Overview of Networking Protocols for Underwater Wireless Communications

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ABSTRACT

Underwater wireless communications can enable many scientific, environmental, commercial, safety, and military applications. Wireless signal transmission is also crucial to remotely control instruments in ocean observatories and to enable coordination of swarms of autonomous underwater vehicles and robots, which will play the role of mobile nodes in future ocean observation networks by virtue of their flexibility and reconfigurability. To make underwater applications viable, efficient communication protocols among underwater devices, which are based on acoustic wireless technology for distances over one hundred meters, must be enabled because of the high attenuation and scattering that affect radio and optical waves, respectively. The unique characteristics of an underwater acoustic channel — such as very limited and distance-dependent bandwidth, high propagation delays, and time-varying multipath and fading — require new, efficient and reliable communication protocols to network multiple devices, either static or mobile, potentially over multiple hops. In this article, we provide an overview of recent medium access control, routing, transport, and cross-layer networking protocols.

INTRODUCTION

Underwater wireless communications can enable many civilian and military applications such as oceanographic data collection, scientific ocean sampling, pollution and environmental monitoring, climate recording, offshore exploration, disaster prevention, assisted navigation, distributed tactical surveillance, and mine reconnaissance. Some of these applications can be supported by underwater acoustic sensor networks (UW-ASNs) [1], which consist of devices with sensing, processing, and communication capabilities that are deployed to perform collaborative monitoring tasks (Fig. 1). Wireless signal transmission is also crucial to remotely control instruments in ocean observatories and to enable coordination of swarms of autonomous underwater vehicles (AUVs) and robots, which will play the role of mobile nodes in future ocean observation networks by virtue of their flexibility and reconfigurability. To make underwater applications viable, real-time communication protocols among underwater devices must be enabled. Wireless acoustic networking is the enabling technology for underwater applications to cover distances in excess of one hundred meters, whereas shorter distances can be covered using electro-magnetic waves. Radio frequency (RF) waves, in fact, propagate through conductive salty water only at extra-low frequencies (30–300 Hz), which require large antennae and high transmission power. 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.

Many researchers have been engaged in developing networking solutions for terrestrial wireless ad hoc and sensor networks. Although many recently developed network protocols for wireless sensor networks exist, the unique characteristics of the underwater acoustic communication channel require new efficient and reliable data communication protocols, whose design is affected by many challenges such as:

- The propagation delay is five orders of magnitude higher than in electro-magnetic terrestrial channels due to the low speed of sound (1500 m/s).
- The underwater acoustic channel is severely impaired, especially due to time-varying multipath and fading.
- The available acoustic bandwidth depends on the transmission distance due to high environmental noise at low frequencies (lower than 1 kHz) and high-power medium absorption at high frequencies (greater than 50 kHz); only a few kHz may be available at tens of kilometers, and tens of kHz at a few kilometers.
- High bit error rates and temporary losses of connectivity (shadow zones) can be experienced.
- Underwater devices are prone to failures because of fouling and corrosion.
- Batteries are energy constrained and cannot be recharged easily (solar energy cannot be exploited underwater).

For further details on the physical characterization of the underwater acoustic medium, refer

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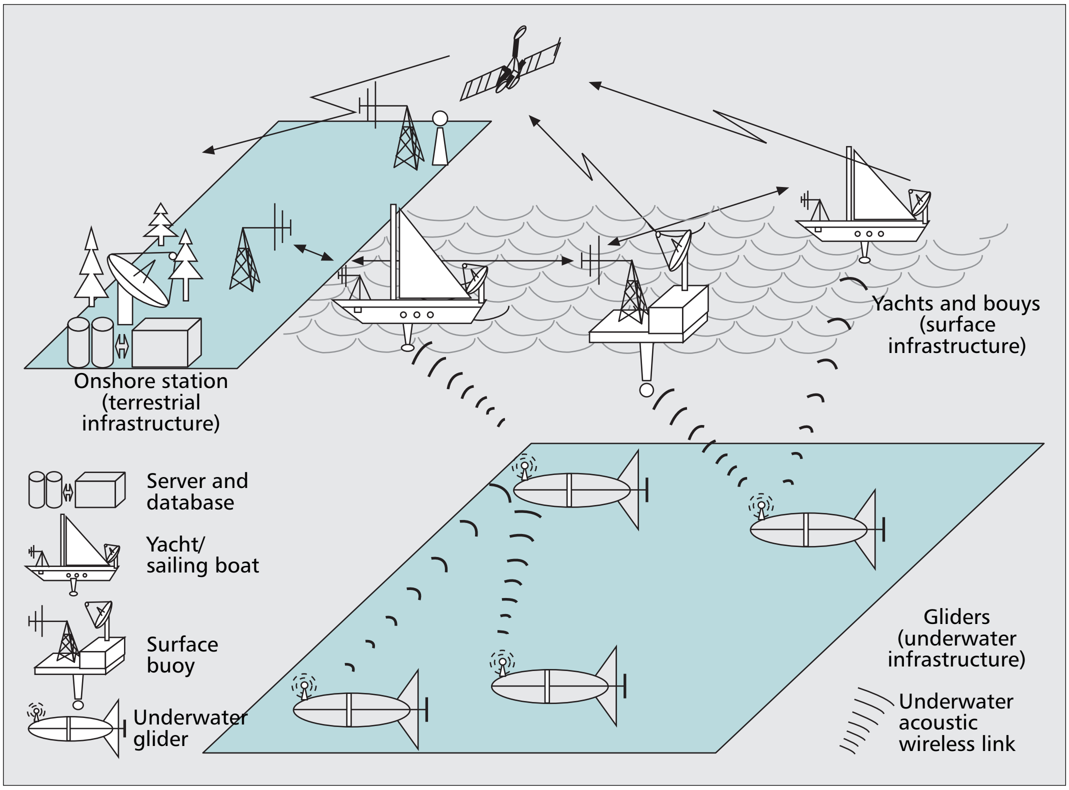

■ **Figure 1.** *Scenario of a UW-ASN composed of underwater and surface vehicles.*

CDMA is a promising physical and MAC layer technique in this environment because it is robust to frequency-selective fading, it compensates for the effect of multipath by exploiting Rake filters at the receiver, and it enables receivers to distinguish among signals simultaneously transmitted by multiple devices.

to the article by Stojanovic and Preisig in this issue.

Most impairments of the underwater acoustic channel can be addressed at the physical layer by designing receivers that are capable of dealing with high bit error rates, fading, and the intersymbol interference (ISI) caused by multipath. Conversely, characteristics such as the extremely long and variable propagation delays, limited and distance-dependent bandwidth, and temporary loss of connectivity, must be addressed at higher layers.

In this survey we discuss key aspects of underwater acoustic communications that influence network protocol design. In the next two sections, we explain why existing terrestrial medium access control (MAC) and routing protocols are unsuitable for the underwater environment and review the latest solutions for underwater communications. We then present the main shortcomings of existing wireless terrestrial window- and rate-based transport-layer mechanisms. We then claim that improved performance in wireless underwater networks can be obtained with a cross-layer protocol design, and we briefly describe our solution. In the final section, we conclude the article.

Medium Access Control Protocols

Due to the unique characteristics of the propagation of acoustic waves in the underwater environment, existing terrestrial MAC solutions are unsuitable for this environment. Channel access control in wireless underwater networks, in fact, poses additional challenges due to the limited bandwidth, very high and variable propagation delays, high bit error rates, temporary losses of connectivity, channel asymmetry, and heavy multipath and fading phenomena. Current underwater 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 the underwater environment due to the narrow bandwidth in underwater acoustic (UW-A) channels and the vulnerability of limited band systems to fading and multipath. Moreover, time-division multiple access (TDMA) shows a limited channel utilization efficiency in large-scale networks because of the long time guards required in long-haul UW-A links. Furthermore, the variable delay caused by multipath makes it very challenging to implement a precise synchronization with a common timing reference. CDMA is a promising *physical* and *MAC layer* technique in this environment because it is robust to frequency-selective fading, it compensates for the effect of multipath by exploiting Rake filters at the receiver, and it enables receivers to distinguish among signals simultaneously transmitted by multiple devices.

In [2], two spread-spectrum physical layer techniques, namely, direct-sequence spread spectrum (DSSS) and frequency-hopping spread spectrum (FHSS), were compared for shallow water communications.[1] Whereas in DSSS, data is spread to minimize the mutual interference; in FHSS, simultaneous communications use different frequency hopping sequences, thus transmitting on different frequency bands. Interestingly, it is shown that in the underwater environment,

[1] *Shallow water refers to depths of less than 100 m.*

FHSS leads to a higher bit error rate than DSSS. Another attractive physical layer technique (whose properties can be leveraged to design a MAC as well) combines DSSS CDMA with multicarrier transmissions, which may offer higher spectral efficiency than its single-carrier counterpart. In this way, high data rate can be supported by increasing the duration of each symbol, which reduces the ISI.

Multicarrier transmissions, however, may not be suitable for low-end underwater devices because of their high complexity. Therefore, in [3], we propose UW-MAC, a distributed single-carrier CDMA solution that keeps the complexity of resource-limited transceivers lower. UW-MAC aims at achieving three objectives, namely, to guarantee high network throughput, low channel access delay, and low energy consumption. It has been demonstrated that UW-MAC simultaneously achieves these three objectives in deep water communications, which usually are not severely affected by multipath. In shallow water communications, which may be heavily affected by multipath, it dynamically finds the optimal trade-off among these objectives according to the application requirements. UW-MAC is the first protocol that leverages CDMA properties to achieve multiple access to the scarce underwater bandwidth, whereas existing underwater CDMA solutions have considered CDMA merely from a physical layer perspective.

In [4], a random channel-access protocol for ad hoc underwater acoustic networks that saves transmission energy by avoiding collisions while maximizing throughput is proposed. The protocol minimizes the duration of a handshake by taking advantage of the tolerance to interference of the receivers when the two nodes are closer than the maximal transmission range. In this protocol, nodes are not required to be synchronized, can move, are half-duplex, and use the same transmission power.

In [5], the proposed MAC protocol divides a time frame into two slots, where one is used by the nodes to transmit data using TDMA techniques, and the other is used for unscheduled access to the channel adapting to variable traffic conditions. The TDMA time slots assigned to a node have a longer duration to avoid collision from other packet transmissions in adjacent slots. The unscheduled time slots are used by nodes for exchanging data in the case of a large traffic load. The strategy of setting the slot to be long enough so as to transmit a maximum-length packet plus longest propagation delay may lead to under utilization of the channel and increase latency in the network.

In [6], two Aloha-based protocols, one called Aloha with carrier sense (Aloha-CS) and the other, Aloha with advance notification (Aloha-AN), are proposed. In Aloha-CS, the sender-receiver information extracted from the overheard packet along with the propagation delay of the packet is used to estimate the duration for which the channel would be busy. Based on these calculations, each node decides the time for transmitting its packet to avoid collisions. Aloha-AN is an improved version of Aloha-CS; it transmits a small advance notification (NTF) packet prior to transmitting the data packet so that other nodes have prior information about the data packet arrival.

UW-MAC is a distributed single-carrier CDMA solution that keeps the complexity of resource-limited transceivers low, and is the first protocol that leverages CDMA properties to achieve multiple access to the scarce underwater bandwidth, whereas existing underwater CDMA solutions have considered CDMA merely from a physical layer perspective.

Routing Protocols

There are several drawbacks with respect to the suitability of the existing terrestrial routing solutions for underwater wireless communications. Routing protocols can be divided into three categories, namely, *proactive*, *reactive*, and *geographical*.

Proactive protocols (e.g., destination-sequenced distance vector [DSDV], optimized link state routing [OLSR]) provoke a large signaling overhead to establish routes for the first time and each time the network topology is modified because of mobility, node failures, or channel state changes because updated topology information must be propagated to all network devices. In this way, each device can establish a path to any other node in the network, which may not be required in underwater networks. Also, scalability is an important issue for this family of routing schemes. For these reasons, proactive protocols may not be suitable for underwater networks.

Reactive protocols (e.g., ad hoc on-demand distance vector [AODV], dynamic source routing [DSR]) 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 may be unsuitable for underwater networks because they also cause a high latency in the establishment of paths, which is amplified underwater by the slow propagation of acoustic signals.

Geographical routing protocols (e.g., greedy-face-greedy [GFG], partial-topology knowledge forwarding [PTKF]) are very promising for their scalability feature and limited signaling requirements. However, global positioning system (GPS) radio receivers do not work properly in the underwater environment. Still, underwater-sensing devices must estimate their current position, irrespective of the chosen routing approach, to associate the sampled data with their 3D position.

In [7], the authors propose a localization scheme for underwater sensor networks that reduces the 3D localization problem to a 2D problem by a non-degenerative projection technique preserving network localizability. The scheme is based on the fact that there should be at least $d + 1$ anchor nodes to uniquely localize a network in d dimensions. Projections of these anchors are taken in a 2D plane containing the node to be localized. Based on these projections and its own depth information, the node can localize itself successfully if the x and y co-ordinates of the anchor are distinct.

Some recent work proposed network-layer

The results obtained suggest that a smaller ratio of propagation delay to packet length further reduces spatial uncertainty. It can be deduced from these findings that short-range communication increases the reliability in underwater networks by reducing spatio-temporal uncertainty of the channel.

In multihop networks, reliability can be defined on a hop-by-hop and an end-to-end basis. However, a sequence of hop-by-hop guarantees does not necessarily add up to an end-to-end guarantee.

protocols specifically tailored for underwater wireless networks. In [8], a long-term monitoring platform for underwater sensor networks consisting of static and mobile nodes, also called mules, is proposed, and hardware and software architectures are described. The nodes communicate point-to-point, using a high-speed short-range 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 mules are in close proximity.

In [9], the authors propose a geographical routing protocol that favors paths with minimal amount of "zigzagging" and that can find all possible paths to reach the destination. Initially, data packets are routed with minimum energy in a cone-shaped region whose axis passes through the sender and the receiver. The transmission power is increased until an intermediate relay node is found. If there are no nodes in that region, the axis of the cone is shifted until the packet is forwarded to a relay node.

In [10], two distributed routing algorithms for delay-insensitive and delay-sensitive applications are introduced, which allow each node to select the optimal next hop, transmit power, and strength of the forward error correction algorithm. Their objective is to minimize the energy consumption, while taking the condition of the underwater acoustic channel and different application requirements into account.

Analysis of multihop versus single-hop routing solutions is performed in [11, 12]. In [11], the authors investigate the delay-reliability trade-off for multihop underwater acoustic networks and compare multihop versus single-hop routing strategies while considering the overall throughput. The analysis shows that increasing the number of hops improves both the achievable information rate and reliability, which captures the decay rate of the decoding error probability because the coding block length increases asymptotically. In [12], a multihop underwater acoustic network is analyzed to understand the effect of frequency and reuse factor on signal-to-noise-ratio (SNR) and interference strength. Based on numerical analysis, the article concludes that most of the interference at the sender is contributed by the two or three nearest interfering nodes. Although the analysis provides interesting insights, it relies on the limiting assumption that nodes are arranged in a line.

TRANSPORT-LAYER PROTOCOLS

A transport-layer protocol is required to achieve *reliable transport* of event features and to perform *flow* and *congestion control*. Most existing Transport Control Protocol (TCP) implementations are unsuited for the underwater environment because the flow control functionality relies on *window-based* mechanisms that require an accurate estimate of the round trip time (RTT). The long RTT, which is caused by the low sound speed affecting the propagation delay on each underwater link composing the end-to-end path, would affect the throughput of most TCP implementations. Furthermore, the variability of the underwater RTT, mainly due to multipath, would make it hard to effectively set the timeout for packet retransmissions. Existing *rate-based* transport protocols seem to be unsuited for this challenging environment, as well, because 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, new strategies must be devised to achieve flow and congestion control in underwater networks and thus, to guarantee end-to-end reliability.

Owing to the peculiar characteristics of the underwater environment, reliable communication is a fundamental primitive for underwater networks. In multihop networks, reliability can be defined on a *hop-by-hop* and an *end-to-end* basis. *However, a sequence of hop-by-hop guarantees does not necessarily add up to an end-to-end guarantee*. A transport-layer solution specifically designed for the underwater environment should:

- Correctly handle shadow zones by predicting losses of connectivity and also interfacing with the routing layer.
- Minimize energy consumption by using the selective ACKnowledgment paradigm (SACK), which also helps preserve capacity on the reverse path.
- Rely on rate-based transmission of data as this approach enables nodes to have a flexible control over the rates.
- Properly handle out-of-sequence packet forwarding.
- Timely react to local traffic impairments by relying on intermediate nodes so as to accelerate the response time in case of congestion.
- Leverage information from lower layers to predict, and then react to, losses of connectivity or partial packet losses.
- Be seamlessly integrated with hop-by-hop reliability mechanisms so as to locally recover packet losses without triggering costly end-to-end retransmission mechanisms (that cannot be replaced totally by local recovery schemes, however, because hop-by-hop reliability does not guarantee end-to-end reliability).

A transport layer protocol designed for the underwater environment, Segmented Data Reliable Transport (SDRT), recently was proposed. The basic idea of SDRT is to use Tornado codes to recover error 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 until it receives positive feedback and thus, it 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 forward error correction (FEC) block size.

In [13], to reduce the number of end-to-end retransmissions, we rely on lower-layer mechanisms to provide communication reliability. *Specifically, our proposed unicast protocol aims at maximizing the end-to-end reliability by providing high link-layer reliability*. We propose three versions of a reliable unicast protocol, which integrate MAC and routing functionalities while leveraging different levels of neighbor knowledge:

- No neighbor knowledge
- One-hop neighbor knowledge
- Two-hop neighbor knowledge

The protocols were compared in static, as well as mobile scenarios in terms of different end-to-end networking metrics, leading to the following conclusions:

- The three versions of the proposed reliable protocol outperform protocol solutions that do not fully exploit neighbor knowledge in the design phase.
- For a static environment, one version does not always outperform the others, irrespective of the end-to-end metric considered. In fact, two-hop neighbor knowledge performs the best in terms of packet delivery ratio, one-hop neighbor outperforms the others in terms of end-to-end delay, and no neighbor knowledge performs the best in terms of energy consumption.
- The higher the mobility, the less information is required for making optimum decisions. Because of the mobility, in fact, information becomes outdated, which leads the packet delivery ratio to decrease as mobility increases.

Cross-Layer Protocols

Although most of the research on underwater communication protocol design so far has followed the traditional layered approach, which was originally developed for wired networks, improved performance in wireless networks can be obtained with a cross-layer design, that is, by violating a strictly layered architecture, especially in a harsh environment such as underwater. As presented in the previous sections, several protocols were developed for underwater acoustic communication at different layers of the protocol stack. However, most of the existing protocols for underwater wireless communications do not consider cross-layer interactions, which play a crucial role in the design of wireless networks, especially in harsh environments.

In [14], we claim that wireless underwater communications require that a cross-layer solution enable the efficient use of the scarce resources such as bandwidth and battery energy. However, although we advocate integrating *highly specialized* communication 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 a requirement to redesign the entire communication system. For these reasons, in [14] we propose a *modular* cross-layer communication solution for underwater multimedia applications that is built upon our previous work on underwater routing [10] and MAC [3] and that outperforms protocols developed *in isolation* following the classical layered approach. Our cross-layer solution relies on a distributed optimization problem to jointly control the *routing*, *MAC*, and *physical* functionalities to achieve efficient communications in the underwater environment. Specifically, the proposed solution combines a 3D geographical routing algorithm (*routing functionality*), a hybrid distributed CDMA/ALOHA-based scheme to access the bandwidth-limited high-delay shared medium (*MAC functionality*), and an optimized solution for the joint selection of modulation, FEC, and transmit power (*physical functionalities*).

Conclusion

We presented an overview of some of the recent solutions for medium access control, routing, transport-layer, and cross-layer networking protocols. The goal of this survey is to bring together researchers and practitioners in all areas relevant to underwater networks and to encourage research efforts to facilitate interaction and collaboration for the development of new advanced underwater communication techniques.

Although we advocate integrating highly specialized communication 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.

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