



Underwater acoustic sensor networks: research challenges

Ian F. Akyildiz *, Dario Pompili, Tommaso Melodia

*Broadband and Wireless Networking Laboratory, School of Electrical and Computer Engineering,
Georgia Institute of Technology, Atlanta, GA 30332, USA*

Received 15 July 2004; received in revised form 20 September 2004; accepted 21 January 2005

Available online 2 February 2005

Abstract

Underwater sensor nodes will find applications in oceanographic data collection, pollution monitoring, offshore exploration, disaster prevention, assisted navigation and tactical surveillance applications. Moreover, unmanned or autonomous underwater vehicles (UUVs, AUVs), equipped with sensors, will enable the exploration of natural undersea resources and gathering of scientific data in collaborative monitoring missions. Underwater acoustic networking is the enabling technology for these applications. Underwater networks consist of a variable number of sensors and vehicles that are deployed to perform collaborative monitoring tasks over a given area.

In this paper, several fundamental key aspects of underwater acoustic communications are investigated. Different architectures for two-dimensional and three-dimensional underwater sensor networks are discussed, and the characteristics of the underwater channel are detailed. The main challenges for the development of efficient networking solutions posed by the underwater environment are detailed and a cross-layer approach to the integration of all communication functionalities is suggested. Furthermore, open research issues are discussed and possible solution approaches are outlined.

© 2005 Published by Elsevier B.V.

Keywords: Underwater acoustic sensor networks; Underwater networking; Acoustic communications

1. Introduction

Underwater sensor networks are envisioned to enable applications for oceanographic data col-

lection, pollution monitoring, offshore exploration, disaster prevention, assisted navigation and tactical surveillance applications. Multiple unmanned or autonomous underwater vehicles (UUVs, AUVs), equipped with underwater sensors, will also find application in exploration of natural undersea resources and gathering of scientific data in collaborative monitoring missions. To make these applications viable, there is a need to enable underwater communications

* Corresponding author. Tel.: +1 404 894 5141; fax: +1 404 894 7883.

E-mail addresses: ian@ece.gatech.edu (I.F. Akyildiz), dario@ece.gatech.edu (D. Pompili), tommaso@ece.gatech.edu (T. Melodia).

among underwater devices. Underwater sensor nodes and vehicles must possess self-configuration capabilities, i.e., they must be able to coordinate their operation by exchanging configuration, location and movement information, and to relay monitored data to an onshore station.

Wireless underwater acoustic networking is the enabling technology for these applications. Underwater Acoustic Sensor Networks (UW-ASNs) consist of a variable number of sensors and vehicles that are deployed to perform collaborative monitoring tasks over a given area. To achieve this objective, sensors and vehicles self-organize in an autonomous network which can adapt to the characteristics of the ocean environment [1].

The above described features enable a broad range of applications for underwater acoustic sensor networks:

- *Ocean sampling networks.* Networks of sensors and AUVs, such as the Odyssey-class AUVs [2], can perform synoptic, cooperative adaptive sampling of the 3D coastal ocean environment [3]. Experiments such as the Monterey Bay field experiment [4] demonstrated the advantages of bringing together sophisticated new robotic vehicles with advanced ocean models to improve the ability to observe and predict the characteristics of the oceanic environment.
- *Environmental monitoring.* UW-ASNs can perform pollution monitoring (chemical, biological and nuclear). For example, it may be possible to detail the chemical slurry of antibiotics, estrogen-type hormones and insecticides to monitor streams, rivers, lakes and ocean bays (*water quality in situ analysis*) [51]. Monitoring of ocean currents and winds, improved weather forecast, detecting climate change, understanding and predicting the effect of human activities on marine ecosystems, biological monitoring such as tracking of fishes or micro-organisms, are other possible applications. For example, in [52], the design and construction of a simple underwater sensor network is described to detect extreme temperature gradients (*thermoclines*), which are considered to be a breeding ground for certain marine micro-organisms.
- *Undersea explorations.* Underwater sensor networks can help detecting underwater oilfields or reservoirs, determine routes for laying undersea cables, and assist in exploration for valuable minerals.
- *Disaster prevention.* Sensor networks that measure seismic activity from remote locations can provide *tsunami* warnings to coastal areas [42], or study the effects of submarine earthquakes (*seaquakes*).
- *Assisted navigation.* Sensors can be used to identify hazards on the seabed, locate dangerous rocks or shoals in shallow waters, mooring positions, submerged wrecks, and to perform bathymetry profiling.
- *Distributed tactical surveillance.* AUVs and fixed underwater sensors can collaboratively monitor areas for *surveillance*, *reconnaissance*, *targeting* and *intrusion detection* systems. For example, in [15], a 3D underwater sensor network is designed for a tactical surveillance system that is able to detect and classify submarines, small delivery vehicles (SDVs) and divers based on the sensed data from mechanical, radiation, magnetic and acoustic microsensors. With respect to traditional radar/sonar systems, underwater sensor networks can reach a higher accuracy, and enable detection and classification of low signature targets by also combining measures from different types of sensors.
- *Mine reconnaissance.* The simultaneous operation of multiple AUVs with acoustic and optical sensors can be used to perform rapid environmental assessment and detect mine-like objects.

Underwater networking is a rather unexplored area although underwater communications have been experimented since World War II, when, in 1945, an underwater telephone was developed in the United States to communicate with submarines [39]. Acoustic communications are the typical physical layer technology in underwater networks. In fact, radio waves propagate at long distances

through conductive sea water only at extra low frequencies (30–300 Hz), which require large antennae and high transmission power. For example, the Berkeley Mica 2 Motes, the most popular experimental platform in the sensor networking community, have been reported to have a transmission range of 120 cm in underwater at 433 MHz by experiments performed at the Robotic Embedded Systems Laboratory (RESL) at the University of Southern California. Optical waves do not suffer from such high attenuation but are affected by scattering. Moreover, transmission of optical signals requires high precision in pointing the narrow laser beams. Thus, links in underwater networks are based on *acoustic wireless communications* [45].

The traditional approach for ocean-bottom or ocean-column monitoring is to deploy underwater sensors that record data during the monitoring mission, and then recover the instruments [37]. This approach has the following disadvantages:

- *No real-time monitoring.* The recorded data cannot be accessed until the instruments are recovered, which may happen several months after the beginning of the monitoring mission. This is critical especially in surveillance or in environmental monitoring applications such as seismic monitoring.
- *No on-line system reconfiguration.* Interaction between onshore control systems and the monitoring instruments is not possible. This impedes any adaptive tuning of the instruments, nor is it possible to reconfigure the system after particular events occur.
- *No failure detection.* If *failures* or *misconfigurations* occur, it may not be possible to detect them before the instruments are recovered. This can easily lead to the complete failure of a monitoring mission.
- *Limited storage capacity.* The amount of data that can be recorded during the monitoring mission by every sensor is limited by the capacity of the onboard storage devices (memories, hard disks).

Therefore, there is a need to deploy underwater networks that will enable real-time monitoring of

selected ocean areas, remote configuration and interaction with onshore human operators. This can be obtained by connecting underwater instruments by means of wireless links based on acoustic communication.

Many researchers are currently engaged in developing networking solutions for terrestrial wireless ad hoc and sensor networks. Although there exist many recently developed network protocols for wireless sensor networks, the unique characteristics of the underwater acoustic communication channel, such as limited bandwidth capacity and variable delays [38], require very efficient and reliable new data communication protocols.

Major challenges in the design of underwater acoustic networks are:

- The available bandwidth is severely limited;
- The underwater channel is severely impaired, especially due to multi-path and fading;
- Propagation delay in underwater is five orders of magnitude higher than in radio frequency (RF) terrestrial channels, and extremely variable;
- High bit error rates and temporary losses of connectivity (*shadow zones*) can be experienced, due to the extreme characteristics of the underwater channel;
- Battery power is limited and usually batteries cannot be recharged, also because solar energy cannot be exploited;
- Underwater sensors are prone to failures because of fouling and corrosion.

In this survey, we discuss several fundamental key aspects of underwater acoustic communications. We discuss the communication architecture of underwater sensor networks as well as the factors that influence underwater network design. The ultimate objective of this paper is to encourage research efforts to lay down fundamental basis for the development of new advanced communication techniques for efficient underwater communication and networking for enhanced ocean monitoring and exploration applications. In Table 3, we report a list of research laboratories

and ongoing research projects related to underwater communications and explorations.

The remainder of this paper is organized as follows. In Sections 2 and 3 we introduce the communication architecture and design challenges, respectively, of underwater acoustic sensor networks. In Section 4, we investigate the underwater acoustic communication channel and summarize the associated physical layer challenges for underwater networking. In Sections 5–9 we discuss physical, data link, network, transport and application layer issues in underwater sensor networks, respectively. In Section 10 we describe some experimental implementations of underwater sensor networks while in Section 11 we draw the main conclusions.

2. Underwater acoustic sensor networks: communication architecture

In this section, we describe the communication architecture of underwater acoustic sensor networks. In particular, we introduce reference architectures for two-dimensional and three-dimensional underwater networks, and present several types of autonomous underwater vehicles (AUVs) which can enhance the capabilities of underwater sensor networks.

The network topology is in general a crucial factor in determining the *energy consumption*, the *capacity* and the *reliability* of a network. Hence, the network topology should be carefully engineered and post-deployment *topology optimization* should be performed, when possible.

Underwater monitoring missions can be extremely expensive due to the high cost of underwater devices. Hence, it is important that the deployed network be highly reliable, so as to avoid failure of monitoring missions due to failure of single or multiple devices. For example, it is crucial to avoid designing the network topology with single points of failure that could compromise the overall functioning of the network.

The network capacity is also influenced by the network topology. Since the capacity of the underwater channel is severely limited, as will be discussed in Section 4, it is very important to

organize the network topology such a way that no *communication bottleneck* is introduced.

The communication architectures introduced here are used as a basis for discussion of the challenges associated with underwater acoustic sensor networks. The underwater sensor network topology is an open research issue in itself that needs further analytical and simulative investigation from the research community. In the remainder of this section, we discuss the following architectures:

- *Static two-dimensional UW-ASNs for ocean bottom monitoring.* These are constituted by sensor nodes that are anchored to the bottom of the ocean, as discussed in Section 2.1. Typical applications may be environmental monitoring, or monitoring of underwater plates in tectonics [21].
- *Static three-dimensional UW-ASNs for ocean-column monitoring.* These include networks of sensors whose depth can be controlled by means of techniques discussed in Section 2.2, and may be used for surveillance applications or monitoring of ocean phenomena (ocean bio-geo-chemical processes, water streams, pollution).
- *Three-dimensional networks of autonomous underwater vehicles (AUVs).* These networks include fixed portions composed of anchored sensors and mobile portions constituted by autonomous vehicles, as detailed in Section 2.3.

2.1. Two-dimensional underwater sensor networks

A reference architecture for two-dimensional underwater networks is shown in Fig. 1. A group of sensor nodes are anchored to the bottom of the ocean with deep ocean anchors. Underwater sensor nodes are interconnected to one or more *underwater sinks* (uw-sinks) by means of wireless acoustic links. Uw-sinks, as shown in Fig. 1, are network devices in charge of relaying data from the ocean bottom network to a surface station. To achieve this objective, uw-sinks are equipped with two acoustic transceivers, namely a *vertical* and a *horizontal* transceiver. The horizontal transceiver is used by the uw-sink to communicate with

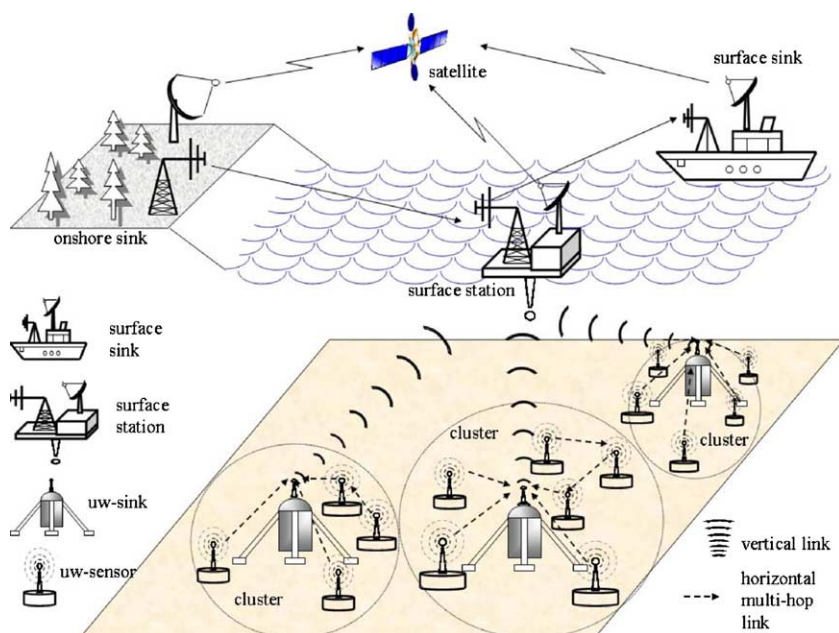


Fig. 1. Architecture for 2D underwater sensor networks.

the sensor nodes in order to: (i) send commands and configuration data to the sensors (uw-sink to sensors); (ii) collect monitored data (sensors to uw-sink). The vertical link is used by the uw-sinks to relay data to a *surface station*. In deep water applications, vertical transceivers must be long range transceivers as the ocean can be as deep as 10 km. The surface station is equipped with an acoustic transceiver that is able to handle multiple parallel communications with the deployed uw-sinks. It is also endowed with a long range RF and/or satellite transmitter to communicate with the *onshore sink* (os-sink) and/or to a *surface sink* (s-sink).

Sensors can be connected to uw-sinks via direct links or through multi-hop paths. In the former case, each sensor directly sends the gathered data to the selected uw-sink. However, in UW-ASNs, the power necessary to transmit may decay with powers greater than two of the distance [44], and the uw-sink may be far from the sensor node. Consequently, although direct link connection is the simplest way to network sensors, it may not be the most energy efficient solution. Furthermore, direct links are very likely to reduce the net-

work throughput because of increased acoustic interference due to high transmission power. In case of multi-hop paths, as in terrestrial sensor networks [10], the data produced by a source sensor is relayed by intermediate sensors until it reaches the uw-sink. This may result in energy savings and increased network capacity, but increases the complexity of the routing functionality. In fact, every network device usually takes part in a collaborative process whose objective is to diffuse topology information such that efficient and loop free routing decisions can be made at each intermediate node. This process involves signaling and computation. Since energy and capacity are precious resources in underwater environments, as discussed above, in UW-ASNs the objective is to deliver event features by exploiting multi-hop paths and minimizing the signaling overhead necessary to construct underwater paths at the same time.

2.2. Three-dimensional underwater sensor networks

Three dimensional underwater networks are used to detect and observe phenomena that cannot

be adequately observed by means of ocean bottom sensor nodes, i.e., to perform cooperative sampling of the 3D ocean environment. In three-dimensional underwater networks, sensor nodes float at different depths in order to observe a given phenomenon. One possible solution would be to attach each uw-sensor node to a surface buoy, by means of wires whose length can be regulated so as to adjust the depth of each sensor node [15]. However, although this solution allows easy and quick deployment of the sensor network, multiple floating buoys may obstruct ships navigating on the surface, or they can be easily detected and deactivated by enemies in military settings. Furthermore, floating buoys are vulnerable to weather and tampering or pilfering.

For these reasons, a different approach can be to anchor sensor devices to the bottom of the ocean. In this architecture, depicted in Fig. 2, each sensor is anchored to the ocean bottom and equipped with a floating buoy that can be inflated by a pump. The buoy pushes the sensor towards the ocean surface. The depth of the sensor can then be regulated by adjusting the length of the wire

that connects the sensor to the anchor, by means of an electronically controlled engine that resides on the sensor. A challenge to be addressed in such an architecture is the effect of ocean currents on the described mechanism to regulate the depth of the sensors.

Many challenges arise with such an architecture, that need to be solved in order to enable 3D monitoring, including:

- *Sensing coverage.* Sensors should collaboratively regulate their depth in order to achieve 3D coverage of the ocean column, according to their sensing ranges. Hence, it must be possible to obtain sampling of the desired phenomenon at all depths.
- *Communication coverage.* Since in 3D underwater networks there may be no notion of uw-sink, sensors should be able to relay information to the surface station via multi-hop paths. Thus, network devices should coordinate their depths in such a way that the network topology is always connected, i.e., at least one path from every sensor to the surface station always exists.

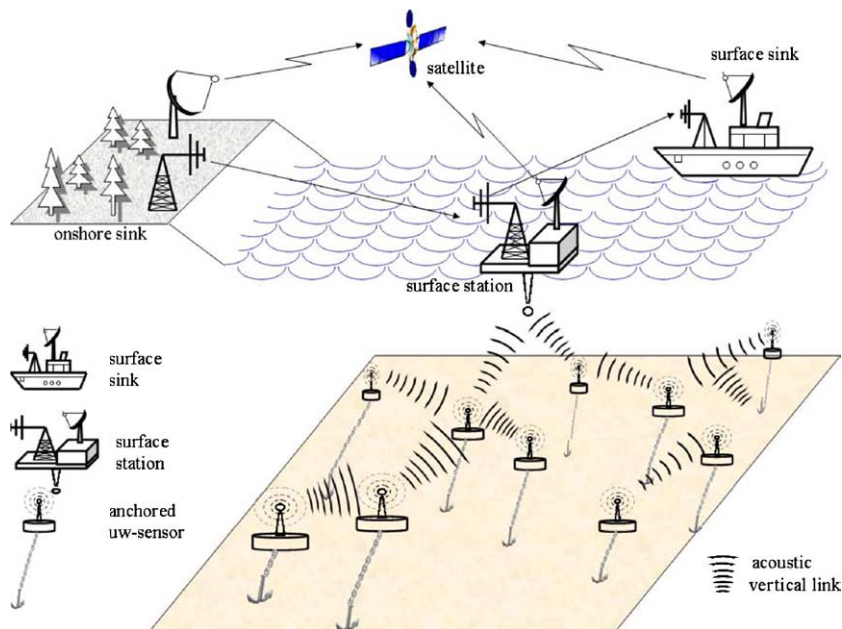


Fig. 2. Architecture for 3D underwater sensor networks.

Sensing and communication coverage in a 3D environment are rigorously investigated in [40]. The diameter, minimum and maximum degree of the reachability graph that describes the network are derived as a function of the communication range, while different degrees of coverage for the 3D environment are characterized as a function of the sensing range. These techniques could be exploited to investigate the coverage issues in UW-ASNs.

2.3. Sensor networks with autonomous underwater vehicles

AUVs can function without tethers, cables, or remote control, and therefore they have a multitude of applications in oceanography, environmental monitoring, and underwater resource study. Previous experimental work has shown the feasibility of relatively inexpensive AUV submarines equipped with multiple underwater sensors that can reach any depth in the ocean [2]. Hence, they can be used to enhance the capabilities of underwater sensor networks in many ways. The integration and enhancement of fixed sensor networks with AUVs is an almost unexplored research area which requires new network coordination algorithms such as:

- *Adaptive sampling.* This includes control strategies to command the mobile vehicles to places where their data will be most useful. This approach is also known as *adaptive sampling* and has been proposed in pioneering monitoring missions such as [4]. For example, the density of sensor nodes can be adaptively increased in a given area when a higher sampling rate is needed for a given monitored phenomenon.
- *Self-configuration.* This includes control procedures to automatically detect connectivity holes due to node failures or channel impairment and request the intervention of an AUV. Furthermore, AUVs can either be used for installation and maintenance of the sensor network infrastructure or to deploy new sensors. They can also be used as temporary relay nodes to restore connectivity.

One of the design objectives of AUVs is to make them rely on local intelligence and less dependent on communications from online shores [25]. In general, control strategies are needed for autonomous coordination, obstacle avoidance and steering strategies. Solar energy systems allow increasing the lifetime of AUVs, i.e., it is not necessary to recover and recharge the vehicle on a daily basis. Hence, solar powered AUVs can acquire continuous information for periods of time of the order of months [27].

Several types of AUVs exist as experimental platforms for underwater experiments. Some of them resemble small-scale submarines (such as the Odyssey-class AUVs [2] developed at MIT). Others are simpler devices that do not encompass such sophisticated capabilities. For example, *drifters* and *gliders* are oceanographic instruments often used in underwater explorations. Drifter underwater vehicles drift with local current and have the ability to move vertically through the water column. They are used for taking measurements at preset depths [24]. Underwater gliders [18] are battery powered autonomous underwater vehicles that use hydraulic pumps to vary their volume by a few hundred cubic centimeters in order to generate the buoyancy changes that power their forward gliding. When they emerge on the surface, global positioning system (GPS) is used to locate the vehicle. This information can be relayed to the onshore station while operators can interact by sending control information to the gliders. Depth capabilities range from 200 m to 1500 m while operating lifetimes range from a few weeks to several months. These long durations are possible because gliders move very slowly, typically 25 cm/s (0.5 knots). In [34], a control strategy for groups of gliders to cooperatively move and reconfigure in response to a sensed distributed environment is presented. The proposed framework allows preserving the symmetry of the group of gliders. The group is constrained to maintain a uniform distribution as needed, but is free to spin and possibly wiggle with the current. In [20], results are reported on the application of the theory in [34] on a fleet of autonomous underwater gliders during the experiment on Monterey Bay in 2003 [4].

3. Underwater acoustic sensor networks: design challenges

In this section, we describe the design challenges of underwater acoustic sensor networks. In particular, we itemize the main differences between terrestrial and underwater sensor networks, we detail key design issues and deployment challenges for underwater sensors, and we give motivations for a cross-layer design approach to improve the network efficiency in the critical underwater environment.

3.1. Differences with terrestrial sensor networks

The main differences between terrestrial and underwater sensor networks are as follows:

- *Cost.* While terrestrial sensor nodes are expected to become increasingly inexpensive, underwater sensors are expensive devices. This is especially due to the more complex underwater transceivers and to the hardware protection needed in the extreme underwater environment.
- *Deployment.* While terrestrial sensor networks are densely deployed, in underwater, the deployment is deemed to be more sparse, due to the cost involved and to the challenges associated to the deployment itself.
- *Power.* The power needed for acoustic underwater communications is higher than in terrestrial radio communications due to higher distances and to more complex signal processing at the receivers to compensate for the impairments of the channel.
- *Memory.* While terrestrial sensor nodes have very limited storage capacity, uw-sensors may need to be able to do some data caching as the underwater channel may be intermittent.
- *Spatial correlation.* While the readings from terrestrial sensors are often correlated, this is more unlikely to happen in underwater networks due to the higher distance among sensors.

3.2. Underwater sensors

The typical internal architecture of an underwater sensor is shown in Fig. 3. It consists of a main

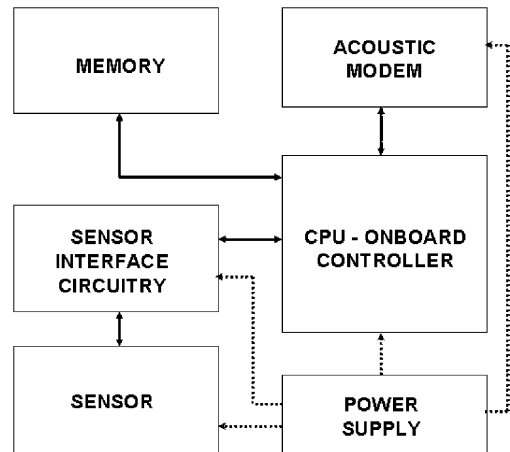


Fig. 3. Internal architecture of an underwater sensor node.

controller/CPU which is interfaced with an oceanographic instrument or sensor through a sensor interface circuitry. The controller receives data from the sensor and it can store it in the onboard memory, process it, and send it to other network devices by controlling the acoustic modem. The electronics are usually mounted on a frame which is protected by a PVC housing. Sometimes all sensor components are protected by bottom-mounted instrument frames that are designed to permit azimuthally omnidirectional acoustic communications, and protect sensors and modems from potential impact of trawling gear, especially in areas subjected to fishing activities. In [16], the protecting frame is designed so as to deflect trawling gear on impact, by housing all components beneath a low-profile pyramidal frame.

Underwater sensors include sensors to measure the quality of water and to study its characteristics such as temperature, density, salinity (interferometric and refractometric sensors), acidity, chemicals, conductivity, pH (magnetoelastic sensors), oxygen (Clark-type electrode), hydrogen, dissolved methane gas (METS), and turbidity. Disposable sensors exist that detect ricin, the highly poisonous protein found in castor beans and thought to be a potential terrorism agent. DNA microarrays can be used to monitor both abundance and activity level variations among natural microbial populations. Other existing underwater sensors include hydrothermal sulfide, silicate, voltammetric sensors

for spectrophotometry, gold-amalgam electrode sensors for sediment measurements of metal ions (*ion-selective analysis*), amperometric micro-sensors for H₂S measurements for studies of anoxygenic photosynthesis, sulfide oxidation, and sulfate reduction of sediments. In addition, force/torque sensors for underwater applications requiring simultaneous measurements of several forces and moments have also been developed, as well as quantum sensors to measure light radiation and sensors for measurements of harmful algal blooms.

The challenges related to the deployment of low cost, low scale underwater sensors, are listed as follows:

- It is necessary to develop less expensive, robust “nano-sensors”, e.g., sensors based on nano-technology, which involves development of materials and systems at the atomic, molecular, or macromolecular levels in the dimension range of approximately 1–500 nm.
- It is necessary to devise periodical cleaning mechanisms against corrosion and fouling, which may impact the lifetime of underwater devices. For example, some sensors for pCO₂, pH and nitrate measurement, and fluorimeters and spectral radiometers, may be limited by bio-fouling, especially on a long time scale.
- There is a need for robust, stable sensors on a high range of temperatures since sensor drift of underwater devices may be a concern. To this end, protocols for in situ calibration of sensors to improve accuracy and precision of sampled data must be developed.
- There is a need for new integrated sensors for *synoptic* sampling of physical, chemical, and biological parameters to improve the understanding of processes in marine systems.

3.3. A Cross-layer protocol stack

A protocol stack for uw-sensors should combine *power awareness* and *management*, and promote *cooperation* among the sensor nodes. It should consist of *physical layer*, *data link layer*, *network layer*, *transport layer*, and *application*

layer functionalities. The protocol stack should also include a *power management plane*, a *coordination plane*, and a *localization plane*. The power management plane is responsible for network functionalities aimed at minimizing the energy consumption (e.g., sleep modes, power control, etc.). The coordination plane is responsible for all functionalities that require coordination among sensors (e.g., coordination of the sleep modes, data aggregation, 3D topology optimization). The localization plane is responsible for providing absolute or relative localization information to the sensor node, when needed by the protocol stack or by the application.

While all the research on underwater networking so far has followed the traditional layered approach for network design, it is an increasingly accepted opinion in the wireless networking community that the improved network efficiency, especially in critical environments, can be obtained with a cross-layer design approach. These techniques will entail a joint design of different network functionalities, from modem design to MAC and routing, from channel coding and modulation to source compression and transport layer, with the objective to overcome the shortcomings of a layered approach that lacks of information sharing across protocol layers, forcing the network to operate in a suboptimal mode. Hence, while in the following sections for the sake of clarity we present the challenges associated with underwater sensor networks following the traditional layered approach, we believe that the underwater environment particularly requires for cross-layer design solutions that allow a more efficient use of the scarce available resources. However, although we advocate integrating functionalities to improve network performance and to avoid duplication of functions by means of cross-layer design, it is important to consider the ease of design by following a *modular design approach*. This also allows improving and upgrading particular functionalities without the need to re-design the entire communication system.

Although systematic research on cross-layer design for underwater communications is missing, a study on the interaction between physical and MAC layers is presented in [29], where a method is proposed based on the sonar equation [49] to

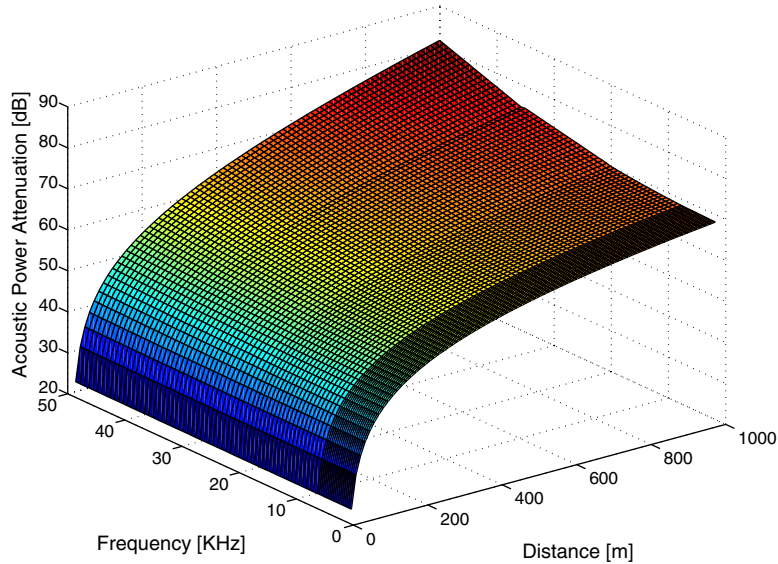


Fig. 4. Path loss of short range shallow UW-A channels vs distance and frequency in band 1–50 kHz.

estimate the battery lifetime and power cost for shallow water underwater acoustic sensor networks for civilian applications. The battery lifetime is modeled as dependent on four key parameters, namely internode distance, transmission frequency, frequency of data updates and number of nodes per cluster. Interestingly, since in shallow water the acoustic propagation loss increases with increasing frequency and distance (as shown in Fig. 4), it is proposed to assign lower frequencies to sensor nodes that are closer to the sink, since they also have to relay data on behalf of more distant nodes. This way, the energy consumption is somehow equalized and the network lifetime is prolonged.

3.4. Real-time vs delay-tolerant networking

As in terrestrial sensor networks, depending on the application, there may be very different requirements for data delivery. For example, surveillance application may need very fast reaction to events and thus networking protocols that provide guaranteed delay-bounded delivery are required. Hence, it is necessary to develop protocols that deal with the characteristics of the underwater environment in order to quickly restore connectiv-

ity when it is lost and that react to unpaired or congested links by taking appropriate action (e.g., dynamical rerouting) in order to meet the given delay bound. Conversely, other applications may produce large bundles of data to be delivered to the onshore sink without particular delay constraints. With this respect, the Delay-Tolerant Networking Research Group (DTNRG) [5,19] developed mechanisms to resolve the intermittent connectivity, long or variable delay, asymmetric data rates, and high error rates by using a *store and forward* mechanism based on a middleware between the application layer and the lower layers. Similar methodologies may be particularly useful for applications, such as those that record seismic activity, that have a very low duty cycle and produce, when activated, large bundles of data that need to be relayed to a monitoring station where it can be analyzed to predict future activity. On the other hand, sensor networks intended for disaster prevention such as those that provide earthquake or tsunami warnings, require immediate delivery of information and hence real-time protocols. Therefore, the design of networking solutions for underwater acoustic sensor networks should always be aware of the difference between real-time and delay-tolerant applications, and

jointly tune existing solutions to the application needs and to the characteristics of the underwater environment.

4. Basics of acoustic propagation

Underwater acoustic communications are mainly influenced by *path loss*, *noise*, *multi-path*, *Doppler spread*, and *high and variable propagation delay*. All these factors determine the *temporal and spatial variability* of the acoustic channel, and make the available bandwidth of the *Under-Water Acoustic channel* (UW-A) limited and dramatically dependent on both range and frequency. Long-range systems that operate over several tens of kilometers may have a bandwidth of only a few kHz, while a short-range system operating over several tens of meters may have more than a hundred kHz of bandwidth. In both cases these factors lead to low bit rate [14], in the order of tens of kbit/s for existing devices.

Underwater acoustic communication links can be classified according to their range as *very long*, *long*, *medium*, *short*, and *very short* links [45]. Table 1 shows typical bandwidths of the underwater channel for different ranges. Acoustic links are also roughly classified as *vertical* and *horizontal*, according to the direction of the sound ray with respect to the ocean bottom. As will be shown later, their propagation characteristics differ considerably, especially with respect to time dispersion, multi-path spreads, and delay variance. In the following, as usually done in oceanic literature, *shallow water* refers to water with depth lower than 100 m, while *deep water* is used for deeper oceans.

Hereafter we analyze the factors that influence acoustic communications in order to state the

challenges posed by the underwater channel for underwater sensor networking. These include:

- *Path loss*:
 - *Attenuation*. Is mainly provoked by absorption due to conversion of acoustic energy into heat. The attenuation increases with distance and frequency. Fig. 4 shows the acoustic attenuation with varying frequency and distance for a short range shallow water UW-A channel, according to the propagation model in [49]. The attenuation is also caused by scattering and reverberation (on rough ocean surface and bottom), refraction, and dispersion (due to the displacement of the reflection point caused by wind on the surface). Water depth plays a key role in determining the attenuation.
 - *Geometric spreading*. This refers to the spreading of sound energy as a result of the expansion of the wavefronts. It increases with the propagation distance and is independent of frequency. There are two common kinds of geometric spreading: *spherical* (omni-directional point source), which characterizes deep water communications, and *cylindrical* (horizontal radiation only), which characterizes shallow water communications.
- *Noise*:
 - *Man made noise*. This is mainly caused by machinery noise (pumps, reduction gears, power plants), and shipping activity (hull fouling, animal life on hull, cavitation), especially in areas encumbered with heavy vessel traffic.
 - *Ambient noise*. Is related to hydrodynamics (movement of water including tides, current, storms, wind, and rain), and to seismic and biological phenomena. In [23], boat noise and snapping shrimps have been found to be the primary sources of noise in shallow water by means of measurement experiments on the ocean bottom.
- *Multi-path*:
 - Multi-path propagation may be responsible for severe degradation of the acoustic communication signal, since it generates inter-symbol interference (ISI).

Table 1
Available bandwidth for different ranges in UW-A channels

	Range [km]	Bandwidth [kHz]
Very long	1000	<1
Long	10–100	2–5
Medium	1–10	≈10
Short	0.1–1	20–50
Very short	<0.1	>100

- The multi-path geometry depends on the link configuration. Vertical channels are characterized by little time dispersion, whereas horizontal channels may have extremely long multi-path spreads.
- The extent of the spreading is a strong function of depth and the distance between transmitter and receiver.
- *High delay and delay variance:*
 - The propagation speed in the UW-A channel is five orders of magnitude lower than in the radio channel. This large propagation delay (0.67 s/km) can reduce the throughput of the system considerably.
 - The very high delay variance is even more harmful for efficient protocol design, as it prevents from accurately estimating the round trip time (RTT), which is the key parameter for many common communication protocols.
- *Doppler spread:*
 - The Doppler frequency spread can be significant in UW-A channels [45], thus causing a degradation in the performance of digital communications: high data rate transmissions cause adjacent symbols to interfere at the receiver. This requires sophisticated signal processing to deal with the generated ISI.
 - The Doppler spreading generates a simple frequency translation, which is relatively easy for a receiver to compensate for; and a continuous spreading of frequencies that constitutes a non-shifted signal, which is more difficult to compensate for.
 - If a channel has a Doppler spread with bandwidth B and a signal has symbol duration T , then there are approximately BT uncorrelated samples of its complex envelope. When BT is much less than unity, the channel is said to be *underspread* and the effects of the Doppler fading can be ignored, while, if greater than unity, it is said to be *overspread* [32].

Most of the described factors are caused by the chemical-physical properties of the water medium such as temperature, salinity and density, and by their spatio-temporal variations. These variations,

together with the wave guide nature of the channel, cause the acoustic channel to be *highly temporally and spatially variable*. In particular, the horizontal channel is by far more rapidly varying than the vertical channel, in both deep and shallow water.

5. Physical layer

Until the beginning of the last decade, due to the challenging characteristics of the underwater channel, underwater modem development was based on *non-coherent* frequency shift keying (FSK) modulation, since it relies on energy detection. Thus, it does not require phase tracking, which is a very difficult task mainly because of the Doppler-spread in the UW-A channel, described in Section 4. In FSK modulation schemes developed for underwater communications, the multi-path effects are suppressed by inserting time guards between successive pulses to ensure that the reverberation, caused by the rough ocean surface and bottom, vanishes before each subsequent pulse is received. Dynamic frequency guards can also be used between frequency tones to adapt the communication to the Doppler spreading of the channel. Although non-coherent modulation schemes are characterized by a high *power efficiency*, their low *bandwidth efficiency* makes them unsuitable for high data rate multiuser networks. Hence, *coherent modulation* techniques have been developed for long-range, high-throughput systems. In the last years, *fully* coherent modulation techniques, such as phase shift keying (PSK) and quadrature amplitude modulation (QAM), have become practical due to the availability of powerful digital processing. Channel equalization techniques are exploited to leverage the effect of the inter-symbol interference (ISI), instead of trying to avoid or suppress it. Decision-feedback equalizers (DFEs) track the complex, relatively slowly varying channel response and thus provide high throughput when the channel is slowly varying. Conversely, when the channel varies faster, it is necessary to combine the DFE with a Phase Locked Loop (PLL) [46], which estimates and compensates for the phase offset in a rapid, stable

Table 2
Evolution of modulation technique

Type	Year	Rate [kbps]	Band [kHz]	Range [km] ^a
FSK	1984	1.2	5	3 _s
PSK	1989	500	125	0.06 _d
FSK	1991	1.25	10	2 _d
PSK	1993	0.3–0.5	0.3–1	200 _d –90 _s
PSK	1994	0.02	20	0.9 _s
FSK	1997	0.6–2.4	5	10 _d –5 _s
DPSK	1997	20	10	1 _d
PSK	1998	1.67–6.7	2–10	4 _d –2 _s
16-QAM	2001	40	10	0.3 _s

^a The subscripts d and s stand for *deep* and *shallow* water.

manner. The use of decision feedback equalization and phase-locked loops is driven by the complexity and time variability of ocean channel impulse responses. Table 2 presents the evolution from

non-coherent modems to the recent coherent modems.

Differential phase shift keying (DPSK) serves as an intermediate solution between incoherent and fully coherent systems in terms of bandwidth efficiency. DPSK encodes information relative to the previous symbol rather than to an arbitrary fixed reference in the signal phase and may be referred to as a *partially coherent modulation*. While this strategy substantially alleviates carrier phase-tracking requirements, the penalty is an increased error probability over PSK at an equivalent data rate.

With respect to Table 2, it is worth noticing that early phase-coherent systems achieved higher bandwidth efficiencies (bit rate/occupied bandwidth) than their incoherent counterparts, but they did not outperform incoherent modulation schemes yet. In fact, coherent systems had lower

Table 3
Research laboratories and ongoing research projects related to underwater acoustic sensor networks

Research lab or project name	Research area	URL
BWN-Lab @ GeorgiaTech	Underwater acoustic sensor networks	http://www.ece.gatech.edu/research/labs/bwn/UWASN/
MIT & Woods Hole O.I.	Underwater acoustic networks	http://www.mit.edu/people/millitsa/research.html
Front Project @ UConn	Spatial sampling of ocean	http://www.nopp.uconn.edu/ADCP/index.html
Autonomous Ocean Sampling Networks II	Adaptive ocean sampling	http://www.princeton.edu/dcs/aoasn/
Adaptive Sampling and Prediction (ASAP)	Adaptive ocean sampling	http://www.princeton.edu/dcs/asap/
Sensor Networks for Undersea Seismic Experimentation (SNUSE) @ USC	Underwater acoustic sensor networks	http://www.isi.edu/ilense/snuse/
AUV Lab @ MIT Sea Grant	AUVs	http://auvlab.mit.edu/
Ocean Engineering @ FAU	Advanced marine systems	http://www.oe.fau.edu/research/ams.html
AOSN	Autonomous ocean sampling networks	http://www.mbari.org/aosn/
Acoustic Research Laboratory (ARL)	Underwater Acoustic Communications	http://www.arl.nus.edu.sg/web/research/acomms
ACME	Acoustic communication network for monitoring underwater environments in coastal areas	http://flipper.ncl.ac.uk/acme/
Underwater Acoustic Research Group @ Loughborough University	Underwater communications	http://sonar-fs.lboro.ac.uk/
Underwater Technologies Laboratory @ Florida Tech	Integrated sustained ocean observing system	http://my.fit.edu/swood/subsea.html
Underwater Research Lab's @ Simon Fraser University	Underwater acoustics, sonar, bottom imaging, bottom and water column surveys with AUVs, signal processing and target detection	http://www.ensc.sfu.ca/research/url/
Autonomous Undersea Systems Institute (AUSI)	Applications of AUVs, platforms and sensors	http://www.ausi.org/

performance than incoherent systems for long-haul transmissions on horizontal channels until ISI compensation via decision-feedback equalizers for optimal channel estimation was implemented [47]. However, these filtering algorithms are complex and not suitable for real-time communications, as they do not meet real-time constraints. Hence, sub-optimal filters have to be considered, but the imperfect knowledge of the channel impulse response that they provide leads to channel estimation errors, and ultimately to decreased performance.

Another promising solution for underwater communications is the orthogonal frequency division multiplexing (OFDM) spread spectrum technique, which is particularly efficient when noise is spread over a large portion of the available bandwidth. OFDM is frequently referred to as multi-carrier modulation because it transmits signals over multiple *sub-carriers* simultaneously. In particular, sub-carriers that experience higher SNR, are allotted with a higher number of bits, whereas less bits are allotted to sub-carriers experiencing attenuation, according to the concept of *bit loading*, which requires channel estimation. Since the symbol duration for each individual carrier increases, OFDM systems perform robustly in severe multi-path environments, and achieve a high spectral efficiency.

Many of the techniques discussed above require underwater channel estimation, which can be achieved by means of probe packets [30]. An accurate estimate of the channel can be obtained with a high probing rate and/or with a large probe packet size, which however result in high overhead, and in the consequent drain of channel capacity and energy.

5.1. Open research issues

In order to enable physical layer solutions specifically tailored to underwater acoustic sensor networks, the following open research issues need to be addressed:

- It is necessary to develop inexpensive transmitter/receiver modems for underwater communications.

- Research is needed on design of low-complexity sub-optimal filters characterized by rapid convergence, to enable real-time underwater communications with decreased energy expenditure.
- There is a need to overcome stability problem in the coupling between the phase locked loop (PLL) and the decision feedback equalizer (DCE).

6. Data link layer

In this section we discuss techniques for multiple access in UW-ASNs and present open research issues to address the requirements of the data link layer in an underwater environment. Channel access control in UW-ASNs poses additional challenges due to the peculiarities of the underwater channel, in particular limited bandwidth, and high and variable delay.

Frequency division multiple access (FDMA) is not suitable for UW-ASNs due to the narrow bandwidth in UW-A channels and the vulnerability of limited band systems to fading and multi-path.

Time division multiple access (TDMA) shows a limited bandwidth efficiency because of the long time guards required in the UW-A channel. In fact, long time guards must be designed to account for the large propagation delay and delay variance of the underwater channel, discussed in Section 4, in order to minimize packet collisions from adjacent time slots. Moreover, the variable delay makes it very challenging to realize a precise synchronization, with a common timing reference, which is required for TDMA.

Carrier sense multiple access (CSMA) prevents collisions with the ongoing transmission at the transmitter side. To prevent collisions at the receiver side, however, it is necessary to add a guard time between transmissions dimensioned according to the maximum propagation delay in the network. This makes the protocol dramatically inefficient for UW-ASNs.

The use of contention-based techniques that rely on handshaking mechanisms such as RTS/CTS in shared medium access (e.g., MACA [31],

IEEE 802.11) is impractical in underwater, for the following reasons: (i) large delays in the propagation of RTS/CTS control packets lead to low throughput; (ii) due to the high propagation delay of UW-A channels, when carrier sense is used, as in 802.11, it is more likely that the channel be sensed idle while a transmission is ongoing, since the signal may not have reached the receiver yet; (iii) the high variability of delay in handshaking packets makes it impractical to predict the start and finish time of the transmissions of other stations. Thus, collisions are highly likely to occur.

Many novel access schemes have been designed for terrestrial sensor networks, whose objective, similarly to underwater sensor networks, is to prevent collisions in the access channel, thus maximizing the network efficiency. These similarities would suggest to tune and apply those efficient schemes in the underwater environment; on the other hand, the main focus in medium access control in terrestrial wireless sensor networks is on energy-latency tradeoffs. Some proposed schemes aim at decreasing the energy consumption by using sleep schedules with virtual clustering. However, these techniques may not be suitable for an environment where dense sensor deployment cannot be assumed, as discussed in Section 2. Moreover, the additional challenges due to the underwater channel, such as variable and high propagation delays, and very limited available bandwidth, further complicate the medium access problem in underwater environments.

Code division multiple access (CDMA) is quite robust to frequency selective fading caused by underwater multi-paths, since it distinguishes simultaneous signals transmitted by multiple devices by means of pseudo-noise codes that are used for spreading the user signal over the entire available band. This allows exploiting the time diversity in the UW-A channel by leveraging *Rake filters* [43] at the receiver. These filters are designed to match the pulse spreading, the pulse shape and the channel impulse response, so as to compensate for the effect of multi-path. CDMA allows reducing the number of packet retransmissions, which results in decreased battery consumption and increased network throughput. For example, in [22], two code-division spread-spectrum access

techniques for underwater communications in shallow water are compared, namely direct sequence spread spectrum (DSSS) and frequency hopping spread spectrum (FHSS). Although FHSS is more prone to the Doppler shift effect, since transmissions take place in narrow bands, this scheme is more robust to multiple access interference (MAI) than DSSS. Furthermore, although FHSS is shown to lead to a higher bit error rate than DHSS, it results in simple receivers and provides robustness to the near-far problem, thus potentially simplifying the power control functionality. One of the most attractive access techniques in the recent underwater literature combines multi carrier transmission with the DSSS CDMA [30], as it may offer higher spectral efficiency than its single carrier counterpart, and increase the flexibility to support integrated high data rate applications with different quality of service requirements. The main idea is to spread each data symbol in the frequency domain by transmitting all the chips of a spread symbol at the same time into a large number of narrow subchannels. This way, high data rate can be supported by increasing the duration of each symbol, which drastically reduces ISI.

In conclusion, although the high delay spread which characterizes the horizontal link in underwater channels makes it difficult to maintain synchronization among the stations, especially when orthogonal code techniques are used [30], CDMA is a promising multiple access technique for underwater acoustic networks. This is particularly true in shallow water, where multi-paths and Doppler-spreading play a key role in the communication performance.

In [41], a protocol is proposed for networks with autonomous underwater vehicles. The proposed scheme is based on organizing the network in multiple clusters, each composed of adjacent vehicles. Inside each cluster, TDMA is used with long band guards, to overcome the effect of propagation delay in underwater. In this case, TDMA is not highly inefficient since vehicles in the same cluster are close to one another. Hence, the effect of propagation delay is limited. Interference among different clusters is avoided by assigning different spreading codes to different clusters. The

proposed protocol sketches also some mechanisms to reorganize clusters after node mobility.

In order to meet a required bit error rate at the data link layer of the deployed underwater sensor networks, it is mandatory to provide error control functionalities for the transmitted data, since path loss and multi-path fading affecting UW-A channels lead to high bit error rates (on the order of 10^{-2} – 10^{-5} [48,44]). While *automatic repeat request* (ARQ) techniques appear not to be suitable for the underwater environment, because they incur a high latency, additional energy cost, and signaling overhead due to retransmissions; *forward error correction* (FEC) techniques can be effectively employed in such an environment. The objective of these techniques is to protect data by introducing redundant bits in the transmission so that the receiver can correct detected bit errors. This way retransmissions are not necessary although both the transmitter and the receiver incur additional processing power drain for encoding and decoding, respectively. There is a trade-off between the robustness of the adopted FEC technique, which depends on the amount of redundant bits injected in the channel, and the channel efficiency. A possible solution to maximize the underwater channel efficiency such a way to effectively exploit its scarce bandwidth would be to dynamically choose the optimal amount of redundant bits according to measurements of the state of the underwater channel.

6.1. Open research issues

In order to enable data link layer solutions specifically tailored to underwater acoustic sensor networks, the following open research issues need to be addressed:

- In case CDMA is adopted, which we strongly advocate, it is necessary to design access codes with high auto-correlation and low cross-correlation properties to achieve minimum interference among users. This needs to be achieved even when the transmitting and receiving nodes are not synchronized.
- Research on optimal data packet length is needed to maximize the network efficiency.
- It is necessary to design low-complexity encoders and decoders to limit the processing power required for forward error correction (FEC) functionalities. Researchers should evaluate the feasibility and the energy-efficiency of non-convolutional error control coding schemes.
- Distributed protocols should be devised to reduce the activity of a device when its battery is depleting without compromising on network availability.

7. Network layer

The *network layer* is in charge of determining the path between a source (the sensor that samples a physical phenomenon) and a destination node (usually the surface station). In general, while many impairments of the underwater acoustic channel are adequately addressed at the physical and data link layers, some other characteristics, such as the extremely long propagation delays, are better addressed at the network layer.

In the last few years there has been an intensive study in routing protocols for ad hoc wireless networks [7] and sensor networks [9]. However, due to the different nature of the underwater environment and applications, there are several drawbacks with respect to the suitability of the existing solutions for underwater acoustic networks. The existing routing protocols are usually divided into three categories, namely *proactive*, *reactive* and *geographical* routing protocols:

- *Proactive protocols* (e.g., DSDV [36], OLSR [26]). These protocols attempt to minimize the message latency induced by route discovery, by maintaining up-to-date routing information at all times from each node to every other node. This is obtained by broadcasting control packets that contain routing table information (e.g., distance vectors). These protocols provoke a large signaling overhead to establish routes for the first time and each time the network topology is modified because of mobility or node failures, since updated topology information has to be propagated to all the nodes in the network. This way, each node is able to

establish a path to any other node in the network, which may not be needed in UW-ASNs. For this reason, proactive protocols are not suitable for underwater networks.

- *Reactive protocols* (e.g., AODV [35], DSR [28]). A node initiates a route discovery process only when a route to a destination is required. Once a route has been established, it is maintained by a route maintenance procedure until it is no longer desired. These protocols are more suitable for dynamic environments but incur a higher latency and still require source-initiated flooding of control packets to establish paths. Thus, both proactive and reactive protocols incur excessive signaling overhead due to their extensive reliance on flooding. Reactive protocols are deemed to be unsuitable for UW-ASNs as they also cause a high latency in the establishment of paths, which may be even amplified underwater by the slow propagation of acoustic signals. Furthermore, links are likely to be asymmetrical, due to bottom characteristics and variability in sound speed channel. Hence, protocols that rely on symmetrical links, such as most of the reactive protocols, are unsuited for the underwater environment. Moreover, the topology of UW-ASNs is unlikely to vary dynamically on a short time scale.
- *Geographical routing protocols* (e.g., GFG [12], PTKF [33]). These protocols establish source–destination paths by leveraging localization information, i.e., each node selects its next hop based on the position of its neighbors and of the destination node. Although these techniques are very promising, it is still not clear how accurate localization information can be obtained in the underwater environment with limited energy expenditure. In fact, fine-grained localization usually requires strict synchronization among nodes, which is difficult to achieve underwater due to the variable propagation delay. In addition, global positioning system (GPS) receivers, which may be used in terrestrial systems to accurately estimate the geographical location of sensor nodes, do not work properly underwater. In fact, GPS uses waves in the 1.5 GHz band and those waves do not propagate in water.

Some recent papers propose network layer protocols specifically tailored to underwater acoustic networks. In [50], a routing protocol is proposed that autonomously establishes the underwater network topology, controls network resources and establishes network flows. The protocol relies on a centralized network manager running on the surface station. The manager implements network management and routing agents that periodically probe the nodes to estimate the channel characteristics. This information is exploited by the manager to establish efficient data delivery paths in a centralized fashion, which allows avoiding congestion and providing forms of quality of service guarantee. The performance evaluation of the proposed mechanisms has not been thoroughly carried out yet.

In [17], a framework is provided for 3D position based routing in ad hoc networks. It is assumed that each node knows its 3D position and the position of the destination node, and a cell structure is leveraged in order to aggregate the topological information at each node. Although it is claimed that the mechanism can be applied to ocean sensor networks, all the experiments performed assume radio frequency communications among terrestrial mobile devices.

In [44], it is shown with simple acoustic propagation models [13] that multi-hop routing saves energy in underwater networks with respect to single hop communications, especially with distances in the order of some kilometers. Based on this, a simple ad hoc underwater network is designed and simulated, where routes are established by a central manager based on neighborhood information gathered by all nodes by means of poll packets.

In general, while most developed protocols for terrestrial ad hoc networks, mostly due to scalability and mobility concerns, are based on *packet switching*, i.e., the routing function is performed separately for each single packet and paths are dynamically established, *virtual circuit* routing techniques can be considered in UW-ASNs. In these techniques, paths are established a priori between each source and sink, and each packet follows the same path. This may require some form of centralized coordination, and implies a less flexible architecture, but allows exploiting powerful

optimization tools on a centralized manager (e.g., the surface station) to achieve optimal performance at the network layer (e.g., minimum delay paths, energy efficient paths), with minimum communication signaling overhead.

Furthermore, routing schemes that account for the 3D underwater environment need to be devised. Especially, in the 3D case the effect of currents should be taken into account, since the intensity and the direction of currents are dependent on the depth of the sensor node. Thus, underwater currents can modify the relative position of sensor devices and also cause connectivity holes, especially when ocean-column monitoring is performed in deep waters.

7.1. Open research issues

There exist many open research issues for the development of efficient routing solutions for underwater acoustic sensor networks, as outlined below:

- There is a need to develop algorithms to provide strict or loose latency bounds for time critical applications. To this respect, it should be considered that while the delay for an acoustic signal to propagate from one node to another mainly depends on the distance of the two nodes, the delay variance also depends on the nature of the link, i.e., the delay variance in horizontal acoustic links is generally larger than in vertical links due to multi-paths [45].
- For delay-tolerant applications, there is a need to develop mechanisms to handle loss of connectivity without provoking immediate retransmissions. Strict integration with transport and data link layer mechanisms may be advantageous to this end.
- It is necessary to devise routing algorithms that are robust with respect to the intermittent connectivity of acoustic channels. The quality of acoustic links is highly unpredictable, since it mainly depends on fading and multi-path, which are hard phenomena to model.
- Accurate modeling is needed to better understand the dynamics of data transmission at the

network layer. Moreover, credible simulation models and tools need to be developed.

- Algorithms and protocols need to be developed that detect and deal with disconnections due to failures, unforeseen mobility of nodes or battery depletion. These solutions should be local so as to avoid communication with the surface station and global reconfiguration of the network, and should minimize the signaling overhead.
- Local route optimization algorithms are needed to react to consistent variations in the metrics describing the energy efficiency of the underwater channel. These variations can be caused by increased bit error rates due to acoustic noise, or relative displacement of communicating nodes due to variable currents.
- Mechanisms are needed to integrate AUVs in underwater networks and to enable communication between sensors and AUVs. In particular, all the information available to sophisticated AUV devices (trajectory, localization) could be exploited to minimize the signaling needed for reconfigurations.
- In case of geographical routing protocols, it is necessary to devise efficient underwater location discovery techniques.

8. Transport layer

The transport layer of UW-ASNs is a totally unexplored area. In this section we discuss the fundamental challenges for the development of an efficient *reliable transport layer* protocol which addresses the requirements of UW-ASNs. We also discuss some existing reliable data transport solutions for wireless sensor networks, along with their shortcomings in the underwater environment.

Noticeably, in sensor networks, reliable event detection at the sink should be based on collective information provided by source nodes and not on any individual report from each single source [8]. Hence, conventional end-to-end reliability definitions and solutions can be inapplicable in the underwater sensor field, and could lead to waste of scarce sensor resources. On the other hand, the absence of a reliable transport mechanism alto-

gether can seriously impair event detection due to the underwater challenges. Thus, the UW-ASN paradigm necessitates a new *event transport reliability* notion rather than the traditional end-to-end approaches.

A transport layer protocol is needed in UW-ASNs not only to achieve *reliable collective transport* of event features, but also to perform *flow control* and *congestion control*. The primary objective is to save scarce sensor resources and increase the network efficiency. A reliable transport protocol should guarantee that the applications be able to correctly identify event features estimated by the sensor network. Congestion control is needed to prevent the network from being congested by excessive data with respect to the network capacity, while flow control is needed to avoid that network devices with limited memory are overwhelmed by data transmissions.

Most existing TCP implementations are unsuited for the underwater environment, since the flow control functionality is based on a window-based mechanism that relies on an accurate estimate of the round trip time (RTT), which is twice the end-to-end delay from source to destination. The underwater RTT can be modeled as a stochastic variable with a high mean value, which reflects the sum of the high delays on the links composing the end-to-end path, and a high delay variance, which reflects the sum of the high delay variances on the composing link. This high-mean/high-variance RTT would affect the throughput of most TCP implementations. Furthermore, the high variability of the RTT would make it hard to effectively set the timeout of the window-based mechanism that most current TCP implementations adopt.

Rate-based transport protocols seem also unsuited for this challenging environment. In fact, although they do not adopt a window-based mechanism, they still rely on feedback control messages sent back by the destination to dynamically adapt the transmission rate, i.e., to decrease the transmission rate when packet loss is experienced or to increase it otherwise. The high delay and delay variance can thus cause instability in the feedback control.

Furthermore, due to the unreliability of the acoustic channel, it is necessary to distinguish between packet losses due to the high bit error rate of the acoustic channel, from those caused by packets being dropped from the queues of sensor nodes due to network congestion. Most TCP implementations, which are designed for wired networks, assume that congestion is the only cause for packet loss. Due to this assumption, when a packet loss occurs, they reduce the transmission rate to avoid injecting more packets in the network. Conversely, in UW-ASNs as in terrestrial wireless networks, it is important to discriminate losses due to impairments of the channel from those caused by congestion. When congestion is the cause of the packet loss, the transmission rate should be decreased to avoid overwhelming the network, while in case of losses due to bad channel quality, the transmission rate should not be decreased to preserve throughput efficiency.

For these reasons, it may be necessary to devise completely new strategies to achieve underwater flow control and reliability.

Several solutions have been proposed to address the transport layer problems in terrestrial wireless sensor networks. For example, in [8], *event-to-sink reliable transport* (ESRT) protocol is proposed to achieve reliable event detection with minimum energy expenditure. However, the ESRT mechanism relies on spatial correlation among event flows which may not be easily leveraged in underwater acoustic sensor networks. In fact, in terrestrial sensor networks nodes are densely deployed, and thus the physical readings of spatially close nodes may be correlated (*spatial correlation*). Conversely, underwater sensor nodes may be more expensive and complex devices, and are usually more sparsely deployed. Hence, correlation among sensor readings from different sensors may not be significant in UW-ASNs.

Transport layer functionalities can be tightly integrated with data link layer functionalities in a cross-layer module. The purpose of such an integrated module is to make the information about the condition of the variable underwater channel available also at the transport layer. In fact, usually the state of the channel is known only at the

physical and channel access sub-layers, while the design principle of layer separation makes this information transparent to the higher layers. This integration allows maximizing the efficiency of the transport functionalities, and the behavior of data link and transport layer protocols can be dynamically adapted to the variability of the underwater environment.

8.1. Open research issues

In order to develop a new efficient cross-layer reliable protocol specifically tailored to underwater acoustic sensor networks, the following issues must be studied:

- New flow control strategies need to be devised in order to tackle the high delay and delay variance of the control messages sent back by the receivers.
- New effective mechanisms tailored to the underwater acoustic channel need to be developed, in order to efficiently infer the cause of packet losses.
- New event transport reliability metric definitions need to be proposed, based on the event model and on the underwater acoustic channel model.
- Optimal update policies for the sensor reporting rate are needed, to prevent congestion and maximize the network throughput efficiency as well as the transport reliability in bandwidth limited underwater networks.
- The effects of multiple event occurrences on the reliability and network performance requirements must be studied, as well as efficient mechanisms to deal with it.
- It is necessary to statistically model loss of connectivity events in order to devise mechanisms, to enable delay-tolerant applications tailored to the specific underwater requirements.
- Different functionalities at the data link and transport layer such as channel access, reliability and flow control, should be jointly designed and studied. A cross-layer approach is highly recommended to accordingly optimize these mechanisms and make them adaptable to the variability of the characteristics of the underwater channel.

9. Application layer

Although many application areas for underwater sensor networks can be outlined, to the best of our knowledge the definition of an application layer protocol for UW-ASNs remains largely unexplored.

The purpose of an application layer is multi-fold: (i) to provide a network management protocol that makes hardware and software details of the lower layers transparent to management applications; (ii) to provide a language for querying the sensor network as a whole; (iii) to assign tasks and to advertise events and data.

No efforts in these areas have been made to date that address the specific needs of the underwater acoustic environment. A deeper understanding of the application areas and of the communication problems in underwater sensor networks is crucial to outline some design principles on how to extend or reshape existing application layer protocols [10] for terrestrial sensor networks.

Some of the latest developments in middleware may be studied and adapted to realize a versatile application layer for underwater sensor networks. For example, the San Diego Supercomputing Center Storage Resource Broker (SRB) [6,11] is a client-server middleware that provides a uniform interface for connecting to heterogeneous data resources over a network, and accessing replicated data sets. SRB provides a way to access data sets and resources based on their attributes and/or logical names rather than their names or physical locations.

10. Implementations of underwater sensor networks

A few experimental implementations of underwater acoustic sensor networks have been reported in the last few years. In this section we describe two of them, one mainly concerned with military applications and the other with oceanographic observations.

The Front-Resolving Observational Network with Telemetry (FRONT) project at the University of Connecticut relies on acoustic telemetry and ranging advances pursued by the US Navy

referred to as “telesonar” technology [16]. The Seaweb network for FRONT Oceanographic Sensors involves telesonar modems deployed in conjunction with three types of nodes, namely *sensors*, *gateways* and *repeaters*. Sensors are oceanographic instruments serially connected to an acoustic modem. Gateways are surface buoys that relay data from the subsurface network to the shore. Repeaters are acoustic modems that relay data packets. In the various Seaweb/FRONT experiments, 20 sensors and repeaters have been deployed in shallow water (20–60 m deep). By means of long range ocean bottom active sensors, acoustic correlation current profilers (ACCP), sampling of the 3D water column is achieved with a 2D network architecture (Section 2). The network enables sensor-to-shore data delivery and shore-to-sensor remote control.

Researchers from different fields gathered at the Monterey Bay Aquarium Research Institute (MBARI) in August 2003 for a month-long experiment to quantify gains in predictive skills for principal circulation trajectories, i.e., to study upwelling of cold, nutrient-rich water in the Monterey Bay. Autonomous vehicles (AUVs, gliders), as well as other ships, vessels and platforms, enabled unexampled observational capabilities that are reported on the experiment web site [4]. Extensive data are reported that show the variation of the characteristics of the circulation of water during the various days of the experiment.

11. Conclusions

In this paper, we presented an overview of the state of the art in underwater acoustic sensor network. We described the challenges posed by the peculiarities of the underwater channel with particular reference to monitoring applications for the ocean environment. We discussed characteristics of the underwater channel and outlined future research directions for the development of efficient and reliable underwater acoustic sensor networks. The ultimate objective of this paper is to encourage research efforts to lay down fundamental basis for the development of new advanced communication techniques for efficient underwater communi-

cation and networking for enhanced ocean monitoring and exploration applications. We strongly advocated the use of a cross-layer approach to jointly optimize the main networking functionalities in order to design communication suites that are adaptable to the variability of the characteristics of the underwater channel and optimally exploit the extremely scarce resources.

Acknowledgement

The authors wish to thank Dr. Ozgur B. Akan, Dr. Eylem Ekici, Vehbi C. Gungor and Mehmet C. Vuran for their valuable comments that improved the quality of this paper. This work was supported by the Office of Naval Research under contract N00014-02-1-0564.

References

- [1] UnderWater Sensor Networks at BWN Laboratory, Georgia Institute of Technology, Available from <<http://www.ece.gatech.edu/research/labs/bwn/UWASN/>>.
- [2] AUV Laboratory at MIT Sea Grant, Available from <<http://auvlab.mit.edu/>>.
- [3] Ocean Engineering at Florida Atlantic University, Available from <<http://www.oe.fau.edu/research/ams.html>>.
- [4] Second field test for the AOSN program, Monterey Bay August 2003, Available from <<http://www.mbari.org/aosn/MontereyBay2003/MontereyBay2003Default.htm>>.
- [5] The Delay Tolerant Networking Research Group, Available from <<http://www.dtnrg.org>>.
- [6] SDSC Storage Resource Broker, Available from <<http://www.npaci.edu/DICE/SRB/>>.
- [7] M. Abolhasan, T. Wysocki, E. Dutkiewicz, A review of routing protocols for mobile ad hoc networks, *Ad Hoc Networks* 2 (1) (2004) 1–22.
- [8] O.B. Akan, I.F. Akyildiz, Event-to-sink reliable transport in wireless sensor networks, *IEEE/ACM Transactions on Networking*, in press.
- [9] K. Akkaya, M. Younis, A survey on routing protocols for wireless sensor networks, *Ad Hoc Networks* 3 (3) (2005) 325–349, in this issue.
- [10] I.F. Akyildiz, W. Su, Y. Sankarasubramaniam, E. Cayirci, Wireless sensor networks: A survey, *Computer Networks* 38 (4) (2002) 393–422.
- [11] C. Baru, R. Moore, A. Rajasekar, M. Wan, The SDSC storage resource broker, in: *Proceedings of the 1998 Conference of the Centre for Advanced Studies on Collaborative Research*, 1998.

- [12] P. Bose, P. Morin, I. Stojmenovic, J. Urrutia, Routing with guaranteed delivery in ad hoc wireless networks, *ACM Wireless Networks* 7 (6) (2001) 609–616.
- [13] L. Brekhovskikh, Y. Lysanov, *Fundamentals of Oceans Acoustics*, Springer, New York, 2001.
- [14] J. Catipovic, Performance limitations in underwater acoustic telemetry, *IEEE Journal of Oceanic Engineering* 15 (3) (1990) 205–216.
- [15] E. Cayirci, H. Tezcan, Y. Dogan, V. Coskun, Wireless sensor networks for underwater surveillance systems, *Ad Hoc Networks*, in press; doi:10.1016/j.adhoc.2004.10.008.
- [16] D.L. Codiga, J.A. Rice, P.A. Baxley, Networked acoustic modems for real-time data delivery from distributed subsurface instruments in the coastal ocean: Initial system development and performance, *Journal of Atmospheric and Oceanic Technology*, in press.
- [17] S. Das (Bit), R. Ragupathy, Routing in manet and sensor networks—a 3d position based approach, submitted for publication.
- [18] R. Davis, C. Eriksen, C. Jones, Autonomous buoyancy-driven underwater gliders, in: G. Griffiths (Ed.), *The Technology and Applications of Autonomous Underwater Vehicles*, Taylor and Francis, London, 2002.
- [19] K. Fall, A delay-tolerant network architecture for challenged internets, in: *Proceedings of ACM SIGCOMM'03*, August 2003.
- [20] E. Fiorelli, N. Leonard, P. Bhatta, D. Paley, R. Bachmayer, D. Fratantoni, Multi-AUV control and adaptive sampling in Monterey Bay, in: *Proceedings of IEEE Autonomous Underwater Vehicles 2004: Workshop on Multiple AUV Operations (AUV04)*, June 2004.
- [21] L. Freitag, M. Stojanovic, Acoustic communications for regional undersea observatories, in: *Proceedings of Oceanology International*, London, UK, March 2002.
- [22] L. Freitag, M. Stojanovic, S. Singh, M. Johnson, Analysis of channel effects on direct-sequence and frequency-hopped spread-spectrum acoustic communication, *IEEE Journal of Oceanic Engineering* 26 (4) (2001) 586–593.
- [23] S.A.L. Glegg, R. Pirie, A. LaVigne, A study of ambient noise in shallow water, Florida Atlantic University Technical Report, 2000.
- [24] M. Hinchey, Development of a small autonomous underwater drifter, in: *Proceedings of IEEE NECEC'04*, October 2004.
- [25] B.M. Howe, T. McGinnis, H. Kirkham, Sensor networks for cabled ocean observatories, *Geophysical Research Abstracts* 5 (2003).
- [26] P. Jacquet, P. Muhlethaler, T. Clausen, A. Laouiti, A. Qayyum, L. Viennot, Optimized link state routing protocol for ad hoc networks, in: *Proceedings of IEEE INMIC*, Pakistan, 2001.
- [27] J. Jalbert, D. Blidberg, M. Ageev, Some design considerations for a solar powered AUV: Energy management and its impact on operational characteristics, *Unmanned Systems* 15 (4) (1997) 26–31.
- [28] D.B. Johnson, D.A. Maltz, J. Broch, DSR: The dynamic source routing protocol for multi-hop wireless ad hoc networks, in: C.E. Perkins (Ed.), *Ad Hoc Networking*, Addison-Wesley, Reading, MA, 2001, pp. 139–172.
- [29] R. Jurdak, C.V. Lopes, P. Baldi, Battery lifetime estimation and optimization for underwater sensor networks, in: *Sensor Network Operations*, IEEE Press, New York, 2004.
- [30] D.N. Kalofonos, M. Stojanovic, J.G. Proakis, Performance of adaptive MC-CDMA detectors in rapidly fading rayleigh channels, *IEEE Transactions on Wireless Communications* 2 (2) (2003) 229–239.
- [31] P. Karn, MACA—a new channel access method for packet radio, in: *Proceedings of the 9th ARRL Computer Networking Conference*, London, Ontario, Canada, 1990.
- [32] D.B. Kilfoyle, A.B. Baggeroer, The state of the art in underwater acoustic telemetry, *IEEE Journal of Oceanic Engineering* 25 (1) (2000) 4–27.
- [33] T. Melodia, D. Pompili, I.F. Akyildiz, Optimal local topology knowledge for energy efficient geographical routing in sensor networks, in: *Proceedings of IEEE INFOCOM'04*, Hong Kong SAR, PRC, March 2004.
- [34] P. Ogren, E. Fiorelli, N.E. Leonard, Cooperative control of mobile sensor networks: Adaptive gradient climbing in a distributed environment, *IEEE Transactions on Automatic Control* 49 (8) (2004) 1292–1302.
- [35] C.E. Perkins, E.M. Belding-Royer, S. Das, Ad hoc on demand distance vector (AODV) routing, IETF RFC 3561.
- [36] C.E. Perkins, T.J. Watson, Highly dynamic destination sequenced distance vector routing (DSDV) for mobile computers, in: *Proceedings of ACM SIGCOMM'94*, London, UK, 1994.
- [37] J.G. Proakis, J.A. Rice, E.M. Sozer, M. Stojanovic, Shallow water acoustic networks, in: J.G. Proakis (Ed.), *Encyclopedia of Telecommunications*, John Wiley and Sons, 2003.
- [38] J.G. Proakis, E.M. Sozer, J.A. Rice, M. Stojanovic, Shallow water acoustic networks, *IEEE Communications Magazine* 39 (11) (2001) 114–119.
- [39] A. Quazi, W. Konrad, Underwater acoustic communication, *IEEE Communications Magazine* 20 (2) (1982) 24–30.
- [40] V. Ravelomanana, Extremal properties of three-dimensional sensor networks with applications, *IEEE Transactions on Mobile Computing* 3 (3) (2004) 246–257.
- [41] F. Salva-Garau, M. Stojanovic, Multi-cluster protocol for ad hoc mobile underwater acoustic networks, in: *Proceedings of IEEE OCEANS'03*, San Francisco, CA.
- [42] N.N. Soreide, C.E. Woody, S.M. Holt, Overview of ocean based buoys and drifters: Present applications and future needs, in: *16th International Conference on Interactive Information and Processing Systems (IIPS) for Meteorology, Oceanography, and Hydrology*, January 2004.
- [43] E.M. Sozer, J.G. Proakis, M. Stojanovic, J.A. Rice, A. Benson, M. Hatch, Direct sequence spread spectrum based modem for underwater acoustic communication and channel measurements, in: *Proceedings of OCEANS'99*, November 1999.

- [44] E.M. Sozer, M. Stojanovic, J.G. Proakis, Underwater acoustic networks, *IEEE Journal of Oceanic Engineering* 25 (1) (2000) 72–83.
- [45] M. Stojanovic, Acoustic (underwater) communications, in: J.G. Proakis (Ed.), *Encyclopedia of Telecommunications*, Wiley, New York, 2003.
- [46] M. Stojanovic, J. Catipovic, J.G. Proakis, Phase coherent digital communications for underwater acoustic channels, *IEEE Journal of Oceanic Engineering* 19 (1) (1994) 100–111.
- [47] M. Stojanovic, J.G. Proakis, J. Catipovic, Analysis of the impact of channel estimation errors on the performance of a decision feedback equalizer in multipath fading channels, *IEEE Transactions on Communications* 43 (2/3/4) (1995) 877–886.
- [48] M. Stojanovic, J.G. Proakis, J. Catipovic, Performance of high-rate adaptive equalization on a shallow water acoustic channel, *Journal of the Acoustical Society of America* 100 (4) (1996) 2213–2219.
- [49] R.J. Urick, *Principles of Underwater Sound*, McGraw-Hill, 1983.
- [50] G. Xie, J.H. Gibson, A network layer protocol for UANs to address propagation delay induced performance limitations, in: *Proceedings of IEEE OCEANS'01*, vol. 4, Honolulu, HI, November 2001, pp. 2087–2094.
- [51] X. Yang, K.G. Ong, W.R. Dreschel, K. Zeng, C.S. Mungle, C.A. Grimes, Design of a wireless sensor network for long-term, in-situ monitoring of an aqueous environment, *Sensors* 2 (2002) 455–472.
- [52] B. Zhang, G.S. Sukhatme, A.A. Requicha, Adaptive sampling for marine microorganism monitoring, in: *IEEE/RSJ International Conference on Intelligent Robots and Systems*, 2004.



Ian F. Akyildiz is the Ken Byers Distinguished Chair Professor with the School of Electrical and Computer Engineering, Georgia Institute of Technology and Director of Broadband and Wireless Networking Laboratory. He is the Editor-in-Chief of *Computer Networks* (Elsevier) and *Ad Hoc Networks* (Elsevier) Journal. He is an IEEE FELLOW (1995), an ACM FELLOW (1996). He served as a National Lecturer for ACM from 1989 until 1998 and received the ACM

Outstanding Distinguished Lecturer Award for 1994. He received the 1997 IEEE Leonard G. Abraham Prize award (IEEE Communications Society) for his paper entitled “Multimedia Group Synchronization Protocols for Integrated Services Architectures” published in the *IEEE Journal of Selected Areas in Communications* (JSAC) in January 1996. He received the 2002 IEEE Harry M. Goode Memorial award (IEEE Computer Society) with the citation “for significant and pioneering contributions to advanced architectures and protocols for wireless and satellite networking”. He received the 2003 IEEE Best Tutorial Award (IEEE Communication Society) for his paper entitled “A Survey on Sensor Networks”, published in *IEEE Communication Magazine*, in August 2002. He received the 2003 ACM SIGMOBILE award for his significant contributions to mobile computing and wireless networking. His current research interests are in Sensor Networks, InterPlanetary Internet, Wireless Networks and Satellite Networks.



Dario Pompili received the “Laurea” degree in Telecommunications Engineering in 2001, magna cum laude, from the University of Rome “La Sapienza”. From June 2001 he has been working at the same university on the European Union IST Brahms and Satip6 projects. In 2004 he earned from the University of Rome “La Sapienza” the Ph.D. degree in System Engineering. In 2003 he worked on Sensor Networks at the Broadband and Wireless Networking Laboratory, Georgia Institute of Technology, Atlanta, as a visiting researcher. Currently he is pursuing the Ph.D. degree in Electrical Engineering at the Georgia Institute of Technology. His main research interests are in Wireless Sensor Networks, Underwater Acoustic Sensor Networks, and Satellite Networks.



Tommaso Melodia received the “Laurea” degree in Telecommunications Engineering from the University “La Sapienza”, Rome, Italy, in 2001. He then worked on a national research project on Mobile Networking and Wireless Personal Area Networks at the same University. He is currently pursuing his Ph.D. and working as a research assistant at the Broadband and Wireless Networking Laboratory, Georgia Institute of Technology, Atlanta. His main research interests are in Wireless Ad Hoc and Sensor Networks, Wireless Sensor and Actor Networks, Underwater Acoustic Sensor Networks, Personal and Mobile Communications.