Underwater Wireless Networking Technologies

M.P. Malumbres[1], P. Pablo Garrido[1], Carlos T. Calafate[2] and Jose Oliver[2]
[1]Miguel Hernandez University, Spain
[2]Technical University of Valencia, Spain
E-mail: mels@umh.es

Introduction

Underwater sound has probably been used by marine specimens for millions of years as a communication capability among the members of a same species. It is said that in 1490, Leonardo Da Vinci wrote the following sentence "If you cause your ship to stop and place the head of a long tube in the water and place the outer extremity to your ear, you will hear ships at a great distance from you" (Urick, 1983); being perhaps the first recorded experiments about hearing underwater sounds.

In 1826 on Lake Geneva, Switzerland, the physicist Jean-Daniel Colladon, and his mathematician friend Charles-Francois Sturm, made the first recorded attempt to determine the speed of sound in water. In their experiment, the underwater bell was struck simultaneously with ignition of gunpowder on the first boat. The sound of the bell and flash from the gunpowder were observed 10 miles away on the second boat. The time between the gunpowder flash and the sound reaching the second boat was used to calculate the speed of sound in water. Colladon and Sturm were able to determine the speed of sound in water fairly accurately with this method. (Colladon, 1893).

This experiment on sound propagation through water laid the foundation for underwater acoustic technology that paved the way for the development of this technology up to our days. In 1906, Lewis Nixon invented the very first Sonar type listening device, increasing the demand of this technology during World War I to detect submarines. In 1915, the physicist Paul Langévin and the engineer Constantine Chilowski, invented the first sonar type device for detecting submarines called an "echo location to detect submarines" using the piezoelectric properties of the quartz. He was too late to offer any help to the war effort; however, Langévin's work heavily influenced future sonar designs.

After using underwater sound technology for measuring the proximity to the shore and other ships, researchers soon realized that, if the sound device was pointed down at the seafloor, the depth could be accurately determined. So, new applications of sonar devices were discovered, like active depth measuring (bathymetry), seafloor shape registering, search for geological resources (i.e. oil, gas, etc.), detecting and tracking fish banks, submarine archeology, etc.

Although the underwater acoustic applications were mainly focused in ranging applications, exploration of seafloor and fishery by means of sonar devices, the interest in underwater multipoint communications was stressed in the 90’s, were synoptic, spatially sampled oceanographic surveillance has provided an impetus to the transfer of networked communication technology to the underwater environment. One of the former deployments was the Autonomous Oceanographic Surveillance Network (AOSN), supported by the US Office of Naval Research (ONR) (Curtin, Bellingham, Catipovic, and Webb, 1993). It calls for a system of moorings, surface buoys, underwater sensor nodes and Autonomous Underwater Vehicles (AUVs) to coordinate their sampling via an acoustic telemetry network.

Background

Wireless networking technologies have experienced a considerably development in the last fifteen years, not only in the standardization areas but also in the market deployment of a bunch of devices, services and applications. Among this plethora of wireless products, wireless sensor networks are exhibiting an incredible boom, being one of the technological areas with greater scientific and industrial development pace (Akyildiz, Sankarasubramaniam, and Cayirci, 2002). The interest and opportunity in working on wireless sensor network technologies is endorsed by (a) technological indicators like the ones published by MIT (Massachusetts Institute of Technology) in 2003 (Werff, 2003) where wireless sensor network technology was defined as one of the 10 technologies that will change the world, and (b) economic and market forecasts published by different economic magazines like (Rosenbush, Crockett, and Yang, 2004), where investment in Wireless Sensor Network (WSN) ZigBee technology was estimated over 3.500 Million dollars during 2007.

Recently, wireless sensor networks have been proposed for their deployment in underwater environments where a lot of applications like aquiculture, pollution monitoring, offshore exploration, etc. would benefit from this technology (Cui, Kong, Gerla, and Zhou, 2006).

Despite having a very similar functionality, Underwater Wireless Sensor Networks (UWSNs) exhibit several architectural differences with respect to the terrestrial ones, which are mainly due to the transmission medium characteristics (sea water) and the signal employed to transmit data (acoustic ultrasound signals) (Akyildiz, Pompili, and Melodia, 2006). Then, the design of appropriate network architecture for UWSNs is seriously hardened by the conditions of the communication system and, as a consequence, what is valid for terrestrial WSNs is perhaps not valid for UWSNs. So, a general review of the overall network architecture is required in order to supply an appropriate network service for the demanding applications in such an unfriendly submarine communication environment.

Major challenges in the design of underwater acoustic networks are:

- Battery power is limited and usually batteries can not be recharged because solar energy cannot be exploited;
- The available bandwidth is severely limited;
- The channel suffers from long and variable propagation delays, multi-path and fading problems;
- Bit error rates are typically very high;
- Underwater sensors are prone to frequent failures because of fouling, corrosion, etc.

In the next section, the main issues in the design of efficient underwater wireless sensor networks. Following a bottom-to-top approach, we will review the network architecture, highlighting some critical design parameters at each of the different network layers, and how to overcome the limitations and problems introduced by UWSN environments.

Underwater Wireless Networking Technologies

Basically, an UWSN is formed by the cooperation among several nodes that establish and maintain a network through the use of bidirectional acoustic links. Every node is able to send/receive messages from/to other nodes in the network, and also to forward messages to remote destinations in case of multi-hop networks. Every node may have one or several sensors that are actively recording environmental data which should be forwarded to special sink nodes, typically platforms or buoys at the surface. Sink nodes have communication channels to forward and/or local store the collected data to the remote control station in the coast, typically through a Radio Frequency (RF) link.

So, the UWSN allows an interactive environment where scientists can extract real-time data from multiple distant underwater sensor instruments. After evaluating the obtained data, control messages can be sent to individual network nodes so the overall network can be adapted to changing situations.

Topology.
In (Partan, Kurose, and Levine, 2006), taxonomy of UWSN regimes is proposed. They classify different UWSNs in terms of both spatial coverage and node density. For every kind of network topology, different architectural approaches have to be considered in order to improve the network performance (throughput, delay, power consumption, packet loss, etc.). So, it is important to design the network architecture taking into account the intended network topology.

Physical layer: Acoustic Link.
The most common way to send data in underwater environments is by means of acoustic signals, just like dolphins and whales use to do for communicating between them. Radio frequency signals have serious problems to propagate in sea water as shown in (Schill, Zimmer, and Trumpf, 2004), being operative for radio-frequency only at very short ranges (up to 10 meters) and with low-bandwidth modems (tens of Kbps).When using optical signals the light is strongly scattered and absorbed underwater, so only in very clear water conditions (often very deep) does the range go up to 100 meters with high bandwidth modems (several Mbps) and blue-green wavelengths.

Since acoustic signals are mainly used in UWSNs, it is necessary to take into account the main aspects involved in the propagation of acoustic signals in underwater environments, including: (1) the propagation speed of sound underwater is around 1500 m/s (5 orders of magnitude slower than the speed of light), and so the communication links will suffer from large and variable propagation delays and relatively large motion-induced Doppler effects; (2) phase and magnitude fluctuations lead to higher bit error rates compared with radio channels' behaviour, being mandatory the use of forward error correction codes (FEC); (3) as frequency increases, the attenuation observed in the acoustic channel also increases, being this a serious bandwidth constraint; (4) multipath interference in underwater acoustic communications is severe due mainly to the surface waves or vessel activity, being a serious problem to attain good bandwidth efficiency. Several approaches were taken to combat multipath effects, being the use of Multiple-Input Multiple-Output (MIMO) transducer arrays (Freitag, Stojanovic, Singh, and

Jhonson, 2001) a good solution for reduce multipath effects and therefore increase the link throughput.

Several works in the literature propose models for an acoustic underwater link, taking into account environment parameters as salinity degree, temperature, depth, environmental interference, etc. In (Harris and Zorzi, 2007) you will find a clear description of the different issues that take part on the development of an acoustic channel model.

Medium Access Control (MAC) Layer

The main task of MAC protocols is to provide efficient and reliable access to the shared physical medium in terms of throughput, delay, error rates and energy consumption. However, due to the different nature of the underwater environment, there are several drawbacks with respect to the suitability of the existing terrestrial MAC solutions for the underwater environment. In fact, channel access control in UWSNs poses additional challenges due to the aforementioned peculiarities of underwater channels.

As shown in (Akyildiz et al, 2006), existing MAC solutions are mainly focused on Carrier Sense Multiple Access (CSMA) or Code Division Multiple Access (CDMA). However, Frequency Division Multiple Access (FDMA) is not suitable for UWSNs due to the narrow bandwidth available in underwater acoustic channels, and the vulnerability of limited band systems to fading and multipath effects. Moreover, Time Division Multiple Access (TDMA) shows limited bandwidth efficiency because of the long time guards required in the underwater acoustic channel. Furthermore, the variable delay makes it very challenging to achieve a precise synchronization through a common timing reference.

CSMA-Based.

In general, CSMA-based protocols are vulnerable to both hidden and exposed terminal problems (Karl and Willig, 2005). In order to reduce the effects of hidden terminals, MAC proposals should include techniques similar to the ones used in terrestrial networks like MACA (Karn, 1990), that uses RTS/CTS/DATA packets to reduce the hidden terminal problem, and MACAW (Bharghavan, Demers, Shenker, and Zhang, 1994), which adds to the previous one an ACK packet at the link-layer, which can be helpful in an unreliable underwater channel. FAMA (Fullmer and Luna-Acebes, 1995) extends the duration of RTS and CTS packets in order to avoid data packet collisions, and so contention is managed at both sender and receiver sides before sending data packets. The efficiency of these protocols is heavily impacted by propagation delays due to their multiple handshakes.

A number of adaptations have been proposed to adopt MACA, MACAW, and FAMA for underwater networks. In (Molins and Stojanovic, 2006), there was proposed the Slotted FAMA approach, adding timeslots to the FAMA protocol to limit the impact of propagation delays. (Kebkal A., Kebkal K., and Komar, 2005) proposed a means to reduce the impact of propagation delay on FAMA and MACAW-based protocols, with ACK and DATA packets simultaneously in flight. They also suggest an extension to FAMA, using CDMA for the RTS packets, to develop a collision-free FAMA protocol.

CDMA-Based.

CDMA is a contention-free multiple access method which is promising for future underwater networks. 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.

In (Freitag et al, 2001), two code-division spread-spectrum physical layer techniques for underwater communications in shallow water are compared, namely Direct Sequence Spread Spectrum (DSSS) and Frequency Hopping Spread Spectrum (FHSS). In the case of DSSS, limitations in temporal coherence of the channel affect the maximum spreading factor, leading to situations that may be better suited to FHSS signals. Conversely, the multipath resolving properties of DSSS minimize the effects of frequency-selective fading that degrade the performance of FSK modulation of FHSS systems.

More recently, (Stojanovic and Freigtag, 2006) reported very promising CDMA experimental results. An important caveat for this work, however, is that the received power for each of the users should be similar. If the received power for all users is not roughly similar, signals from distant users cannot be received successfully. This is known as the near-far problem, and requires the transmit power of each user to be controlled when switching the channel.

In (Pompili, Melodia, and Akyildiz, 2007) the authors propose a distributed Medium Access Control (MAC) protocol called UW-MAC. It defines 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 a low number of packet retransmissions.

Network Layer

This layer is mainly responsible of routing packets to the proper destinations. So, a routing protocol is required when a packet must go through several hops to reach its destination. It is responsible for finding a route for the packet and making sure it is forwarded through the appropriate path. The way paths are selected for every source-destination pair will have a direct impact on the overall network performance.

Most of the routing proposals for UWSN are based on the ones developed for terrestrial ad-hoc and wireless sensor networks. An overview of the different approaches proposed in the literature can be found in (Abolhasan, Wysocky, and Dutkiewicz, 2004).

Nevertheless, as stated by (Akyildiz et al 2006), proactive and reactive routing protocols are not suitable for UWSNs. The former introduce large signalling packet exchanges every time the network changes, so that each network node knows the path to the rest of nodes. Concerning the latter, reactive routing protocols, these require a source-initiated flooding of control packets to establish the path(s), and so the latency to establish the path is usually high, being further amplified in the underwater environment due to the slow propagation of acoustic signals.

Therefore, it seems that geographical routing protocols are the most promising approaches for their use in UWSNs. However, the GPS (Global Positioning System) radio receivers (around 1.5 GHz band) do not work properly in underwater environments as explained before. There are some works related to underwater localization, also required for AUV navigation systems, and the need of mapping sensor data with spatial localization become evident, representing an open problem that requires further research. So, in the following we will briefly describe several examples of routing protocols especially devoted to underwater sensor network scenarios. Most of the proposals take into account the energy consumption constraint.

In (Xie and Gibson, 2001), a routing protocol for UWSNs is proposed, being able to initialize the network topology and work in a centralized manner at the surface station (typically the sink node). The paths to the sink are established by the central manager avoiding congestion, introducing quality of service (QoS) support, and managing the overall network energy consumption; it operates in a similar fashion to the Point Coordination Function (PCF) of IEEE 802.11 networks.

Another proposal can be found in (Xie, Chui, and Lao, 2006), where a routing protocol called Vector-Based Forwarding (VBF) is described. With VBF, each packet carries the positions of the sender, the destination and the forwarder. Packets are forwarded along redundant and interleaved paths (routing pipes) from a source to a destination node, being robust against packet loss and node failure. Jointly with the routing strategy, a localized and distributed self-adaptation algorithm is proposed to enhance the performance of VBF. This algorithm allows the nodes to weigh the benefit of forwarding packets, reducing energy consumption by discarding low benefit packets.

The solution proposed in (Pompili et al 2006) relies on the use of virtual circuits which are established a priori between each source and sink. So, every packet associated with a particular connection follows the same path. This requires centralized coordination from a sink node (station usually located at the surface) and leads to a less flexible routing architecture. However, as other centralized proposals, it is able to exploit optimization tools in order to achieve optimal network layer performance with minimum signalling overhead. In order to increase the reliability of network due to potential node failures, the algorithm finds two paths, primary and backup virtual circuits, between every source-destination pair of nodes.

Applications

As mentioned in the introduction, underwater sensor networks can enable a broad range of applications, following the same path than the terrestrial sensor networks. So, we can use UWSN technology for:

- *Ocean Sampling Networks*. Networks of sensors and AUVs with the ability to perform synoptic, cooperative adaptive sampling of the 3D coastal ocean environment in order to build geology information databases.
- *Environmental Monitoring*. UWSNs can perform pollution monitoring (chemical, biological, and nuclear), monitoring of ocean currents and winds, improved weather forecast, detecting climate changes, understanding and predicting the effect of human activities on marine ecosystems, and biological monitoring such as tracking of marine biology activity or aquaculture industry.
- *Undersea Explorations*. Underwater sensor networks can help at detecting underwater oilfields or reservoirs, determining routes for laying undersea cables, and assisting in the exploration for valuable minerals. Also, it can be used to find out wrecks or as an invaluable tool for submarine archaeology.

- *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.
- *Assisted Navigation*. Sensors can be used to identify hazards on the seabed, locate dangerous rocks or shoals in shallow waters, mooring positions, locating submerged wrecks, and performing bathymetry profiling.
- *Distributed Tactical Surveillance*. AUVs and fixed underwater sensors can collaboratively monitor areas for surveillance, reconnaissance, targeting, and intrusion detection.

Future trends

Underwater sensor networks represent an emerging technology that needs a lot of research effort in the following years. The benefits that this technology would offer to maritime industry are invaluable. However, there are a lot of open issues that would require further research in the future.

More effort is required at the physical layer in order to develop efficient, low-power acoustic modems that are able to maximize the available bandwidth and minimize the delivery error rates by using proper FEC coders.

Currently there is a lot of works related to MAC layer proposals since this is one of the more sensible parts of the UWSN architecture. It seems that distributed CDMA-based schemes are the candidates for underwater environments, but it depends of many factors such as the application and network topology. Also, MAC protocols should be designed taking energy consumption into account as a main design parameter.

With respect to routing protocols, they heavily depend on other design factors such as network topology (even application requirements), node mobility patterns, and energy consumption. Up to now, geographically-based routing algorithms seem to be the most adequate for UWSNs, despite requiring the use of localization schemes. Most of the research efforts should be applied to algorithms and protocols that detect and deal with disconnections due to failures, unforeseen mobility of nodes or battery depletion. Also, due the underwater nature, cross-layer interaction between all layers should be required in order to make a better use of the available resources, and to be able to perform fast adaptations in such a continuously changing environment.

Conclusion

Underwater Sensor Networks is a very recent technology that tries to follow the same steps than terrestrial wireless networks in a very different and challenging network environment. There is an increasing interest in USWN technologies and their potential applications. However, there are several open issues to solve in order to provide an efficient and reliable data transport to the applications.

In years to come, it is expected that UWSNs technology is widely adopted by the industry, resulting in the deployment of new commercial products and solutions that will represent very important revenues to the maritime technology market.

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Terms and definitions

SONAR (SOund NAvigation and Ranging) is a device that uses the properties of underwater sound propagation to communicate, navigate or detect other vessels. It sends pulses of sound to probe the sea, and the echoes are then processed to extract information (shape, distance, composition, etc.) about the sea, its boundaries and submerged objects.

Hydrophone is a microphone designed to be used underwater for recording or listening to underwater sound. Most hydrophones are based on a piezoelectric transducer that generates electricity when subject to a pressure change.

AUVs (Autonomous Underwater Vehicles) are those underwater vehicles able to navigate autonomously to collect sensor data in a specific control area. The most common use of these vehicles is related with the oil and gas industry, allowing obtaining maps of the seafloor before starting to build the subsea infrastructure.

MANETs (Mobile Ad-hoc NETworks) refer to those wireless networks composed of mobile nodes that can communicate between them without the need of any kind of infrastructure (base stations).

WSNs (Wireless Sensor Network) can be defined as a particular case of MANETs in the sense that each node is required to record and wirelessly distribute environmental data obtained through a set of sensors attached it. They are typically small and low-power consuming devices, and use to be deployed in high node density networks

Direct Sequence Spread Spectrum (DSSS) it is a modulation technique where the data signal is multiplied by a pseudo-random binary sequence at a frequency much higher than that of the original signal, thereby spreading the energy of the original signal into a much wider band.

Frequency Hopping Spread Spectrum (FHSS) it is a modulation technique that can be described as a frequency modulation that is repeatedly changing the frequency of the carrier signal in the full available spectrum for transmission.

Pro-active and Reactive routing protocols represent two different styles of routing packets. The former ones maintain updated the routing info by periodically distributing routing tables throughout the network. In contrast, a reactive routing protocol finds a route on demand by flooding the network with Route Request packets.

Point Coordination Function (PCF) is a MAC protocol used in Wireless Local Area Networks (WLANS) that relays in central coordinator, usually known as an Access Point (AP). The access to the medium is governed by APs unit allowing an ordered and collision-free access to the network.