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Underwater Ad-Hoc Networks: A Review

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Abstract

Underwater sensor networks have become increasingly interesting in the past four decades. They can be used in a multitude of scenarios, commercial and military alike. Underwater networks can communicate in several ways, but when nodes are far apart, underwater acoustic communication is the only feasible way. The complex underwater acoustic channel puts high demands on the network protocols. The physical layer needs to contend with short coherence times, high intersymbol interference and significant Doppler spread. The routing protocol needs to handle intermittent connectivity and mobile network topologies, such as autonomous underwater vehicle networks. The medium access control protocol needs to manage medium access with high latency and potentially high packet loss ratios without congesting the network. The available acoustic modems are still rather expensive, which limits the size of a sensor network. Voices have also been raised from the academia for a paradigm shift, from hardware-defined, proprietary modems to software-defined, open-architecture modems, in order to accelerate research in the field and enable interoperability. This paper reviews the recent advancements in designing and implementing underwater networks on several levels and discusses some interesting approaches to underwater ad-hoc networking. The focus lies on acoustic communication.

Index Terms

Underwater acoustic communication, underwater networks, underwater ad-hoc networks.

I. Introduction

Underwater acoustic communication has seen an increase in demand in the last four decades. There are many applications of underwater acoustic networks, including, but not limited to, wave power site monitoring [1], natural disaster warning systems, sea bottom mapping and

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exploration [2], oceanographic data acquisition, strategic surveillance, oceanic pollution detection [3] and aquaculture plant monitoring, service and maintenance [4].

While there is plenty of research on terrestrial wireless networks and technology has advanced very far, underwater acoustic networks are still in an early stage. Experiments with underwater communication were made in the 1980's, but the experiments used peer-to-peer communication. Underwater networking experiments began in the late 1990's, and with them came the rise in demand for underwater acoustic communication. In fact, the concept of the Internet of Underwater Things (IoUT) as an underwater parallel to the Internet of Things was discussed only a decade ago [5]. The IoUT is envisioned as an underwater network of sensors and other underwater digital devices. It enables monitoring of large bodies of water and can readily be used in the previously mentioned applications.

Also, underwater communication was not mainstream because the actors in the field were few. Kongsberg Maritime was the first commercial actor, and their autonomous underwater vehicle (AUV) Hugin, which they developed in the 1990's in cooperation with the Norwegian Defence Research Establishment (FFI), Norwegian Underwater Intervention (NUI) and Statoil (called Equinor today), is well used in the offshore industry [6].

Earth's surface is dominated by oceans, but the underwater environment is largely unexplored. Going out to sea to undertake an offshore mission with human personnel and remotely operated vehicles (ROVs) is risky, as the open seas can be unforgiving. AUVs, which act on their own, can be used instead. Using several AUVs can speed up the mission, and they can also communicate with each other by forming an ad-hoc acoustic network.

Underwater sensor networks were expensive to deploy in the early days [7], [8]. While costs have fallen significantly thanks to advancements in battery technology, sensor technology, additive manufacturing and other relevant technologies, nodes have finite battery life and might not be rechargeable while deployed. This means there is much to be gained from an energy-efficient communication protocol. Some nodes may be mobile, represented by AUVs or ROVs. This means that they might not always be in communication range of a given node, and if the mobile nodes act relays in routing, the connection could break. The complex channel makes medium access control even more difficult, as distant nodes might falsely think the channel is free and transmit in a way that causes packet collision at the intended receiver.

The underwater channel is diverse and is affected by multipath propagation, very long delay, Doppler shift, whose severity depends on the environment, and fading. All of these phe-

nomena make underwater acoustic communication much more difficult than terrestrial radio frequency (RF) communication. Thus, early acoustic communication relied on incoherent modulation schemes or differential schemes. It was robust, but the achievable symbol rate-range product was low [9]. More recent networks can use coherent modulation schemes thanks to more advanced receiver structures and the development of decision feedback equalisers (DFEs) and phase-locked loops (PLLs). However, they still have to contend with the difficult time-varying channel.

In this article, we review the state of the art in underwater ad-hoc networking. A wireless ad-hoc network is a network formed by wireless nodes without intervention from a base station or similar network master [10]. An example of such a network is an AUV network. While there is plenty of research on terrestrial ad-hoc wireless networks, most of the research on underwater ad-hoc wireless networks has come in the last decade. Our article focuses on acoustic communication and networking.

The remainder of this article is structured as follows. Section II discusses the underwater acoustic channel, motivates the need for underwater acoustic communication, presents some channel models and discusses standardisation. Section III discusses acoustic modems, how they are designed, transducer design and some software-defined approaches. Section IV discusses the physical layer, challenges that are best handled at the physical layer, and others' efforts in the physical layer. Section V discusses medium access control (MAC), which is an important feature in the data link layer, challenges in underwater MAC and others' approaches to MAC. Section VI discusses routing, which is an important feature in the network layer, along with challenges in routing in underwater networks and what others have done within routing. Section VII discusses some approaches to networking and some notable perspectives of underwater networks. Section VIII concludes the paper.

II. Underwater acoustic channel

The acoustic channel in one geographical location can be completely different to the channel in another location, and there is no way to define a "typical" underwater acoustic channel, nor is there any widely accepted set of canonical acoustic channels or channel simulators. [11] studies the acoustic channel in several waters in northern Europe, including the continental shelf, the Baltic sea, and Norwegian fjords. It was found that the channel can be overspread, which means the product of its delay spread and Doppler spread is large, or reverberant; stationary,

cyclostationary or nonstationary; suffer from frequency-selective fading or flat fading; or in the best of worlds even be benign. There are more traits of the underwater channel, and not all of them can be adequately explained. The underwater acoustic channel is thus an extreme environment from an engineering perspective, and it is also very diverse.

There have been numerous research efforts in the field of underwater acoustics. There are several environmental parameters that influence acoustic waves, including, but not limited to, temperature, pressure, oceanic currents, salinity, surface activity and the channel depth. As indicated in the previous paragraph, the underwater channel may be affected by fading, which can be modelled as Rayleigh [12], Rician [13] or Nakagami- m -distributed [14]. The underwater channel is therefore a very complicated channel, compared to the terrestrial radio channel.

A. Motivation

Terrestrial networks use electromagnetic (EM) waves to relay information to other nodes. This works because air is an insulating medium. Water is a conductive medium, and so it absorbs RF waves. In fact, EM waves must be sent at frequencies down to 30 Hz to propagate any significant distance through water [7]. To make matters worse, this would require a prohibitively big antenna and cause high power consumption, which is infeasible.

Underwater networks can use optical communication. It has some advantages over acoustic communication. First, light propagates at over $2.2 \times 10^8 \text{ m s}^{-1}$ in water, compared to 1500 m s^{-1} of sound. Second, visible light has extremely high frequency, so the achievable data rates are limited by other factors. Third, optical communication offers higher bandwidth than acoustic communication thanks to the higher carrier frequency that optical communication uses.

Still, there are situations where acoustic communication is preferred over optical communication. First, water absorbs light; while not as strongly as RF waves, it means the range is confined to tens of metres [15]. Using acoustic waves is feasible even at distances on the order of kilometres given an appropriate frequency band, which makes acoustics a popular choice for sensor networks. Second, optical communication works best with line of sight, which acoustics does not need.

B. Challenges

The underwater acoustic channel is much more complicated than the wireless terrestrial channel. [7] notes six challenges with designing an underwater network, some of which are

due to the nature of the channel.

- The acoustic waves propagate very slowly, compared to radio waves in air. This means latency will be extremely high. It also varies significantly over time.
- The acoustic waves can travel from the source to the receiver in multiple ways due to surface or bottom reflection as well as the sound speed profile. This is known as multipath propagation. This, along with fading, impairs the channel greatly.
- The bandwidth available to the network is very limited.
- Multipath propagation impairs the channel, and the underwater channel contains shadow zones, where the transmission loss is even stronger. Their location depends on range, the transmitter depth, the sound speed profile and bathymetry and may vary over time.
- Most sensors are battery-powered, and there is typically no way for them to recharge their batteries. This raises the need for low-power solutions in underwater sensor networks, especially in long-lived networks.
- The underwater environment is extreme. Sensors are constantly exposed to corrosion and other types of degradation.

Efforts have been made to overcome these challenges. [16] presents the design of an energy-harvesting sensor. It extracts energy from ultrasonic waves and stores it in a supercapacitor. This energy can later be expended by the node itself to transmit. The underwater sensor network could thus last longer with energy harvesting.

C. Channel model

There exists a variety of models related to the underwater acoustic channel. One of the first models is the Urick transmission loss model [17], which is an empirical model of how transmission loss increases with range and carrier frequency. Thorp proposed an approximate formula for the absorption coefficient for low frequencies [18]. It states that absorption loss increases with frequency. The Urick model is easy to implement in a resource-limited environment, such as on a microcontroller, but it does not capture the effects of multipath propagation. The ray-tracing software Bellhop [19] provides a more accurate picture of the transmission loss in space, but requires substantial resources to run.

[20] presents a statistical channel model that includes both small-scale and large-scale effects.

From the Urick model, each path acts as a nonlinear low-pass filter with gain

$$\bar{H}_p(f) = \frac{\Gamma_p}{\sqrt{A(\bar{l}_p, f)}}, \quad (1)$$

where $\bar{H}_p$ is the path gain, Γ_p is the combined effect on amplitude and phase of all reflections against the surface and sea bottom, A is the Urick transmission loss, and $\bar{l}_p$ is the path length. The transfer function is then separated into $\bar{H}_0(f)$ and h_p . [20, fig. 1] shows the reference $\bar{H}_0(f)$ for path length $\bar{l}_0 = 1$ km and spherical spreading ($k = 2$). $\bar{h}_p = \Gamma_p \left((\bar{l}_p/\bar{l}_0)^k a_0^{\bar{l}_p - \bar{l}_0} \right)^{-1/2}$ is the path-specific gain relative to $\bar{H}_0$. Combining the transfer functions of each path gives the nominal channel transfer function

$$\bar{H}(f) = \bar{H}_0(f) \sum_{p=1}^N \bar{h}_p e^{-j2\pi f \bar{\tau}_p}, \quad (2)$$

where $\bar{\tau}_p$ is the nominal propagation delay relative to a reference delay τ_0 and j is the imaginary unit. The path gain follows a log-normal distribution, provided the deviation in path length is Gaussian.

The path gain captures the large-scale effects well, but not the small-scale effects. [20] treats them on a per-path basis. Scattering occurs when a ray strikes a rough surface or a small object and splits into several smaller rays. Each smaller ray has a fading coefficient $\gamma_{p,i}$ and a phase distortion that depends on $\delta\tau_{p,i}$. Summing over each micropath gives a cumulative fading coefficient

$$\gamma_p = \sum_i \gamma_{p,i} e^{-j2\pi f \delta\tau_{p,i}}, \quad (3)$$

whose distribution converges to a complex Gaussian by the central limit theorem. The $\gamma_{p,i}$ can be assumed to be independent of each other. It is conditioned on both large-scale effects (delay and gain) and the mean and variance, and it may also vary over time by an autoregressive stochastic process. The delay can also be modelled on state space form, where the noise term is a complex Gaussian process. The resulting distribution becomes statistically equivalent to the previously mentioned one.

[20] also treats Doppler shift as a small-scale effect, which affects the exponent in (2). It varies slowly, so it can be considered piecewise constant. There are several sources of Doppler shift, including, but not limited to, surface motion, drifting, and intended motion. These sources can be assumed independent of each other, so the autocorrelation function, which can be used to characterise Doppler shift, becomes a product of expected values. Any factor that is deemed deterministic will not contribute to the autocorrelation. This autocorrelation becomes a product of

Bessel functions of the first kind and order zero; see [20, §4] for details. All of these phenomena combined results in the “complete” channel model [20]

$$H(f, t) = \bar{H}_0 \sum_p h_p \bar{\gamma}_p(f, t) e^{j2\pi f \tau_p}, \quad (4)$$

where the quotation marks stress that not all small-scale phenomena are included in the model.

D. Shallow and deep channels

The underwater acoustic channel is treated differently depending on its depth. Shallow channels are typically a few hundred metres deep at most, and deep channels are deeper than that.

The shallow channel typically experiences multipath propagation due to surface and sea bottom interaction more than refraction, particularly at shorter range. The sound speed profile can in some cases be considered constant. Multipath in the deep channel is more often caused by signal refraction due to the nonhomogeneous sound speed profile. This normally creates convergence zones, where the signal is stronger, and shadow zones, where the signal is remarkably weaker.

[21] considers the shallow harbour environment and how the stronger reverberation affects communication performance. The channel was measured by transmitting trains of variable-rate linear frequency modulation (LFM) probe signals over a wide frequency band. Shorter pulses helps with estimating small-scale variability, and longer pulses helps with capturing late arrivals. Two experiments were analysed: one at 100 m range, one at 2.5 km range. Somewhat surprisingly, the results indicate that short-range communication is more difficult than long-range communication. Structures in the harbour do not appear to affect signals remarkably, unless they are near either node that is involved in communication.

E. Standardisation

Despite the fact that there are a handful of manufacturers of acoustic modems available on the market [22]–[25], there has been little development on standards for underwater acoustic communication. There are no canonical underwater acoustic channels or underwater network simulators available, although there exist research efforts to establish them [26]. Researchers that have designed their own algorithms for underwater networking have often had to write their own simulators or extensions of existing simulators, like the discrete-event network simulator ns-2, as a consequence. The limitations of their simulators are often not given in their work, which means it is difficult to determine their validity [27].

Due to the absence of underwater acoustic communication standards, most modem manufacturers develop their own protocols, architecture and system. This is a major obstacle for manufacturer interoperability and also communication efficiency [28].

To the best of our knowledge, the only standard that exists to this day is Janus, which was developed by NATO [29]. It is robust and easy to implement by design. Janus uses frequency-hopping binary frequency shift keying (FHBFSK) with 13 frequency pairs that together span a frequency band about one third of the centre frequency wide. It also employs convolutional coding at 1/2 data rate, interleaving and 8-bit cyclic redundancy check (CRC). Also, Janus has a detailed packet specification. It uses carrier sense multiple access (CSMA) with exponential backoff for medium access control. [29] defines Janus only mathematically, but there exist implementations of the protocol online [30]. Extensions to and derivative works of Janus have been developed [31].

[32] compares the performance of Janus against an frequency-repetition spread spectrum (FRSS)-based physical layer protocol. The conclusion made from the results is that Janus may become the weakest link in the SALSA stack without enhancements to the Janus receiver.

[28] presents four services that could use Janus. The first is making first contact and switching language, where Janus would serve as a common language, or *lingua franca*, to enable modems from different manufacturers to communicate. The second is an underwater automatic identification system, which can be used to help prevent accidents between underwater assets, such as submarines, and surface vessels. The third is underwater meteorology and oceanography, which is about forecasting the underwater environment. The forecasting data can be used by AUVs to adapt and make decisions about their current mission. Janus has been an attractive means of communication in search and rescue operations, so the fourth case is thus supporting distressed submarine operations. In conclusion, Janus can supersede or complement the underwater telephone.

III. Acoustic modems

Digital underwater acoustic communication is made possible by acoustic modems. An acoustic modem consists of a transducer for sending and receiving acoustic signals, an analogue transceiver that preprocesses signals for transmission and received signals, signal converters and a digital hardware platform that performs signal processing and control [33].

There exist many different underwater acoustic modems and manufacturers. [34] offers an exhaustive study on existing modems, reviewing their hardware and comparing research modems to commercial modems. The significant difference between research and commercial is that commercial modems generally achieve higher bit rates at the cost of higher power consumption, while research modems are more energy-efficient and better suited for deployment in sensor networks. There is still a need for more energy-efficient modems, however.

Terrestrial RF modems are available for consumers and can typically be bought at any electronics store for less than 100 euros today. Buying acoustic modems, however, is very difficult¹ if the buyer is not a company in academy or industry, as one modem typically costs thousands of euros. This makes them monetarily intractable for sensor networks.

Research efforts have been made to design low-cost modems; for instance, [33] presents an acoustic modem that would cost 600 US dollars (2010, estimated) per unit if constructed in bulk. The modem had not been tested in the ocean because not all components had been developed at that time. On the other hand, [35] presents their “nanomodem” that costs only £50 per unit to manufacture. This modem has been tested in sea trials in conjunction with a MAC protocol that is proposed in [36].

A. Transducer design

The transducer is perhaps the most important component in an acoustic modem, as it is responsible for producing sound. According to the authors of [33], the transducer is also the most expensive component.

The transducer is usually omnidirectional, which means it produces sound waves in all directions. This is problematic for full-duplex modems, as it causes self-interference. [37] proposes a beamforming method to reduce this self-interference. The transducer used is a phased array transducer, which in this scenario is a 12×12 array of piezoelectric ceramic elements. A subset of them is used for beamforming, and the beam can be rotated electronically to a certain extent, as overdoing it causes grating lobes to appear. The range of suitable angles depends on the frequency used and the element spacing.

¹The buying process often involves requesting a quote, and the process from start to finish could easily take months.

B. *Software-defined modems*

The early commercial off-the-shelf acoustic modems have a proprietary architecture, which often is hardware-based and rigid in its design. They rarely allow any reconfiguration, and when they do, the available settings are few. This makes them unfit for adaptive solutions to underwater networking and inhibits research efforts like IoUT. Consequently, groups of researchers have argued for the need for a paradigm shift towards software-defined architecture [27], [38]–[40].

[41] conducts a review of the literature on software-defined modems and academic and industrial advancements in this field. The early modems were black-box, as the physical layer was firmware-defined and the network protocol held fixed. Later modems supported reconfiguration, letting the user adjust coding scheme and bit rate on the fly. There were also reprogrammable modems. Those modems allowed the user to redefine one or more layers in the network stack, but this would often mean programming a digital signal processor (DSP) or field programmable gate array (FPGA), or programming in a specialised language, unless the modem is software-defined. Open-source and open-architecture are two features that facilitate accessibility. The authors list and classify a multitude of available modems from four aspects: physical-layer reprogrammability, network-layer reprogrammability, architecture availability and architecture generalisation. They also present the NILUS node, whose modem is explicitly designed to support operation on a general-purpose processor and be independent of specialised hardware.

[38] presents a real-time adaptive software-defined modem. Most of the adaptive functionality is implemented in the physical layer. Commercially available modems normally achieve data rates short of 35 kbit/s, but as mentioned in Section IV-B, their modem achieves 260 kbit/s under certain conditions.

[39] proposes a software-defined architecture called SoftWater, which uses network virtualisation concepts to incorporate energy-efficient and robust underwater communication solutions. SoftWater supports acoustic communication, but also optical communication and magnetic induction-based communication. Programmability, cooperativeness, openness and virtualisability are the four core features of SoftWater. Network function virtualisation leads to a flexible architecture and facilitates network management and control in a centralised network topology. Network virtualisation lets isolated virtual networks share physical network infrastructure without interfering with each other.

[40] introduces the SEANet project as a step towards enabling IoUT on an open architecture

and a software-defined platform. There is the need for a modem that can sacrifice acoustic range in exchange for data rate and a transducer that can operate at a wide range of frequencies. The prototype uses two transducers: one commercial off-the-shelf transducer for communication at up to 170 kHz and one custom-made microelectromechanical systems (MEMS) piezoelectric micromachined transducer array for communication about 700 kHz with a bandwidth of 500 kHz. The modem can achieve data rates near 600 kbit/s at bit error rate (BER) not exceeding 0.01 and signal to noise ratio (SNR) at least 10 dB.

[42] outlines a software-defined open-architecture modem, where the architecture is based on a high-level OSI generalisation. Each layer is represented by a module with a policy engine providing layer functionality. A cross-layer framework allows additional information to be aggregated in the data packets.

IV. Physical layer

The physical layer is the lowest layer in the OSI stack model, and interacts directly with the transmitter and receiver. This layer supports data coding, modulation, demodulation and decoding as well as signal detection, to mention some of its important features [43]. This section discusses physical layer features and the challenges that the physical layer faces in the field of underwater networking.

A. Challenges in the physical layer

As mentioned in Section II-C, underwater sensor nodes are typically battery-powered and cannot recharge. Energy efficiency is therefore important, especially if the network should operate for weeks or longer periods of time.

Unless the channel is particularly benign, it will distort the phase of acoustic signals significantly. This puts great demands on the receiver side of the physical layer if signals are to be modulated in phase domain, such as by phase shift keying (PSK) or quadrature amplitude modulation (QAM). Frequency shift keying (FSK) is easier on the receiver side, but it uses more bandwidth than other modulation schemes [7].

B. Approaches to the physical layer

In [38], a software-defined modem with real-time adaptivity in the physical layer is presented. The adaptive physical layer is based on an optimisation problem, with the modulation order and

coding rate as optimisation variables, the bit rate as objective function to maximise, and a bit error rate constraint that also depends on the estimated signal to interference plus noise ratio. It is shown by experiment that the modem achieves data rates up to 260 kbit/s and with BER not exceeding 0.01, given signal to interference plus noise ratio (SINR) 32 dB, a very shallow body of water, and 200 m communication range.

It is highly beneficial to have channel state information available to the user. As the underwater acoustic channel is complex, it cannot be known exactly, but the channel parameters can be estimated or computed from measurements. There exist techniques for channel estimation and channel measurement, and many articles use channel estimation in their solutions [20], [26], [38], [44]–[47].

[44] combines machine learning and channel estimation to choose between a set of PSK modulations. To estimate the channel, they assume that the transmitter has channel state information. The receiver estimates required channel parameters, and relays them to the transmitter. The transmitter then uses decision trees to choose a modulation that would give sufficiently low BER. This approach assumes that the channel is varying slowly as the signal travels back and forth. The trees are trained in advance.

[45] proposes path identification as a means of channel estimation. Path identification iteratively estimates the path delay and gain and phase shift as a complex amplitude. Paths can be adaptively precombined if they are correlated. Orthogonal matching pursuit could be used, but it becomes less useful when the sample space increases due to the increased space requirements. It also risks introducing spectral leakage due to the discrete delay space.

[46] uses a decision feedback equaliser based on a channel estimate by an algorithm known as the Improved-Proportionate M-estimate Affine Projection Algorithm. It estimates the channel filter taps as if the channel was a discrete-time noncausal linear, time-varying filter.

[26] presents a Matlab-based benchmarking software called Watermark. The purpose of Watermark is to provide a standard test bench such that physical-layer algorithms can be tested in a standardised way. It uses channel estimates that are derived from measured impulse responses and relies on libraries with measured underwater channels from different geographical sites.

[47] presents an experiment that took place in an area in the Grevelingen estuary, the Netherlands. The channel estimates were obtained by probing. Also, the nodes used two different frequency bands, where each band had specific physical layer functionality. Using two different frequency bands allows a node to serve as a potential bridge between two networks

that communicate at different frequencies.

[48] investigates a variety of sparse channel estimators, based on a finite number of propagation paths and suited for multicarrier systems. Each path has an associated attenuation, delay and Doppler rate. The methods considered are the subspace methods root-MUSIC and ESPRIT, and the compressed sensing methods Orthogonal Matching Pursuit and Basis Pursuit. These methods are compared to a traditional least squares method. Simulation results and experimental results find that subspace methods perform better than least squares if diffuse multipath arrivals do not dominate the received energy, and compressed sensing methods consistently perform better than least squares.

[49] uses data-driven reinforcement learning and channel physics models together to tune acoustic links. This is the multi-armed bandit problem, which is well known in the field of reinforcement learning [50]. The model is trained by an algorithm that classifies orthogonal frequency division multiplexing (OFDM) schemes as “viable” or “not viable” depending on how many OFDM carriers are used and the length of the cyclic prefix. The boundary of the viable region changes as the model learns from real-world data. The presence of a channel model in the agent policy gives significant improvements in average data rates.

[51] explores FRSS and direct sequence spread spectrum (DSSS) modulation and FSK modulation in a diverse array of channels. The modulation schemes are compared against each other through a validated, measured impulse response-based channel simulator. The experiment uses packet delivery ratio as performance metric, and the results show that no particular modulation scheme is universally optimal.

C. Receiver design

Receiver design is a topic that is relevant in the physical layer. Since the underwater acoustic channel is highly variable in gain and phase shift, using phase-coherent modulation schemes such as QAM or PSK out of the box is infeasible except in benign channels [11]. A well designed receiver, on the other hand, enables the use of phase-coherent modulation schemes even in non-benign channels.

[52] considers phase-coherent communication in both deep and shallow channels. The receiver consists of a DFE and second-order phase-locked/delay-locked loops. The receiver first estimates the synchronisation parameters from a packet preamble, then uses them in RLS to adjust the DFE. The DFE has a feedforward filter that allows it to handle future intersymbol interference

(ISI) and estimate the symbols with ISI, and a feedback filter that estimates the ISI from a sequence of recent symbols and eliminates it. The adaptive receiver is shown by experiment to successfully detect QPSK and 8PSK symbols in both deep and shallow water, even when the input symbols are smeared beyond recognition by inspection.

V. Medium access control

Medium access control, or MAC for short, is a core feature of the data link layer. It governs how the users in a network can use the available spectrum and ensures that the sent packets are successfully received, whether the users employ multiple access or random access [10]. Multiple access splits a channel in one of its dimensions, such as time, frequency or coding, into subchannels that different users can be assigned. It also involves control mechanisms for assigning channels and refusing users that do not fit in the system. Random access is a MAC strategy where users are assigned a channel dynamically. Unlike multiple access, assigning channels and refusing users to transmit is embedded in the protocol.

A. Challenges in MAC

As with many other network features, the challenging underwater acoustic channel makes MAC more difficult in underwater acoustic networks. [7], [53], among others, say that not all of the traditional multiple or random access protocols work well underwater. Frequency division multiple access (FDMA) does not work well due to multipath and frequency-selective fading. Time division multiple access (TDMA) typically does not work well due to propagation delay. The slow propagation speed is usually an inconvenience, as it makes contention-based MAC difficult to implement. However, [54] showed that the long propagation delay can be exploited to drastically increase potential network throughput. CSMA helps preventing packet collisions at the transmitting side, but it needs guard time to prevent receiver-side collisions. Code division multiple access (CDMA) is a more promising MAC technique, as it lets users exploit time diversity by Rake filters.

B. Approaches to MAC

TDMA, as discussed in Section V-A, does not work very well underwater due to the long guard times necessary, unless propagation delay is exploited. [54] proposes a schedule-based TDMA strategy, where nodes can either transmit, receive or be idle in one time slot. Packets may collide

with each other as they traverse the channel. The simplest case considers networks where the distance between all pairs of nodes is an integer, and it can be extended to rational distances. It is shown that the upper bound on the throughput of the delay-exploiting TDMA strategy equals half the number of nodes in the network. An algorithm for finding near-optimal schedules in polynomial time for a given network topology is also presented. The reverse problem, finding a suitable network topology for a given schedule, is also considered. This puts strict requirements on clock synchronisation between the nodes, for clock drift could easily ruin a carefully designed schedule.

[55] proposes DACAP, a distance-aware collision avoidance protocol, for ad-hoc underwater acoustic networks with long delay. It lets nodes adjust the handshake length to the intended receiver to reduce average handshake duration. The protocol is request to send (RTS)/clear to send (CTS)-based, and nodes that have CTS listen for warning packets or other packets before transmitting, entering a back-off state if any such packets are overheard. Incoming RTS packets are treated separately. Acknowledgement packets are optional.

[56] analyses the MAC strategies frequency-hopping spread spectrum (FHSS) and DSSS and presents two direct-sequence receivers. FHSS divides the available band in bins and hops between them in a minimal-interference way, and DSSS uses codes with suitable correlation to spread the PSK-modulated data. The DSSS receivers are tested with FHSS and DSSS signals in shallow water and at short range. FHSS is very simple to implement, but has higher BER than DSSS at the same SNR.

[57] discusses the Stop and Wait protocol type. When the transmitter has sent a packet, it waits for an acknowledgement for a set duration. Unless it receives a positive one, it sends the packet again, and on receiving a positive acknowledgement, the transmitting node moves on to the next packet. This works in half-duplex systems, but the efficiency degrades remarkably with latency. Solutions exist where several packets are sent at once to make better use of the channel, and they achieve higher throughput efficiency than the single-packet S&W. Throughput efficiency is a measure of how well the channel is exploited and is defined as the ratio of useful packet time to expected total packet transmission time.

[58] proposes a distributed MAC protocol that builds on lightweight and distributed non-cooperative optimisation algorithms. Each transmitter optimises a local transmission probability profile from past observations of interference. It can proactively adapt its transmission strategy to keep packet losses down to a minimum, but also keep transmission probability high as to avoid

unnecessarily long packet delay. The optimisation problem that the nodes solve is quasiconvex. Also, it has room for enhancement by integrating CDMA or FDMA.

VI. Routing

Routing is an important feature in the network layer. It is used in networks where transmitting data between two distant nodes is too difficult or would require too much power. Rather than sending data to a destination directly, the source node can use intermediate nodes as data relays, although there exist techniques that make better use of multiuser diversity [10].

Routing protocols can generally be divided in three classes [7], [17], [53]. *Proactive* protocols focus on establishing routes as soon as the network is enabled and when its topology changes. This approach does not scale well and is not always necessary in underwater networks. *Reactive* protocols focus on on-demand route discovery. While it does not require activation time, it does require a wave of control packets for route building. Also, static network topologies are unlikely to need routing in this way. *Geographical* protocols require positional information, but typically scale better than proactive and reactive protocols. The long propagation delay underwater can be exploited to localise other nodes and establish routes.

A. Challenges in routing

Routing is a considerable challenge in ad-hoc wireless networks, especially when nodes are nonstationary. A route that works well at one occasion may not work at all at the next occasion. There is thus the need for dynamically reconfiguring routing protocols in ad-hoc networks [10]. There are several types of underwater networks. Sensor networks could span several kilometres in range, and fully mobile networks (of AUVs/ROVs) may experience rapidly varying channels. As such, all networks cannot rely on a universal routing protocol and always expect good performance.

[7] formulates eight research challenges in the network layer. Some of them are beyond the scope of this article and are not listed here.

- Delay-sensitive applications need algorithms that impose bounds on data latency.
- Routing protocols that handle unexpected disconnections in a local context should be developed.
- Consistent variations in energy efficiency metrics need local route optimisation algorithms to handle them.

- AUV-to-sensor communication and AUV integration in networks needs special mechanisms.

B. Approaches to routing

A common approach to routing in ad-hoc networks is to use a distributed strategy for routing. Nodes broadcast information about their connectivity to nearby nodes, then the nodes compute new routes from it. This reduces routing overhead and is easy to adapt to changes in connectivity and links, but it is normally suboptimal and may result in routing loops [10].

The type of routing protocol that best fits the network at hand depends on its topology. [59] explores routing protocols in underwater acoustic networks. It presents an array of routing protocols that others have designed and that have made at least one of the following assumptions about its features.

- Clocks run in sync and without drift
- Static network
- Specialised hardware
- Location or geographical information known
- Predefined network settings
- Predefined network architecture
- Vertical communication only
- Reliable MAC dependent
- Sink node, to which all data flows, exists, is static and known

In contrast, the protocol in [59] makes none of them, as it strives to be a universal solution. Not only that, but it should also be able to handle long propagation delay well. The routing procedure starts with a node broadcasting a routing request. The packet header has an ID that blocks arrivals after the first from affecting the routing tables. When the routing request reaches the target node, it unicasts a response to the node that is associated with the first arrival to backtrack the route. Routes are maintained by data packets in that the receiver acknowledges received packets. If the receiver fails to deliver an acknowledgement in any form back to the sender, the route is considered broken and a new route is formed. The protocol is reactive.

[17] presents two geographical routing strategies that intend to solve the data gathering problem. Both delay-tolerant and delay-sensitive networks are considered. These strategies work in static network topologies, and their experiments do not appear to use any mobile nodes. The modems transmit packets back-to-back, not letting go of the channel until the packets are all

sent. The routing algorithms are based on solving two similar optimisation problems, where the delay-sensitive problem has extra constraints. The interested reader may refer to [17, §§5–6] for further details.

[60] proposes a cross-layer protocol for adaptive routing. The nodes acquire information about the network by a first phase of exchanging control messages, then begin routing packets in the network. When routing, the proposed protocol, which is called NADIR, uses link quality, remaining energy of neighbours, energy needed and estimated hop count to select the next hop. The factors are normalised and weighted before the decision is made. The protocol is reactive.

[61] proposes an energy-aware routing protocol. It relies on “hello” messages to keep track of neighbours and computes an eligibility value from the residual energy and distance information. These factors are clumped together in a convex combination. The protocol is reactive.

[62] considers AUV networks in which the AUVs follow a predictable path. The routing solution used here is based on regions of uncertainty. Each AUV node estimates its own region, which is a cylinder, and shares the estimate with other AUVs. When a node wants to transmit data to a distant node, it uses local information to choose the neighbour that it thinks is the closest to the destination.

[39] presents a software-defined architecture that uses network function virtualisation to implement some of the OSI layers, including the network layer. Routing functionality is embedded in the control plane. This architecture, which is called SoftWater, has enabled several routing solutions. First, the network controllers can run routing optimisation algorithms. Second, SoftWater supports reactive strategies for handling node failure. Third, routes can be proactively redefined when mobile nodes, such as AUVs, are about to relocate.

[63] proposes a fusion between the network layer and data link layer. The proposed cross-layer model has only three layers, where its network layer contains both aforementioned layers.

[64] presents a class of energy-efficient routing strategies. Specifically, the energy required to reach a distant node with respect to the hop count is analysed, and using shorter and more hops is more efficient than using longer and fewer hops. There is also an optimal hopping distance. An array of hop destination selection strategies are presented. Most of them are distributed and can be implemented in practice. Some of them base their choice on a cone that faces the destination, some of them use circles and/or lines, one always chooses the nearest node that lies in the aforementioned cone, and the remainder are based on the shortest path and are there for reference only. This solution is geographical since the nodes know the network topology.

There exist alternatives to routing. One of them is network coding [65], in which nodes combine incoming data packets and relay the combined packet. For example, two packets of equal length can be merged by applying bitwise XOR to them. [65] shows by experiment that using network coding results in higher packet delivery to packet transmission ratio than a traditional first in, first out approach.

VII. Approaches to networking

In underwater acoustic networking, using a layered stack model like the OSI stack model creates excessive packet overhead, which reduces the effective throughput in the network. This makes them unfit for most underwater working applications, so researchers have proposed software-defined, cross-layer or agent-based network protocols instead. Those protocols allow much greater flexibility by design and make information visible to all network features. This section discusses some approaches to networking in underwater networks.

Many sensor networks use a stationary node as a data sink. AUV networks might follow a predefined course instead, which means they could be out of range from a possible sink at times. If something goes wrong while out of range, the mission might fail such that it must start over, which means money and time have gone to waste. This can be alleviated by adding a flying node that can sink data. [66] uses an unmanned aerial vehicle with an acoustic modem attached that acts as a relay to the base station. In contrast to prior efforts to combine AUVs and unmanned aerial vehicles (UAVs), as in [67], the AUVs need not resurface to contact the flying node. The UAV, also called a flying acoustic modem, knows where the AUVs begin, mission progress and AUV velocity, and plans a round trip to all AUVs to gather data. The planning problem is NP-complete, so it does not scale well with the AUV count. The authors assume all AUVs relay data directly to the flying modem.

[68] presents an agent-based network architecture called UnetStack, which can be used in both simulation and real-world experiments. Each agent provides some functionality, which can be to represent a layer in a traditional network stack model. The agents run in parallel and in a non-hierarchical fashion, which means agents are free to interact as the application sees fit. Multiple agents may provide the same service, and the end user can develop agents of their own to extend UnetStack. More details can be found in [68, §2] and in the Unet handbook [69]. Later work based on UnetStack has been published. [70] presents three applications that use baseband signal processing to demonstrate the flexibility of UnetStack. All applications involved developing a

Unet agent. [71] uses UnetStack agents to implement a TDMA MAC protocol, based on the work in [54], and tested it at sea.

A. Cognitive acoustics

An underwater network is not alone in general, but shares the medium with marine mammals or other underwater networks. This means some frequency bands might be occupied when a new network is deployed. Few networks consider this possibility, but there exists a variant of acoustic communication that does. Cognitive acoustics, as presented in [72], lets underwater acoustic nodes sense the channel for other acoustically communicating entities and adapt themselves to what they hear.

[72] investigates the challenges with cognitive acoustics. Most modems use frequency bands that overlap with those that sonars and marine mammals use, and concerns have been raised regarding the impact of anthropogenic acoustic noise on marine life. The spectrum can be underutilised in time and space. Temporal underutilisation occurs when nodes having low transmission duty cycle or mobile nodes using a frequency band. Spatial underutilisation occurs when one subspace of a network experiences more traffic than the rest of the network. Cognitive acoustics can be used to better utilise the spectrum by having it sense where the spectrum is used more and where it is used less. It consists of three elements. Spectrum sensing is the listening part of cognitive acoustics, which can be based on energy detection, power spectral density (PSD) estimation, waveforms or cyclostationarity. Spectrum management is a MAC protocol that consists of three blocks: sensing strategy, decision and sharing. Dynamic power control is the third part of cognitive acoustics.

The challenges with cognitive acoustics are plenty. First, spectrum sensing must handle attenuation and silently listening marine mammals. Second, the channel is highly variable, so the cognitive radio approach to dynamic power control will not extend to cognitive acoustics. Third, the sensing strategy needs to be considered from a practical perspective. Fourth, the decision method is prone to false alarms and missed transmissions due to propagation delay. Fifth and last, sharing resources is difficult due to the exposed terminal problem and limited bandwidth.

VIII. Conclusion

Underwater communication has become more interesting to industry and research groups around the world, whether sound, light or magnetic induction is used. This is thanks to the wide

array of applications that underwater networking has in both industry and academia.

We have reviewed and presented a variety of advancements in underwater acoustic networking. Many of the research challenges that are presented in [7] have been addressed to a varying extent, although not all of them apply to all types of underwater networks. Researchers have called for a paradigm shift towards software-defined, open-architecture modems to accelerate research on IoUT. Modem manufacturers have introduced software-defined functionality in their products. At the same time, acoustic modems are still quite expensive (with a few exceptions), so there is still the need for designing more economic modems without giving up too much performance.

Standardisation and standardised testing methods will play an important role in the development and comparison of novel networking protocols, adaptive algorithms and MAC strategies.

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