# An overview of project COMPOUND: Cooperative Communications and Positioning in Mobile Underwater Networks


## Abstract

One of the challenges faced by future networks is to integrate heterogeneous segments whose protocols are optimized for very different conditions. This work provides an overview of project COMPOUND, which tackles problems in this class to interface an underwater acoustic network comprising both static and mobile nodes to the Internet. The main goal is to create value and foster new applications in a niche but strategically important area by making the data and assets in the network easily available to a wide community. This will reduce the time, effort, and cost needed to customize the network to suit a specific need. A key insight in COMPOUND is to extensively exploit knowledge of node positions, including submerged ones with no access to GPS, to configure the network parameters at multiple levels, from the Internet gateway down to a node's physical layer. In turn, positioning is derived from observed data traffic on the network and collaborative exchanges between nodes, resulting in a system that tightly integrates positioning and communications. The paper discusses the proposed approach within the scope of current research on underwater acoustic communications and networking, describes application scenarios, envisaged technical solutions, planned developments, and identifies some of the possible impacts of this work.



## Keywords:

Underwater communications, underwater networks, collaborative localization,


## 1. Introduction

One of the main trends in the development of the future Internet is the integration of heterogeneous segments of the network to let different systems like satellites, cellular networks, fiber backbones etc. interoperate effectively. Many technical challenges are to be solved in this respect, especially those related to the interworking of different protocols that are optimized for very different operating conditions. A paradigmatic example is the difficulty of integrating satellite segments into an all-IP geographical network. A similar situation is experienced when it comes to integrating one more segment into that picture, one that is admittedly to be considered as a niche, but whose relevance is growing in a number of contexts and applications: Underwater acoustic networks.

Future systems for ocean exploration and surveillance or monitoring of underwater structures and sites will comprise multiple devices (e.g., ships, underwater vehicles, drifting or moored instruments) operating in a coordinated way to carry out complex missions. Wireless underwater communications and networking play a key role in such systems, while facing challenges that are often much harder than those found in terrestrial applications [2]. Foremost, communication over distances larger than a few tens of meters must resort to acoustic waves, as electromagnetic waves (radio) and light are strongly attenuated in sea water, making them ineffective to convey information-bearing signals except at very short ranges. However, the bandwidths that can be used in practice for acoustic transmission are narrow, on the order of a few tens of kHz, and acoustic signals undergo severe distortion due to multipath propagation over multiple surface and bottom bounces, and wideband Doppler compression/expansion of waveforms due to environmental fluctuations or motion at the source or receiver. Moreover, sound propagates in water five orders of magnitude slower than the speed of radio waves, leading to high latency over typical communication ranges around 1 km that are poorly matched to the assumptions underlying the development of current networking protocols.

Much of the work on underwater communications has focused on improving the reliability of point-to-point data links, usually by adapting techniques originally developed for terrestrial radio channels [1, 2]. Recently, underwater networking aspects have gained prominence, in line with trends towards networked systems in other areas (e.g., wireless sensor networks, networked control systems) [2, 3]. Underwater networking is still very much a research topic, and commercial modems include, at best, only basic (and vendor-specific) functionality to support routing and multiple-access over acoustic channels. Recent research projects where underwater networking plays a prominent role emphasize military/security or environmental monitoring applications [4, 5, 6] using both static and mobile assets, such as autonomous underwater vehicles (AUVs). The latter actually compound the inherent difficulties of underwater communications by exacerbating the dynamic behavior of point-to-point channels.

Project COMPOUND aims to develop methodologies for enhancing the value of underwater networks that integrate mobile nodes. A key insight in this proposal is to extensively exploit the side information gained from two-way data exchanges between nodes to improve the efficiency of communications and derive localization information. Another major aspect is to emphasize the interconnection between such networks and the Internet to foster new applications that are enabled by timely remote access to the data collected by underwater nodes.

The paper is organized as follows. Section 2 outlines the objectives of project COMPOUND. Section 3 provides a brief overview of relevant prior work, and of other related projects in the area, and lists some of the envisaged application scenarios. Section 4 presents the methodologies and the work plan. Finally, Section 5 discusses the potential impacts of this work and summarizes the key points.

## 2. Objectives

The proposal for the COMPOUND project puts forth the following scientific objectives:

1. Develop methodologies for extracting ranging information and channel state information from communication signals.
2. Develop algorithms for self-localization and collaborative localization of nodes in underwater networks from measured pairwise ranges, taking into account the stark constraints imposed by bandwidth, latency, and link intermittency.
3. Develop feedback schemes to exploit the localization and channel state information gained at a given node to improve the communications performance by adapting the parameters used for physical transmission (e.g., modulation type, modulation parameters, coding schemes).

4. Similarly, leverage the spatial information to develop effective schemes for channel sharing (MAC protocols), routing, for automatically setting up an ad-hoc network, and for coping with dynamic effects such as node mobility and intermittencies.
5. Design a software-defined transceiver that will serve as a flexible network node, enabling the experimental assessment under realistic at-sea deployments of various physical-level transmission schemes and network-level protocols.
6. Develop methodologies for interfacing a dynamic underwater network to the Internet. As in planetary networks, and other so-called challenged networks, standard IP is poorly matched to the specificities of underwater propagation and a protocol conversion scheme is needed.
7. Characterize the performance of the proposed approaches under controlled experimental conditions and also in real tests conducted at sea.

Meeting the above objectives will materialize the key concept of joint communication and positioning proposed in project COMPOUND, thus leveraging the spatial information to a degree that significantly exceeds what has been accomplished in current underwater networks. Additionally, the proposal pursues the strategic objectives of reducing the technology gap between European Union and other countries developing underwater communication networks, and testing the applicability of the COMPOUND concept to scientific, technical and business activities.

## 3. Motivation, Related Work, and Application Scenarios

Much progress has been attained in underwater communications over the past decades, spurred by the needs for ocean exploration, oceanography, the military, and oil exploitation. Initial communication systems encoded the digital information incoherently (FSK-type modulation), as these modulations can tolerate, to some extent, the severe distortions induced by multipath and Doppler at the expense of bandwidth efficiency [1]. Incoherent techniques are still widely used today, and have been adopted in most commercial underwater modems to deliver data rates up to a few kbit/s. Standardization efforts are under way to facilitate the interoperability of such modems [7].

Coherent modulations can deliver data rates that are at least an order of magnitude larger than their incoherent counterparts, but this comes at the cost of high sensitivity to channel conditions and variations, which requires powerful signal processing methods at the receiver to track and compensate for these distortions [1]. Multicarrier modulations such as OFDM have recently attracted much interest, as FFT-based receivers are easier to parameterize than conventional equalizers for single-carrier modulations, and have been shown to offer improved consistency in channels with moderate delay and Doppler spreads [2]. Underwater OFDM is still being intensively researched, e.g., by combining it with state-of-the art coding techniques such as LDPC [8] for improved error rate performance, or with multiple transmit/receive elements (MIMO) for higher spectral efficiencies through spatial multiplexing [2]. Recent work suggests that channel characteristics may be predicted reasonably well at a receiver over a time span on the order of one second [9], and this side information may be fed back to the transmitter for bit loading in OFDM [9] or for coarse power control [10].

Regarding networking, there is currently an intense research effort to develop protocols for medium access control (MAC), routing, and transport due to the significant differences between underwater and conventional radio networks in terms of propagation delays (1.5 km/s vs. 300000 km/s) and intermittency (similarly, e.g., to contemporary vehicular networks), that lead to very poor performance of existing protocols for terrestrial applications [11, 2, 3]. So far, this has been almost exclusively a research topic, and networking capabilities are almost totally lacking in commercial modems. At-sea validation of protocol performance has been difficult, as the logistics are somewhat complex and practical implementations require some interaction with the physical layer (e.g., channel sensing, precise timing of signal-processing functions) that is typically not supported in commercial modems.

At the European level, relevant present and past projects in underwater networking include UAN [6], CLAM [5] (both FP7 funded), and RACUN [4] (European Defense Agency). The recently completed UAN project [6] (Underwater Acoustic Network) developed and demonstrated in sea trials a wireless network integrating fixed and mobile submerged, terrestrial and aerial sensors for the protection of offshore and coastline critical infrastructures. The proposed network architecture relies on the presence of a central node with powerful demodulating capabilities to which most of the data gathered by the network nodes is directly sent. Local exchanges between nodes are supported at lower data rates. RACUN [4] (Robust Acoustic Communications in Underwater Networks) similarly aims to develop and demonstrate a rapidly deployable underwater network of autonomous sensors and underwater vehicles (AUVs). The focus is on military missions in remote and littoral locations, where this type of ad-hoc network would provide advanced surveillance capabilities in a cost effective way, and at reduced risk to personnel and ships. Its proposed work plan calls for development and assessment of various signaling schemes and transmitter/receiver architectures for the physical layer, testing of candidate MAC and routing protocols, and development of communication simulation tools, including acoustic channel models, link-layer and network topology. CLAM [5] (Collaborative Embedded Networks For Submarine Surveillance) aims at developing a collaborative embedded monitoring and control platform for submarine surveillance by combining acoustic vector sensor technology and sensor arrays, underwater wireless sensor networks protocol design, advanced techniques for acoustic communication, new solutions for collaborative situation-aware reasoning and distributed data and signal processing and control methods. The work plan envisions an adaptation to underwater environments of many concepts related to collaborative/distributed information processing that have been recently proposed for terrestrial wireless sensor networks. The concept revolves around the availability of numerous and low-cost underwater nodes with advanced sensing capability, an appealing concept that significantly departs from what current technology can offer.

### *3.1 – Scenarios*

The projects listed above emphasize data-collection aspects of underwater networking, and tacitly assume that issues related to position estimation of nodes have been resolved. Still, positioning of nodes remains a crucial issue, as data collected on a given area is usually only useful if the sampling locations are known with reasonable accuracy. In the ocean robotics community, by contrast, dynamic positioning of surface or underwater vehicles plays a central role that strongly constrains what is technically feasible. As in other areas, the field of control and robotics has recently shifted in focus towards distributed and collaborative systems, and this trend carries over to ocean robotics as well.

At the European level we highlight projects GREX [12] and CO3AUVs [13] (both FP7 funded). GREX [12] demonstrated distributed surveying and data collection missions at sea carried out jointly by a team of coordinated ocean vehicles, the rationale being that over a relatively large area this can be done more cost-effectively and with fewer risks of catastrophic equipment failure than using a single, more expensive, vehicle. Cooperative positioning through (parsimonious) inter-vehicle exchanges of navigation and location information is at the heart of GREX, as it allows the vehicles to maintain formation while moving, or synchronously conduct a desired survey. The low reliability and interoperability issues of underwater modems impacted the chosen demonstration trials, which favored cooperation scenarios involving mostly surface vehicles. The on-going CO3AUVs project [13] aims to develop, implement and test advanced cognitive systems for coordination and cooperative control of multiple AUVs. Several aspects are addressed, including 3D perception and mapping, cooperative situation awareness, deliberation and navigation, as well as behavioral control strictly linked with the underwater communication challenges. One of the issues under investigation is cooperative localization, where GPS-enabled surface vehicles exchange location and inter-vehicle range information with underwater vehicles, so that the latter can determine their own positions in the water column (thus creating a type of pseudolite system). Ranges are determined using the commercial underwater modems' built-in functionality, and positions are computed through extended Kalman filtering, which provides a proper framework for examining observability issues.

While COMPOUND project mainly addresses networking issues, the prominence of positioning and its tight integration with communications are strongly reminiscent of the context of ocean robotics described above, and this influences the choice of scenarios that are put forth to illustrate the concept.

**Sampling in the water column with drifting nodes:** Fixed observatories can be installed on the sea floor to acquire environmental data in a given area over a long period, but these measurements (with known sampling locations) cannot capture the dynamics of the water column. Similarly, drifting surface buoys can readily georeference their measurements through GPS, but they, too, cannot sample the whole water column. Relatively simple drifting sensors with controlled buoyancy can be easily deployed and have the potential to provide a more complete picture of the spatial distribution of an environmental variable of interest (e.g., salinity, temperature, turbidity, or concentration of some compound). Such deployments could last for days, during which the variable spatial configuration of the network of drifting sensors needs to be continuously updated at the sensors themselves, and also centrally at a control site, so that decisions on suitable sampling depths for all deployed devices can be taken, depending on actual measurements.

Ensuring connectedness of the network as the drifting sensors disperse in the water might require deploying surface vehicles to act as relays in strategic points, so that all submerged sensors can retain a (possibly multihop) connection to the surface and, ultimately, to the Internet. On-line monitoring of sensor positions also simplifies retrieval operations once the mission is completed. This application scenario illustrates several innovative features of COMPOUND, as it calls for the ability to continuously update submerged node positions with limited aid from GPS-enabled surface nodes, remotely access measurements from selected individual nodes, and act on measurements and positions by sending commands in the reverse direction, or changing the network topology.

**Patrol against intrusions:** A set of AUVs may collaborate to patrol a given area against intrusion detection, ensuring full coverage of their objective. They exchange information about possible detection and cooperate in the investigation by spreading the notice and/or by taking joint actions (for example one moves to the threat while the other transfers the information via an acoustic modem, or it comes to the surface to communicate via radio link with the common control station).

**Environmental monitoring of underwater infrastructures:** A collaborative set of AUVs can be used to monitor the status of big underwater infrastructures (like pipelines, offshore oil platforms, etc), taking pictures and/or other data at the same time on a wide area. This application resembles environmental mapping, but it is more relevant to business activities.

## 4. Project Description

At the physical level, work will address methods for exploiting positioning information and channel state information gained through bidirectional transmissions (possibly coupled with channel prediction). This knowledge might be used, e.g., to select a type of modulation that can tolerate the expected channel impairments; to optimize the allocation of bits to subcarriers in an OFDM waveform; to set the parameters used for channel coding; to appropriately choose the transmit power to conserve battery life and limit the interference with other transmissions that might be occurring elsewhere in the network. When ranging information is derived as a by-product of data transmissions between nodes, the associated precision trade-offs attainable by different modulation schemes will also be examined.

At the network level, work will entail the assessment of MAC, error control, and routing protocols. Intermittency in internode connections is typical of underwater channels, particularly in the presence of mobility, and should be taken into account from the outset. The analysis of possible transport-level functions (such as buffering, e2e error control, topology/duty cycle control and congestion avoidance) that may be implement in COMPOUND will contemplate functionality for delay-tolerant networking to support long outages in internode links. The operational goal is to develop all the necessary tools that allow a set of mobile and static underwater nodes to self-organize into a network effectively and seamlessly, supporting different degrees of mobility, intermittent connections, as well as different types of traffic. A layered protocol stack will be adopted, but provisions for cross layering will have to be made so that higher-level localization information becomes available at lower layers while preserving a compact software architecture. Similarly, localization relies on ranging information derived from data packets (and, possibly, specialized waveforms) and will require cross layer access to some of the quantities made available by the physical layer.

Given the measurements from internal node sensors (e.g., pressure/depth, IMU), range measurements between nodes, location information exchanged between neighbouring nodes, and mobility models, cooperative localization algorithms will be developed. One possibility is to apply concepts from cooperative Bayesian filtering [15], resulting in a distribution over all possible positions for every node in the network. In some deployments where nodes have a large communication radius relative to the network size the number of GPS-enabled neighbours for any given submerged node may be sufficiently large for its position to be computed using stand-alone (GPS-like) self-localization techniques.

A selection of the algorithms for communication and localization described above will be implemented into an integrated flexible testbed to be used in field tests. This will consist of a commercial modem wet-end (i.e., electro-acoustic transducer and required signal conditioning stages) driven by an embedded PC, and possibly complemented by specialized programmable signal processing hardware. As in [14] a modular and open software design will be pursued, so that the full protocol stack can seamlessly interact either with the actual transducer and electronics (for field testing), or with a software channel and network emulator (during algorithm development).

One of the innovative features of this proposal is to integrate the COMPOUND system with the Internet at all levels, up to the application level. This makes it possible for nodes to access the Internet and be accessible from the Internet, through specifically derived routing and network protocols, as well as protocol translation gateways. The status of the network (e.g., location of nodes, data traffic parameters, battery levels) can thus be accessed using web-based applications, which are envisioned to enable management of the COMPOUND system. The flexible nodes, based on a software-defined architecture, could even conceivably be updated/upgraded in-place using the Internet connection, although this may not be practical given the scarce available bandwidth. In practice, the interconnection between the COMPOUND architecture and the Internet can be implemented by designing and developing a software-defined Internet router, whose main task is to translate the internal protocols within the COMPOUND network into Internet protocols at the different OSI-stack layers, and vice-versa. This router, physically connected to the Internet, can be either co-located, or connected via a radio link, with a number of surface buoys, which represent the collection points of the COMPOUND network.

A comprehensive testing methodology is envisaged to characterize the overall system and its individual components. To make efficient use of valuable testing resources (tank and sea trials), initial testing and assessment of algorithms for the various components will be done in simulation. Communication algorithms will be tested using a ray-tracing channel model, while a network simulation tool (also incorporating an underlying underwater channel model) will enable testing of protocols and localization algorithms, and optimization of cross-layer interactions. Available tank facilities will be regularly used throughout the project duration to provide more realistic test conditions that incorporate transducers and signal conditioning electronics. At least one sea trial will be conducted to demonstrate the performance of the complete COMPOUND network.

## 5. Business Benefits and Concluding Remarks

Commercial modems incorporating modest networking capabilities (MAC/routing protocols) are only now becoming available. These systems tend to be rather closed, making it difficult or altogether impossible to customize some of the layers of the protocol stack. The emphasis of COMPOUND on openness, modularity of components, and modular testing/simulation of algorithms and subsystems provides an alternative approach that may lead to shorter and more cost-effective product development cycles. It may also increase the potential customer base for network-capable underwater modems, as it incentivates interoperability and, to some extent, frees users from the need to commit to a particular implementation of the protocol stack.

Built-in support for full collaborative positioning significantly extends the capabilities of current underwater modems beyond simple ranging. Potential customers may value not only the availability of spatial information *per se* for data georeferencing, but also the cognitive abilities of the modem to adapt its operating parameters based on that and other side information to make efficient use of acoustic channel conditions.

Finally, integration of the COMPOUND network with the Internet is an innovative and valuable asset that opens up vast opportunities for flexible monitoring and adaptation of network settings using widely available tools. This ultimately translates into lower effort and costs in customizing the system to carry out a desired task.

## 6. References


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