Mobile Underwater Sensor Networks for Protection and Security: Field Experience at the UAN11 Experiment

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The EU-funded project UAN (Underwater Acoustic Network) was aimed at conceiving, developing, and testing at sea an innovative and operational concept for integrating underwater and above-water sensors in a unique communication system to protect offshore and coastline critical infrastructures. This work gives details on the underwater part of the project. It introduces a set of original security features and gives details on the integration of autonomous underwater vehicles (AUVs) as mobile nodes of the network and as surveillance assets, acoustically controlled by the command and control center to respond against intrusions. Field results are given of the final UAN project sea trial, UAN11, held in May 2011 in Norway. During the experimental activities, a UAN composed of four fixed nodes, two AUVs, and one mobile node mounted on the supporting research vessel was operated continuously and integrated into a global protection system. In this article, the communication performance of the network is reported in terms of round-trip time, packet loss, and average delivery ratio. The major results of the experiment can be thus summarized: the implemented network structure was successful in continuously operating over five days with nodes seamlessly entering and exiting the network; the performance of the network varied greatly with fluctuations in the acoustic channel; the addition of security features induced a minor degradation in network performance with respect to channel variation; the AUVs were successfully controlled from a remote station through acoustic signals routed by the network.

1. INTRODUCTION

Increased interest in ocean natural resources has resulted in a growing number of infrastructures located near the sea. New generations of wave-based power plants have been recently tested, not to mention the renewed tendency to exploit deep-water oil and gas drills to tackle the exhaustion of ground wells. These new ocean-based installations create new and great economic opportunities as they pose new challenges for their protection. Their location, which is usually far from the coast, their exposure against intrusions or natural disasters (such as earthquakes, hurricanes, etc.), and their high structural complexity, with many moving underwater and floating parts, make the security issues of such vital areas particularly delicate, requiring an integrated approach from air coverage to underwater defense. It is clear that in such scenarios, requirements such as flexibility, rapid reaction, resilience, fast deployment (the possibility to plug and play new components), as well as having a high level of automation and modularity play a key role. In this regard, research on security has been concentrated thus far on the optimization of fixed sensors to guarantee the best static anti-intrusion configuration (Becker et al., 2008). As a recent example, in Caiti et al. (2012b), a software simulator is used to determine the deployment of underwater sensors. The protection system can include unmanned surface vessels, but the skeleton of the monitoring system is

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only composed of fixed sonars or magnetometers. Of course, the presence of mobile nodes or agents adds an enormous amount of flexibility, as it would enable the system's online adaptation to the variation of the environment. This becomes of paramount importance in the underwater domain, which is characterized by very variable conditions; an anti-intrusion system optimized for a given environment may become useless when oceanic conditions vary, e.g., the presence of rain, temperature changes, etc. One of the first at-sea experiments of adaptive behavior for autonomous underwater vehicles (AUVs) is described in Hamilton et al. (2010), with an explicit reference to antisubmarine warfare. The AUV represented the entire surveillance system, and no cooperation with additional sensors was included. Of course, when several mobile and fixed nodes cooperate to reach a common goal, the communication infrastructure becomes of key importance. Although the solution of having fixed sensors that are interconnected through cables is enticing, due to high-bandwidth and low-delay communication links, when moving assets are in the system, going wireless remains the only option. In this case, even more problems arise with respect to the terrestrial case (Akyildiz et al., 2005). The physics of acoustic propagation, the main means of underwater communication, is strongly dependent on the specific environmental conditions, and during the life of the network each node can experience abrupt changes in the channel, producing a consequent variation in communication performance. Acoustic communication is severely band-limited and range-limited. A sudden reduction of the channel capacity and bandwidth, or even a temporary loss of connectivity, are frequent conditions for underwater communications (Caiti et al., 2010; Stojanovic, 2007), influencing the node's ability to continue its mission.

Given the current limitations of acoustic-based devices, a robust implementation of underwater acoustic networks (UANs) is still an open research field. An interesting theoretical overview of recent protocols for underwater networks is provided in Pompili and Akyildiz (2009), where the main advantages and disadvantages of various network designs are pointed out. Field examples of UANs with measured performance in the field are, however, scarce; results are available for vehicle-to-vehicle acoustic communication or one-to-many broadcasting (Hamilton et al., 2010; Schneider and Schmidt, 2010b), or for partial network implementation as in Petrioli et al. (2011). The lack of results is also due to the complexities of at-sea experimentations. On the other hand, it is well known that in a marine scenario, simulations are of limited value, as it is very difficult to properly represent the constraints and disturbances of a real underwater environment, both for communication and for autonomous vehicle operations.

In the above context, the FP7 UAN project (UAN, 2012) was aimed at conceiving, developing, and testing at sea an operational concept for integrating submerged, surface, and aerial sensors in a unique communication system with the objective of protecting offshore and coastline critical infrastructures. The UAN project ended in 2011 with the UAN11 sea trial. In this paper, we focus on the underwater network part of the project, reporting on the implemented solutions and the performance as measured in the field. We believe that the reporting of the field performance is of value in itself, since it may enable the research community to orient toward either refinements or different approaches with the long-term objective of achieving operational implementations of underwater networks integrating AUVs. To properly assess the measured performance, it is important to have a clear description of what has been implemented; therefore, the paper reports in some detail the implementation choices and the rationale behind them, even if our implementation is mostly based on known protocols and technologies.

It is important to stress that communication is not only the simple sharing of information. In operative scenarios, secure communication becomes a key issue to ensure that the correct data are transmitted and received by the right nodes, and only among the desired group. The possibility to securely share necessary information may, in fact, determine the success or failure of a mission. Listening to private messages and modifying or injecting fake data are typical threats in communication networks, and they become even more critical in the context of a distributed cooperation of autonomous agents/nodes for surveillance applications. Cooperation for protection may be achieved only when all the components receive the expected data from legitimate peers. Underwater communication introduces additional peculiarities with regard to network security. In contrast to traditional wired networks, an adversary equipped with an acoustic modem can easily eavesdrop as well as modify and insert fake messages. Furthermore, the variability in communication performance together with bandwidth and range limitation make the simple adaptation of traditional security solutions (e.g., digital signatures) practically infeasible. In this regard, the approach proposed in this work constrains all the protocols for protection of communication at the middleware level of the acoustic network. To the best of our knowledge, the only middleware already available for UANs is Seaware (Marques et al., 2006b). Seaware is a publish/subscribe (pub/sub) system that has the advantage of being adaptable to both radio-based and acoustic communications; however, this system requires direct access to the node transmission devices without any intermediate network layers, such as transport or routing, hence reducing network modularity and flexibility. Furthermore, it does not include any form of network security. In this work, we present a different and original design and implementation of a network security system at the middleware level, built on top of the MOOS (Mission Oriented Operating Suite) pub/sub system (Benjamin et al., 2009, Newman, 2012). We are not aware of any previously published attempt to introduce security mechanisms to

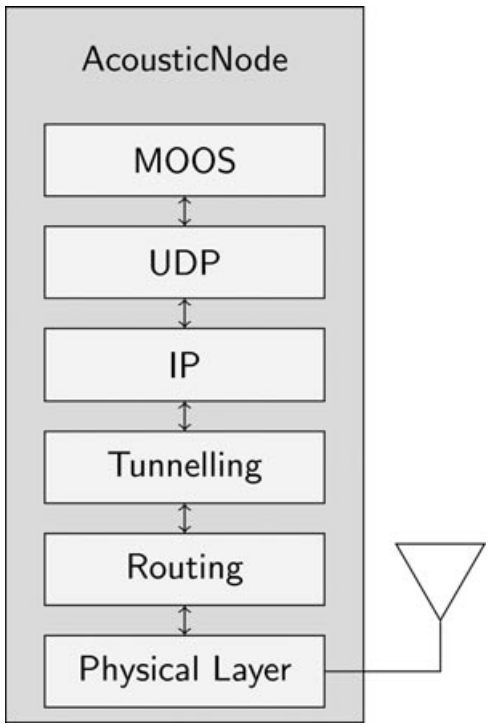

Figure 1. UAN network layers.

underwater networked communications, not even at a theoretical level.

In summary, the UAN11 network was composed of up to four fixed nodes, two autonomous mobile nodes [AUVs of Folaga class (Caffaz et al., 2010)], and one additional node mounted on the supporting research vessel. Each node implemented the network architecture depicted in Figure 1: the physical layer was supported by the acoustic modems built by Kongsberg Maritime (KM), which were capable of transmitting up to 500 bps and which also implemented the MAC protocol, the routing layer, and the multihop strategies. The network architecture was completed by implementing a tunneling mechanism to establish the Internet protocol (IP) connection by using UDP as transport protocol, and finally by the custom-developed secure version of MOOS as the middleware/application level. MOOS also represented the basic infrastructure for the software onboard the AUVs. The acoustic network was finally integrated into a global protection system (Casalino et al., 2010), which combined above-water and underwater protection sensors (e.g. cameras, radars, sonars, etc.) into a unique system.

The paper is organized as follows: Section 2 gives an overview of the UAN11 sea trial, describing the equipment and algorithms used. Section 3 describes the objectives of the sea trial and defines the figures of merit used to evaluate the communication performance. Section 4 shows results from the sea trial, and comments are made on expected and obtained results. Section 5 sums up the lessons learned and suggests some future improvements. Finally, Section 6 draws conclusions.

2. DESCRIPTION OF THE UAN11 SEA TRIAL

The UAN11 experiment was the final experimental activity of the project UAN (UAN, 2012). The sea trial took place between May 23 and May 29, 2011 in the Trondheim fjord, off the coast of Norway. The area was ideally suited to acoustic network testing because of its varying bathymetry, with depth varying from 40 to 150 m. Moreover, the fjord is in a commercial area, with daily commercial and tourist routes, so the system could be tested in operative conditions. Our primary platform of operation was the Gunnerus Research Vessel of the Norwegian University of Science and Technology (NTNU). The fixed nodes of the network were deployed form Gunnerus and left in place for three days in continuous operation, then recovered for battery recharging and redeployed for the remaining period. The AUVs were deployed either from rubber boats or from Gunnerus. The goals of the experiment included a great deal of testing and data collection. Its main objectives, however, were to demonstrate the acoustic network functionalities and the integration of the underwater mobile sensors into the global protection system.

Figure 2 shows the network setup superimposed on the bathymetric lines of the area of the sea trial. The underwater network was hence integrated into the air/land security system Archimede of the UAN partner Selex. The command and control center was located on shore, close to the pier.

The envisaged UAN scenario consists of (see Figure 3):

- A land station which acts as a Command and Control (C^2) center, for the physical defense of a critical infrastructure;
- A terrestrial/air protection system controlled by the C^2 and composed of fixed and mobile sensors;
- An underwater base station wired to the shore with a high bandwidth link. This station represents the connection between the above and below water environments; for this reason, this element is part of both the acoustic network and a traditional wired communication infrastructure;
- Fixed and mobile nodes (n) acoustically connected in an underwater network which includes the base station. Each node is equipped with onboard sonar for intrusion detection and with an acoustic modem for communication purposes.

One of the critical aspects is related to the integration between such different systems, which include above-water and underwater components. In the case of the UAN system, this integration has been realized using two basic components or network layers: the IP, which permits us to create a standard interface toward the higher layers of the network, and the use of a publish/subscribe system to abstract the

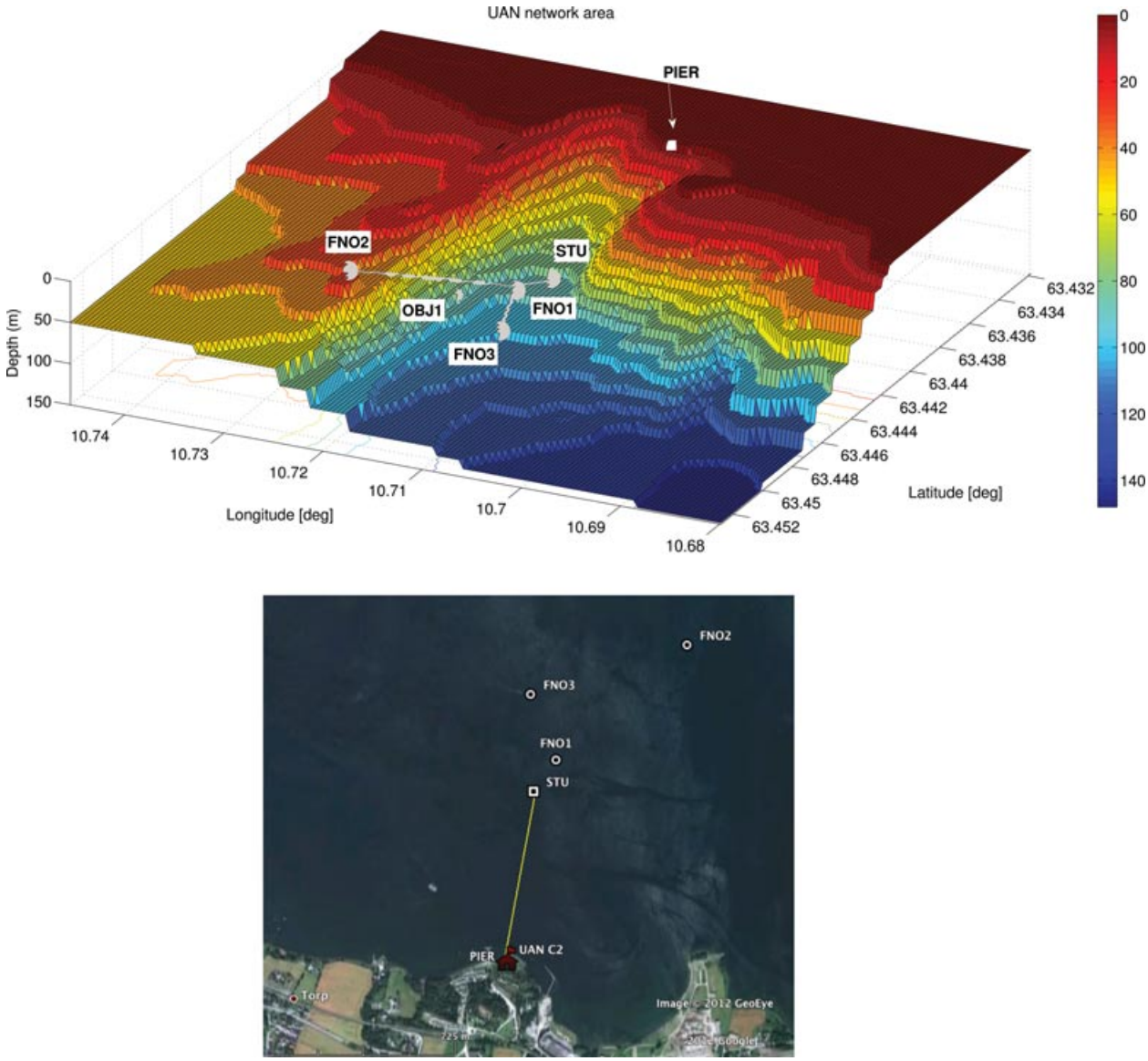

Figure 2. UAN11 experimental area. **Top:** network geometry shown on bathymetric contours. STU is the UAN base station. FNO1, FNO2, and FNO3 are the fixed nodes; OBJ1 is the location of a simulated threat. The gray lines connecting the nodes represent the shortest path between two nodes and are shown only to indicate the distance (i.e., they are not representative of the network topology). PIER represents the location of the UAN command and control center placed on shore. **Bottom**: aerial overview of the UAN area. The path of the cable, which links the underwater network to the terrestrial part, is highlighted.

specific characteristics of the components. In the remainder of the paper, we focus on the middleware and application level of the UAN concept, and we assume the presence of a reliable network able to support the physical communication. More details on the UAN lower-level hardware can be found in Husoy et al. (2011).

The following sections describe the experimental equipment, the node control, and communication algorithms used during the sea trial.

2.1. Equipment

2.1.1. The eFolaga AUV

The mobile node of the acoustic network was the eFolaga AUV, which was modified to accommodate the KM acoustic modem. The eFolaga is a torpedo-like vehicle consisting of two fiberglass water-proof cylinders, which compose the main hull, and one or more additional modules that can be mounted at midvehicle to host a mission-driven

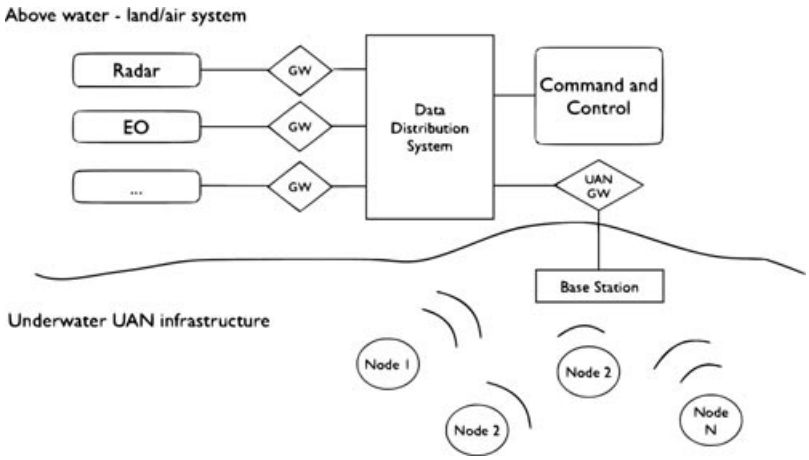

Figure 3. Conceptual overview of the UAN scenario: integration of above-water and underwater systems.

payload. The two main cylinders are connected to two wet ends where jet-pumps are located for steering, and the propeller for the surge direction. More specifically, yaw, sway, and heave thrusters are distributed both fore and aft; furthermore, the forward section contains a ballast for buoyancy control. The eFolaga truster distribution guarantees a great amount of maneuverability and permits vehicle motion in all directions. As an example, the vehicle is capable of moving vertically in the water column at a desired pitch angle; this is a desirable property for a mobile node of a network that may need to adapt its position to follow the best acoustic channel. The addition of a new module requires mechanically splitting the vehicle to graft in the additional part. The main vehicle computer is located in the aft section, and the availability and the control of the components in the fore part must be communicated to the main computer through the module stack (electrical connections between sections are made through flying leads). Eight power conductors have to be carried through to enable the bow and stern sections to operate. Of these, the module may tap into four: a common high-current Analogue Ground Return Line, a +12 VDC Power Supply Line, and a +12VDC Power Demand Line together with a low-current Digital Ground Return Line. The Demand Line supplies power to start up or shut down the module stack under control of the vehicle's computer. Modules may draw up to 100 mA from the Power Supply Line to power communication hubs, enable sleep modes, etc. Maximum peak current drawn by a module from the Power Demand Line during a mission is 8 Amps, with a maximum total power consumption from this line of 100 Whrs during a mission. In addition to the power lines, the module stack is also required to carry through USB and Ethernet (100 Mbps) connectivity from the aft section for any module that may need it.

When at the surface, the vehicle has continuous GPS (global positioning system) contact and land-station contact through a multiradio link. The land-station link allows for on-line modification of the mission requirements and for almost real-time data transmission. A summary of the main technical characteristics of the eFolaga is reported in Table I.

Table I. eFolaga AUV, main technical characteristics.

Item	Description
Diameter (m)	
External	0.155
Length (m)	2.222
Mass (kg)	32.0
Mass variation range (kg) (assuming water density 1027 kg/m^3)	0.5
Range of moving mass displacement (m)	0.050
Energy storage	NiMh batteries, 12 V, 45 Ah
Autonomy (hrs)	8 at full speed
Diving scope (m)	0–80
Break point in depth (m)	100
Speed	
knots	2 (jet pumps)/4 (propeller)
m/s	1.01/2.02
Communication	multiradio link (when on surface)

To integrate the eFolagas within the UAN network, a specific payload with dedicated hardware (Table II) has been realized to connect the acoustic modem to the vehicle electronics. The main hardware of the payload is represented by a PC-104 board with serial lines to communicate with the modem and the CTD probe, which is available for continuous monitoring of the water conditions. The Ethernet line is used for communication between the board and the eFolaga native computer. Figure 4 shows the Folaga AUVs with the UAN module mounted at midvehicle (and

Table II. Payload hardware: main board characteristics.

Item	Description
CPU	1GHz, VIA EDEN, Ultra Low Voltage
DRAM	1GB, DDR2, 533/400 on SO-DIMM socket
Chipset	VIA CX700M
Serial ports	1 RS232 Full modem 1 RS232FM/422/485 Configurable
USB ports	2 × USB 2.0
Hard disk	4 GB Internal Flash Disk

Figure 4. Folagas on shore; the UAN module is visible, mounted at midvehicle.

in one case, a CT probe). Figure 5 shows the AUV deployment from Gunnerus during one of the trials.

2.2. Network base station and fixed nodes

The remaining nodes of the network were composed of a Subsurface Telemetry Unit (STU) and by underwater Fixed Nodes (FNOs). The STU represented the UAN base station and was cable-connected to shore with a high-bandwidth no delay link to integrate the acoustic part into the wide area network. On the acoustic side, it was equipped with a KM modem, with a vertical hydrophone array for unidirectional high-bandwidth communication, and with a thermistor chain to measure the vertical temperature distribution. The STU is depicted in Figure 6 during a communication test on the Gunnerus deck before deployment at UAN11. Three FNOs were used during the sea trial, with one of them (FNO3) only implementing the lowest layers of the network (physical, MAC, routing). Each FNO was equipped with an acoustic modem and with a vertical chain of thermistors similar to the one installed on the STU. The deployment of one of the FNOs during the sea trial is shown in Figure 7. Further information on the STU can be found in Zabel et al. (2011), while the FNOs will be treated in more detail in a separate paper.

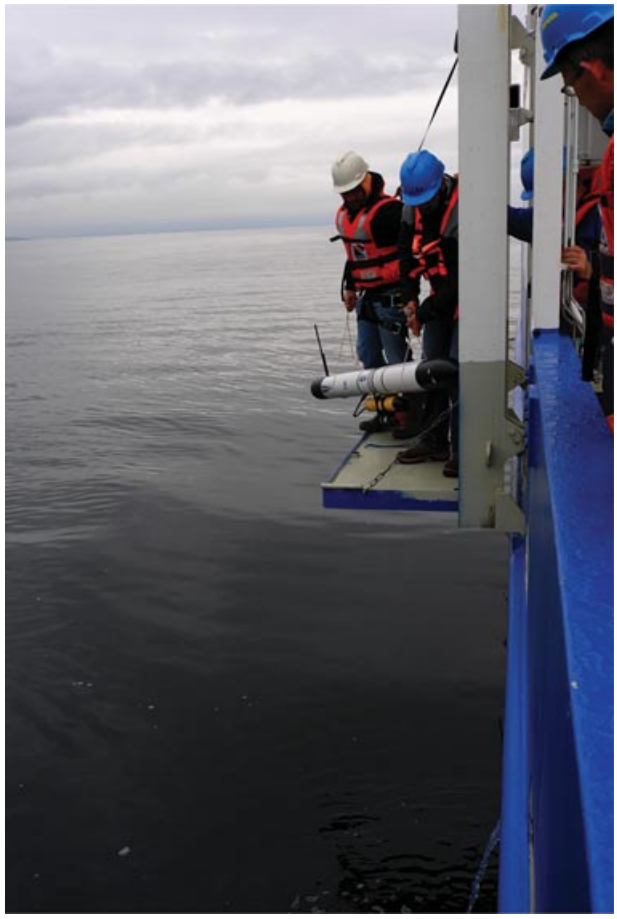

Figure 5. Folaga AUVs deployed from Gunnerus during the UAN11 experimental activities.

Figure 6. STU during a communication test on the Gunnurus deck before deployment. The two yellow cylinders are the KM modems, of which one is the STU's and the other is for testing. The gray box contains the STU electronics. Also visible in the photo is the blue cable used to connect the STU to shore, the black thermistor chain, and the hydrophone array.

Figure 7. Deployment of a FNO from Gunnerus.

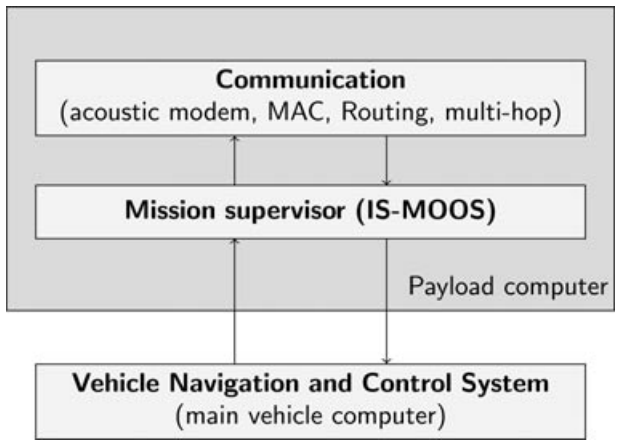

Figure 8. Conceptual architectural scheme of the implemented system.

2.3. Algorithms and software implementation

2.3.1. eFolaga mission supervisor

From an architectural perspective, the goal is that of implementing a mission supervisor capable of interpreting and generating messages to the other network nodes, and to give commands to the vehicle native Guidance, Navigation, and Control (GNC) system. The approach followed is the *back-seat driver* paradigm, pioneered by the MIT group and co-workers (Balasuriya et al., 2009; Benjamin et al., 2010; Eickstedt and Sideleau, 2008): the mission supervisor must be able to make decisions and give high-level commands to the native GNC vehicle system, which is solely responsible for the low-level execution of the commands. Similarly, the supervisor must handle the communication tasks at the application level, while the lower-level communication is left to the software implemented in the acoustic modem itself. In this way, as conceptually depicted in Figure 8, it is possible to integrate in a modular way all the system components regardless of the specific nature of the vehicle, the acoustic modem, and the MAC and routing strategy of the communication network. The Folaga mission supervisor is divided into different modules, called virtual bots, each of which is assigned to a specific task, and which is independent from the others as long as it shares a common interface to exchange data. Each virtual bot has its own input, which is dependent on the task it has to perform (e.g., the communication bot receives inputs from the acoustic modem) and produces an output toward a *central or decision bot*, which can be thought of as the commander of the vehicle. The central bot decides the next step of the mission depending on the user requirements and on the basis of the output produced by the other modules. The decision bot of the mission supervisor is implemented as an event-driven Mealy finite state machine, which generates an output based on its current state and input. Each one of the states of the machine is related to a desired mission task to be executed by the Folaga vehicle (e.g., the Navigation task), or a task to be executed by a specific module of the system (e.g., the MOOS pub/sub system to send a specific acoustic message), or a waiting condition. One of the most critical parts in the described architecture is represented by the interface between the mission supervisor on the payload computer and the eFolaga existing software. Two specific modules of the mission supervisor, Folaga Controller and Radio Controller, are dedicated to this task, and each one has a counterpart on the vehicle. Figure 9 shows the block diagram of the main processes running on the AUV. In particular:

- The Folaga Controller connects to a dedicated process (Payload Control Server) on the eFolaga. It is responsible for the communication between the Folaga Control System and the mission supervisor (e.g., communication of mission commands, errors, etc.).
- The Radio Controller represents the radio operator of the payload, as it connects to the Radio Modem Client on the eFolaga. It is responsible for receiving user commands when the eFolaga is on the surface and for transmitting

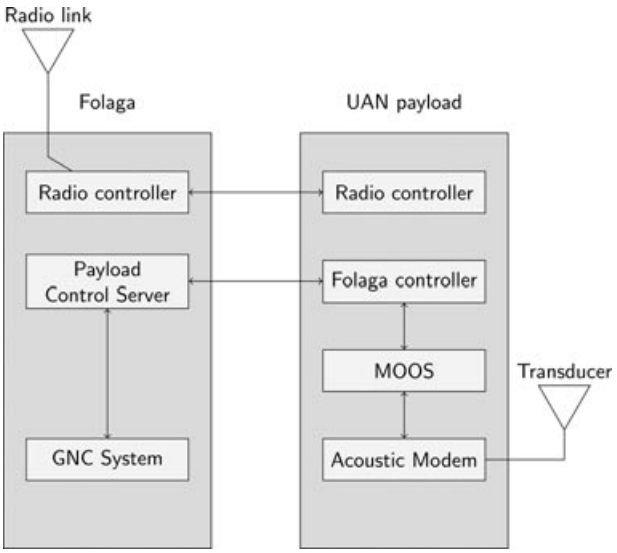

Figure 9. Interface between the eFolaga GNC and the UAN payload.

logs and requests from the mission supervisor. The availability of the radio for the mission supervisor permits a real-time monitoring of the mission.

Communication at the mission supervisor level is handled through the MOOS system, as described in the next section.

Finally, a dedicated *cooperation module* is responsible for the management of the cooperation with the other vehicles and fixed nodes of the network. Each agent, on the basis of the information received acoustically from its teammates (e.g., location), and on the basis of the environmental measurements periodically performed or transmitted by other nodes, is able to autonomously adapt its position to the specific communication and detection performance encountered as its mission proceeds. The cooperative algorithm is based on distributed decisions, and each vehicle must make individual choices to achieve the final goal, handling situations in which it is completely disconnected from the network. From the standpoint of the mission supervisor, the presence of a cooperative module does not pose additional complexity as its output is utilized by the decision module in composition with the user requests and the output coming from the other modules. Specifically, the decision bot uses the commands coming from the cooperative module if no other commands from the C^2 are scheduled to be executed. We do not go further with the description of the cooperative algorithm as it would go beyond the scope of this work; however, more information on its theoretical aspects can be found in Caiti et al. (2012a) for the area coverage problem, and in Munafò et al. (2011) for cooperative explorations of marine areas.

2.3.2. IS-MOOS: autonomous node integration into UAN

Real-world integration and distributed application development for underwater acoustic networks is quite a difficult task. However, an appropriate middleware may make application development easier by providing common programming abstractions, by masking the heterogeneity and the distribution of the underlying hardware and operating systems, and by hiding low-level programming details (Bernstein, 1993). In underwater acoustic networks, the MOOS middleware has gained great popularity (Benjamin et al., 2009; 2010). In short, MOOS is a publish/subscribe system for *intravehicle* interprocess communication (IPC), which supports dynamic, asynchronous, many-to-many distributed communication (Oxford Mobile Robotics Group, 2012). In MOOS, a *dispatcher* is responsible for routing messages from *publishers* to *subscribers*. Messages are routed according to their *topics*, which are message descriptors contained in the messages themselves. Subscribers declare their interests in specific topics by issuing *subscriptions* to the dispatcher, while publishers send the dispatcher messages belonging to the various topics. In MOOS parlance, the dispatcher is called MOOSDB.

The publish/subscribe paradigm is particularly suitable for distributed cooperative applications (Marques et al., 2006a; 2006b; Schneider and Schmidt, 2010a). Therefore, a natural choice would be to adopt MOOS for *intervehicle* interprocess communication too. In so doing, an application developer would experience a single communication abstraction and interface for interprocess communication. Unfortunately, MOOS presents severe limitations when employed for interprocess communication in an acoustic network. First of all, the communication between a client and the MOOSDB is usually based on a transmission control protocol (TCP), an end-to-end protocol that requires an always-up connection. Whenever a client loses its connection to the MOOSDB, the system tries to reestablish it. Whereas this approach is effective for traditional radio-based networks, in the case of underwater networks it creates undesired traffic and network overload. The underwater communication between any two nodes depends strongly on oceanic conditions, which in general vary continuously, making it impossible to guarantee a reliable end-to-end communication (Akyildiz et al., 2005).

Furthermore, since each client tries to reconnect to the MOOSDB as soon as it loses its connection [e.g., for a decrease in the channel capacity or bandwidth (Caiti et al., 2010)], this creates an additional communication overhead just in those moments when the acoustic channel is likely to be very poor, thus causing, as a consequence, network congestions and message loss. The second problem is that each client that wants to connect to the database must perform a preliminary handshake to register and enter into the system, specifying its topics of interest. Since this process is particularly delicate, MOOS ensures its robustness and coherence, reinitializing it whenever a problem is encountered. Again,

while the approach may be successfully utilized for high-bandwidth and no-delay communications, it makes the entire client registration process unfeasible in the presence of frequent disconnections and message loss. Finally, as was thought for intravehicle interprocess communication, the MOOS system does not provide any network security mechanism. In the case of open communication channels, as in the underwater one, this means that a *spoofing attack* (i.e., impersonation of a node) or a *snooping attack* (i.e., unauthorized eavesdropping of messages) may compromise the entire system's integrity and confidentiality.

To cope with these limitations, within the UAN project, the basic MOOS system was extended in two ways: first of all, it was modified to improve efficiency and robustness of intervehicle interprocess communication; second, network security solutions were integrated into the MOOS intervehicle communication protocol. The resulting middleware is called the *Intervehicle Secure MOOS* (IS-MOOS).

The IS-MOOS middleware represents a key point in the UAN proposed architecture. Actually, the resulting unified publish-subscribe communication framework allows for the integration of all the heterogeneous autonomous mobile and fixed nodes into the application level of the UAN. With reference to the Folaga control architecture (Figure 9), the communication module of the mission supervisor is, in fact, realized as an IS-MOOS client. Through IS-MOOS, the client can thus convert the messages coming from other network nodes (e.g., the Command and Control Center) into information for the decision module of the vehicle, and hence into vehicle commands. Conversely it can translate information on the vehicle's status into messages to be transmitted acoustically to other interested readers (e.g., other network nodes for cooperative mission planning). In this sense, the IS-MOOS system realizes the concept of a network, which, being composed of autonomous nodes, adapts its behavior (i.e., topology) to tackle changes in the surrounding environment (e.g., change in the communication performance).

In the next two sections, we will provide some insights regarding IS-MOOS solutions for communication efficiency and security. The source code of IS-MOOS and the related user manual can be downloaded from the project web site (UAN, 2012).

IS-MOOS solution for efficiency

Figure 10 shows the general architecture of IS-MOOS. Rendering the MOOS system able to support the communication between different nodes of the underwater network means that the MOOSDB becomes an external server located in one of the network nodes, while the communication with the clients exploits the underwater channel. The use of acoustics implies that each node of the network must be extremely robust and able to autonomously adapt to the unexpected changes of the channel, avoiding, as much as possible, sending unnecessary messages. In UAN, this has been achieved in two ways: using the User Datagram Protocol (UDP) as the transport protocol of the network, and modifying the MOOSDB and client's structure to enhance the communication. UDP presents several advantages when used for the underwater channel. In particular, it does not require an end-to-end connection, thereby entirely avoiding management issues (e.g., handshake at the connection level) typical of connection-oriented protocols, such as TCP. Its main drawback is that, of course, it does not provide the same level of reliability in message delivery: additional services, such as packet retransmission and delivery warranties, must therefore be transposed either to the lower layers of the network (e.g., MAC) or directly to the application level.

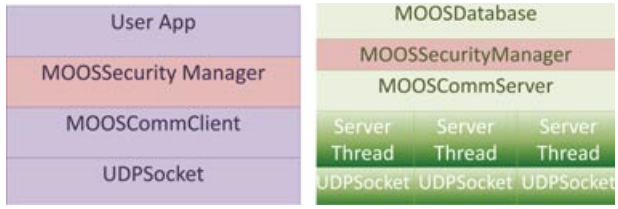

Figure 10. The IS-MOOS software architecture: client-side (left); server-side (right).

Furthermore, the MOOSDB structure has been modified to increase its robustness and capability to deal with delays, communication uncertainty, and the unreliabilities of the acoustic channel. Specifically, it has been given a multithreaded architecture to completely isolate each client from the others. In practice, each client C is associated with a thread T_C on the database of which the client must know the address and the port in advance. In this way, while a unique link between each client and the database (sandbox) is created, the need for initial handshaking to establish the communication parameters is also avoided: if the client C wants to send a message m_C, it simply starts its transmission toward its related address and port, while the dedicated thread T_C will be waiting for it. When the thread T_C has a message m_T for C, it sends C the message m_T together with the information for clock synchronization. However, since there is no preliminary handshake, the described communication technique makes the system very fragile with respect to authentication issues. It may easily happen that a client C' begins to send messages to the thread T_C simply using the C's address and port. To avoid this problem, all messages have to be authenticated as described in the next section, and upon receiving a message, the thread T_C verifies the authenticity of its source. How IS-MOOS addresses these security issues will be discussed in next section.

The IS-MOOS security suite

Confidentiality of messages (i.e., communication between two nodes is "privileged" and may not be discussed or

divulged to third parties) is achieved through encryption. In UAN, the specific encryption technique used is the symmetric one. Encryption is realized by splitting cleartext in blocks of fixed, predefined bit-length and encrypting each single block. In the most general case, cleartext length is not a multiple of the block length, thus padding is necessary. However, padding has the negative effect that the ciphertext may turn out to be up to one block longer than the corresponding cleartext. This effect is called ciphertext expansion. While the ciphertext expansion overhead is negligible in a traditional network, it becomes relevant in wireless sensor networks and, in particular, in underwater acoustic networks where the message size is typically quite small (because of energy and communication constraints). To avoid such a problem, the IS-MOOS security suite has been based on the CipherText Stealing (CTS) technique. According to this approach, we alter the processing of the last two blocks of plaintext, resulting in a reordered transmission of the last two blocks of ciphertext without the need for any ciphertext expansion (Schneier, 1995). The sole encryption without authentication is insecure (Menezes et al., 1996). For example, an adversary may flip bits in unauthenticated ciphertext and cause predictable changes in the plaintext that receivers are not able to detect. To address this vulnerability, the IS-MOOS system always authenticates messages. Security of hash functions is directly related to the length of the digest. However, as a digest is appended to the message, it becomes another source of message expansion and consequent communication overhead. UAN features a trade-off between security and performance by using 4-byte digests resulting from truncating the real hash function value. Using such a short hash function value is not detrimental to security (Dini and Lo Duca, 2011). An adversary has a 1 in 2^{32} chance to blindly forge a digest. If an adversary repeatedly tries to forge it, he/she needs on average 2^{31} trials, which, however, cannot be performed offline. This means that the adversary has to validate a given forgery only by sending it to an authorized receiver. This implies that the adversary has to send 2^{31} messages in order to successfully forge a single malicious message. While in a conventional network this number of trials is not large enough, it is clear that in an underwater acoustic network this should provide an adequate level of security. An adversary can try to flood the network with forgeries, but on a 500-bps channel with 184-bit messages, he/she can only send about 2.71 attempts per second. Thus, sending 2^{31} messages requires around 306 months, i.e., about 25 years. Battery-operated vehicles do not have enough energy to receive that many messages. Furthermore, the integrity attack would translate into a denial of service attack since the adversary needs to occupy the acoustic channel for a long time, and it is feasible to detect when such an attack is underway. Simple heuristics have been used in UAN: vehicles signal the base station (command and control) when the rate of digest/MAC failures exceeds a predetermined threshold.

Table III. Position of network fixed nodes.

Node	lat, lon (decimal deg)	depth (m)
STU	63,44171873; 10,71354497	90.3
FNO1	63,44285603; 10,71539267	96
FNO2	63,44698453; 10,72613567	39
FNO3	63,44524920; 10,71338701	98

Table IV. KM modem technical characteristics.

info	settings
Model	Km cNode mini transponder
frequency (kHz)	25.6
Source Level (dB re 1 μPa@1m)	173–190
Rate (bps)	200–500

2.4. Mission setup for UAN11

This section describes specific settings for the network and for the algorithms used during the UAN11 activities. On May 23, 2011 the STU node was deployed. The network was used with a temporary topology composed of the STU and two fixed nodes, both located close to the pier. On May 24, two FNOs were deployed at their final location, as shown in Table III. FNO3 was finally deployed on May 26 to substitute FNO1, which was lost at sea (a rope broke during its recovery for recharging). Each node was equipped with the same acoustic modem, provided by the UAN partner Kongsberg Maritime. This modem represented the physical layer of the UAN. Table IV shows the main modem settings as used during the tests. The modem DSP board also implemented the link and network layers to execute medium access control (MAC) and data packet switching and forwarding. In particular, the medium access was realized through a Carrier Sense Multiple Access/Collision avoidance (CSMA/CA) mechanism, while the routing protocol was based on the FLOOD algorithm (Rudstad, 2009). Finally, the network stack was completed, as described in Section 2.3.2, using IP/UDP as internetworking and transport protocols, and IS-MOOS as a middleware and application level, which included network security mechanisms (see Figure 1). The underwater network was integrated as part of the global protection system as described in Section 2. According to the MOOS paradigm, all the network nodes were connected to the central database (IS-MOOSDB), which was physically located onshore, and logically on the UAN base station (STU). The network traffic was mainly composed of environmental data, transmitted periodically (once every $T_s = 120$ s) from both the fixed and mobile nodes. In addition, further information could be requested by the C^2 when needed (e.g., node battery status, etc.). The average message size at the application level was 150 bytes. Note

that the transmission parameter T_s 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.

3. SEA TRIAL OBJECTIVES AND COMMUNICATION METRICS

As for the network operability, the sea trial objectives can be summarized as follows:

- Network robustness: how well the network is able to cope with changes in topology, nodes entering/exiting, channel variability.
- Communication performance: in absolute terms and the relative variations with respect to environmental changes (e.g., due to varying oceanographic conditions) and due to the overhead implied by the application of the security features.
- Proof of concept of feasibility in using the network also as an integrated part of a wider asset security system, allowing detection and reaction to underwater intrusion events, and effectiveness in commanding AUV missions through the network by the remote C^2 station.

The network communication performance has been evaluated at the application level using three different metrics:

- Round-Trip Time (RTT), computed as the time in seconds for a message to go back and forth from a client to the database. This time encomposses the propagation time of the message in the water and the time required to get through all the network layers, both at the client and at the database.
- Packet Loss (PL), computed as the number of packets sent by a client and received by the database, and viceversa. Note that the PL could differ from the packet loss at the physical level, as each acoustic packet can be transmitted up to three times by the modems, if a reception acknowledgment is not received.
- Average Delivery Ratio (ADR), defined as the average ratio between the number of received messages by a node and the number of sent messages to that node.

Oceanographic environmental conditions were monitored by measuring temperature and salinity as a function of depth and time, and deriving the associated sound speed profile using the well-known Chen-Millero equation (Millero, 2010). These measurements were taken by deploying Conductivity-Temperature-Depth (CTD) probes from the Gunnerus R/V at different times of the day, typically three to four casts per day.

4. RESULTS

The UAN network was continuously operated during the five days of the UAN11 sea trial, from May 23 to May 27, 2011. During this period, the entire network stack was fully tested. Nodes were routinely added and/or removed: eFolaga AUVs were deployed within the existing fixed network, and both fixed and mobile nodes were recovered for battery recharging and then redeployed. Overall, the underwater network showed a quite impressive level of robustness in terms of capability to tackle variations in the oceanic conditions and modification in its topology.

The channel conditions were very unstable, and the communication performance quite variable. Usually a 500 bps data rate was used with success in the early hours of each day, but 200 bps was often necessary, especially in the afternoon. Partial explanation may be found in the fresh water coming from rivers and rain, and in the persistent presence of wind. Figures 11 and 12 show Sound Speed Profiles (SSP) and salinity profiles, during three days of experiment, between May 25 and May 27, 2011, taken at various hours of the day. The presence of more fresh water in the upper layers is visible.

The first two days of the experiment were, for the most part, devoted to the network setup and to testing the lowest levels of the UAN, from the physical transmission up to the MAC and routing layers. Multihop was successfully tested with the mobile nodes acting as relays, usually between the STU and the furthest node, FNO2. Between May 23 and May 24, 2011 IS-MOOS was used during limited periods of time, mainly to test its integration with the lower-level components.

Between May 25 and May 26, 2011 the IS-MOOS system was used continuously, as shown in Figure 13 in terms of Packet Reception Ratio (PRR) at the middleware level. From the figure, which represents the messages transmitted back and forth from the FNO2 to the MOOSDB, a variation in the communication performance is clearly visible. Such behavior was related both to the changes in the acoustic channel and to the periods of network overload with message drops due to too many messages transmitted with respect to the available bandwidth. It must be pointed out that such effects are, however, correlated, and at the current state it is difficult to separate the two contributions. A decrease in the acoustic channel may easily cause network congestion, which lasts as long as the network itself is not able to adapt to the new conditions (e.g., acoustic modem SL increase, decrease of the transmission bit rate, and modification in the network topology to improve the communication). Network security was activated on May 26, 2011, at 3.14 pm and left on from that moment. On May 26, FNO2 was left in nonsecure modality in order to verify the overall behavior of the security mechanisms implemented. For this reason, all the packets received by the DB and coming from FNO2 were considered as coming from an intruder and

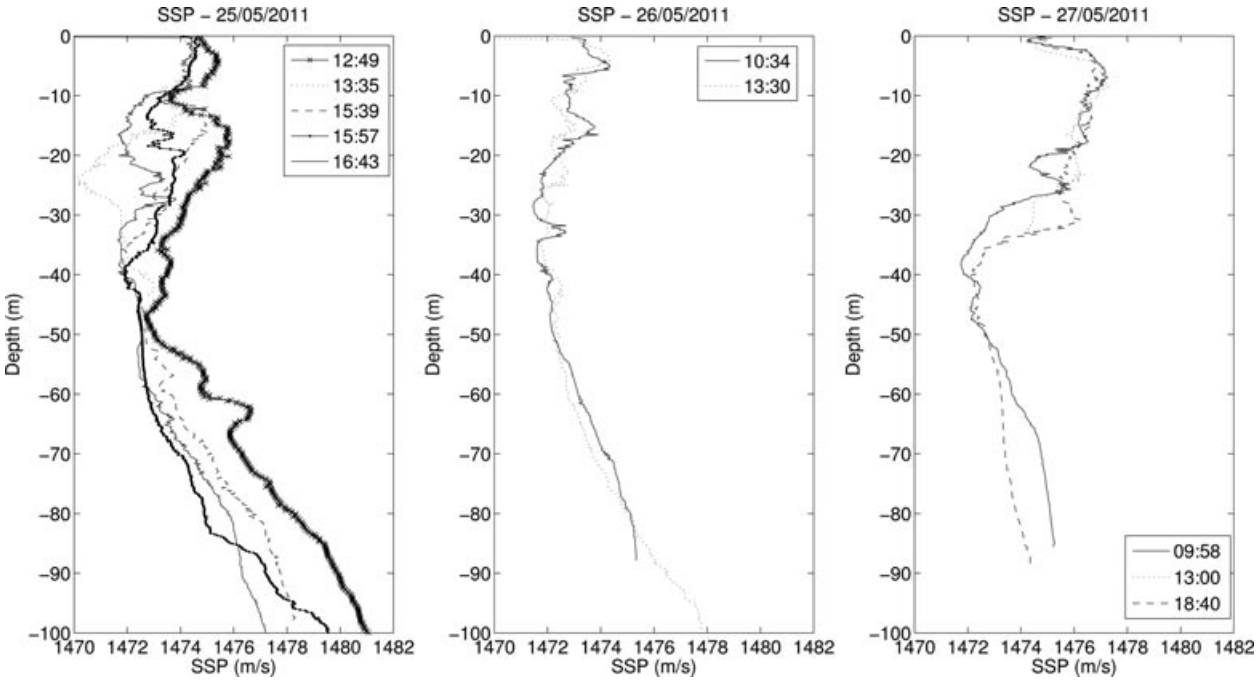

Figure 11. Sound speed profiles measured between May 25 and May 27, 2011.

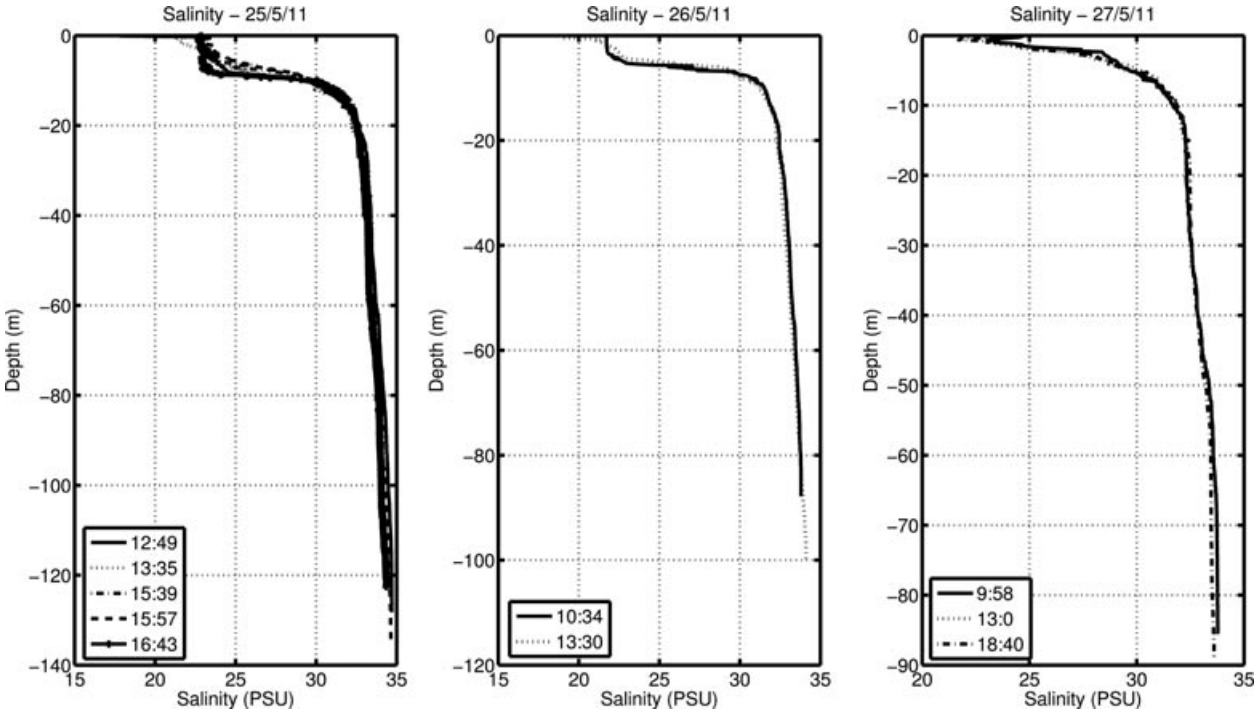

Figure 12. Salinity profiles measured between May 25 and May 27, 2011.

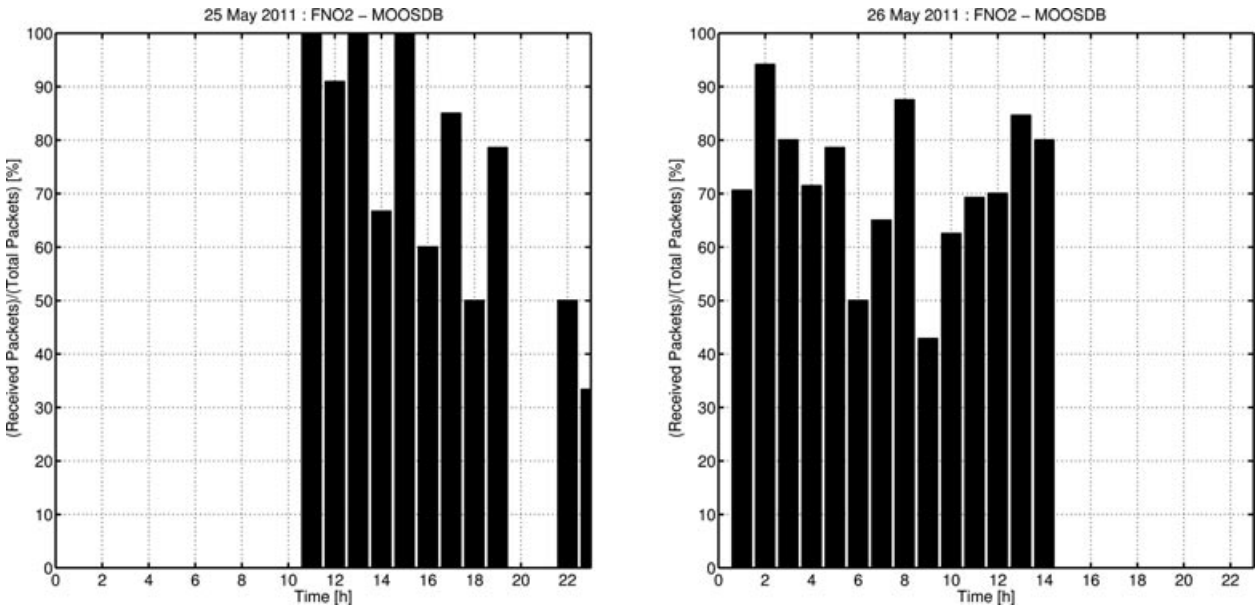

Figure 13. Packet reception ratio recorded on May 25–26, 2011 along the link FNO2 - MOOSDB. One can clearly see the variation in the communication performance during the operation days. Network security was kept off for most of the period and activated on May 26, 2011 at 15.14 pm. From that moment on, FNO2 was maintained out of the network by the DB as the node was not switched to the secure communication mode, and hence was considered to be an intruder. It reentered into the UAN on May 27, 2011 when it was switched to the secure IS-MOOS (see Figure 14).

consequently dropped (and not shown in the figure). On May 27, all the nodes (including FNO2) were in secure communication, and the PRR in the link between FNO2 and the MOOSDB is shown in Figure 14. The first part of the day was devoted to low-level communication tests, hence no packets were received at the middleware level. Figure 15 shows a comparison between the network ADR for two different nodes, without security features and with cryptography, integrity, and authentication services enabled. It is clear from the picture that when the security was activated, the network was subjected to an ADR decrease of 8%. This decrease was due to two concurrent effects:

- The message expansion caused by the authenticator, which in turn increases the probability of packet loss.
- A decrease in acoustic communication conditions.

Since these two effects are strictly interconnected, it is not possible to separate the specific weight of each of the two components in the mix. However, the ADR decrease is sustainable and the effect of the use of network security appears not to be critical with respect to the decrease in performance due to the degradation of the communication channel.

A global overview of the middleware performance is given in Tables V and VI in terms of average packet loss for each node of the network, and in terms of average RTT.

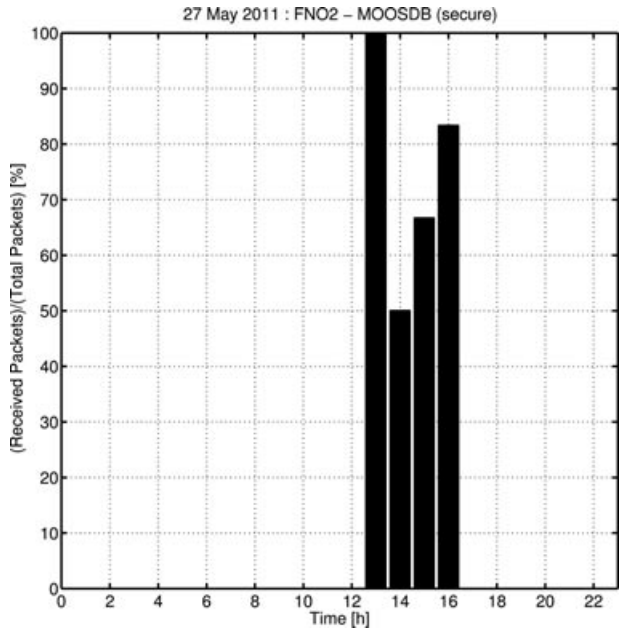

Figure 14. Packet reception ratio recorded on May 27, 2011 along the link FNO2 - MOOSDB. Network security services were activated. Variations in communication performance are clearly visible.

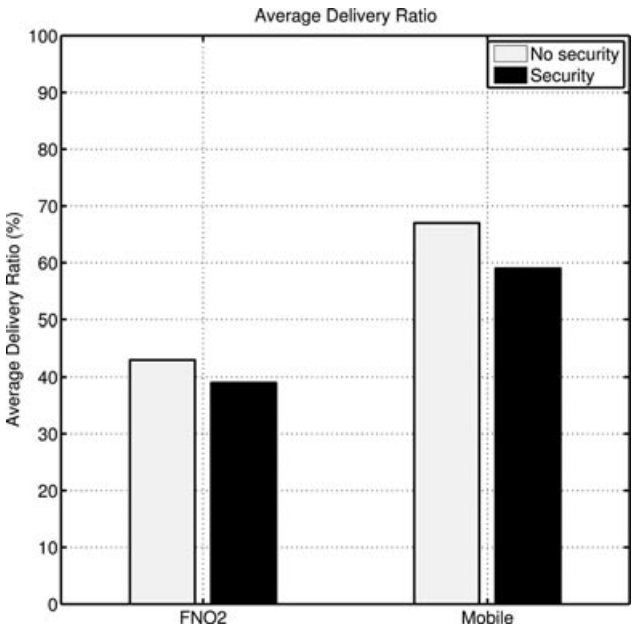

Figure 15. Average delivery ratio (ADR) performance. When the security was activated there was a decrease of 8% in the ADR. The decrease was due to two concurrent conditions: a decrease in the acoustic channel and in the message expansion due to the authenticator. Even though, at the current stage, we are not able to separate the two contributions, the ADR decrease is sustainable and the effect of the use of network security appears not to be critical.

Table V. Packet loss 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 not very accurate as the IS-MOOS system was activated only for a few hours of operation.

Date	Node	Average Paket Loss (%)
23 May 2011	FNO1	0
	FNO2	29.37
24 May 2011	FNO1	11.11
25 May 2011	FNO2	58.75
26 May 2011	R/V	32.76
	FNO2	54.76
27 May 2011	Folaga1	18.31 (until 2.00 pm)
	Folaga2	49.64 (after 3.00 pm)
	R/V	40.58
	FNO2	68.38

Except for the STU, which was always operative, not all of the nodes were in the water at the same time, and the network often had to change topology to adapt to the varying oceanic conditions, and to route the messages via the best communication path. On May 23, the network was composed of the STU with direct hops to the fixed nodes, which were located close the pier in very shallow water. On May 23 and 24, the IS-MOOS system was up for less than 4 h the first day, and only for 1 h the second day. Only a few messages were exchanged, and thus the corresponding statistics might be less accurate. Also note that, due to the loss of the node, RTT statistics for FNO1 on May 23 and 24 are currently not available, even though the node was operative. On May 25, one Folaga was used in the morning as a bridge to reach FNO2 from the STU, while in the afternoon FNO2 was routed directly, with a single hop. On May 26, FNO1 was substituted by FNO3, which was used to relay FNO2.

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

Date	Node	Average RTT (s)
23 May 2011	FNO2	17.39
25 May 2011	FNO2	58.71
26 May 2011	R/V	248.91
	FNO2	54.39
27 May 2011	Folaga1	38.81 (up to 2.00 pm)
	Folaga2	112.95 (after 3.00 pm)
	R/V	35.28
	FNO2	107.42

Finally, on May 27, 2011, the protection system was tested completely, including above-water and underwater sensors. The two mobile nodes were used as active surveillance assets, and kept mostly on surface, but with only acoustic communication available for messaging with C^2. Figures 16 and 17 show the vehicle trajectories in the morning and in the afternoon, respectively. In particular, in the afternoon of May 27, a complete anti-intrusion demonstration was carried out. With reference to Figure 17, the AUV was put in the water at about 4.10 pm, when it received a first mission to reach $WP1$. At 4.30 pm, an intrusion was detected by FNO2 at location $OBJ_1 = (63, 44891470; 10, 71229367)$, and communicated via UAN to the C^2. As a response, the C^2 sent the AUV to location OBJ_1 for further investigation. When the vehicle reached the point, it found itself out of the network, without acoustic connectivity with the remaining nodes. For this reason, the mission supervisor onboard the vehicle autonomously planned a new mission (red line pointing toward the STU in Figure 17) to move the vehicle closer to the STU, where it was able to reestablish the connection. With the vehicle again in the network, the command and control was able to take over its control to request a new mission (manually aborted on the spot to

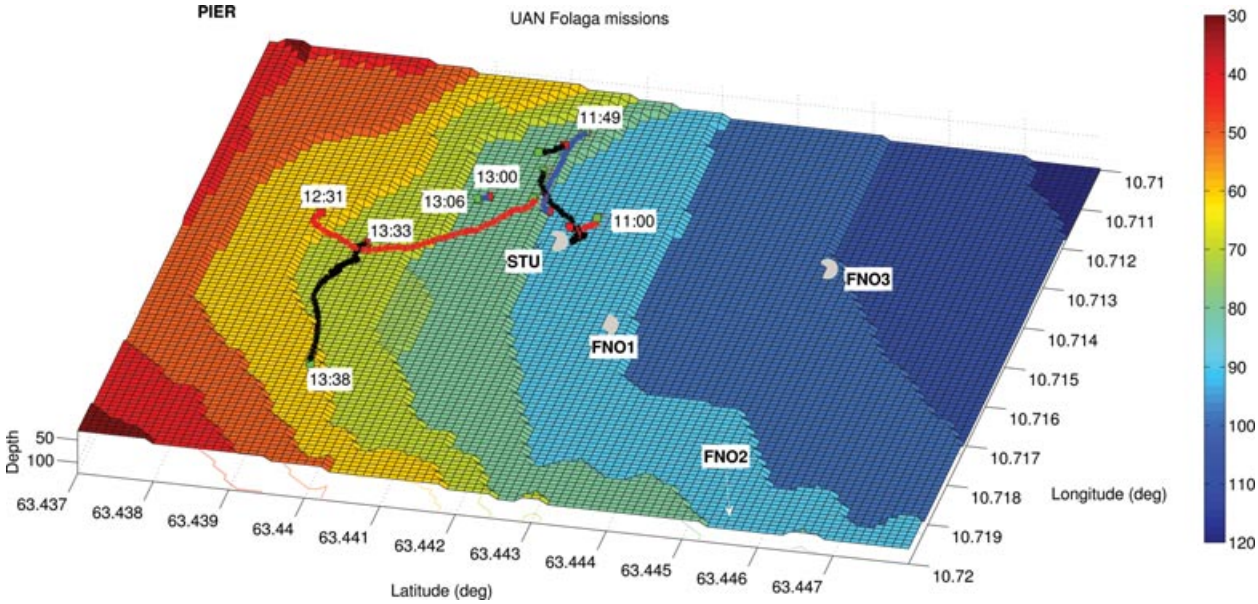

Figure 16. Folaga AUVs path during the experimental activity on May 27. In the first part of the day, the vehicle in the water was acoustically controlled by the UAN command and control center to perform several missions (each line represents a different mission).

proceed with other communication tests and hence not shown in the picture).

5. LESSONS LEARNED AND OPEN RESEARCH ISSUES

On the basis of the UAN11 results and considering the stated sea trial objectives, several lessons can be drawn. First of all, the implemented solution showed robustness in preserving network connectivity and functionality at a basic level. The network operated continuously for five days, without any major malfunctioning, and was able to seamlessly cope with variations in the number of nodes, changes in topology, and communication channel variations. Communication performance, however, varied greatly depending on oceanographic conditions, and in general has to be considered quite limited. Packet loss at the application level was significant. This fact, coupled with the large round-trip time (order of tens of seconds), makes it clear that, at least with the implemented structure and in the experimental conditions, the network cannot be used to exchange very frequent messages among the nodes. In this respect, it can be fairly said that the decrease in performance due to the presence of security features (Figure 15) is of second-order effect with respect to performance variations due to environmental changes. Given the variability and the limitation of the communication, the autonomy of the nodes becomes even more important. Each node must be able to make autonomous decisions to perform its tasks without continuous supervision by the command and control, and often even disconnected from the rest of the network for quite long periods of time. Furthermore, delays and packet loss are so high that cooperation algorithms requiring a great deal of message exchange, such as consensus-based methods, become operatively infeasible.

Since the achievable communication performance is so limited, it becomes important to reduce as much as possible the network communication overhead (e.g., signaling traffic, etc.) so as to leave the bandwidth available for the applications. In this sense, the ideas described in this paper in the case of the IS-MOOS to reduce the traffic at the middleware level could be pushed further. The use of a centralized pub/sub system has the advantage of concentrating all the information exchanged within the network into a single node. While this is useful in the case of the protection of critical infrastructures, where the C^2 requires complete control of the system, it creates an additional communication burden and may limit the network scalability. It is hence foreseeable that in other applications more suited middleware may be utilized. For example, the deployment of distributed pub/subs in terrestrial networks is currently, being researched. This would also have the advantage of reducing the number of messages exchanged. Similar approaches can also be extended to other network layers.

Notwithstanding the above limitations, the proof of concept of underwater network integration in a wider security system has been achieved, as demonstrated by the May 27 operations. Such a successful integration was favored by the use of a unified programming model, namely publish/subscribe, and a unified middleware layer, namely

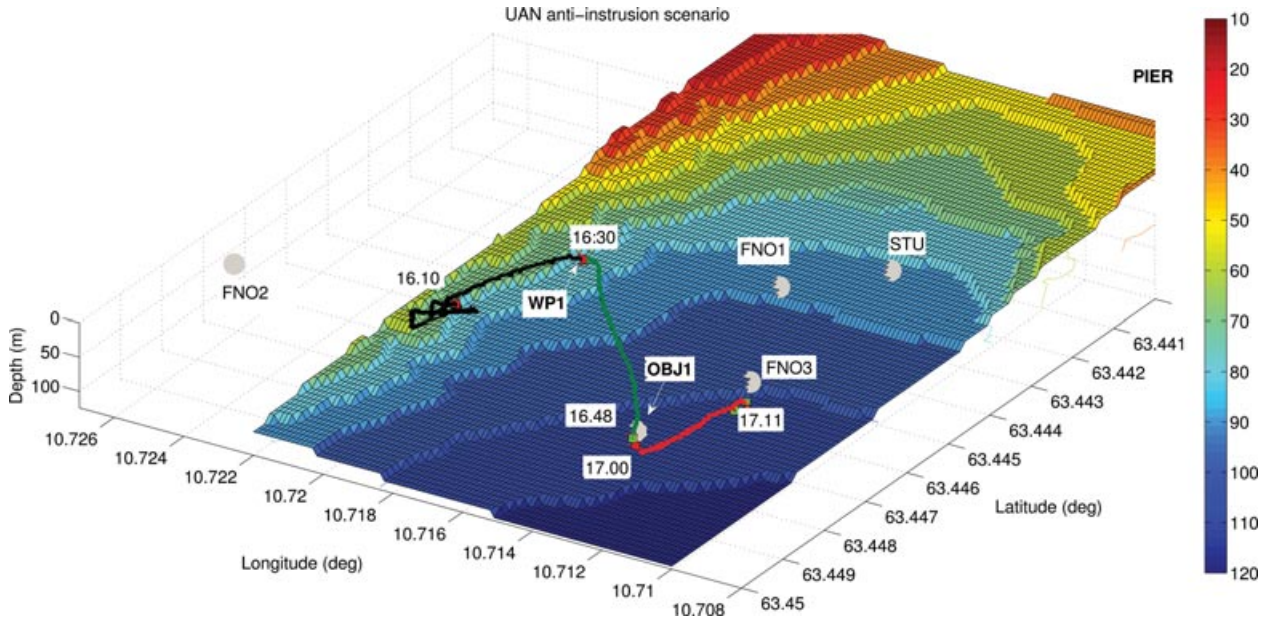

Figure 17. In the afternoon of May 27, 2011, the vehicle was used as a surveillance asset. The C^2 sent the AUV in an area of possible intrusion (OBJ_1) to proceed to further investigation. Once on location, the AUV found itself out of the network. According to the behavior described in Section 2.3, the mission supervisor autonomously planned a new mission to move toward the high value asset (the UAN base station), where it could reenter the network.

IS-MOOS, both for intra- and intervehicle communication, which simplified the development of secure and reliable applications.

6. CONCLUSIONS

This work described the implementation and test at sea of an underwater acoustic network composed of fixed and mobile nodes, including multihop capabilities. The network showed a level of robustness beyond expectations as it was able to tackle variations in its structure, with nodes routinely added and removed, e.g., for battery recharging, and to adapt to the modifications of the oceanic environment. To the best of our knowledge, this was the first time that such a complex UAN was deployed and successfully operated.

The paper has reported details on the performance of the acoustic communication, evaluated in terms of round-trip time, packet loss, and average delivery ratio. The data gathered during the experimental activities showed that the communication performance was poor, with large and variable delays and packet loss depending on day and network configuration.

The mobile nodes of the UAN were implemented on eFolaga AUVs, and they were used in the following ways: as communication nodes and movable relays to reach fixed nodes with poor acoustic connectivity; to autonomously adapt in response to variations of the network performance; and as surveillance assets of the UAN wide-area protection system, acoustically controlled by the C^2.

The UAN network was also equipped with network security features (IS-MOOS) to guarantee the confidentiality, authenticity, and integrity of the exchanged messages. This is of paramount importance in the context of underwater harbor protection, where the communication channel is open and often easily accessible. The UAN11 sea trial demonstrated that, as long as the security features are tailored to the limitations of the communication medium, the inclusion of network security is indeed feasible even with the bandwidth and capacity constraints that characterize the underwater environment. The recorded data show that the security overhead does not worsen the performance of the network very much, especially when compared to the communication degradation due to the acoustic channel itself.

ACKNOWLEDGEMENTS

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