Chapter 1

Research Challenges in Communication Protocol Design for Underwater Sensor Networks

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Underwater networks of sensors have the potential to enhance our ability to observe and predict the ocean by enabling many applications such as oceanographic data collection, pollution monitoring, offshore exploration, disaster prevention, assisted navigation, and tactical surveillance. Underwater acoustic networking is the enabling technology for these applications. In this chapter, fundamental key aspects of underwater acoustic communications are investigated, and architectures for two-dimensional and three-dimensional underwater sensor networks are proposed. A detailed overview on the current acoustic communication solutions for medium access control, network, and transport layer protocols is given and open research issues for protocol design are discussed.

1.1. Introduction

Underwater networks of sensors have the potential to enable unexplored applications and to enhance our ability to observe and predict the ocean. Unmanned or Autonomous Underwater Vehicles (UUVs, AUVs), equipped with underwater sensors, are also envisioned to find application in exploration of natural undersea resources and gathering of scientific data in collaborative monitoring missions. These potential applications will be made viable by enabling communications among underwater devices. UnderWater Acoustic Sensor Networks (UW-ASNs) will consist of sensors and vehicles deployed underwater and networked via acoustic links to perform collaborative monitoring tasks.

Underwater acoustic sensor networks enable a broad range of applica-

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tions, including:

- **Ocean Sampling Networks**. Networks of sensors and AUVs can perform synoptic, cooperative adaptive sampling of the 3D coastal ocean environment.
- **Environmental Monitoring.** UW-ASNs can perform pollution monitoring (chemical, biological, and nuclear), ocean current and wind monitoring, and biological monitoring such as tracking of fish or micro-organisms. Also, UW-ASNs can improve weather forecast, detect climate change, and understand and predict the effect of human activities on marine ecosystems.
- **Undersea Explorations.** Underwater sensor networks can help detect 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, or study the effects of submarine earthquakes (*seaquakes*).
- **Seismic Monitoring.** Frequent seismic monitoring is of great importance in oil extraction from underwater fields to asses field performance. Underwater sensor networks would allow reservoir management approaches.
- **Equipment Monitoring.** Sensor networks would enable remote control and temporary monitoring of expensive equipment immediately after the deployment, to assess deployment failures in the initial operation or to detect problems.
- **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*.
- **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.

Acoustic communications are the typical physical layer technology in underwater networks. In fact, radio waves propagate at long distances through conductive salty water only at extra low frequencies ($30-300\,\mathrm{Hz}$), which require large antennae and high transmission power. Optical waves do not suffer from such high attenuation but are affected by scattering. Furthermore, transmitting optical signals requires high precision in pointing the narrow laser beams. Thus, links in underwater networks are typically based on *acoustic wireless communications*.[1]

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.[2] 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).

These disadvantages can be overcome by connecting untethered underwater instruments by means of wireless links that rely on acoustic communications. 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 high and variable propagation delays,[2] 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 impaired because of multipath and fading;

- Propagation delay is five orders of magnitude higher than in Radio Frequency (RF) terrestrial channels, and variable;
- High bit error rates and temporary losses of connectivity (shadow zones) can be experienced;
- Underwater sensors are characterized by high cost because of a small relative number of suppliers (i.e., not much economy of scale);
- Battery power is limited and usually batteries cannot be recharged;
- Underwater sensors are prone to failures because of fouling and corrosion.

In this survey, we discuss the factors that influence protocol design for underwater sensor networks. The remainder of this chapter is organized as follows. In Sections 1.2 and 1.3 we introduce the main design challenges and the reference communication architectures, respectively, of underwater acoustic networks. In Sections 1.4, 1.5, and 1.6 we discuss medium access control (MAC), network, and transport layer issues in underwater sensor networks, respectively. Finally, in Section 1.7 we draw the main conclusions.

1.2. Design Challenges

In this section, we itemize the main differences between terrestrial and underwater sensor networks, detail the key challenges in underwater communications that influence protocol development, and give motivations for a cross-layer design approach to improve the efficiency of the communication process in the challenging underwater environment.

1.2.1. *Differences with Terrestrial Sensor Networks*

The main differences between terrestrial and underwater sensor networks can be outlined 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. Also, because of the low economy of scale caused by a small relative number of suppliers, underwater sensors are characterized by high cost.
- **Deployment.** While terrestrial sensor networks are densely deployed, in underwater, the deployment is generally more sparse.

- **Power.** The power needed for acoustic underwater communications is higher than in terrestrial radio communications because of the different physical layer technology (acoustic vs. RF waves), the higher distances, and more complex signal processing techniques implemented 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.

1.2.2. *Underwater Sensors*

The typical internal architecture of an underwater sensor is shown in Fig. 1.1. It consists of a main 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. The protecting frame should be designed so as to deflect trawling gear on impact, by housing all components beneath a low-profile pyramidal frame.[3]

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*

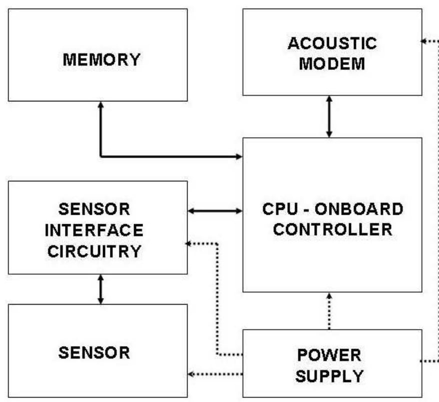

Fig. 1.1. Internal organization of an underwater sensor node

analysis), amperometric microsensors for H_2S 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.

1.2.3. *Factors Influencing Underwater Protocol Design*

In this section we analyze the main factors in UnderWater Acoustic (UW-A) communications that affect the design of protocols at different communication layers. Acoustic communications in the underwater environment are mainly influenced by *transmission loss*, *noise*, *multipath*, *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 underwater acoustic channel 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,[4] in the order of tens of kbps for existing devices.

Underwater acoustic communication links can be classified according to their range as *very long*, *long*, *medium*, *short*, and *very short* links.[1] Table 1 shows typical bandwidths of the underwater acoustic channel for different

	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

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 discussed later, their propagation characteristics differ considerably, especially with respect to time dispersion, multipath 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 briefly analyze the factors that influence acoustic communications in order to state the challenges posed by the underwater channels for sensor networking. These include:

Transmission loss. The underwater transmission loss describes how the acoustic intensity decreases as an acoustic pressure wave propagates outwards from a sound source. The transmission loss $TL(d, f)$ [dB] that a narrow-band acoustic signal centered at frequency f [KHz] experiences along a distance d [m] can be described by the Urick propagation model,[5] $TL(d, f) = \chi \cdot Log(d) + \alpha(f) \cdot d + A$. The first term account for *geometric spreading*, which 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, spreading coefficient $\chi = 20$), which characterizes deep water communications, and *cylindrical* (horizontal radiation only, spreading coefficient $\chi = 10$), which characterizes shallow water communications. In-between cases show a spreading coefficient χ in the interval $(10, 20)$, depending on water depth and link length. The second term accounts for *medium absorption*, where $\alpha(f)$ [dB/m] represents an absorption coefficient that describes the dependency of the transmission loss on the frequency band, as shown in Fig. 1.2. Finally, the last term, expressed by the quantity A [dB], is the so-called *transmission anomaly*, and accounts for the degradation of the acoustic intensity caused by multiple path propagation, refraction, diffraction, and scattering of sound caused by particulates, bubbles, and plankton within the water column. Its value is higher for shallow-water horizontal links

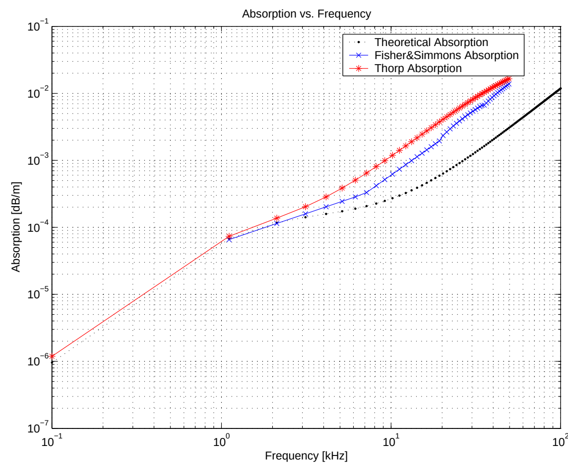

Fig. 1.2. Theoretical, Fisher&Simon's, and Thorp's medium absorption coefficient $\alpha(f)$ vs. frequency $f \in [10^{-1}, 10^{2}]$ KHz

(up to 10 dB), which are more affected by multipath.[5] More details can be found in the literature[6].[7]

Noise. It can be classified as *man-made noise* and *ambient noise*. The former is mainly caused by machinery noise (pumps, reduction gears, power plants), and shipping activity (hull fouling, animal life on hull, cavitation), while the latter is related to hydrodynamics (movement of water including tides, current, storms, wind, and rain), and to seismic and biological phenomena. The unique *'V' structure* of the underwater acoustic noise p.s.d. (which has a minimum of $20\,\text{dB}_{\text{re}\,\mu\text{Pa}}/\text{Hz}$ at about 40 kHz), depicted in in Fig. 1.3, makes *non-trivial* the choice of the bandwidth, Interestingly, in acoustic communication transmissions, when the central frequency is low, e.g., $f_0 = 10$ kHz, a higher relative signal-to-noise-ratio SNR is achieved with a narrow bandwidth (e.g., $B = 3$ as opposed to 9 kHz); conversely, when the central frequency is high, e.g., $f_0 = 100$ kHz, a higher relative SNR is achieved with a wide bandwidth (e.g., $B = 90$ as opposed to 30 kHz). This implies that if a high central frequency is used, a large bandwidth can be exploited for communication, although a high transmit power would be needed to compensate for the higher transmission loss. Acoustic communication solutions tailored for the underwater environment should take into account this unique effect, which is caused by the peculiar 'V' structure of the noise p.s.d. and by the fact that the difference between the slopes of the noise and transmission loss decreases with increasing central

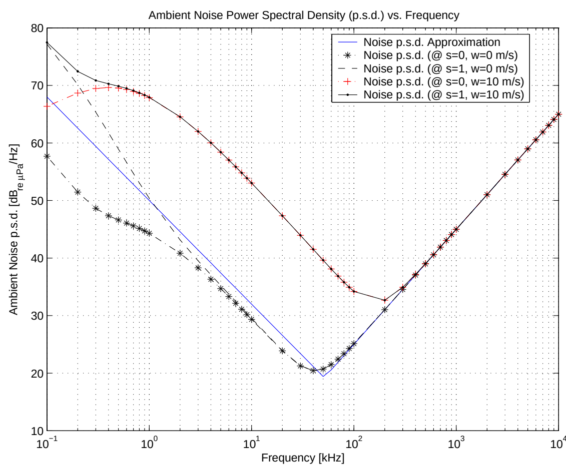

Fig. 1.3. Underwater ambient noise power spectrum density $N(f)\,[\mathrm{dB}_{\mathrm{re}\,\mu\mathrm{Pa}}/\mathrm{Hz}]$ at different shipping activities $s = 0, 1$ and surface wind $w = 0, 10\,\mathrm{m/s}$.

frequency (e.g., positive for low frequencies and negative for high ones).

Multipath. Multipath propagation may be responsible for severe degradation of the acoustic communication signal, since it generates Inter Symbol Interference (ISI). The multipath geometry depends on the link configuration. Vertical channels are characterized by little time dispersion, whereas horizontal channels may have long multipath 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 ($0.67\,\mathrm{s/km}$) and its variance can reduce the system throughput. Specifically, the underwater acoustic propagation speed $q(z, S, t)\,[\mathrm{m/s}]$ is accurately modeled[5]as $q(z, S, t) = 1449.05 + 45.7 \cdot t - 5.21 \cdot t^2 + 0.23 \cdot t^3 + (1.333 - 0.126 \cdot t + 0.009 \cdot t^2) \cdot (S - 35) + 16.3 \cdot z + 0.18 \cdot z^2$, where $t = T/10$ (T is the temperature in °C), S is the salinity in *ppt*, and z is the depth in km. The above expression provides a useful tool to determine the propagation speed, and thus the propagation delay, in different operating conditions, and yields values in $[1460, 1520]\,\mathrm{m/s}$, centered around $1500\,\mathrm{m/s}$.

Doppler spread. The Doppler frequency spread can be significant in UW-A channels,[1] causing a degradation in the performance of digital communications: transmissions at a high data rate cause many adjacent symbols to interfere at the receiver. The Doppler spreading generates two

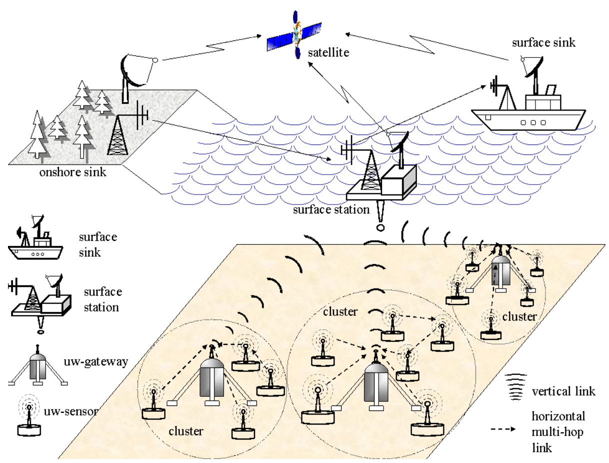

Fig. 1.4. 2D Underwater Sensor Networks

effects: a simple frequency translation and a continuous spreading of frequencies, which constitutes a non-shifted signal. While the former is easily compensated at the receiver, the effect of the latter is harder to be compensated for.

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 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, especially in shallow water.

1.3. Communication Architectures

In this section, we present some reference communication architectures for underwater acoustic sensor networks, which constitute a basis for discussion of the challenges associated with the underwater environment.

1.3.1. *2D Underwater Sensor Networks*

A reference architecture for two-dimensional underwater networks is shown in Fig. 1.4. A group of sensor nodes are anchored to the bottom of the ocean. Underwater sensor nodes are interconnected to one or more *underwater gateways* (uw-gateways) by means of wireless acoustic links. Uw-

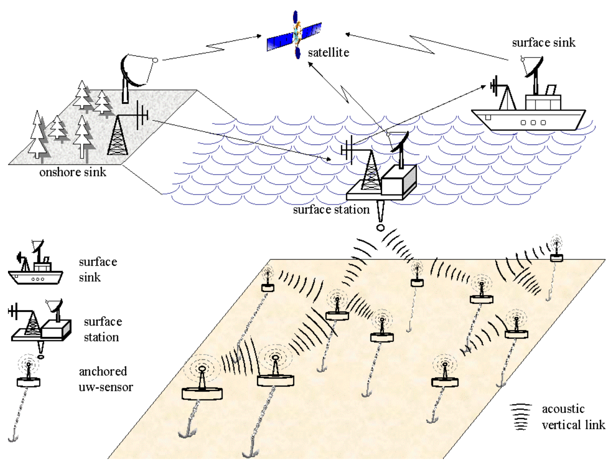

Fig. 1.5. 3D Underwater Sensor Networks

gateways are network devices in charge of relaying data from the ocean bottom network to a surface station. To achieve this objective, they are equipped with two acoustic transceivers, namely a *vertical* and a *horizontal* transceiver. The horizontal transceiver is used by the uw-gateway to communicate with the sensor nodes in order to: i) send commands and configuration data to the sensors (uw-gateway to sensors); ii) collect monitored data (sensors to uw-gateway). The vertical link is used by the uw-gateways to relay data to a *surface station*. In deep water applications, vertical transceivers must be long range transceivers. The surface station is equipped with an acoustic transceiver that is able to handle multiple parallel communications with the deployed uw-gateways. 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). In shallow water, bottom-deployed sensors/modems may directly communicate with the surface buoy, with no specialized bottom node (uw-gateway).

1.3.2. *3D 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 to observe a phenomenon. In this architecture, given in

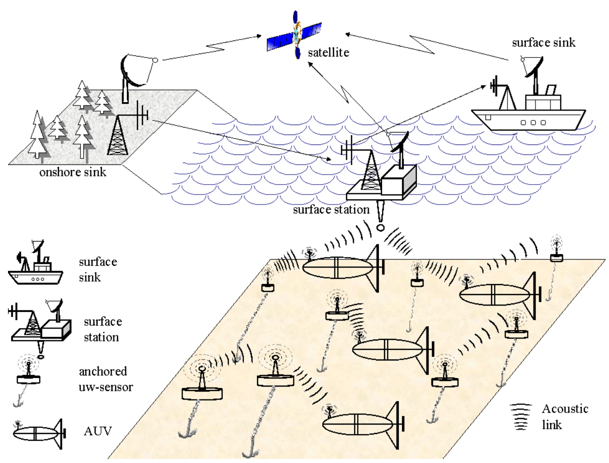

Fig. 1.6. 3D Underwater Sensor Networks with AUVs

Fig. 1.5, 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.

Sensing and communication coverage in a 3D environment have been rigorously investigated.[8] 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.

We presented a statistical analysis for different deployment strategies for 2D and 3D communication architectures for UW-ASNs.[9] Specifically, we determined the minimum number of sensors needed to be deployed to achieve the optimal sensing and communication coverage; we provided guidelines on how to choose the optimal deployment surface area, given a target region; we studied the robustness of the sensor network to node failures, and provided an estimate of the number of redundant sensors to be deployed to compensate for possible failures.

1.3.3. *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 studies. 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. The integration of UW-ASNs with AUVs 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. 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.

One of the design objectives of AUVs is to make them rely on local intelligence and be less dependent on communications from online shores.[10] 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. A reference architecture for 3D UW-ASNs with AUVs is shown in Fig. 1.6.

Several types of AUVs exist as experimental platforms for underwater experiments. Some of them resemble small-scale submarines (such as the Odyssey-class AUVs 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, and are used for taking measurements at preset depths.[11] Underwater gliders[12] 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.

1.4. Medium Access Control Layer

There has been intensive research on MAC protocols for ad hoc[13] and wireless terrestrial sensor networks[14] in the last decade. However, due to the different nature of the underwater environment and applications, existing terrestrial MAC solutions are unsuitable for this environment. In fact, channel access control in UW-ASNs poses additional challenges due to the peculiarities of the underwater channel, in particular limited bandwidth, very high and variable propagation delays, high bit error rates, temporary losses of connectivity, channel asymmetry, and extensive time-varying multipath and fading phenomena.

Existing MAC solutions are mainly focused on Carrier Sense Multiple Access (CSMA) or Code Division Multiple Access (CDMA). This is because Frequency Division Multiple Access (FDMA) is not suitable for UW-ASN due to the narrow bandwidth in UW-A channels and the vulnerability of limited band systems to fading and multipath. Moreover, Time Division Multiple Access (TDMA) shows a limited bandwidth efficiency because of the long time guards required in the UW-A channel. Furthermore, the variable delay makes it very challenging to realize a precise synchronization, with a common timing reference.

1.4.1. *CSMA-based MAC Protocols*

Slotted FAMA[15] is based on a channel access discipline called floor acquisition multiple access (FAMA). It combines both carrier sensing (CS) and a dialogue between the source and receiver prior to data transmission. During the initial dialogue, control packets are exchanged between the source node and the intended destination node to avoid multiple transmissions at the same time. Although time slotting eliminates the asynchronous nature of the protocol and the need for excessively long control packets, thus providing savings in energy, guard times should be inserted in the slot duration to account for any system clock drift. In addition, due to the high propagation delay of underwater acoustic channels, the handshaking mechanism may lead to low system throughput, and the carrier sensing may sense the channel idle while a transmission is still going on.

The impact of the large propagation delay on the throughput of selected classical MAC protocols and their variants was analyzed, and the so-called propagation-delay-tolerant collision avoidance protocol (PCAP)[16] was introduced. Its objective is to fix the time spent on setting up links for data frames, and to avoid collisions by scheduling the activity of sensors. Although PCAP offers higher throughput than widely used conventional protocols for wireless networks, it does not provide a flexible solution for applications with heterogeneous requirements.

A distributed energy-efficient MAC protocol tailored for the underwater environment was proposed, whose objective is to save energy based on sleep periods with low duty cycles.[17] The proposed solution is strictly tied to the assumption that nodes follow sleep periods, and is aimed at efficiently organizing the sleep schedules. This protocol tries to minimize the energy consumption and does not consider bandwidth utilization or access delay as objectives.

1.4.2. *CDMA-based MAC Protocols*

CDMA is the most promising physical layer and multiple access technique for UW-ASNs. In fact, CDMA is robust to frequency selective fading caused by multipath since it is able to distinguish among signals simultaneously transmitted by multiple devices through codes that spread the user signal over the entire available band. This allows exploiting the time diversity in underwater acoustic channels by leveraging Rake filters[18] at the receiver, so as to compensate for the effect of multipath. In this way, CDMA increases channel reuse and reduces packet retransmissions, which result in decreased battery consumption and increased throughput.

Two code-division spread-spectrum physical layer techniques were compared[19] in shallow water underwater communications, namely Direct Sequence Spread Spectrum (DSSS) and Frequency Hopping Spread Spectrum (FHSS). While in DSSS data is spread using codes with good auto- and cross-correlation properties to minimize the mutual interference, in FHSS different simultaneous communications use different hopping sequences and thus transmit on different frequency bands. Interestingly, it is showed that in the underwater environment FHSS leads to a higher bit error rate than DSSS. Another attractive access technique in the recent underwater literature combines multi-carrier transmission with the DSSS CDMA[20][21] as it may offer higher spectral efficiency than its single-carrier counterpart, and may 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 reduces intersymbol interference (ISI). However, multicarrier transmissions may not be suitable for low-end sensors due to their high complexity.

A MAC solution was also introduced for underwater networks with AUVs.[22] The 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. Since vehicles in the same cluster are assumed to be close to one another, the negative effect of very high underwater propagation delay and efficiency loss, which is caused by the long time guards required when TDMA is used underwater,[23] are limited. Interference among different clusters is minimized by assigning different spreading codes to different clusters. The proposed solution assumes a clustered network architecture and proximity among nodes within the same cluster.

We proposed a distributed MAC protocol, called UW-MAC,[24] for UW-ASNs. UW-MAC is a transmitter-based CDMA scheme that incorporates a novel closed-loop distributed algorithm to set the optimal transmit power and code length to minimize the near-far effect. It compensates for the effect of multipath by exploiting the time diversity in the underwater channel, thus achieving high channel reuse and low number of packet retransmissions, which result in decreased battery consumption and increased network throughput. UW-MAC leverages a multi-user detector on resource-rich devices such as surface stations, uw-gateways and AUVs, and a single-user detector on low-end sensors. UW-MAC aims at achieving a threefold objective, i.e., guarantee high network throughput, low access delay, and low energy consumption. It is shown that UW-MAC manages to simultaneously meet the three objectives in deep water communications, which are not severely affected by multipath, while in shallow water communications, which are heavily affected by multipath, UW-MAC dynamically finds the optimal trade-off among high throughput, and low access delay and energy consumption, according to the application requirements. Main features of UW-MAC are: i) it provides a *unique and flexible solution* for different architectures such as *static* 2D deep water and 3D shallow water, and architectures with *mobile* AUVs; ii) it is fully *distributed*, as code and transmit power are distributively selected by each sender without relying on a centralized entity; iii) it is intrinsically *secure*, as it uses chaotic codes; iv) it efficiently *supports multicast transmissions*, as spreading codes are decided at the transmitter side; v) it is *robust* against inaccurate node position and interference information caused by mobility, traffic unpredictability, and packet loss due to channel impairment. The distributed power and code self-assignment problem to minimize the near-far effect is also formulated, and a low-complexity yet optimal solution is proposed. It is worth noting that UW-MAC is the first protocol that leverages CDMA properties to achieve multiple access to the scarce underwater bandwidth, while existing papers analyzed CDMA only from a physical layer perspective.

Open Research Issues

- In case CDMA is adopted, which we advocate, it is necessary to design access codes with high auto-correlation and low cross-correlation properties to achieve minimum interference among users.
- It is necessary to design low-complexity encoders and decoders to limit the processing power required to implement Forward Error Correction (FEC) functionalities.
- Distributed protocols should be devised to reduce the activity of a device when its battery is depleting without compromising on network operation.

1.5. Network Layer

In recent years there has been a great interest to develop new routing protocols for terrestrial ad hoc[25] and wireless sensor networks.[26] However, there are several drawbacks with respect to the suitability of the existing terrestrial routing solutions for underwater networks. The existing routing protocols are divided into three categories, namely *proactive*, *reactive*, and *geographical* routing protocols.

Proactive protocols (e.g., DSDV,[27] OLSR[28]) cause 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 must be propagated to all network devices. This way, each device is able to establish a path to any other node in the network, which may not be needed in UW-ASNs.

Reactive protocols (e.g., AODV,[29] DSR[30]) are more appropriate for dynamic environments but incur a higher latency and still require source-initiated flooding of control packets to establish paths. Reactive protocols are unsuitable for UW-ASNs as they also cause a high latency in the establishment of paths, which is further amplified in the underwater by the slow propagation of acoustic signals. Moreover, the topology of UW-ASNs is unlikely to vary dynamically on a short-time scale.

Geographical routing protocols (e.g., GFG,[31] PTKF[32]) are very promising for their scalability feature and limited required signaling. However, Global Positioning System (GPS) radio receivers, which may be used in terrestrial systems to accurately estimate the geographical location of sensor nodes, do not properly work in the underwater environment. In fact, GPS uses waves in the 1.5 GHz band that do not propagate in water. Still, underwater devices (sensors, UUVs, UAVs, etc.) need to estimate their current position, irrespective of the chosen routing approach. In fact, it is necessary to associate the sampled data with the 3D position of the device that generates the data, to spatially reconstruct the characteristics of the event. Underwater localization can be achieved by leveraging the low speed of sound in water, which permits accurate timing of signals, and pairwise node distance data can be used to perform 3D localization.[33]

Some recent papers propose network layer protocols specifically tailored for underwater acoustic networks. A routing protocol was proposed that autonomously establishes the underwater network topology, controls network resources, and establishes network flows, which relies on a centralized network manager running on a surface station.[34] The manager establishes efficient data delivery paths in a centralized fashion, which allows avoiding congestion and providing some form of quality of service guarantee. Although the idea is promising, the performance evaluation of the proposed mechanisms has not been thoroughly studied.

A routing protocol called vector-based forwarding (VBF)[35] was proposed, which is based on a geographical routing approach and thus does not require state information on the sensors. In VBF, each packet carries the positions of the sender, the destination and the forwarder. The forwarding path is specified by the so-called *routing vector*, i.e., a vector that connects source and destination. Upon receiving a packet, a node computes its position relative to the forwarder by measuring its distance to the forwarder and the angle of arrival of the signal. Recursively, all the nodes receiving the packet compute their positions. If a node determines that it is close enough to the routing vector (i.e., less than a predefined distance), it includes its own position in the packet and forwards it. Otherwise, it discards the packet. In this way, all packet forwarders form a "routing pipe", and all sensor nodes in the pipe are potential forwarders for the packet. Instead, those nodes which are not close enough to the routing vector, which constitutes the axis of the pipe, do not forward the packet. Packets are thus forwarded along redundant and interleaved paths from source to destination, which makes the protocol robust against packet loss and node failure. The proposed solution can be seen as a form of geographically controlled flooding. However, redundant transmissions are not energy and bandwidth efficient. A localized and distributed self-adaptation algorithm is also proposed to enhance the performance of VBF, which allows the nodes to weigh the benefit of forwarding packets, and accordingly reduce the energy consumption by discarding low benefit packets.

A simple design example of a shallow water network is suggested where routes are established by a central manager based on neighborhood information gathered from all nodes by means of poll packets.[36] However, the routing issues such as the criteria used to select data paths, are not covered. Moreover, sensors are only deployed linearly along a stretch, while the characteristics of the 3D underwater environment are not investigated.

A long-term monitoring platform for underwater sensor networks consisting of static and mobile nodes was proposed, and hardware and software architectures were described.[37] The nodes communicate point-to-point using a high-speed optical communication system, and broadcast using an acoustic protocol. The mobile nodes can locate and hover above the static nodes for data muling, and can perform useful network maintenance functions such as deployment, relocation, and recovery. However, due to the limitations of optical transmissions, communication is enabled only when the sensors and the mobile mules are in close proximity.

The reliability requirements of long-term critical underwater missions, and the small scale of underwater sensor networks, suggest to devise routing solutions based on some form of centralized planning of the network topology and data paths, in order to optimally exploit the scarce network resources. For these reasons, we investigated the problem of data gathering for three-dimensional underwater sensor networks at the network layer by considering the interactions between the routing functions and the characteristics of the underwater acoustic channel.[38] We developed a resilient routing solution for long-term monitoring missions, with the objective of guaranteeing survivability of the network to node and link failures. The solution relies on a *virtual circuit* routing technique, where multihop connections are established *a priori* between each source and sink, and each packet associated with a particular connection follows the same path. This requires centralized coordination and leads to 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 with minimum signaling overhead.

Specifically, the proposed routing solution[38] follows a *two-phase* approach. In the *first phase*, the network manager determines optimal *node-disjoint primary* and *backup* multihop data paths such that the energy consumption of the nodes is minimized. This is needed because, unlike in terrestrial sensor networks where sensors can be redundantly deployed, the underwater environment requires minimizing the number of sensors. Hence, protection is necessary to avoid network connectivity being disrupted by node or link failures. In the *second phase*, an on-line distributed solution guarantees survivability of the network, by locally repairing paths in case of disconnections or failures, or by switching the data traffic on the backup paths in case of severe failures. The emphasis on survivability is motivated by the fact that underwater long-term monitoring missions can be extremely expensive. Hence, it is crucial that the deployed network be highly reliable, so as to avoid failure of missions due to failure of single or multiple devices. The protection scheme proposed can be classified as a dedicated backup scheme with 1:1 path protection, with node-disjoint paths.

We proposed new geographical routing algorithms for the 3D underwater environment,[39] designed to distributively meet the requirements of delay-insensitive and delay-sensitive sensor network applications. The proposed distributed routing solutions are tailored for the characteristics of the underwater environment, e.g., they take explicitly into account the very high propagation delay, which may vary in horizontal and vertical links, the different components of the transmission loss, the impairment of the physical channel, the extremely limited bandwidth, the high bit error rate, and the limited battery energy. In particular, the proposed routing solutions allow achieving two apparently conflicting objectives, i.e., increasing the efficiency of the channel by transmitting a *train* of short packets *back-to-back*; and limiting the packet error rate by keeping the transmitted packets short. The packet-train concept is exploited in the proposed routing algorithms, which allow each node to *jointly* select its best next hop, the transmitted power, and the FEC rate for each packet, with the objective of minimizing the energy consumption, taking the condition of the underwater channel and the application requirements into account.

The first algorithm deals with delay-insensitive applications, and tries to exploit links that guarantee a low packet error rate, to maximize the probability that a packet is correctly decoded at the receiver, and thus minimize the number of required packet retransmissions. The second algorithm is designed for delay-sensitive applications. The objective is to minimize the energy consumption, while statistically limiting the end-to-end packet delay and packet error rate by estimating at each hop the time to reach the sink and by leveraging statistical properties of underwater links. In order to meet these application-dependent requirements, each node *jointly* selects its best next hop, the transmitted power, and the forward error correction rate for each packet. Differently from the previous delay-insensitive routing solution, next hops are selected by also considering maximum per-packet allowed delay, while unacknowledged packets are not retransmitted to limit the delay. The emphasis on energy consumption is justified by the need for extended lifetime deployments of underwater sensor networks.

There are still several open research issues regarding routing algorithms for underwater networks.

- For delay-sensitive applications, there is a need to develop algorithms to provide strict latency bounds.
- For delay-insensitive applications, there is a need to develop mechanisms to handle loss of connectivity without provoking immediate retransmissions. Moreover, algorithms and protocols need to be devised that detect and deal with disconnections due to failures, unforeseen mobility of nodes or battery depletion.
- Accurate network modeling is needed to better understand the dynamics of data transmission at the network layer. Moreover, realistic simulation models and tools need to be developed.
- Low-complexity acoustic techniques to solve the underwater localization problem with limited energy expenditure in the presence of measurement errors need to be further investigated by the research community.
- 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.

1.6. Transport Layer

A transport layer protocol is needed in UW-ASNs to achieve *reliable transport* of event features, and to perform *flow control* and *congestion control*. 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). The long RTT, which characterizes the underwater environment, would affect the throughput of most TCP implementations. Furthermore, the variability of the underwater RTT would make it hard to effectively set the timeout of the window-based mechanism, which most current TCP implementations rely on.

Existing rate-based transport protocols seem to be unsuited for this challenging environment as well, since they rely on feedback control messages sent back by the destination to dynamically adapt the transmission rate. The long and variable RTT can thus cause instability in the feedback control. For these reasons, it is necessary to devise new strategies to achieve flow control and reliability in UW-ASNs.

A transport layer protocol designed for the underwater environment, Segmented Data Reliable Transport (SDRT),[40] has been recently proposed. SDRT addresses the challenges of underwater sensor networks for reliable data transport, i.e., large propagation delays, low bandwidth, energy efficiency, high error probabilities, and highly dynamic network topologies. The basic idea of SDRT is to use Tornado codes to recover errored packets to reduce retransmissions. The data packets are transmitted block-by-block and each block is forwarded hop-by-hop. SDRT keeps sending packets inside a block before it gets back a positive feedback and thus wastes energy. To reduce such energy consumption, a window control mechanism is adopted. SDRT transmits the packets within the window quickly, and the remaining packets at a lower rate. A mathematical model is developed to estimate the window size and the FEC block size. The performance of SDRT is also illustrated by simulations.

Encoding and decoding using Tornado codes are computation-intensive operations even though Tornado codes use only XOR operations. This leads to increased energy consumption. In SDRT, there is also no mechanism to guarantee the end-to-end reliability as an hop-by-hop transfer mode is used. Each node along the path must first decode the FEC block and then encode it again to transmit it to the next hop. Again, the total computation overhead will be too high for the network. Similarly, for hop-by-hop operations, each sensor must keep calculating the mean values of window and the FEC block sizes, which can cause a high computational overhead and accordingly higher energy consumption at each sensor. The overhead due to redundant packets will also be high because of high error probabilities. This overhead is dependent on the accuracy in estimating the window size. If the window size is too large, more packets are sent than necessary. In addition, SDRT does not address one of the fundamental challenges for UW-ASN, i.e., shadow zones, and relies on an in-sequence packet forwarding scheme. While this may be enough for some applications, for time-critical data sensors may need to forward packets continuously even in case of holes in the sequence with an out-of-sequence packet delivery mechanism. SDRT is a first attempt to propose a transport protocol for UW-ASN and addresses some of the aforementioned design principles. However, it is still an evolving work and needs further improvements, as it creates redundant transmissions and is computation-intensive.

A complete transport layer solution for the underwater environment should be based on the following design principles:

- *Shadow zones.* Although correct handling of shadow zones requires assistance from the routing layer, a transport protocol should consider these cases.
- *Minimum energy consumption.* A transport protocol should be explicitly designed to minimize the energy consumption.
- *Rate-based transmission of packets.* A transport protocol should be based on rate-based transmission of data units as it allows nodes flexible control over the rates.
- *Out-of-sequence packet forwarding.* Packets should be continuously forwarded to accelerate the packet delivery process.
- *Timely reaction to local congestion.* A transport protocol should adapt to local conditions immediately, to decrease the response time in case of congestion. Thus, rather than sinks, intermediate nodes should be capable of determining and reacting to local congestion.
- *Cross-layer-interaction-based protocol operation.* Losses of connectivity or partial packet losses (i.e., bit or packet errors) should trigger the protocol to take appropriate actions. Therefore, unlike in the layered communications paradigm, transport protocol operations and critical decisions should be supported by the available information from lower layers.
- *Reliability.* A hop-by-hop reliability mechanism surfaces as a prevalent solution as it provides energy efficient communication. However, there should also be mechanism to guarantee the end-to-end reliability.
- *SACK-based loss recovery.* Many feedbacks with ACK mechanisms

would throttle down the utilization of the bandwidth-limited channel unnecessarily. Thus, the notion of selective acknowledgment (SACK), which helps preserve energy, should be considered for loss scenarios where it is not possible to perform error recovery at lower layers only.

Open research issues for transport layer solutions are given below:

- New flow control strategies need to be devised 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 to efficiently infer the cause of packet losses.
- New reliability-metric definitions need to be proposed, based on the event model and on the underwater acoustic channel model.
- The effects of multiple concurrent events on the reliability and network performance requirements must be studied.
- It is necessary to statistically model loss of connectivity events to devise mechanisms to enable delay-insensitive applications.
- It is necessary to devise solutions to handle the effects of losses of connectivity caused by shadow zones.

1.7. Conclusions

In this chapter, we presented an overview of the state of the art in underwater acoustic sensor networks. 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 chapter is to bring together researchers from different areas relevant to underwater networks and to encourage research efforts to lay down fundamental bases for the development of new advanced communication techniques for efficient underwater communication and networking for enhanced ocean monitoring and exploration applications.

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