acts as a relay of information. The presence of a central database might be seen as a network bottleneck. In the case of the UAN system though, this architecture did not add a significant amount of overhead. It was in fact a requirement for the C2 (collocated with the underwater base station) to have the complete control of the network for node status monitoring, node task allocation, etc. It was hence the same nature and peculiarities of the UAN specific application - monitoring and protection of critical infrastructures - that required all the data to be collected at the C2, naturally leading to the final networking architecture. The layered architecture of the UAN network is reported in Figure 2.

3 Going at Sea: The UAN System in the Field

The UAN project ended at the end of 2011 with the UAN11 final sea trial that took place in May 2011 in the eastern part of Strindfjorden, 17 km from Trondheim, Norway. The area, with varying bathymetry ranging from 40 to 150 m, is close to commercial and touristic routes, allowing to test the system in operative conditions. The deployed underwater sensor network was composed of:

1. the underwater base station (STU - Station Telemetry Unit) [13];
2. up to three fixed nodes (FNOs - Fixed NOdes) [13], equipped with thermistor chains for measuring the water temperature, and with a (simulated) detection sonar to detect possible intrusions;

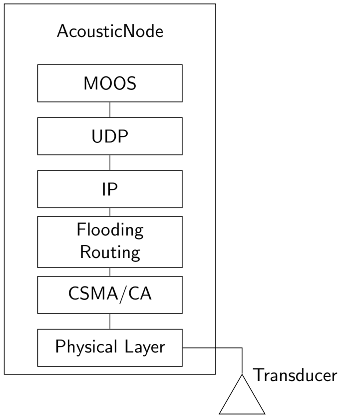

Fig. 2. UAN network layered architecture. The bottom layers up to the routing level are implemented directly on the modem processing board.

3. up to three mobile nodes: two AUVs of e-Folaga class [11] and one additional mobile node set-up on the supporting Research Vessel (R/V) Gunnerus using a transducer located at variable depth between 10 and 20 m. One of the AUVs was also equipped with a conductivity-temperature probe (CT). The ship was equipped with an external CTD; its measurement stations are displayed in Figure 3. Environemtal data collected from the ship was the only one not circulated within the network and analysed offline.

The base station connected the underwater network to the land C2 station, which finally integrated aerial and surface additional sensors and nodes. The complete scenario was hence that of an integrated security system for asset protection.

A three dimentional reconstruction of the bathymetry of the experimental area is depicted in Figure 3, together with FNOs deployment points and CTD casts. The STU was located at 90 m depth, FNO1 was positioned at about 160 m from STU at 96 m depth, FNO2 was deployed in a shallower area, at 39 m depth, and at a distance of about 900 m from STU. Finally, FNO3 was positioned at 98 m depth, and at a range of 400 m from STU. The asset to be protected was co-located with the STU.

The UAN network was continuously operated throughout five days; nodes were routinely added and/or removed, AUVs were seamlessly deployed within the existing fixed network, and both fixed and mobile nodes were recovered for battery recharging and then redeployed without effects on the network operation. Overall, UAN system showed a level of robustness that went beyond expectations. The network traffic was mainly composed of environmental data as measured in the field and transmitted periodically (once every Ts = 120s) from both the fixed and mobile nodes. In addition, further information could be requested by the C2 when needed (e.g. node battery status, etc.). The average message size at application level was 150bytes. Note that the transmission

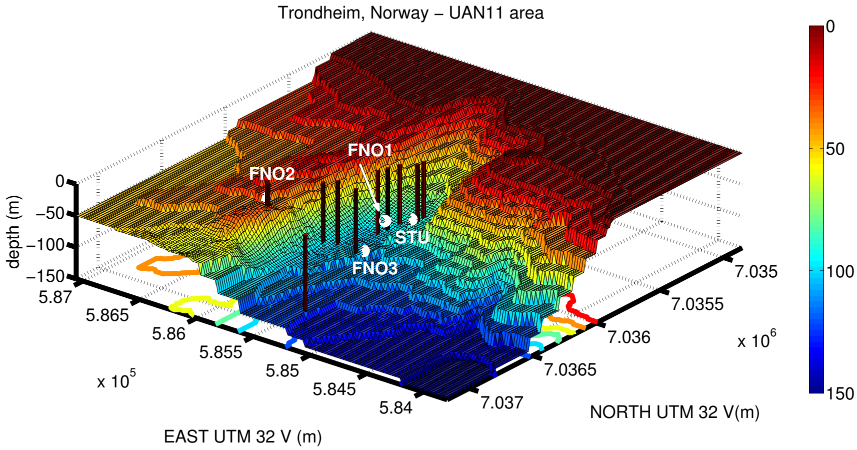

Fig. 3. UAN fixed nodes locations superimposed on the bathymetric map. CTD casts are displayed as vertical black lines at the corresponding locations.

parameter Ts was set up empirically: decreasing or increasing such a parameter would diminish the network throughput due to network congestions or because not all the available bandwidth was used. The AUVs were tested both as relay nodes, and as mobile assets of the protection system directed acoustically from the ground C2, and/or moving autonomously when contact with the network was lost.

3.1 Communication Performance and Anti-intrusion Capabilities

The figures of merit selected to evaluate the network performance are the Packet Loss (PL) and the Round Trip Time (RTT), at application level. PL varied between 0-68% approximately, remaining in most cases between 30% and 50%; RTT (i.e. end-to-end delay, back and forth) went from 7s to 240s, remaining between 60s and 120s most of the time. Table 1 summarizes performance statistics. The performance is strongly related to relative nodes location and to the mobile nodes movement, but also to situations of network congestion with message drops due to too many messages transmitted with respect to the available bandwidth. Further details on the low level acoustic performance of the network and on its coupling with the overall system traffic have been further described in [7].

In several occasions between May 25 and May 27 the AUVs and FNO3 were used as relays, with the AUVs moved in the middle between the STU and the furthest FNO2 node to re-establish the acoustic link. The presence of an intermediate node had the effect of immediately improving the communication performance between the STU and the FNO2, with a subsequent degradation as soon as the multi-hop link was removed (e.g. AUV was commanded to other tasks within the experiment).

As a final example of network operatibility, is now reported the anti-intrusion excercise done on May 27, 2011, where the most complex network was in the water. The sensor network was composed of three fixed nodes (STU, FNO2 and FNO3) plus two mobile nodes. The network was also integrated into the global protection system, composed of underwater, aerial and terrestrial sensors monitored and controlled by a C2. A complex anti-intrusion scenario was set-up to verify the capability of the system to detect and respond to threats. Within this scenario, the e-Folaga AUVs were used as mobile assets of the protection system, i.e. as reactive means acoustically controlled by the C2 to respond to intrusions, and kept mostly on surface. To this aim, when one of the fixed nodes detected a possible intrusion, the C2 sent one of the AUVs to the point of intrusion to investigate the area. When the vehicle arrived to the designated point, however, it found itself out of the network, without acoustic connectivity. After detecting the poor level of communication, the autonomous mission planner onboard the AUV, planned a new mission to move closer to the STU. Note that, the vehicle was not equipped with an acoustic model able to predict its movement towards poorly covered areas, whereas the mission planner was only able to track the packet loss at application level to identify when the AUV was in regions characterized by poor communication conditions. This scenario is represented in Figure 4 in terms of the trajectories followed by the AUV during its mission. The picture also reports the main mission phases.

Table 1. Packet loss and Round Trip Time per day per each node in the water at middleware level. Note that the STU was always operative. Statistics collected on May 23 and May 24, 2011 are less accurate as the IS-MOOS system was activated only for few hours of operation. Note that, due to the loss of the node, RTT statistics for FNO1 on 23 and 24 May are currently not available, even though the node was operative.

Date	*Node*	*Average Paket Loss (%)*	*Average RTT (s)*
23 May 2011	FNO1	0	-
	FNO2	29.37	17.39
24 May 2011	FNO1	11.11	-
25 May 2011	FNO2	58.75	58.71
26 May 2011	R/V	32.76	248.91
	FNO2	54.76	54.39
27 May 2011	Folaga1	18.31 (until 2.00 pm)	38.81
	Folaga2	49.64 (after 3.00 pm)	112.95
	R/V	40.58	35.28
	FNO2	68.38	107.42

4 The Thesaurus Project: Acoustic Communication and AUVs Cooperation

The project Thesaurus, funded by Tuscany Region, aims at developing techniques for systematic exploration of marine areas of archaeological interest

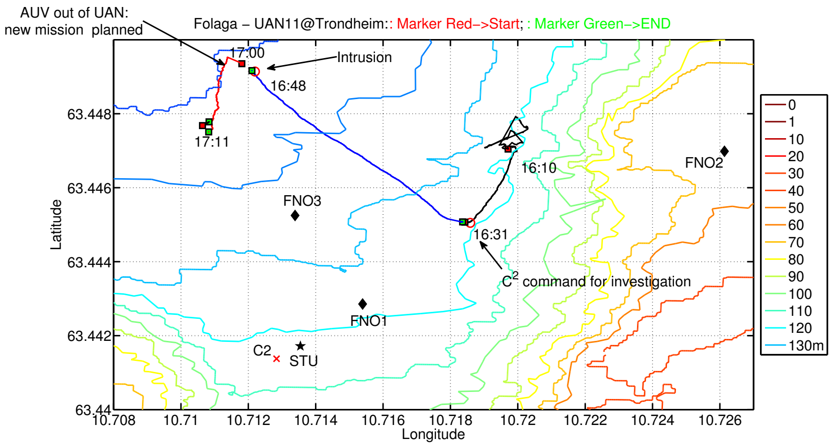

Fig. 4. UAN anti-intrusion scenario, as excercised on May 27, 2011

through team of Autonomous Underwater Vehicles (AUVs). The project has several different specific objectives, ranging from the development of AUVs capable to carry side-scan sonar and optical payloads at depth of 300 m, with 12 hours of autonomy at 2.5 knots cruising speed; to implementation of acoustic communication modalities and procedure for a network of at least three vehicles, that can be flexibly used for robotic cooperative search strategy. The final purpose is to explore marine areas through a team of AUVs. Current state-of-the-art does not offer many examples of cooperative explorations with at least three AUVs. The ambition of the project is to represent a step further towards future developments of multi-agent systems for marine surveys.

The cooperative algorithm developed within the project are based on the use of distributed decisions, where the agents should rely only on nearest neighbour information [14]. The resulting algorithm is intrinsically scalable: i.e., the local computation does not depend on the number of vehicles deployed. One of the design challenges for the network was to provide a communication infrastructure that would not disrupt too much the scalability and the "nearest neighbor only" properties of the cooperation scheme. From this point of view, the UAN infrastructure had to be ruled out, due to its centralized structure, with all the application messages going through the STU. Assuming that the closer the range among any two AUVs, the better the communication performances, it was decided to adopt a simple broadcasting of short messages (e.g. "who I am, where I am, where I am going") the nearest neighbor should be able to receive it, unless it is too far to influence the prosecution of the algorithm. In order to avoid conflicts at the MAC level, a Time Division Multiplexing (TDM) has been adopted, with a daisy-chain mechanism that allows any vehicle to talk only when it is "its time".

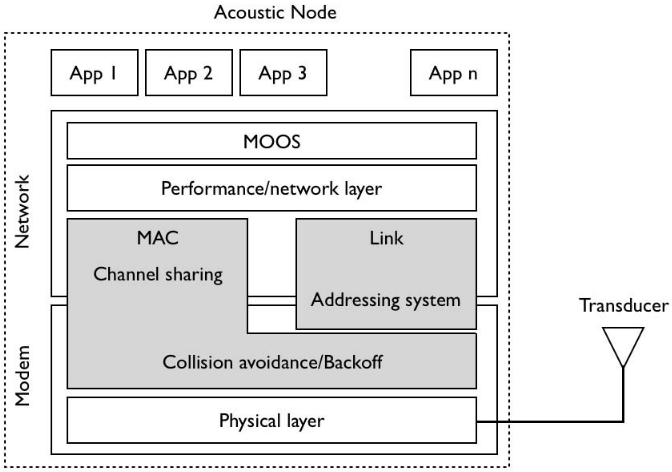

Fig. 5. Layered structure of the Thesaurus underwater network

4.1 Network Architecture

The physical layer of the acoustic network is supported by Evologics acoustic modems. The modems work at a frequency range from 18 to 34 kHz, a nominal operating range of 3500m, and transmission power settable to a level up to 186 dB re 1 $\mu Pa@1m$. The maximum bit rate achievable with the so called **instant messaging** communication scheme provided by the modems is 976 bps (maximum message size 64 bytes). This scheme does not require connection establishment procedures. It also allows for broadcast transmissions to all devices of the network at once. The modems also provide basic network functionalities, including an addressing system that can be exploited at the link layer.

The MAC layer is based on a TDM scheme to handle the shared communication medium, i.e. the acoustic channel. According to this scheme, different communication nodes share the same bandwidth but they avoid conflicts transmitting at different times. Time is divided into slots and each nodes is assigned a slot where it has to concentrate all its communication burden. The set of slots that include all the vehicles is usually called cycle, as it repeats when it reaches its end. The network link layer is composed of a combination of the modem network features and of the MOOS system, which also creates, as in the UAN case, the interface towards the applications. The entire network stack is rapresented in Figure 5.

Since the acoustic channel is characterized by a very limited bandwidth and capacity, it is important to have available a set of networking solutions that can increase the throughput of the network, and the probability that important messages are transmitted as soon as possible. To this aim, the Thesaurus network prioritizes the messages in four levels, going from safety messages that must be communicated to ensure the safety of the vehicles, to localization messages, necessary to guarantee that the vehicles can localize themselves when underwater, to application messages, sent only when no other and more important messages are waiting for transmission. Note that, the priority queue might grow very rapidly when the application is producing messages with a rate higher than the acoustic channel can support. In this case, old messages still waiting for transmission might postpone more important and/or more recent messages. To avoid such a situation, at each step, the messages are filtered on the basis of the time slot duration available for the acoustic transmission. As a result, a reduced message queue is created, whereas the remaining messages, which cannot fit into the available time, are discarded. Note also, that the organization of the queues is performed both during the non-communication periods and during the communication time slots available to the vehicle. In this way the network supports real-time data delivery, meaning that the data are produced, organized and transmitted during the communication period of the node. This becomes important to support localization, permitting the transmission of localization updates as soon as they becomes available.

4.2 Breaking the TDMA: USBL Positioning and Acoustic Ranging

One final important objective of the acoustic communication within the Thesaurus network is related to its usage to support the underwater localization of the vehicles. While a detailed description of the localization issues goes beyond the scope of the discussion, it is important to clarify its impact on the communication network itself. The absence of GPS underwater makes in fact localization and navigation of underwater vehicles dependant on acoustics. More specifically, each acoustic modem is able to provide range measurements (and bearing measurements when coupled with Ultra Short Base Line (USBL) devices) using the RTT of the messages.

Although effective, this acoustic-based localization scheme does not fit into the communication architecture described: the receiver of the modem interrogation must be able to reply (at least with a very short message) inside the time slot assigned to another node, breaking the TDM structure. To maintain the coherence of the network, the network layer of each node works along with a localization layer, with which it negotiates who is in charge of the communication.

5 Going at Sea: The Thesaurus System in the Field

The Thesaurus acoustic network has been recently tested during a project engineering test. The sea trial was held from February 4 to February 8, 2013, at the Bacino di Roffia, a small lake in Tuscany, Italy. Its main objective was on the verification of the newly developed AUV [9], while communication tests were done, when possible, as parallel activities. The network was composed of two fixed nodes and one mobile node mounted on the vehicle. For logistic reasons, the two fixed nodes had to be positioned very close, only 10m apart. An aerial overview of the area of experimentation is shown in Figure 6, together with the

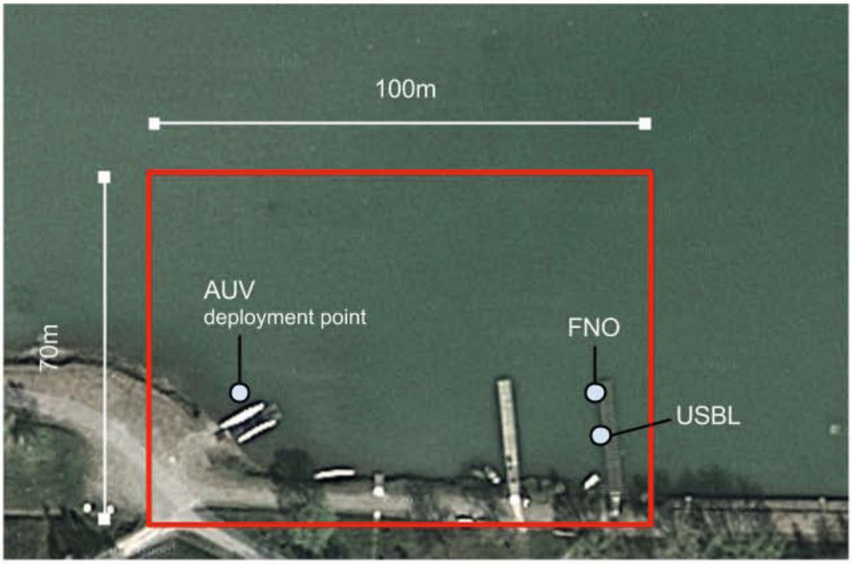

Fig. 6. Aerial view of the area of experimentation. The red rectangle shows where most of the AUV operations took place.

position of the fixed equipment deployed.Operations and deployed equipment are shown in Figure 7 during one communication test on February 7. The AUV is visible in the foreground, while the two fixed nodes (FNOs) are deployed close to the pier, as signalled by a white buoy on the left (FNO with acoustic modem only) and by a grey box connected to the C2 (FNO with modem and USBL).

The lake is very shallow, with depth, in the area of experimentation up to 4m. The modem of FNO was at about 2m depth, pointing upwards; the modem with the USBL was kept on surface pointing downwards, and the AUV, which had its modem transducer mounted upwards, remained most of the time on surface, or within 1m depth. As a result, the acoustic communication performance was extremely poor, with packet loss most of the time well above 50%. The acoustic network was up and running throughout the activities, and it was able to robustly manage parallel communication and localization activities as described in section 4.2. The C2 was able to track the AUV location acoustically, and all the nodes were able to send and receive commands and status updates. Statistics have been collected in terms of packet loss and RTT, for both broadcast messages and unicast localization messages and are reported in Table 2 for February 6 and 7, 2013. Unicast messages were very short messages with acknowledgement used only for localization purposes (4bytes). Broadcast messages were 64bytes messages used for normal network traffic (no acknowledgment required). Note that a unicast message has been considered delivered only when both the message and its acknowledgement was received.

Fig. 7. Area of experimentation during one of the test on February 7. The AUV is visible in the foreground, while the two fixed nodes are deployed in the water close to the pier, as signaled by a white buoy on the left (FNO) and by a grey box connected to the C2 (USBL).

Table 2. Statistics collected for both unicast and broadcast messages during the Thesaurus engineering test held at Bacino di Roffia, Tuscany, Italy, on February 2012. Unicast messages were very short messages used only for localization purposes (4bytes). Broadcast messages were 64bytes messages used for normal network traffic.

Date	*Node*	*Average Paket Loss (%)*	*Average RTT (s)*
6 February 2013	FNO+USBL	73	0.8609
	FNO	44	0.85495
	AUV	76	1.29788
7 February 2013	FNO+USBL	56	0.84390
	FNO	60	0.85597
	AUV	78	1.54749

6 Discussions and Lessons Learned

Field results show that acoustic underwater sensor networks have very variable, and often poor, performance: in all the reported experiments, packet loss and delays were considerably high, with prolonged period of only partial connectivity. The robustness of the network at all levels hence becomes of paramount importance to handle sudden changes in the communication channel. In particular, it is necessary to make all the network layers, including the application, aware of the limitations of the communication medium. In this setting, the presence of movable nodes can be of great help to modify the network geometry and to optimize the communication. However, it is important to underline that the intrinsic limitation of the acoustic communication has in turn a great influence on the capability of the nodes/robots of performing a task. Node cooperation algorithms that require constant communication and message exchange become practically infeasible. The nodes must be able to rely mostly on their own autonomy to successfully fulfil their mission [6].

Finally, it is worth discussing the impact of the network architectures on the overall performance of the systems. The UAN network thanks to its modular complexity was very flexible. It was able to reach greater distances relaying on multi-hop and topological adaptations to the acoustic conditions. Furthermore, its ability to cope with the communication uncertainty was distributed throughout the network stack, enhancing its robustness. For example, the relatively poor performance of the CSMA MAC layer, which was often not able to quickly adapt to the channel variations, was compensated at other network levels (e.g. re-routing messages) [7]. The Thesaurus network looks very promising for short-range communication with a limited number of nodes. In this case, the lean structure of the network reduces the communication overhead due to the network itself, allowing for a more prompt distribution of information among the nodes. This is achieved paying for some flexibility, with a resulting network less able to handle diversity.

7 Conclusions

This paper presented experimental results obtained deploying two underwater sensor networks, within two different research projects, UAN and Thesaurus. The application drove the design of the underwater networks. As a result the deployed systems are very different, in terms of communication performance, maximum range, scalability and autonomy. We showed that the UAN case was more complex in terms of infrastructure, number of network nodes, environmental conditions, time window of operation. The Thesaurus network was instead designed with the explicit objective of being an enabler for the cooperation of AUVs. The resulting network was simpler but limited to much shorter communication ranges. In the field results were presented and discussed to show how the network structure impacts on the underwater robot cooperation and on the overall sensing network performance.

While the field experiments reported in the paper clearly apply to two very diverse situations, one general conclusion can indeed be drawn. Underwater sensor networks with mobile nodes, relying on acoustic communication, have performances that are order of magnitudes poorer with respect to their aerial or terrestrial counterparts. This calls for a parsimonious use of communication and exchange of information among the nodes; moreover, whenever autonomous nodes (as the AUVs of our two experiments) are employed, the nodes must possess a quite evolved capability of autonomous decision making and situation awareness, in order to pursue their mission even in presence of prolonged communication gaps.

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