The NAUTILUS project: Physical Parameters, Architectures and Network Scenarios

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***Abstract*—The NAUTILUS (Network Architecture and protocols for Underwater Telerobotics via acoustIc Links in Ubiquitous Sensing, monitoring and explorations) project aims at providing a comprehensive study of the technical issues related to the realization of a complete solution for the network architecture and the communications protocols needed for the tele-operation of underwater robots. When pursuing this goal, the need to implement realistic scenarios for underwater simulations clearly emerges. In this paper, starting from the investigation on the state-of-the-art carried out for the NAUTILUS project,we list the main concepts and parameters that underlie realistic simulations of underwater scenarios. Also, we present and thoroughly discuss the choices made in terms of parameters, network architectures and models for the NAUTILUS project itself. We believe that the information collected in this paper provides a good starting point for the development of a realistic underwater performance evaluation tool.**

***Index Terms*—underwater parameters, acoustic modems, underwater architecture, mobility models**

I. INTRODUCTION

There is great interest today in monitoring the oceans, which cover two thirds of the Earth. Submarine explorations make it possible to provide key information about the mechanisms that regulate the planet's life as well as the conditions of any equipment deployed underwater.

Recent advances in robotics, acoustic modems, and advanced control, as well as the innovation expected from the research community in the near future, provide most of the ingredients needed for the realization of such a monitoring platform. One of the key missing pieces is, however, a communication and networking architecture that allows heterogeneous nodes to communicate reliably in the underwater environment.

The NAUTILUS (Network Architecture and protocols for Underwater Telerobotics via acoustIc Links in Ubiquitous Sensing, monitoring and explorations) project [1], funded by the *Italian Institute of Technology* (IIT), aims at providing a comprehensive study of the technical issues related to the realization of this vision, and at proposing a complete solution for the network architecture and the communications protocols required for the tele-operation of underwater robots. When pursuing this goal, the need to implement realistic scenarios for underwater simulations clearly emerges. In this paper, we list the main concepts and parameters that underlie realistic simulations of underwater scenarios.

From our experience, we believe that the information here collected provides a good starting point for a comprehensive study of underwater network protocols. For a proper investigation in this direction, in fact, we need to integrate realistic underwater channel traces, or real underwater devices, with the simulation tools that can be realized from the physical parameters, architectures and mobility models presented in this paper, which is organized as follows. In Section II we overview several types of underwater acoustic modem boards which are currently available (see Commercial Acoustic Modems in II-A) or still under development (see Research Acoustic Modems in II-B). In doing so, we focus our presentation especially on those physical parameters that are of primary interest for the development of simulations to test network protocol metrics, e.g., operating frequency range, data rate, power consumption, working range and bit error rate (BER). The different scenarios we want to simulate are described in Section III where we review the main architectures presented so far in the literature for underwater networks. In Section IV, instead, we list the mobility models that can enable the reproduction of typical underwater scenarios with mobile nodes. Furthermore, in Section V, we discuss about the possibility of improving a given simulation framework through its integration with real devices for emulation purposes. Finally, Section VI concludes the paper.

II. ACOUSTIC MODEMS AND PARAMETERS

In this section we review the state-of-the-art of acoustic modems and list physical parameters of primary interest

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for the development of network protocol simulations (e.g., operating frequency range, data rate, power consumption, working distance and bit error rate).

Unfortunately, most of the currently available acoustic modems for underwater applications are not reconfigurable. Usually, their physical layer algorithms and bit stream formats are hard-coded in the firmware. Sometimes, even the communication protocol between modem pairs includes features which are neither controllable nor reconfigurable by the user, such as preliminary or periodic handshakes. These devices, which are reviewed in Sec. II-A, can be used to deploy an available underwater network for immediate use, but cannot be fully controlled to suit well research efforts.

Conversely, reconfigurable devices provide the researchers with the proper tools for technology's advances. Depending on the degree of flexibility sought, acoustic modems can be reconfigurable at the physical layer (e.g., modulation and frequencies to be used), at the network layer (e.g., communication protocols) or both, but are usually unavailable for large-scale purchase. We illustrate the currently active projects in this direction in Sec. II-B.

A. Commercial Acoustic Modems

In this section we summarize and update the survey of commercial acoustic modems in [2]. The objective of this section is to provide a clear picture of the currently available technologies, in the form of an accessible list of parameters and features that can be useful for research purposes (e.g., for the selection of simulation parameters).

AQUAmodem is a system developed by **Aquatec** [3] mainly for vertical applications, but can also be used in shallow water and for long distance, under-ice communications.
Operating frequency range: 8-16 kHz; **Modulation**: DSSS (Direct Sequence Spread Spectrum) or MFSK (M-ary Frequency-Shifty Keying); **Data rate**: 300-2000 bit/s; **Power consumption**: 20 W (transmit mode), 0.6 W (receive mode), 5 mW (sleep mode); **Working range**: up to 20 km; **Storage Capacity**: 2 Gbyte; **Other features**: 24.3 cm long $\times$ 16.5 cm diameter, half duplex, Bit Error Rate (BER) 10^{-7}, operating depths of 200 m (or according to housing).

HAM.NODE is a system developed by **Develogic** [4] to meet the requirements of research and exploration.
Operating frequency range: from 3-6 kHz up to 17-29 kHz; **Modulation**: OFDM-MDPSK (Orthogonal Frequency Division Multiplexing - M-ary Differential Phase Shifting Keying) or MFSK; **Data rate**: up to 3.4 - 7 kbit/s (vertical transmission at 6 and 1.95 km of depth, respectively); **Power consumption**: 30-80 W (transmit mode), less than 3 W (receive mode), less than 1 mW (sleep mode); **Working range**: up to 30 km (horizontal transmission at 145 bit/s); **Storage Capacity**: up to 32 Gbyte; **Other features**: 14.5×10 cm, time division duplexing, operating depths up to 9 km according to housing.

S2C hydroacoustic modem is a system developed by **Evologics** [5] which exploits the Sweep-Spread Carrier (S2C) communication technology for underwater data telemetry.
Operating frequency range: 18-34 kHz or 48-78 kHz; **Modulation**: S2C technology; **Data rate**: up to 33 kbit/s; **Power consumption**: adjustable 10-100 W (transmit mode), 0.2-0.8 W (receive mode), 8 mW (sleep mode); **Working range**: up to 2 km (optionally up to 6 km @ 20 kbit/s); **Storage Capacity**: N/A; **Other features**: 25×13 cm (or 40×13 cm, or 54×13 cm), half duplex, BER less than 10^{-7}, operating depths up to 100 m (optionally up to 6 km).

UM 30 is a digital underwater modem developed by **L3 ELAC Nautik** [6] in 2005 but currently unavailable for purchase.
Operating frequency range: 10-14 kHz (LF) or 25-35 kHz (HF); **Modulation**: MFSK; **Data rate**: 1536 bit/s (LF) or 3840 bit/s (HF); **Power consumption**: 100 W (transmit mode), 3 W (receive mode), 10 mW (sleep mode); **Working range**: N/A; **Storage Capacity**: N/A; **Other features**: 54.1×15.1 cm, half duplex, BER 10^{-4}, operating depths up to 6 km.

uCOMM is a system developed by **Sonardyne** [7] for real-time recovery of data from sensors. It can be found in integrated solutions with positioning and telemetry functionality.
Operating frequency range: 14-22 kHz or 19-36 kHz; **Modulation**: QPSK (Quadrature Phase-Shift Keying); **Data rate**: 1.5-15 kbit/s; **Power consumption**: less than 50 W (transmit mode), 1 W (receive mode), 30 mW (sleep mode); **Working range**: 3, 5 or 7 km; **Storage Capacity**: 256 Kbyte; **Other features**: 50×9.5 cm (or 51×9.5 cm, or 58.5×18.3 cm), full duplex, BER less than 10^{-9}, operating depths up to 3 or 7 km.

Seatooth+acoustic is a hybrid system developed by **WFS Technologies** [8]. It enables through-water (in shallow water) and through-ground radio communication (data

rate up to 156 kbit/s and 1 Mbit/s) over a short range (up to 10 m). Acoustic communications, instead, are employed to communicate underwater at lower data rates over larger distances.
Operating frequency range: N/A; **Modulation**: N/A; **Data rate**: 100 bit/s; **Power consumption**: 16 W (transmit mode), 4 W (receive mode), 5 mW (sleep mode); **Working range**: up to 30 m in seawater; **Storage Capacity**: can be incorporated; **Other features**: half duplex, operating depth up to 350 m, the radio interface can be connected to GSM/GPRS (900-1800 MHz, 850-1900 MHz, 400-450 MHz), VHF (30-300 MHz), UHF (300 Mhz - 3 GHz).

WHOI Micro-Modem[1] is a small-footprint, low-power acoustic modem based on a Texas Instruments DSP and developed by the Woods Hole Oceanographic Institution [9].
Operating frequency range: 3-30 KHz; **Modulation**: several FSK and PSK; **Data rate**: 80-5400 bit/s; **Power consumption**: $<$ 50 W or $<$ 100 W (transmit mode), 158 mW @ 12 V - 211 mW @ 24 V - 230 mW @ 36 V (receive mode), 5.8 mW @ 12 V - 19.3 mW @ 24 V - 39.6 mW @ 36 V (sleep mode); **Working range**: up to 2 km horizontally, up to 9 km vertically; **Storage Capacity**: none; **Other features**: 11.43 cm length $\times$ 4.445 cm width, it provides the use of “minipackets” that do not obey to any of the standard communication protocols implemented in the modem firmware.

B. Research Acoustic Modems

In this section we overview the research projects on reconfigurable modems which, to the best of our knowledge, are currently active. The overall objective of these projects is to provide reconfigurable platforms to the research community, as opposed to commercial modems, which do not typically expose their firmware for customization and reprogramming.

rModem is a software-defined underwater acoustic modem developed by the **Massachusetts Institute of Technology (MIT)** [10], [11]. It is based around the Matlab Simulink package.
Operating frequency range: 1-100 kHz (successfully tested in the 9-14 kHz band); **Modulation**: QPSK; **Data rate**: 550 bit/s; **Power consumption**: N/A (but higher than standard off-the-shelf modems); **Working range**: N/A (from experimental results up to 100 m); **Storage Capacity**: 32 Mbyte SDRAM (for program and memory storage), 32 Mbyte FLASH RAM (for persistent program and data storage); **Other features**: 7.62 cm length $\times$ 17.78 cm width (board size), reconfigurable at both the physical and network layer, tested within a tank (up to 20 m deep).

AquaNode is an acoustic modem also developed by **MIT** [12]. For higher communication speed, it can use also optical signals up to 2.2 m or 8 m if two nodes are aligned to within a tolerance of 90° or 30°, respectively.
Operating frequency range: 30 kHz (carrier), N/A (bandwidth); **Modulation**: FSK (Frequency-Shifty Keying); **Data rate**: 330 bit/s; **Power consumption**: powered by 56 watt-hours of Lithium Ion batteries (1-2 weeks of continuous operations, 1 year of power in sleep mode); **Working range**: up to 400 m; **Storage Capacity**: 4 Kbyte RAM, 128 Kbyte FLASH memory (for program), 512 kbyte external FLASH memory (for data logging/storage); **Other features**: 25 cm long $\times$ 30 cm diameter, reconfigurable at the network layer, tested in freshwater and ocean.

The group of Prof. Shengli Zhou at the **University of Connecticut** has been actively developing an underwater modem based on MIMO-OFDM capabilities [13]- [14].
Operating frequency range: N/A (carrier), 4.8 kHz, 5.5 kHz, 31,25 kHz 62.5 kHz (bandwidth); **Modulation**: QPSK, QAM (Quadrature Amplitude Modulation); **Data rate**: up to 125.7 kbit/s; **Power consumption**: N/A; **Working range**: N/A; **Storage Capacity**: N/A; **Other features**: currently reconfigurable at the physical layer, network layer reconfigurability is envisioned as a future option, tested in a tank (0.5 m deep).

UANT is a platform developed by the **University of California, Los Angeles (UCLA)** [15]. It is mainly composed of widely supported open-source software: GNU Radio and TinyOS.
Operating frequency range[2]: 0-50 MHz ; **Modulation**: GMSK (Gaussian Minimum Shift Keying); **Data rate**: from 244 bit/s to 500 kbit/s; **Power consumption**: N/A; **Working range**: N/A; **Storage Capacity**: 4 GByte; **Other features**: reconfigurable at both the physical and network layer, tested in a pool.

The **University of California San Diego** aims to build

[1]This device is not strictly commercial but is provided with a closed firmware: for this reason, we list it in this subsection.

[2]The reported values are due to the GNU radio specifications, but for acoustic communication they must be set according to values more suitable for the underwater channel.

an underwater modem using only low-cost off-the-shelf components [16].

Operating frequency range: 35 kHz (carrier), 6 kHz (bandwidth); **Modulation**: FSK; **Data rate**: up to 200 bit/s; **Power consumption**: from 1 to 40 W (transmit mode), 1 W (receive mode); **Working range**: up to 2 km; **Storage Capacity**: N/A; **Other features**: reconfigurable at network layer, initial in-water tests done (with depths up to 100 m), BER 10^{-2}.

SDAM is a project carried on by the **Scripps Institution of Oceanography** [17]. It focuses mainly on multichannel and MIMO communications.

Operating frequency range: 10-32 kHz; **Modulation**: Pulse Width Modulation; **Data rate**: 100 or 1000 Mbit/s; **Power consumption**: 150 W (transmit mode), 20 W (receive mode), 2.5 W (sleep mode); **Working range**: N/A; **Storage Capacity**: 1 GByte RAM, 2 TByte (for storage); **Other features**: reconfigurable at both the physical and network layer, tested in shallow waters.

III. Underwater Networking Architecture

The NAUTILUS project vision entails network components able to reorganize themselves into a different topology after a failure. Ideally, data would be continuously processed and disseminated in real time, thereby providing a live view of what is happening in the undersea environment. To realize the NAUTILUS project vision, we need to effectively enable underwater acoustic communications among devices. The main components that interact in underwater networks are reported in Fig. 1 and detailed in the following:

Underwater Sensors are network devices in charge of sensing and communicating oceanographic data of interest. To this end, they are equipped with an acoustic modem and sensors to measure physical quantities to be monitored (e.g., water quality sensors for salinity, temperature, optical quality and so on);

Unmanned or Autonomous Underwater Vehicles (UUVs, AUVs) are mobile nodes equipped with different sensors. These nodes have more energy than normal underwater sensor nodes and can move independently. Further, there is no need for tethers or cables to convey remote control commands to operate them. It is possible to find different kinds of such devices, from more sophisticated solutions, which mimic the shape and functionalities of small submarines, to simpler devices with more limited capabilities. Once surfaced, these devices can often communicate directly to shore via satellites or use satellite-based services such as GPS;

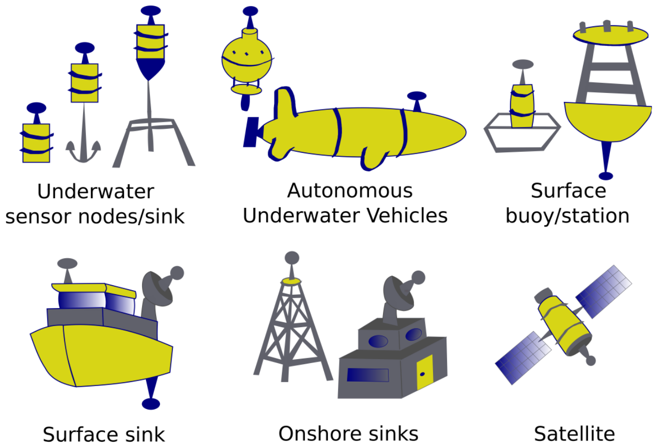

Fig. 1. List of the main components that interact in a typical underwater scenario.

Underwater Sinks are network components that relay the data collected by the sensor nodes from the sea-bottom to the surface. To communicate with undersea devices as well as with surface nodes, the underwater sinks are equipped with both a horizontal (for communicating configuration commands to the sensor nodes or gathering data from them) and a vertical transceiver (for relaying the collected oceanographic measurements to the surface);

Surface Buoys/Stations are devices endowed with an acoustic transceiver designed to handle multiple communications in parallel with the deployed under-water sinks. They can also be equipped with radio-frequency or satellite transmitters to communicate over the air;

Surface Sinks are further network components that allow to coordinate different surface stations and thus the overall underwater network. Commonly, surface sinks are located on ships from where the research teams can control and coordinate the different activities (these components can therefore be considered as mobile nodes). Generally, surface sinks communicate with the other surface components via radio transmission or satellite links;

Onshore Sinks are additional network components, placed on the shore, that can communicate with the rest of the network via radio or acoustic links (these latter can be placed underwater by means of cables). These nodes can be used to easily access the underwater network by means of the surface stations or for particular applications (e.g., assisted navigation along the coast);

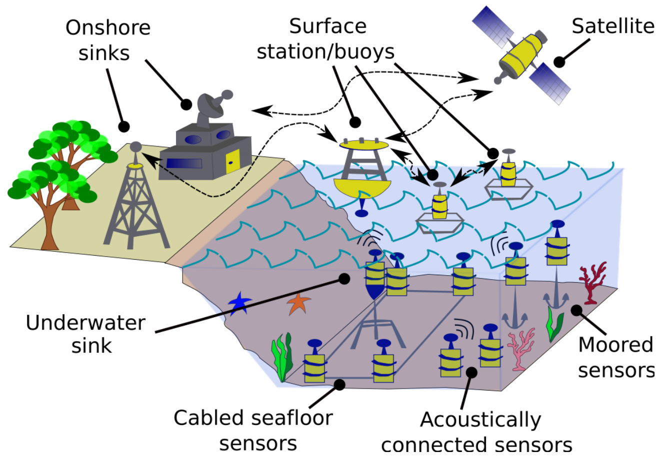

Fig. 2. Illustration of an underwater static architecture.

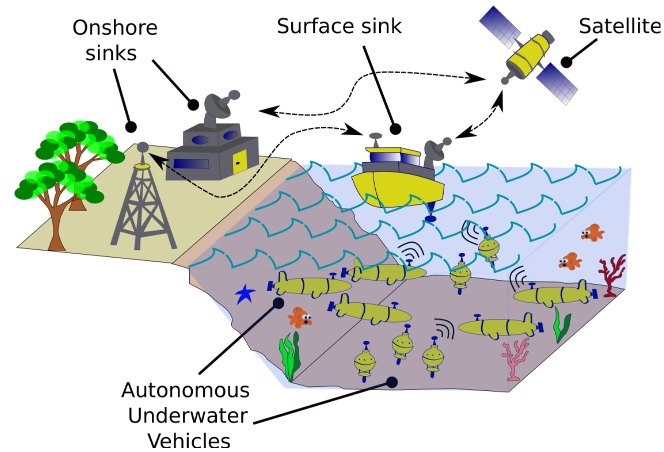

Fig. 3. Illustration of an underwater mobile architecture.

Satellites are important network components. They can be used to access the underwater network, e.g., via radio links to surface buoys, and especially to provide necessary information such as the absolute and relative node positioning.

To design an effective solution for wireless underwater acoustic communications, we need a networking architecture that enables the heterogeneous nodes listed above to organize themselves and reliably communicate in the harsh underwater environment.

Following [18] and [19], we discuss the possible underwater network architectures classifying them in three classes according to their topological characteristics, node mobility and applications. For further discussion on underwater networking issues, the reader is referred to [20]–[22].

A. Static Architecture

We design a static architecture when the network topology remains relatively static (or pseudo-static) after the node deployment. In these kind of networks, see Fig. 2, (sensor) nodes can be moored to the sea-floor so that their movements are negligible. Over a 2D plane (e.g., the sea-floor), nodes can be organized according to the same topologies that we have for terrestrial networks (e.g., line, tree, grid, clusters); however, in underwater environments 3D configurations easily show up, where moored devices float at different depths. In [23], for example, three different strategies to realize such deployments are presented. In particular, one possible solution, which leads to easy deployment, would be to attach each underwater sensor to a surface buoy by means of a wire, the depth of each sensor is then chosen by adjusting the length of this wire; as a drawback, floating buoys may obstruct shipping and are vulnerable to weather conditions (and can also be subject to tampering or stolen). Alternatively, nodes can be anchored to the sea-floor and equipped with a buoy: underwater sensors can be placed at the desired depth by deflating or inflating such buoy with a pump. Typical applications for this kind of architecture may be environmental monitoring and surveillance, e.g., see [18].

B. Mobile Architecture

According to this architecture, all nodes in the network can move freely so that the overall topology is variable over time. Typically, this kind of architecture is made of two layers as depicted in Fig. 3. Devices floating on the sea surface form the first layer; they are equipped with wireless transceivers for data communications and can be exploited for temporary monitoring applications (e.g., water quality sampling). Moreover, the surface layer can communicate with an underwater layer made of mobile nodes which can work without cables or remote control at any desired depth. Generally, these mobile devices are UUVs or AUVs: several types exist as experimental platforms or commercial products. As detailed in [18], some AUVs resemble small-scale submarines whereas others are simpler devices with no sophisticated features; examples of this second kind can be the “drifters”, i.e., vehicles that drift with currents and can move vertically through the water column, or the “gliders”, underwater devices that use hydraulic pumps to vary their volume and thus power their forward movement (gliding). A mobile architecture is particularly suitable for monitoring tasks that entail reconnaissance missions (especially when organized in different paths) and/or tracking of objects (especially those moving with water currents).

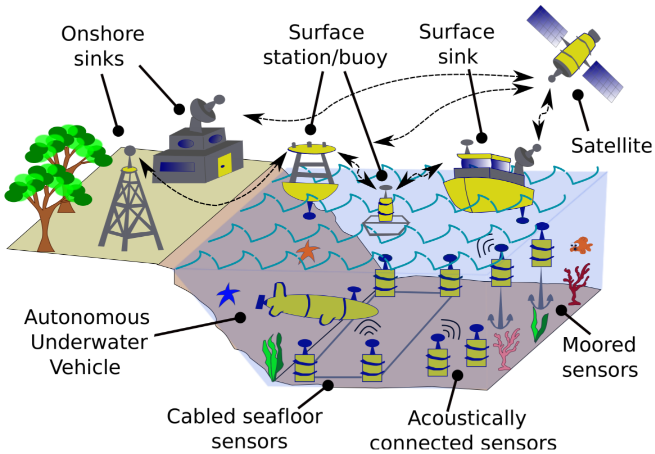

Fig. 4. Illustration of an underwater hybrid architecture.

C. Hybrid Architecture

Finally, a hybrid architecture would include fixed portions of anchored devices integrated with mobile nodes as AUVs. This solution, depicted in Fig. 4, is particularly appealing for highly coordinated undersea explorations (e.g., detection of underwater oil fields or route determination of undersea cables) and to perform complex tasks such as rapid environmental assessment or detection and disposal of undersea mines. Clearly, this architecture calls for the study and design of new network coordination algorithms. In particular, we need suitable solutions for: 1) "adaptive sampling", namely algorithms that allow the mobile nodes to be placed where they can be more useful (e.g., augmenting the AUVs density in those areas where a higher sampling rate is required for a given observed phenomenon), and 2) "self-configuration", i.e., automatic procedures to detect and compensate for connectivity holes (e.g., due to node failures or channel impairments) or to maximize the overall network capacity.

According to the goals of the NAUTILUS project, we need flexible architectures where mobile nodes can easily adapt to network changes (e.g., due to node failures, channel condition changes, or on-demand requests by the users) since they are free to move. In light of the above descriptions, this can be achieved by using either 1) a mobile architecture (that allows us to design protocols which make different Autonomous Underwater Vehicles, AUVs, collaborate in patrols to guarantee full connectivity of the network and/or satisfy Quality of Service, QoS, constraints), or 2) a hybrid architecture (where AUVs are, for example, exploited as efficient and controllable underwater sinks which can travel through the entire undersea network, collect measurements and bring them back ashore for processing and examination).

Which architecture is best clearly depends on the considered underwater environment and task to perform.

IV. Mobility Models for Underwater Scenarios

When we want to evaluate a protocol for underwater networks, the tested solution should be investigated under accurate models that encompass, among other things, the use of realistic mobility patterns. These traces, in fact, often determine fundamental characteristics for communications such as network connectivity, connection time or percentage of link breakages. This, in turn, causes the results of simulations to be very sensitive to the mobility models chosen to simulate how nodes move within a given area, as pointed out by the survey on mobility models for ad hoc networks in [24].

The plethora of mobility models found in the literature are generally divided in two classes, the "entity models" and the "group models". The first are simpler, and assume random movement patterns, independent for each node. For instance, the well known "Random Way-Point" and "Random Walk" mobility models [25] belong to this category. The second are more advanced modeling solutions that take into account possible interactions among nodes causing, for instance, aggregation of movements (namely, a group of entities moving together). The "Reference Point Group Model" [26] and the "Structured Group Mobility Model" [27], for instance, belong to this class. Furthermore, in underwater environments, nodes can move both horizontally and vertically so that the typical 2D implementations of most of the currently used mobility models must be adapted to 3D scenarios.

In the following we provide a list and a brief description of the most used mobility models for ad hoc networks that can be readily applied to underwater network simulations with minor modifications. Moreover, considering the NAUTILUS project objectives, we will specifically discuss the group models leading to the simulation of the so-called "correlated mobility". These models, in fact, are particularly appealing for the NAUTILUS project, because they enable the simulation of tracking applications, whereby a set of AUVs must follow one or more targets within a given area.

A. Entity Models

The following entity mobility models can be used when we need to simulate an underwater scenario with no correlation among moving nodes. These kinds of scenarios can be, to some extent, similar to those depicted in Sections III-A or III-C. Referring to Fig. 2, in fact, we can for example assume that, despite the desired fixed positioning, floating nodes may randomly oscillate around their mooring points due to waves or marine currents. Referring to Fig. 4, instead, we can image groups of AUVs moving randomly and independently (i.e., with no coordination) to gather sensed data from the undersea network infrastructure.

Random Walk Mobility Model [28]. This model generates random patterns independently of the previous node movements and may be characterized by sudden stops and sharp turns. In detail, according to this model each node moves from the current position to the next by choosing an angular direction in the 2D or 3D space, and picking a speed from the predefined range $[v_{\min}, v_{\max}]$. Each node's movement lasts for either a constant time t or a constant distance d. As an example, this algorithm can easily simulate the oscillating behaviour of moored nodes by setting either t or d to sufficiently small values.

Random Way-Point Mobility Model [29]. This model, similar to the previous one, adds pause times between changes of direction. In detail, each node moves from the current position by choosing the next position within a given area $\mathcal{A}$ (that can be either 2-dimensional, e.g., the plane of the sea-surface, or 3-dimensional, e.g., the marine environment from the sea-bottom to the surface) and speed in the predefined range $[v_{\min}, v_{\max}]$. The pause $t^{(p)}$ between any two periods of time during which a given node moves can be fixed or randomly chosen in a predefined range $[t^{(p)}_{\min}, t^{(p)}_{\max}]$. Also in this case it would be possible, for example, to simulate the oscillating behaviour of anchored nodes by properly reducing and centering $\mathcal{A}$.

Random Direction Mobility Model [30]. This model is a further modification of the Random Walk Mobility Model, designed to cope with the so called *density waves* phenomenon, e.g., see [24]. According to this algorithm, a node is forced to travel until the border of the simulation area is reached; then, it pauses a given amount of time and, after choosing a new angular direction, departs again. This model may be adopted, for instance, to simulate the monitoring of a given area by means of randomized paths. Forcing the AUVs to reach the boundaries of the monitored area, in fact, guarantees a fair exploration also of its edges; this is not the case for the other models presented so far whose generated traces make the nodes more likely to be found around the center of the considered area.

Gauss-Markov Mobility Model [31]. This model has been designed to produce smoother and more realistic traces, and is tuned via a correlation parameter α. Once we fix the desired mean speed v_{mean}, through α we can control the correlation between the speed vector at time instant k and that at $k-1$. In detail, with this model each mobile entity keeps moving over time and for each k (over fixed intervals of time) the speed v_k and is updated as follows:

$$v_k = \alpha v_{k-1} + (1-\alpha)v_{\text{mean}} + \sqrt{(1-\alpha^2)}v_{\text{rand}}$$

where v_{rand} is a random value with zero-mean, unit-variance Gaussian statistics. The update equation for the direction of movement is the same. In underwater scenarios, this model can be particularly useful to simulate realistic traces of objects to track, e.g., a school of fishes.

Probabilistic Random Walk Mobility Model [32]. This model is based on an alternative approach to generate mobility traces which are still correlated over time. As in the Gauss-Markov model, the position of a given object is updated at fixed time intervals; here, however, we need to define a probability matrix which describes the possible transitions to new positions. The actual shapes of the mobility traces generated by this method clearly depend on the definition of the transition matrix. For underwater simulations, we can take into consideration this solution since it can be, for instance, a handy tool to model the waving movements typical of objects floating in the water.

B. Group Models

The following group mobility models can be used when we need to simulate applications in underwater environments that require coordination, and therefore correlation, of the node movements. These kinds of scenarios can be as those depicted in Sections III-B and, to some extent, III-C. For the environment in Fig. 3, in fact, we can easily see applications in which AUVs are required to move in patrols for the monitoring of a given area or to track a given object (e.g., a school of fishes). In Fig. 4, instead, we can image AUVs involved in the monitoring of underwater infrastructures: in this context, they should be able to move according to precise patterns as those determined by communication cables deployed on the sea-floor or submarine oil-pipes.

Column Mobility Model [28]. This model allows to simulate a group of mobile nodes moving around an ideal line that proceeds along some direction. The idea behind this model is to mimic soldiers or organized groups of entities marching towards their destination. The local movement of each node around the moving line aims to make the generated traces more realistic by adding some random displacements. In underwater scenarios, this model can be employed to simulate patrols of AUVs organized for scanning, research or monitoring purposes.

Pursue Mobility Model [28]. This model aims to generate mobility patterns that can be seen as the result of one or more mobile nodes pursuing a given target. For each follower, we compute its updated position as the vector sum of three terms: 1) the previous position of the node, 2) the distance between the target and follower multiplied by a given acceleration factor, and 3) a random vector that can be obtained through one of the entity models above. The position update steps can be performed at fixed times or once a given event occurs (e.g., a sudden movement of the target). Clearly, in the context of our interest, this model appears suitable to be exploited for simulating underwater tracking applications.

Reference Point Group Mobility Model [26]. This model separates the group movements from those of each individual node. Group movements are determined by the path traveled by a "virtual" center. Whilst nodes in the group update their reference points according to the virtual center's movements so as to follow it, the actual position of each node is also characterized by a further movement that is chosen independently for each mobile. The movements of both the virtual center and the single nodes can be determined via one of the entity models above. As pointed out by [24], this model is very general and, depending of its actual implementation, it can mimic the behavior of other group mobility models. Therefore, it is worth to consider also this model for underwater simulations since, with slight modifications, it can be easily adapted to different applications.

Structured Group Mobility Model [27]. The main objective of this model is to refine the previous solution to generate more realistic traces for collaborative contexts. In detail, this model stems from the fact that it is rather difficult to observe entities moving independently of each other when they are performing a collaborative task (e.g., think of a team of firemen involved in a rescue mission). Therefore, the Structured Group Mobility model, differently from the Reference Point Group Mobility one, forces nodes in the same group to move according to precise relationships. In underwater scenarios, therefore, this model can be taken into consideration to simulate patrols of AUVs moving in an actual coordinated fashion.

Attraction-based Mobility Model [33]. This model, as the last two, separates the movements of the group (identified now by a leader chosen among all the nodes composing the group) from those of the single nodes in the network. However, in this solution, the overall group movement is determined by an "attraction field" existing between the node leader and every other node. This model is particularly appealing to simulate applications that imply a given hierarchy among nodes. For underwater scenarios, e.g., we can think of a monitoring application in which patrols of AUVs are required to converge towards those regions where one or mode devices notified something of interest.

V. Building an Experimental Platform for the Emulation of Underwater Systems

As a concluding remark, we also want to push our discussion beyond simulations. Implementing research solutions on actual devices, in fact, plays a key role in the NAUTILUS project. Testing different network protocols and/or physical layer solutions in real environments is a valuable way to provide a comprehensive study for the realization of an effective communication architecture. On one hand, this activity strengthens the study because it allows researchers to support theoretic and simulation results via experimentation; on the other hand, it may pinpoint bottlenecks or practical issues that can hardly be observed in simulations or captured by theoretical models.

A possible way to address this issue would be the integration of simulation tools with actual underwater hardware. In fact, laptops or PCs could be connected to the currently available modem platforms described in Sec. II via serial cables. This way, the computers can simulate and control all the high-level features of a performance evaluation task such as applications, connectivity traces, MAC and data link protocols, whilst the actual acoustic transmission of data can be performed by the real modems (whose electro-acoustic transducers can be placed in a water tank, a pool or the open sea). Within the NAUTILUS project, we foresee the possibility of extending the well-known and wide-spread **NS-Miracle** [34] library, developed at the University of Padova, to move from simulation towards emulation. NS-Miracle enhances the network simulator **ns2** [35] by providing an efficient engine for handling cross-layer messages and, at the same time, enabling the coexistence of multiple modules within each layer of the protocol stack. As a matter of fact, NS-Miracle shows a high modularity and has been designed to simulate nodes whose logical architecture is as close as possible to the one found on the actual devices. Moreover, the use of mobile software development platforms such as the **BeagleBoard-xM** [36] or the **PandaBoard** [37], that can replace actual computers, would allow us to build more portable, autonomous and realistic testbeds. We believe that such activity, according to what done in the recent papers [38], [39], represents a fundamental step for the study of effective underwater network protocols, moving from simulations to the real world.

VI. Conclusions

In this paper we surveyed the state-of-the-art of important underwater communications aspects, focusing on three areas, namely: i) currently available technologies for underwater acoustic modems; ii) network architecture and iii) mobility models.

In view of this initial study, we collected in this paper a list of useful parameters and considerations that establish a good starting point for the development of a reliable and accurate underwater performance evaluation tool. In doing so, we highlighted especially those physical parameters that are of primary interest in realistic network simulations (e.g., operating frequency range, data rate, power consumption, working range and BER).

Furthermore, under the NAUTILUS project we have identified some reference scenarios and architectural approaches that will be the starting point for our networking investigations in the rest of the project. In particular, we will focus on solutions for both mobile and hybrid architectures, using a static network topology only as a benchmark. In a fully mobile architecture, in fact, we can design protocols to make different AUVs collaborate in patrols or we can establish navigation traces to guarantee full connectivity of the network and/or satisfy QoS requirements (e.g., real time constraints).According to the hybrid architecture, instead, we can exploit AUVs as efficient and controllable underwater sinks that can travel through the entire undersea network, collect measurements, and bring them back ashore for processing and examinations.

Finally, we discussed about both the need and the possibility of moving from simulation to emulation by integrating real devices within network simulators. We recognized this activity as a key effort to profitably realize real world applications.

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