CoLlAborative eMbedded networks for submarine surveillance (CLAM)

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Roadmap

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Future directions in underwater networked sensing

A Roadmap and Strategic Research and Technology Agenda

of the FP7 project CLAM

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1. Introduction

In this Roadmap and Strategic Research and Technology Agenda (SRA), the CLAM project consortium presents its vision on the further development of underwater networked sensing technologies. This report identifies inhibitors of successful developments and proposes solutions to mitigate potential barriers. It is meant to inform the general public, politicians and decision makers, and funding organizations about the importance of networked sensing, the state-of-the-art and the steps needed to create and strengthen a strong and profitable knowledge and technology base.

Monitoring the underwater world is a formidable task due to its complexity, size and extreme harshness, and due to the limited technology we can count on today, whose use needs costly installations, sea trips, specialized personnel, and sometimes dangerous operations. Once installed, collecting the data from the sensor systems used is by no means simple. Long cables may be needed to connect underwater sensors to sea-surface equipment from which data can be collected or transmitted. In addition very costly communications systems may be required.

The demand for underwater acoustic telemetry has in the past been mostly limited to systems for simple controlling, sensing, and activating functions with very low data rate and relatively shallow waters. Examples are acoustic releases of moorings and systems for remote activation of shut-down valves in underwater production of oil and gas. More recently there has been a significantly increased need for underwater communication systems with higher data rates over considerably longer distances for military, security, and civilian applications including fields of energy production (oil, gas extraction), and energy distribution (e.g., oil plants, oil transport, seaport monitoring), and monitoring wellbeing of marine life. Products claiming to meet these needs are appearing, but are still not technically mature as for instance have quite complex Peer-2-Peer communication schemes unsuitable for resource constraint wireless sensor networks.

Even though today's networked embedded systems provide solutions for many challenges, monitoring platforms for underwater applications bring forward yet new unanswered questions and issues. For instance, effective cooperation between individual entities is a necessity, because isolated entities may not be able to perform their tasks with sufficient quality or efficiency, or are unable to reach the required distributed control objectives. Nodes deployed in deep water cannot even reach the surface and deliver their message without cooperation. Making efficient use of scarce resources independent of scale and in such a way that the system adapts to a dynamically changing environment is crucial. Unreliability is extreme due to resource constraints and harsh environment in which nodes are deployed. Situation-awareness about phenomenal changes makes centralized processing an impossible solution.

Despite all odds, today's technology is in fact very close to opening up new ways of tackling submarine surveillance challenges and of monitoring, learning and understanding the complexity of submarine life. The key missing ingredient for turning the vision of continuous fine-grained monitoring and control of shallow/deep water into reality is the availability of an effective and cooperative underwater sensing, reasoning and communication platform, which enables sensing and actuating devices to exchange data, network together, and collaboratively and locally asses their observation environment and act upon it.

2. Underwater Sensor Networks

The first decade of the century, the interest in underwater wireless sensor networks (UWSN) has grown dramatically. This interest is the result of new technological opportunities offered by the ongoing miniaturization of electronic building blocks. The result of Moore's Law: more functionality, smaller dimensions, cheaper, lower energy consumption. IC-technology, MEMS-technology (Micro-Electro-Mechanical System) and NEMS (Nano- Electro-Mechanical-System) cause a true paradigm change in the world of sensor network technology.

Underwater wireless sensor networks show a great diversity. Some are cabled, others are wireless. In some cases, networks consist of sophisticated nodes, for instance heterogeneous networks combining intelligent acoustic sensors with other sensing devices for security purposes like boarder protection. In most cases however, the future underwater wireless sensor networks will consist of a large number of underwater nodes with memory, processing capacity, wireless communication facilities and power. These networks differ as to the architecture, the way intelligence and processing is distributed over the network, the energy conservation mechanisms of the nodes, the powering (batteries, harvesting), etc.

In this roadmap we focus on UWSNs which are wireless mesh networks that link devices that contain a wireless transceiver, a communication protocol handler, an application specific processor with appropriate storage, an onboard power source, and at least one sensor and/or actuator. In a UWSN mesh network, any node can electronically talk to any other node that is in range. UWSN nodes are self-forming - put them in the range of the network and they automatically join - and the network is self-healing - it finds a way to signal around any failed nodes because the mesh of communicating nodes allows multipath hopping of the signals in and out of the network. To that extent a UWSN is comparable with the Internet, but whereas the Internet has TCP/IP as the standard transport protocol, UWSNs lack a common stack on which all applications are implemented.

Lessons learned indicate that the real world in which underwater wireless sensor networks have to operate is hard and continuously confronts researchers and developers with the harsh physical reality. Challenges include the stringent resource constraints of such systems, dynamicity in a real world, heterogeneity of devices, protocols and applications, and complexity when dealing with a large number of autonomous devices. The increasing complexity of such systems can be seen across all these domains. This places strong demands on the needs for advanced new technologies for monitoring and control as well as the underpinning methodologies and theories.

Although currently various underwater sensor node platforms are commercially available, no operational large-scale network of underwater nodes exists. Therefore, it is time to identify what it takes to go beyond small-scale prototypes.

Roadmap and Strategic Research and Technology Agenda

In this *Roadmap and Strategic Research and Technology Agenda*, the CLAM project consortium presents its vision on the further development of this important technology. The technology is entering a new phase aimed at a more mature profile and easy deployment. This implies amongst others the use of standardized tools, which are necessary to turn special-purpose solutions into generic network facilities which can be applied for a variety of purposes and in different operating conditions. Efficiency considerations still play an important part in this context. Part of the future research and development program will be focused on the know-how that is needed to apply this more generic network technology in the near future. The real potential of underwater wireless sensor networks will become clear when the new phase of 'know-how' has passed, after which the new underwater wireless sensor networks will not only be deployable in a cost effective way, they will also be complex. In order to profit optimally from full fledge underwater wireless sensor networks, a number of problems have to be solved. Some of them are quite challenging. To name a few: networks should be scalable whenever extra sensors are added, which means that they still function and even perform better. Future underwater wireless sensor networks will become parts of bigger sensor structures. Other questions that should be answered concern the way information is processed: locally, centrally, in combinations. Future underwater wireless sensor networks will be more mobile and dynamic. They should be adaptive to changing conditions. Last but not least, we will need new concepts for powering the sensor nodes. In many cases, underwater wireless sensor networks of the future should take care of their own energy supply so that the use of batteries can be skipped. These and other technological challenges are described in this roadmap.

3. Underwater application classes and taxonomy

The diversity of applications for underwater monitoring is very high. Examples of underwater applications are:

- **Offshore oil production monitoring**. Traditionally, an offshore oil rig is broadly defined as a construction being either floating and fixed positioned via anchors, or standing on the sea bottom. Today some of the fixed rigs are installed as subsea constructions not visible at the sea surface. The mission of the rigs is twofold. One type is the drilling rigs and the other is the oil/gas production platforms. A monitoring application developed for an oil rig must thus encompass and support a versatile set of purposes. These are related to the (i) business oriented operations of the rig like drilling or oil/gas production, and the (ii) more general responsibilities like being environmentally sustainable and supporting public interests in many aspects.

- **Environmental monitoring**. Environmental monitoring of the oceans can be categorized in pollution monitoring, ocean current, and wind monitoring. The underwater sensor network deployments for environmental monitoring can be random or planned, depending on, among others, the water depth, weight of the sensor nodes, and costs. In case of a fixed deployment nodes are accurately positioned by for instance divers and anchored either at the surface or at the sea bottom.

- **CO2 storage**. The geological Carbon Capture and Storage (CCS) technique consists of capturing CO2 from power and industrial activities and storing it in deep geological reservoirs. CO2 can be stored underground by direct injection into porous reservoir rocks such as those found in depleted oil and gas fields and in regional saline aquifers. Storing CO2 underground is volumetrically very efficient. As CO2 is injected into the subsurface it undergoes an increase in density. Ideal conditions for subsurface storage are at depth of about 1000m where CO2 is in the supercritical conditions, pore-water are saline and porosities, in many sedimentary basin, are likely to be high. However, the selection of appropriate storage sites is crucial to ensure that the stored CO2 will be completely and permanently contained. Each of the chosen sites will need to undergo a rigorous set of controls to ensure the integrity of the storage reservoir and to guarantee human and ecosystem safety.

- **Safety and security**. Safety and security monitoring applications include monitoring underwater structures and infrastructures such as harbors and pipelines as well as monitoring borders trespassing. This may encompass both security in terms of intruders in harbors and safety at sea supporting the supervision of the conditions of ship wrecks and other underwater constructions possibly causing harm to the environment and to people traveling and operating at sea.

- **Marine species monitoring**. Underwater sensor networks can also be utilized to enable data harvesting related to marine life, including for example: Monitoring marine ecosystems like reefs, Tracking of fishes, Monitoring fish farm conditions, Monitoring underwater man-made noise and their impact on marine life

- **Military activities**. Underwater acoustics was developed during war time, where submarine vehicles with Sonars (Sound Navigation and Ranging) could detect location and range to e.g. other submarine vehicles. In the later years network centric warfare has also pushed for sensor and communication network in the underwater environment. In this application group the following domains can be mentioned: Inter-submarine telephony and data communication, anti-submarine warfare, Mine detection (AUV and optical sensors needed, or active sonars), ship and intruder detection. Both passive and active sonars are in used for object detection. For the communication aspects, acoustic transducers and hydrophones has been used to communicate both clear voice and modulated voice. Early data communication used Morse code. Modern digital communication enables data encryption, which is highly relevant in this domain, which can be used both for voice communication and data communication.

- **Underwater cultural heritage**. Protection of and access to underwater cultural heritage sites can be enabled via underwater sensor networks. The protection is important due to divers and other possible surrounding activities. The enabling of access can be done via underwater images, sound recording, sonar mapping, etc. This will cause awareness of the presence of these sites and findings and can be used to support archeological research and presentation to the public.

- **Commercial fishery**. Ocean commercial fishing vessels continue to grow in size, making efficient harvesting of the resources possible. Likewise are the size of the trawls and the purse seines. As the size and cost of the equipment continue to increase, the relative cost of instrumenting the equipment is reduced. Instrumenting the equipment has the potential of even higher increase of the selectiveness of the catch and the attainability of the fisheries. Increased efficiency and control of the condition of the equipment also follows.

Taxonomy of underwater applications

The applications can have very different requirements: mobile or fixed, short or long lived, highly reliable or best effort, high density or low density, etc. Based on the taxonomy presented by Partan et al. [2], which is based on variance in node population and network coverage area of underwater applications and also the taxonomy of IP applications, we define a new taxonomy for underwater sensor network classes. In what follows, we describe the six classes defined.

Class 1: delay and disruption tolerant networks

In this class, the node density is so low that there is no guarantee that sensor nodes will have an acoustic connectivity towards the sink(s) at all times. In order for these networks to function, several or all nodes are mobile (and may in fact move in a randomized-like manner within a predefined area) so that each node's connectivity is given as a stochastic process.

Class 2: elastic multi-hop

In elastic multi-hop networks the node density is high enough to ensure that the sensor nodes will have an acoustic connectivity (either directly or via multi-hop) towards the sink(s) almost at anytime. However, due to the variability of channel conditions, there will still be a small probability of link outage. Redundant paths should however ensure that new routes are discovered and effectuated within reasonable time. Class 2 mobile nodes are optional.

Class 3: elastic dense

In elastic dense networks the sensor nodes will typically all have a direct link towards the sink(s). However, due to the variability of channel conditions, there will still be a small probability of link outage. Multi-hop will therefore in rare cases be necessary. Class 3 mobile nodes are not necessary for networking operations.

Class 4: real-time multi-hop

In real-time multi-hop networks the node density is high enough to 1) ensure that the sensor nodes will achieve acoustic connectivity (either directly or via multi-hop) towards the sink(s) almost at any time, and 2) that redundant paths to the sink are available at any time to ensure that in case of connection failure alternative routes can be effectuated within very short time. Class 4 mobile nodes are optional.

Class 5: real-time dense

In real-time dense networks the node density is so high that the sensor nodes will typically all have a direct link towards the sink(s). However, due to the variability of channel conditions, there will still be a small probability of link outage. Multi-hop will therefore in rare cases be necessary. Class 5 mobile nodes are not necessary for networking operations.

Class 6: real-time loss-intolerant

In real-time loss-intolerant networks the node density is so high that the sensor nodes will typically all have a direct link towards the sink(s). Variability of channel conditions must be handled by always having uncorrelated redundant paths towards the sinks. Multi-hop will therefore in rare cases be necessary. Class 6 mobile nodes are not necessary for networking operations.

4. Market trends in sensors and instrumentation

This section is largely based upon a recent market study as published in the November/December 2012 edition of Marine Technology Reporter [1]. The study is based on trade information as presented by the Harmonized System (HS) code 9014 and 9015 of the United Nation's Comtrade database. HS 9014 and 9015 capture all navigational and survey instruments, and thus includes above water sensors and instrumentation also. Nevertheless, it is expected that the trends as indicated in these numbers are clear indicators for underwater equipment also.

The report shows that the world's exports of navigational and survey instruments nearly doubled in 2001-2011. In 2011, 63% of the exports, €8 billion, were accounted for by surveying, hydrographic, oceanographic, hydrological, meteorological or geophysical instruments and appliances, while navigational instruments represented 37%, or €4.3 billion.

4.1 Exports

As shown in Figure , Europe is the world's leading exporter in navigational and survey instruments, representing more than 35% of exports in 2011 from the United Kingdom, Germany and France. The United States are the world's single largest country, with 22% market share. Canada was the world's fifth largest exporter of underwater instruments in 2011.

In the period 2001-2011 the world market share increased for the top exporters, Germany, China and Canada by 6%, 3% and 2% respectively. Meanwhile, the United Kingdom and the United States lost market share during the same period by 10% and 7%, respectively. China's exports of surveying instruments in 2001 was only a half of what Canada exported, but in 2011 the value of China's exports surpassed Canada's exports, accounting 6.3% of the world exports.

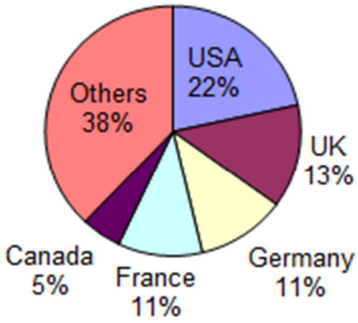

Figure 1: Leading exporters of underwater sensors 2011 (based on data from[1])

4.2 Imports

In terms of imports, Europe is the largest import market for navigational and surveying instruments, the two largest markets Germany and the United Kingdom together cover already 18% of the market in 2011. The market in the United States comprises 17% of the world imports in 2011. Canada (6.7%) and China (6.6%) closely follow Europe and the US. Among the top 20 importers, China's and Singapore's markets have expanded the most in recent years. Their share of world imports increased in 2005-2011 by 2.2% and 1.4%, respectively.

Meanwhile, import markets for underwater instruments in the United Kingdom and France declined during the same period in terms of their share in world imports by 4.6% and 1.3%. Overall, these figures demonstrate the dominant position of Western economies in navigational and survey instruments as both exporters and importers.

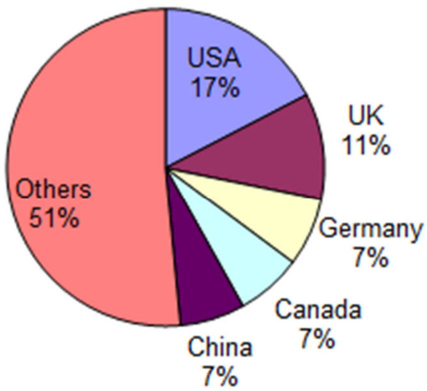

Figure 2: Leading importers of underwater sensors 2011 (based on data from[1])

4.3 Growing markets

Developing countries are becoming important markets for underwater sensors and instrumentation. The most rapid market growth for navigational and surveying instrumentation is found outside Western developed economies.

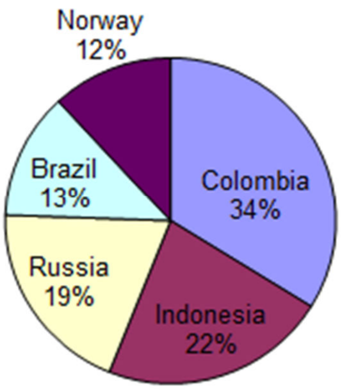

Figure 3: Fastest growing overseas markets 2011 (based on data from[1])

Figure shows the countries with the fastest growing markets for underwater instruments in 2005-2011. This figure clearly indicates that the largest market for underwater sensor systems is related to offshore oil activities. Among the top 20 importers in 2011, Colombia's imports grew fastest over the period, recording a 452% import increase, followed by Indonesia (279%), Russia (245%) and Brazil (158%). In navigational instruments, China, Russia and Hong Kong experienced the most rapid growth of their import markets, while Colombia, Norway and Russia have emerged as rising markets of surveying instrumentation. Brazil will likely be a strong growth market for underwater acoustic technologies such as side-scan and multibeam sonars in the near future as it develops its offshore oil resources. China has significantly expanded their imports, and, to a lesser extent, their exports, in the past decade. Some global lead firms have started to manufacture sensors in emerging markets to tap into the growing demand for acoustic and non-acoustic sensors and instrumentation.

One example is Kongsberg Maritime's sensor factory in China, which was established in 2009 to sell its products to a growing number of customers in China and across Asia. The sensor production lines are intended for larger volumes and mass production for these customers, while in Trondheim, Norway, the company will take care of customer specific sensors, spare parts and European orders.

4.4. Market consolidation

An additional trend is the growing consolidation of the marketplace. In an effort to provide a wide range of products for many different end-markets, some large firms are buying smaller firms. Acquiring smaller, more specialized firms enables technological acquisition and helps firms to attain scales of economy in research and development, marketing, and end-market coverage. This trend will likely continue in the future, especially as a way for large firms to acquire innovative technology.

One example in the industry is Teledyne Technologies (profiled in the September 2012 issue of Marine Technology Reporter). Since 2005, it has acquired 26 firms: in 2005, Cougar Components, RD Instruments, Benthos; in 2006 Rockwell Scientific, Ocean Design, CollaborX; in 2007, D.G. O'Brien, Tindall Technologies, Judson Technologies; in 2008, Impulse Enterprise, TSS International, Judson Technologies, Webb Research, Filtronic Plc (defense electronics), Cormon, Odom Hydrographic Systems, Demo Systems; in 2010, Optimum Optical Systems, Intelek plc, Hafmynd (Gavia's AUV maker), DALSA Corporation, and Nova Sensors. In 2012, Le Croy, PDM Neptec, Blueview Technologies, and VariSystems were acquired by Teledyne Technologies.

5. Inhibitors of UWSN systems

This section identifies inhibitors and hard-to-solve challenges of successful developments and proposes solutions to mitigate potential barriers. In this context, networked sensing technology can be broken down into the following four themes.

1. *System engineering and platforms*: the technology that interacts with the physical world, further specified in sensing, analysis, synthesis, and actuation,

2. *Processing and networking*: the technology that facilitates communication and cooperation among interacting nodes, and

3. *System cycle*: the technology that manages the thus formed system

4. *Business and society:* the aspects that constrain the whole system, its concepts, its fundamental principles, and the effectiveness of business processes.

For each theme we have identified inhibitors, roadblocks that hinder the application of underwater sensor networks. To quantify the inhibitors, we have made a questionnaire and asked experts in the field from industry and research, to rank the significance of the current inhibitors as being either strong, neutral, or little. This represents then similarly challenges that are either hard, medium, or easy to solve. The outcome of the survey is shown in the related sections.

5.1 System engineering and platforms

System engineering and platforms concern the capturing of data, the actuation, and the interface to support efficient, flexible, and accurate control over the fundamental processes of underwater sensor networks. From this theme's perspective it is imperative to design and develop energy efficient and reliable hardware, for integrated and multi-functional sensing, for analogue and digital signal processing, and for effective actuation. Flexibility is ensured through the use of energy harvesting and energy storage mechanisms. Special attention is required for packaging for deployment in harsh environments.

Ease of deployment and accurate control will be provided through the design and development of energy efficient communication, synchronization, collaboration, and co-location techniques.

Inhibitors for system engineering and platforms include:

- **Energy.** Many sensors and actuators have limited access to energy, which makes it the single most scarce resource in sensor networks. Power hungry designs may increase the functionality of devices, but will considerably reduce their lifetime. Energy is generally not ubiquitously available. It is either limited in capacity by the battery, or only available at specific times in case of energy harvesting. Large batteries contradict miniaturization and frequent replacement of batteries is uneconomical. Since deployment and retrieval of underwater sensors can often be very expensive (i.e., ship or aircraft time, ROV/AUV operations), extending the operational duration of instruments underwater is a major factor pushing innovation in the industry [market study]. Exploiting energy harvesting is essential for long lasting underwater network operations.

- **Node size**. Sensor and actuator nodes are deployed close to an object under observation or control. Big integrated nodes generally require too much energy, too much space, and too much maintenance to be merged in the environment and to be economical. Large size and high cost (in terms of purchase, installation, and maintenance) are obstacles towards easy and widespread deployment of current monitoring systems. In addition, periodic manual calibration needed to ensure that systems continue to operate reliably is a labour-intensive procedure and greatly contribute to this issue.

- **Integrated sensing**. Another key trend is the bundling of numerous sensors and instruments on a single platform, and consequentially, the importance of system integrators in the underwater sensor value chain. Systems integration is rapidly evolving. Improvements in software and hardware have facilitated the integration of multiple sensors on single platforms. Integrators are combining instruments into "sub-systems" to develop measurement, wireless/satellite communication, and data collection/processing/storage sensor suites. Integrators also are pushing the development of modular "plug-and-play" technologies easily integrated with a number of platforms brands and types (i.e., ships, moorings, and ROVs/AUVs).

- **Heterogeneity.** An enabling, universal, underwater wireless sensor network technology must be able to cope with diversity of node platforms that differ in time scale, in semantics, in size, and in distortion. Current systems lack effective provisions to deal with this heterogeneity.

- **Environmental disruption.** Nodes are deployed in harsh or aesthetically appealing environments. This requires appropriate packaging. At the end of their lifetime, nodes become electronic-waste. Just leaving them behind is a high burden on the environment and a potential destruction of assets. Acoustic disturbance is potentially harming nature.

- **Harsh environments**: The expansion of human activity in the ocean and the deep sea has led to a demand for sensors and instrumentation capable of surviving extreme conditions. For work in these environments, end-users will increasingly demand equipment with greater energy efficiency, longer mission life, and capable of automated or remote control. The key technology challenges are increasing the reliability and resilience of sensitive instruments on ships, underwater vehicles, and other marine platforms to allow for continued remote operation with minimal maintenance, repair or human supervision. The fact that only a single underwater sensing system is used to cover a large geographic area means that such systems are not robust as the failure of a single sensor may result in an important event being undetected. Harshness of the underwater environment also contributes to more frequent failure and mis-calibration of the sensing devices, routing faults, failures at the network level, and loss of measurements.

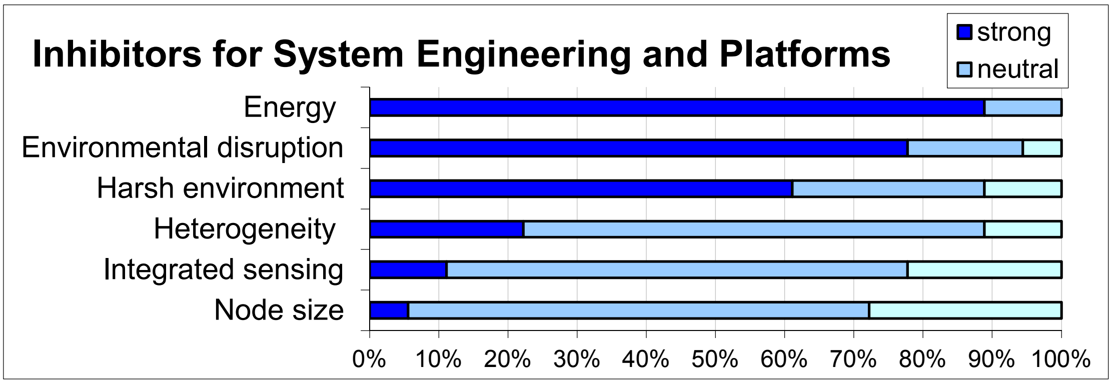

Figure 4: Inhibitors for system engineering and platforms

5.2 Processing and networking

Information processing concerns all necessary steps from the sensing of data to be presented to applications for further processing and interpretation. Networking concerns the process of propagating data through a network that is in a constant state of flux.

Inhibitors for processing and networking include:

- **Low performance of acoustic communication.** One of the main challenges of UWSNs is the inherent spatial and temporal heterogeneity of the underwater environment and the relative underwater acoustic channel. This heterogeneity derives from the strong variations in water temperature and salinity profiles (e.g., arctic sea vs. tropical or temperate seas, lake vs. seas, summer vs. winter profiles), water depths and bottom slopes, seaweb types and stratification, wind and water currents, fresh water run off and solar insolation, ice cover and surfactants, surface waves and breaking events, etc. All these factors significantly affect underwater acoustic communications and therefore the performance of protocol solutions for underwater sensor networks. Delays are five orders of magnitude longer than the ones experienced in terrestrial wireless networks and the bandwidth of an acoustic channel is much lower than over wireless RF links. Operating in an insufficient data rate acoustic channels and in a single-hop network is a normal practice in existing underwater monitoring systems. This, however, is not adequate for underwater monitoring applications where higher data rates over considerably larger areas and longer distances are required to deliver the necessary communications capabilities.

- **Sparse deployment and scalability**. To sense and monitor submarine environments, sensor nodes should be deployed in 3D and their location is usually controlled (as nodes are attached to buoys and float at different controllable depths, or are anchored to the seafloor). Given the higher cost of underwater sensors, and the higher size of areas over which they are deployed underwater sensor nodes tend to be much sparser than in wireless sensor networks deployed in land. This demands or a careful 3D topology planning and routing to enable node connectivity on the one hand and to optimize placement for better performance on the other hand. Additionally, the fact that current underwater sensor networks are sparse prevents from exploiting a high degree of redundancy which is the basis for many current cross-layer optimized MAC/routing wireless sensor network protocols. On the other hand, adding redundancy increases collisions and noise, which may lead to performance loss, or even breakdown, when deployed at sea in large numbers. Ideally, adding more nodes to a network should improve the performance rather than attenuate it. Networks must be reliable and easy to maintain. Ideally, systems are self-healing and optimally redundant.

- **Resource scarcity.** Underwater wireless sensor networks suffer constantly from a lack of resources. When energy consumption, bandwidth, processing power, and storage capacity are wrongly managed, the lifetime of a system is affected in a negative way. Real-time behavior is a crucial factor enabling efficient resource usage, and is also essential for quite a range of applications: prompt response to observations and immediate action.

- **In-network processing support.** Future underwater wireless sensor systems must be flexible and functional. Without the ability to support multiple applications, to maintain concurrent modes of operation, and to reconfigure seamlessly, the acceptance in the value chain is confined to niche markets. Additionally, as processing data is much more energy efficient than communication a proper system support for an in-network processing is essential.

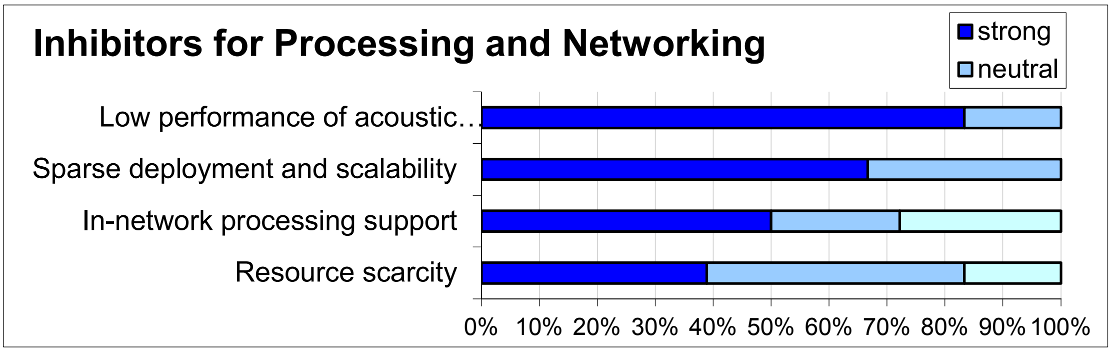

Figure 5: Inhibitors for processing and networking

5.3 Service architecture and system cycle

A platform approach aims at a service architecture, tooling and middleware that is independent from the hardware platform, supporting a wide range of information processing and networking paradigms and applications. Thus creating a service architecture.

An operational networked sensing and actuation system is the result of a development and deployment process. In a fairly standardized approach, the following steps are involved: analysis, design, implementation, testing and maintenance. We call this the system cycle.

Inhibitors to the service architecture and system cycle include:

- **Long development cycle.** The acceptance of underwater sensor systems is hindered by long development times, and high cost of equipment and experimentation. Without proper programming models and tools that provide support to simulate, emulate, and test in real-life new protocol stack solutions, and that can handle heterogeneity of networking technologies, this situation will remain to exist. In order to prove the value of models, integration with testbeds is required. Proper tools for in-system diagnosis, debugging, control and general management support are invaluable.

- **Lack of experimental facilities**. Successful evaluation and validation of novel technologies for underwater wireless sensor networks require large scale, experimental facilities enabling open experimentation of key underwater sensor network technologies, in heterogeneous application domains and in realistic settings. Also experimental facilities should be easily usable by end users without an ICT background, with the objective to involve them in the definition of the application and service logic, and in the usability tests of the applications developed.

- **System flexibility.** System flexibility is a requirement for many announced applications of sensor networks. Proper mechanisms to support migration of processing and services, as well as reconfiguration after node failures, topology or environmental changes, currently prevent universal application of sensor networks.

- **Need for open standard protocols and solutions.** Interoperability is a key issue also for underwater wireless sensor networks. Without proper alignment of design principles and standardization of sensor and actuator configurations and their data, system composition will remain a tedious and labor intensive process. Systems are frequently made of heterogeneous platforms; assets belong to and are under the responsibility of different authorities. Allowing heterogeneous assets to discover each other and being able to communicate and cooperate is a key target. In addition, developing standardized node level adaptive architectures, thus increasing flexibility and allowing to experiment with novel paradigms, and reference protocol stacks and network architectures, as well as standard interfaces to integrate underwater sensor and actuator networks to the Internet, is a key issue that has not been pursued yet.

- **Combining technology domains.** The effective combination of locally sensed and globally accumulated data gives a performance boost to services of sensor networks. However, currently the technology does not enable semantically supported combinations of multi-layered data, which makes it virtually impossible to create a platform that supports heterogeneous data sets. In addition to the inability to combine data from various sources, often the various technology domains are ill connected. A generic platform that semantically supports combinations of multi-layered technology domains would be a true asset.

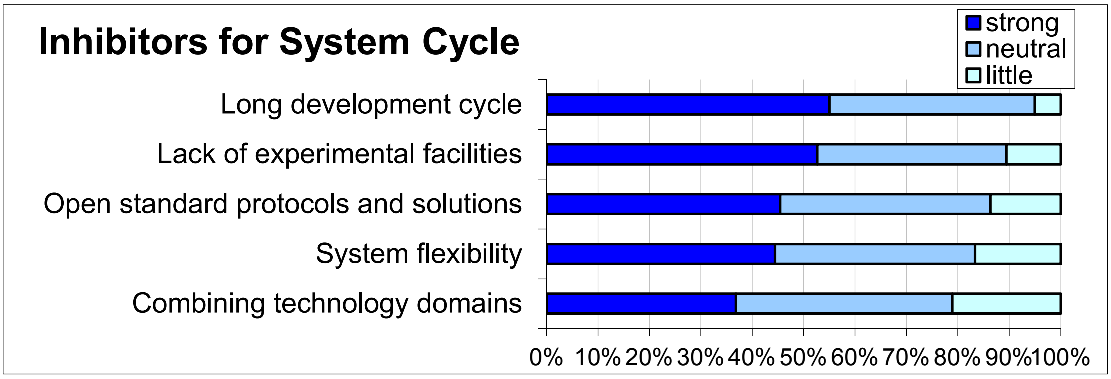

Figure 6: Inhibitors for system cycle

5.4 Business and Society: vertical issues

The value chain of underwater wireless sensor networks contains integral aspects that cannot be confined to specific layers of technology, design, processing or networking. These aspects constrain the whole system, its concepts, its fundamental principles, and the effectiveness of business processes. Important issues include encouragement for innovative application of underwater wireless sensor networks, fostering cross-sector partnerships built around the value chain, and leveraging underwater wireless sensor networks as user-based open innovation schemes.

In addition, the regulatory and policy issues must be addressed to create interoperability, openness, lawful interception, and privacy to name but a few. All aforementioned issues originate from business enablers, business opportunities, and political and societal concerns.

Inhibitors for vertical issues include:

- **Open chain market.** Until now, underwater wireless sensor networks have been treated as a technology for niche markets, and for applications that are clearly needed. In order to conquer the world, viable innovative business models are crucial.

- **Dependable systems.** Social and business acceptance requires reliable and trustworthy systems. Failing systems are a cause of frustration for users, which has its effects on business opportunities. Even more sincere is the dependability on accurate observation systems for monitoring of critical infrastructures. For harsh environment of underwater wireless sensor networks autonomy of nodes and the network is an absolute must. Typical characteristics such as self-supporting, self-configuring, and maintenance-free must be achieved.

- **Sustainable systems.** Social and political acceptance of underwater wireless sensor systems demands efficient use of resources and of the public water spaces.

- **Security**. Acceptance of sensor networks requires trustworthy methods for selective disclosure of data and revocation of data if expedient. In order to generate value by a sensor network, inherent support for authentication, authorization, and accounting is crucial.

- **Accountability and transparency.** Users are accountable for their actions while they should rely on being in control. The system must accommodate both properties for successful business deployment and acceptance. Large-scale networks may have different hardware owners and different service providers. The lack of clear models of ownership and management of data and infrastructure hinders the acceptance and use of these systems.

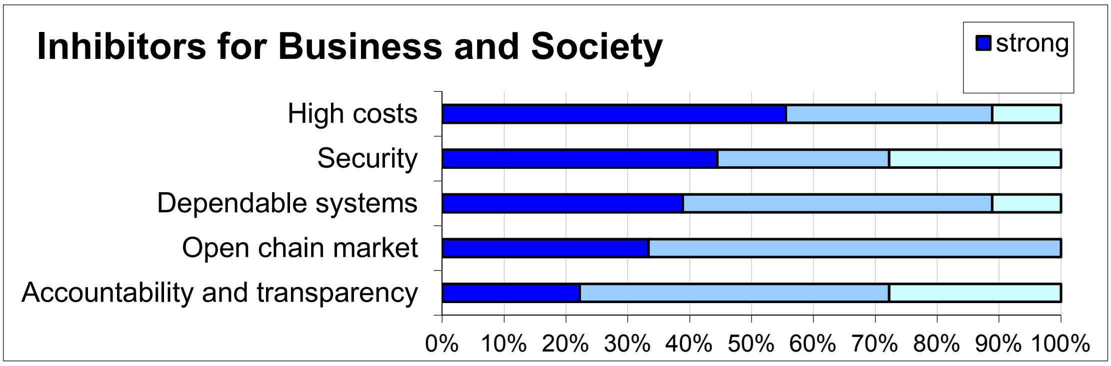

Figure 7: Inhibitors for business and society.

6. Enablers and future directions

In the previous sections, we have presented a range of inhibitors and challenges for each of the themes. A number of them include an obvious solution, while others will benefit from a more general approach.

The urgency and importance of the technological enablers and future challenges vary depending on (i) scope and applications, (ii) current maturity of technology, and (iii) market demands and developments. In what follows we consider a timeline of the next decade and indicate when we expect to realize these enabling technologies.

The non-exhaustive list of solution directions for research and development in each of the four identified domains is as follows:

6.1 System Engineering and Platform

Short term (within 5 years)

- **Auto calibration.** Maintenance-free nodes are enablers for many business models. Unmanned calibration of measurements is generally a hard problem, which becomes even more problematic when nodes are inaccessible and when the number of nodes is large.
- **Sensor/actuator platform.** For the flexible deployment of underwater wireless sensor networks, a standardized platform is essential. A platform allows for efficient reuse, effective resource sharing, and easy configuration and deployment.
- **High performance wireless.** The low performance of underwater wireless communication is a clear bottleneck for widening applications of underwater monitoring systems. Special attention is required related to bandwidth improvements, and increasing reliability.

Long term (between 5-10 years)

- **Ultra-low power.** Flexibility, accuracy, and response time come with a requirement on the processing bandwidth of sensor and actuator nodes. Development of high-precision, high-speed, yet low-power digital signal processing units is crucial. Sensors and actuators operate in the physical, thus analogue, domain, while data management and control processing are generally in the digital domain. Conversions from one domain to the other are loss-free only at the cost of a significant amount of energy. Better and scalable conversions will help to exploit opportunities to reduce energy costs.

- **Energy harvesting.** Sensor nodes are often surrounded by energy sources. However, most of the time the energy is not in the right form to be used by the node directly. New means are needed to harvest these energy sources. The ultimately goal is a generation of self-supporting nodes.

- **Reconfigurable radio design.** Reconfigurable radios yield highly sensitive, flexible, and energy efficient radio components. Special attention is required to make them context aware, which enables efficient use of resources. Examples include quality-aware MAC, time synchronization and localization.

- **Recycling.** The ecological footprint of large-scale underwater wireless sensor networks is quite significant. Careful design to minimize the waste, during production, operation, and at the end of their lifetime is required to guarantee societal acceptance. Solutions are sought to structurally develop systems that enable reuse and repurpose end-of-life equipment, and that annihilate worn-out infrastructures.

6.2 Processing and Networking

Short term (within 5 years)

- **Network protocols.** In designing resource-sharing schemes, the peculiar characteristics of underwater channels have a large impact. Dedicated medium access schemes are needed to improve performance and efficiency. The design of routing and transport is in particular critical, because due to the low throughput and high latencies the traditional radio based protocols are highly ineffective and not efficient. Keeping a strict separation between communication layers is known to result in suboptimal use of the available channel capacity. Cross-layer optimization of information and communication may increase the information capacity of a network considerably.

- **Adaptive sampling and censoring.** By exploring the networked capabilities of sensors, it is possible to reduce energy consumption while still being effective. Adaptive sampling methods, that is scheduling and assignment of nodes, in time, in space, and in information, potentially improves efficiency. Suppose that we can build a decision making hierarchy, based on the amount and accuracy of the available data. At some point in the decision tree the outcome is not likely to change. This decision can be used, irrespective of the fact that the data is complete or not.

- **Localization and time synchronization.** These network services are of particular interest due to the applicability in many scenarios and protocol performance optimizations. Localization, time-synchronization and communication scheduling are closely related, and exploring the interactions among those is a viable research direction.

Long term (between 5-10 years)

- **Adaptive distribution.** Processing and storage nodes can be scattered over the network or can be concentrated in a central area. An adaptive arrangement of processing and storage sites configures and reconfigures the networks of these resources depending on the actual state of the network and the nature of the application. Applications benefit from the appropriate organization of a network. Sometimes a centralized approach is adequate, while at other times application infer data in a distributed way.

- **Semantic data aggregation.** Data that comes from different sources is difficult to combine. In case of a semantic annotation, data can be transferred automatically to a common domain, which simplifies complex applications. Semantic aligning and standardized tagging of information across heterogeneous node sets is a solution to selfcalibration, automatic mashing of data, and business integration.

6.3 Service architecture and system cycle

Short term (within 5 years)

- **Sensor testbed.** In order to enable fundamental, creative, and technology-rich solutions, alignment of efforts and resources is an absolute must. To validate methods individually as well as in cooperation with each other, large-scale field laboratories must be developed. To exploit the opportunities offered by this huge potential new sector, the sector needs shared, easy to use, experimental facilities representing a diversity of relevant underwater domains and applications, thus eliminating the current barriers (in terms of high cost infrastructures and long training) that prevent access to the underwater market segment and the underwater research field today.

- **Platform models for nodes and networks.** Uniform abstractions and transparencies are absolute prerequisites to develop model-based composition methods and tools. Given these models, networks of underwater sensors can be deployed off the shelve.

Long term (between 5-10 years)

- **Programming models.** Generic application rules, with accompanying programming primitives, and proxies provide the basis for compiler-founded techniques in the programming and configuration of sensor networks. The application rules include technical aspects as well as political aspects. Dissemination of these rules and their acceptance are important assets.

- **System wide resource management.** The setting of individual nodes and the overall objective of the system may not be in line. Aligning methods may help to mitigate interference and scaling problems.

6.4 Business and society: vertical issues

Short term (within 5 years)

- **Application driven development.** Before true multidisciplinary development in underwater wireless sensor networks can be effective, interdisciplinary projects that accelerate public acceptance and business in this field have to be initiated.

- **Business model development.** For the broad acceptance of underwater wireless sensor network technology properly aligned business models must be developed. From past experience expedient business models include: Monopoly, Open source, and Service Oriented Architecture. Research and development activities for these markets are notoriously difficult.

Long term (between 5-10 years)

- **Future Internet.** As for the terrestrial world, where the Internet has provided the enabling technologies to acquire and share knowledge at levels previously unavailable, Internet Technologies have the potential to take a key role in the technological uptake driving the growth and development of the marine economy, through exploration and understanding of the marine environments. In particular, the combination of an underwater Internet of Things (IoT), implemented through Underwater Wireless Sensor Networks (UWSNs) with underwater robotics technologies, novel underwater communication technologies and paradigms, and the integration of the resulting underwater IoT system into the Future Internet can provide the missing effective, pervasive means to sense, monitor and control ocean processes to sustainable manage our planet resources. This is the missing technological enabler for the marine sector.

7. Concluding remarks and points of action

In this Roadmap and Strategic Research and Technology Agenda we have structured the field of underwater sensor networks. We have spotted a trend that sensor network technology for underwater is still lagging behind the traditional sensor network technologies. Still, many lessons can and have been learned, and we already see the move from pure sensing and communication towards the inclusion of networking, reasoning, control and management. In other words, sensor network technology is maturing in this domain already. The same trend is observed in the way the field is approached nowadays. Initially, the development was interdisciplinary with distinct applications and experiences. Now the time has come to move over to a more multidisciplinary approach with more generic results.

There is significantly growing interest in the deployment of underwater sensor networks. Even though a number of acoustic modems that are needed to create these networks are currently available as commercial and academic projects, these existing systems suffer from several drawbacks, which hinder the rapid take-up in many commercial applications. Dependability, cost, difficult deployment, scaling, trustworthiness, time to market, business alignment, and integration are all potential showstoppers for successful facilitation. Yet there is a universal consent that it can be done. The way to proceed is to develop models for many of the identified issues and their expected solutions. Proper models will guarantee seamless interaction. In addition, validation and exploration is important to keep in touch with the market. In parallel, innovative business models must be explored.

The structuring of the field of sensor networks gives us a platform to identify the hard problems, the challenges, and the conceivable solutions. Our enumeration is far from complete.

Recommendations

The clearly identified inhibitors and solutions that require immediate attention are the following:

- Energy consumption and energy storage are show stoppers for underwater sensor networks. Unlike terrestrial solutions, for underwater not much progress has been achieved in this area. Work on reducing energy consumption within the whole system is essential.

- Low performance of the wireless communication is a clear inhibitor, and solutions to increase bandwidth and reliability are urgently needed.
- Adaptability and reconfiguration are essential to achieve interoperability and efficiency. Work should be intensified to realize flexible (software defined) platforms.
- Scalability, heterogeneity and resource scarcity are clear inhibitors. Potential solutions that require attention are adaptive sampling and censoring, and cross-layer networking protocols.
- Rapid development, network maintainability, and proper methods for process and service migration are an absolute must. Work on platforms and programming models should have the highest priority, supported by underwater sensor testbeds and field labs.
- For the vertical issues, the inability to build proven dependable and secure systems is an absolute showstopper. Urgent actions are necessary on shared infrastructures, security, business models, and an overall efficiency gain of the value chain.

Final recommendations:

- Experience in the field should be exploited to create viable business models. High costs of equipment and the long development cycle are clear inhibitors for that. It is absolute indispensable to keep building an active community through networking, joined projects, shared testbed facilities and standardized products.
- Underwater sensor networks will become mainstream commodities, thus entering the human ecosystems. The sensor network community should be aware of ethical issues that will come along with its success.

How to implement the recommendations

The recommendations as outlined in this section need to be implemented by a diversity of organizations, research institutes, industries, and funding organisations. We can identify the following actions that are needed to be implemented:

- **Bringing research and development together**. Underwater research is evolving quickly, and in the recent years many new projects and conferences on this topic emerged. In order to effectively take-up the results of this research effort, it is important to align the research and development effort, and bring both together. It is essential for national and international funding agencies to perceive this need, and develop specific programs in which the scientific community is encouraged to work together with industrial partners in further developing robust and versatile underwater monitoring solutions. Industry is encouraged to streamline its product development with recent research efforts, and to combine efforts thereby enabling a wider scope of technologies and application areas.

- **Mobilizing community**. The underwater sensor network community has been working so far rather isolated on each area, which has led to isolated and sub-optimal solutions. In order to be more effective, and be able to standardize and use existing solutions, it is essential that the community is being made aware of each other, and is encouraged to share their results. The establishment of a dedicated special interest groups on underwater monitoring systems could be a first step towards this vision. The upcoming Horizon 2020 program provides a multi-year framework to strengthen cross-links between actors and communities and building and exploiting new forms of cooperation. To enable this cooperation, the FP7 FIRE program aims at fulfilling a specific role as the research and innovation "engine" of the evolving European Future Internet ecosystem. Synergies should be explored between initiatives and programs such as FIRE, EIT ICT Labs, FI-PPP, the new 5G PPP initiative, as well as national research networking initiatives (Géant) and Future Internet initiatives worldwide.

- **Widening application scopes**. The combination of an underwater Internet of Things (uIoT), implemented through Underwater Wireless Sensor Networks (UWSNs) with underwater robotics technologies, novel underwater communication technologies and paradigms, and the integration of the resulting underwater IoT system into the Future Internet can provide the missing effective, pervasive means to sense, monitor and control ocean processes to sustainable manage our planet resources. The outreach programs can help creating awareness for end-users and the industry about the potential and capabilities of underwater sensor systems. This awareness will breach the technological push and market developments.

- **Standardization**. Interoperability and standardization is a key issue for underwater wireless sensor networks. Allowing heterogeneous assets to discover each other and being able to communicate and cooperate is a key target. The various standardization bodies (such as IEEE, IETF, IPv6 Task Force) should become aware of this new emerging field, and standardization activities should be started soon. Cooperation should be explored between initiatives and programs such as FIRE, and EIT ICT Labs. The Internet Research Task Force (IRTF) focuses on longer term research issues related to the Internet while the parallel organization, the Internet Engineering Task Force (IETF), focuses on the shorter term issues of engineering and standards making. An example of an emerging standard on signaling standard is JANUS [3]. JANUS is a simple, robust signaling method for underwater communications. It has been developed at the Centre for Maritime Research and Experimentation (CMRE) with the collaboration of academia, industry and government with the intention that it should be freely distributed and available to all. It is on the path to become a NATO standard for underwater communication. Within CLAM the Sunset framework has been developed which enables a separation of concerns between high level programming and low level characteristics.

Acknowledgements

This roadmap and strategic research and technology agenda resulted from input from the CLAM advisory board, the CLAM consortium partners, and external experts in the field of underwater networking and applications.

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[3] http://www.januswiki.org/tiki-index.php

Appendix 1. Implementing the recommendations

In this Roadmap and Strategic Research and Technology Agenda, the CLAM project consortium presented its vision on the further development of this important technology. The technology is entering a new phase aimed at a more mature profile and easy deployment. The CLAM project contributed to several challenging aspects for underwater sensor networking, e.g. in the area of architectures and common frameworks, platform development, and protocols. The results of the CLAM project have drawn significant attention by leading international institutions in the field of maritime science and engineering.

The roadmap also identified recommendations on for future work, and provided some actions for implementation. It identified:

- Bringing research and development together
- Mobilizing community
- Widening application scopes
- Standardization

CLAM partners are actively implementing these actions. Already during the project CLAM partners have benefitted from the collaboration with institutions such as University of Porto, the NATO STO Centre for Marine Research and Experimentation. The good results of the collaboration, the reliability and high performance of CLAM results such as SUNSET and CLAM communication protocols have strengthened such ties, leading to new opportunities for collaboration. After the end of the project for instance, University of Rome La Sapienza and University of Padova have participated to NATO organized at sea campaigns and the collaboration with CMRE is ongoing on multiple initiatives. Many international organizations have expressed interest in collaborating with the groups involved in the CLAM consortium, including SUNY Buffalo, Northeastern University, University of Porto, Italian marine parks. This is leading to multiple opportunities for testing in field the results of the project in different environments and application domains.

FIRE project Sunrise

Another example of implementing the recommendations and effective utilization of CLAM results in future research projects, is the FIRE project Sunrise (http:// http://fp7-sunrise.eu/). This is a 3-years project, led by the University of Rome, and started in September 2013. In this project CLAM partners University of Rome, CINI, University of Twente, and the CLAM spin-off WSENSE collaborate with several other institutes in Europe to create a federated underwater testbed. Other partners include: University of Porto, SUASIS, NATO science and technology organisation, Evologics, Nexse, and the University at Buffalo. In this project all identified actions in the roadmap will be implemented.

The SUNRISE objectives are to develop:

- Five federated underwater communication networks, based on pilot infrastructure already designed, built and deployed by consortium partners, in diverse environments (Mediterranean, Ocean, Black Sea, Lakes, Canals), web-accessible and interfaced with existing FIRE facilities to experiment with Future Internet technologies.
- A software-defined open-architecture modem and protocol stack that will empower open collaborative developments.
- Standard platforms for simulation, emulation and replay testing to estimate underwater communication networks at a fraction of time, cost, complexity of current at-sea experiments, validated by tests conducted on the SUNRISE networks over a variety of applications and environments.
- A user-friendly interface for diverse users to interact with SUNRISE systems to conduct trials and benefit from databases of underwater Internet of Things performance data gathered over long periods from the SUNRISE infrastructure.

SUNRISE directly addresses FIRE objectives by combining technology with novel paradigms in new, open experimental facilities, integrating physical systems with software development into the Internet of Underwater Things. SUNRISE will also provide a way to select underwater Internet of Things standards based on objective measures of performance, strengthening in its facilities as more sites are added in the future as a result of the two envisioned open calls.

SUNRISE Testbeds

An invaluable resource to achieve an accurate and as far as possible complete understanding of the underwater channel would be the availability of several testbeds placed at different and heterogeneous locations over long periods with continual access. These testbeds have to be deployed for long periods of time in order to collect data sets that will allow us to characterise the time-varying effects of the underwater channel in the given scenarios. This motivates the added value of a the SUNRISE federation of testing infrastructures.

The federation will span different underwater environments that are representative of the typical different marine environments. In the initial stage, the deployment sites will coincide with some of the SUNRISE partners facilities, namely the Atlantic ocean, the Mediterranean, the Black Sea, as well as lakes and canals in central Europe.

The selected deployments will also represent different classes of applications (e.g., port monitoring, marine park protection, search and rescue operation, fisheries surveying, etc.), providing a unique testbed to be able to assess the proposed solutions in a variety of different domains, and providing excellent testing sites for heterogeneous applications and services.

The SUNRISE Underwater testing infrastructures will be able to:

- Support different application domains;
- Enable testing of solutions for all the system components and at all the different layers of the system in a very natural way;
- Have a level of heterogeneity (in terms of supported sensors and underwater platforms, communication technologies, marine environment, and thus acoustic channel features) that allows to assess and evaluate the performance of the proposed IoT systems in the whole spectrum of relevant marine domains and applications;
- Allow testing of solutions for static networks, mobile networks, hybrid network integrating underwater and terrestrial monitoring systems (e.g., Autonomous Unmanned Vehicles, or AUVs, and flying drones);
- Support scalability, allowing seamless integration of additional platforms and devices made available by partners or by third parties;
- Support security, privacy and trust by providing an environment in which solutions for underwater security can also be developed and tested;
- Expose UWSN IoT islands as an element of the Future Internet, thus allowing integration of heterogeneous information for value added

application and service development. It should therefore be also combined with a toolchain that allows:

- Allow users to select the most appropriate set of platforms, sensors, protocols for their objectives, getting the needed resources allocated and the needed code automatically generated;
- Monitor performance during the test operation, being able to reconfigure and reprogram the network upon need;
- Support data analysis (in real time and in a post deployment phase), integrating heterogeneous flows of information for real-time decision-making and underwater system control, and for advance processing of information according to the logic of the developed application, and to the skills of the end users.

Results from CLAM used in the testbeds include cNode mini, SUNSET framework, CLAM system architecture, and networking protocols.