nature reviews electrical engineering

https://doi.org/10.1038/s44287-024-00122-w

Review article

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Underwater acoustic communications

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Abstract

Underwater wireless communication is an enabling technology for various applications, ranging from basic sciences such as oceanography and marine biology to offshore industries such as fish farming or oil and gas drilling, search and rescue operations, and military and exploratory missions. It is also critical for climate monitoring, pollution control and military operations. Radio frequencies do not propagate well through water except over short distances, making acoustic waves the preferred choice for many of these applications. However, acoustic waves are confined to low frequencies, limiting the communication bandwidth. Additionally, sound travels underwater at a relatively low speed and propagates over multiple paths. Delay spreading over tens of milliseconds results in frequency-selective distortion, whereas motion induces significant Doppler effects. The worst properties of radio channels — poor link quality of a mobile terrestrial channel and long delay of a satellite channel — are combined in an underwater acoustic channel, which is often said to be the most challenging communication medium in use today. In this Review, we discuss existing efforts in modelling underwater acoustic propagation channels, processing communication signals and establishing networks. We then summarize some of the future research directions in underwater acoustic communications.

Sections

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Key points

- Underwater acoustic channels are characterized by limited bandwidth, a propagation speed that is 100,000 times lower than the speed of light, an extended multipath and severe Doppler effects.

- Signal processing techniques and network layer protocols for underwater acoustic communications are often uniquely tailored to the specific characteristics of the channel.

- Future directions, including standardized channel models, new modulation and coding schemes, and feedback-based communications, are essential for advancing the design and development of next-generation underwater acoustic networks.

- The application of data-driven solutions to underwater acoustic communications is a trending research area. The scientific machine learning approach aims to leverage domain-specific knowledge to enhance data-driven solutions, requiring significantly fewer data recordings.

Introduction

Thinking of underwater communication, one might picture a person diving in a tropical sea while texting a video of the nearby colourful fish to a friend. That would not be an unusual reaction in this day and age when our lives have become inseparable from smartphones, and when the word 'text' is used more often as a verb than as a noun. The technology, however, is not there yet. Although deep-space communications grant us glimpses into faraway planets and stars, the underwater world remains comparatively unexplored, as high-speed wireless transmission of information under the surface of the ocean presents considerable technical challenges.

Electromagnetic waves do not propagate well through the water except over very short distances. Radio-frequency waves can travel a few metres at about 10 kHz (ref. 1). Optical frequencies fare somewhat better, notably in the blue–green region (450–550 nm) where the absorption of light is the lowest; however, they too cannot travel further than about 100 m, depending on the clarity of water[1]. This leaves acoustic waves as the choice for transmitting information wirelessly over a considerable distance. As a pressure wave, sound can propagate over tens or even hundreds of kilometres, but the acoustic band is severely limited, offering transmission at bit rates much lower than those we are used to with terrestrial radio technology, for instance, a few kilobits per second over 10 km. More specifically, acoustic communication links are distinguished as vertical or horizontal. Horizontal links are further categorized as short (up to a few hundred metres), medium (several kilometres or tens of kilometres) and long-range (a hundred kilometres or more) links, as well as shallow or deep-water links. In addition to the absolute range, the ratio of range to depth is an important parameter that influences the multipath characteristics of the acoustic communication channel. Horizontal links exhibit much more distortion than vertical links, with propagation characteristics that vary with both distance and depth, and with bandwidth that decreases with distance.

In this Review, we provide an overview of the recent achievements in underwater acoustic communications and outline the directions in which new research is moving. We begin with an overview of the history of underwater acoustic communications. We showcase propagation mechanisms and channel modelling, emphasizing the differences between acoustic and radio propagation and the implication that they have on the communication system design. We discuss signal processing for communications, while keeping an eye on the network architecture and protocols. Finally, we outline the future research directions.

History

Band-limited as it might be, underwater acoustic communication has fascinated engineers for centuries, with the earliest written material pointing to Leonardo da Vinci, who supposedly experimented with sound transmission using a long tube submerged under the surface of the water[2]. Much has been accomplished since then, ushering us into the present day when both commercially available acoustic modem technology and research prototypes are used to unlock various applications, including those that support basic sciences (oceanography, marine biology), offshore industry (oil and gas, fish farming), exploration and discovery, search and rescue, climate monitoring and pollution control, as well as military operations. All these areas benefit from transmitting information wirelessly, as cables limit manoeuvrability and can be very heavy (tons). Acoustic communication enables data collection from submerged sensors, control of underwater robots and coordination of autonomous underwater vehicles. In addition to the transmit power and the frequency band used, the range at which a modem can reliability communicate is highly dependent on surface and water column conditions as well as water depth and sea-bed properties. A vision of an underwater network is illustrated in Fig. 1, where multiple assets are connected wirelessly. Last but not least, the recent tragedy of the submersible Titan serves as a reminder that human progress cannot be stopped, and that perhaps one day we shall be able to safely enjoy underwater tourism. Indeed, Titan was equipped with an acoustic modem, and its last message was successfully received onboard the mother ship, albeit indicating potential stress.

The history of modern underwater acoustic communications is traced back to the closing stages of World War II, when an underwater telephone was developed in the United States for communication with submarines. It used analogue technology based on single-sideband amplitude modulation in the 8–11 kHz acoustic band[3]. Digital signal processing and field programmable gate array technology followed, making it possible to implement more sophisticated algorithms at the submerged end of the link[4,5]. In terms of digital communication technology, non-coherent modulation/detection methods based on frequency-shift keying were developed in the 1970s and 1980s (ref. 6) and successfully used in the field[7,8]. These methods offer a robust communication capability and are in regular use today. Their only disadvantage is poor bandwidth efficiency, as measured in bits per second transmitted per hertz of occupied band (<1 bps Hz^{-1}), the fact that drove the quest for phase-coherent modulation/detection methods in the 1990s (ref. 9). These methods, which are based on phase-shift keying or quadrature amplitude modulation, make efficient use of the available bandwidth, offering more than 1 bps Hz^{-1}, but they require relatively complex signal processing algorithms to overcome the distortions of the acoustic channel.

An acoustic communication signal experiences multiple types of distortion as it propagates underwater. The power attenuates with distance, but also with frequency. The signal bounces off the surface and bottom, resulting in multipath propagation which causes echoes, or delay spreading of the signal. The corresponding transfer function of the channel is frequency-selective, such that some frequencies are

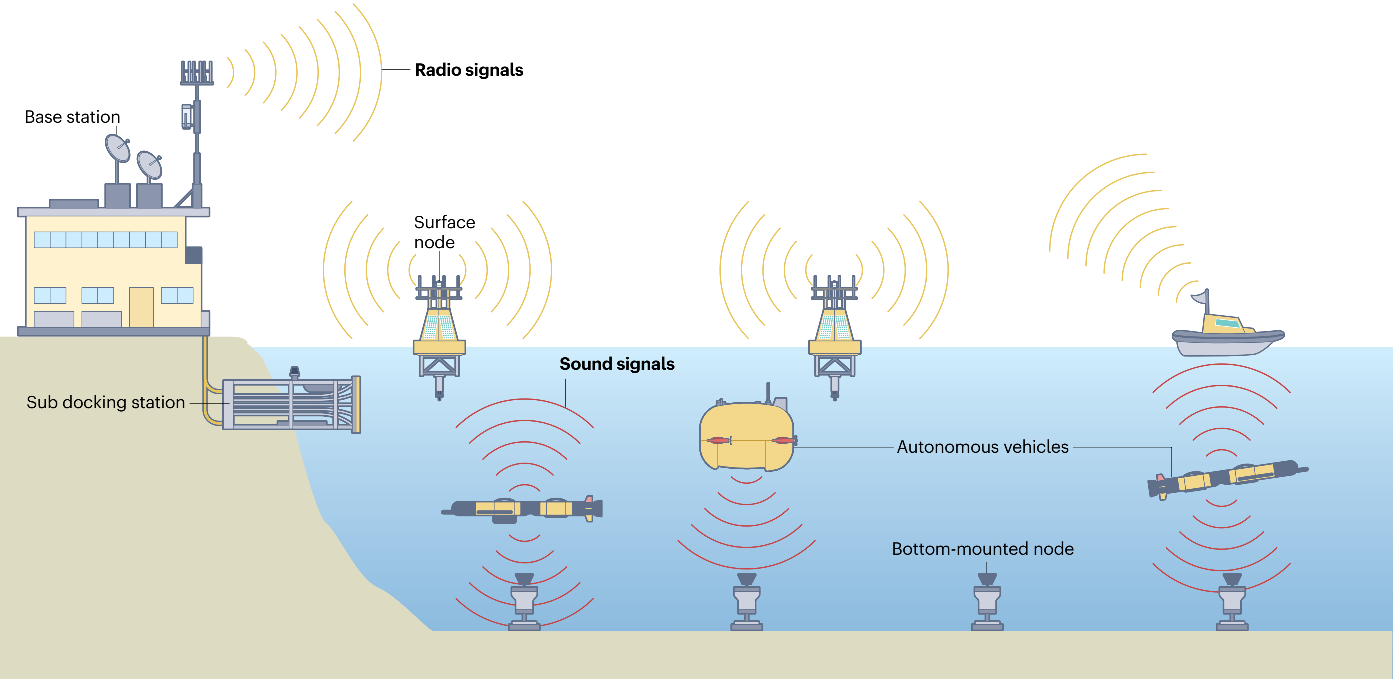

Fig. 1 | A vision of an underwater acoustic network. An underwater network often consists of fixed, bottom-mounted nodes, mobile nodes on autonomous vehicles and surface nodes that can be linked by radio to shore.

favoured whereas others are diminished. The uneven, rough surface and bottom cause scattering of the signal, whereas constant motion of the surface, as well as any drifting of the transmitter/receiver, causes the channel response to vary in time. This variation appears random, causing unpredictable signal fading. In addition, any relative motion between the transmitter and the receiver, be it unintentional (drifting with currents and waves) or intentional (in mobile systems), causes Doppler effects which are evident as time dilation/compression or frequency shifting. These effects are quantified by the ratio of the relative transmitter and receiver velocities, which could be in the order of a metre per second, to the speed of sound propagation, about 1,500 m s^{-1} in water. The resulting Doppler distortion is about 100,000 times more pronounced than in land-mobile radio systems, where the signal travels at the speed of light. The accompanying propagation delay is anything but negligible, causing high system latency. The worst properties of radio channels – poor link quality of a mobile terrestrial channel and long delay of a satellite channel – are thus combined in an underwater acoustic channel, necessitating a dedicated design of communication functions on all layers of a network architecture. In addition to long propagation delay, outage statistics of networked underwater links are also not similar to their radio counterparts. Protocol designs that fail to consider such distinct features often fail catastrophically in underwater scenarios.

Propagation channel

Propagation of acoustic waves is governed by a power loss that occurs because of energy spreading as well as absorption, that is, transfer of acoustic energy into heat. Acoustic power is measured in pascals (commonly, in decibels relative to a micropascal). In seawater, 1 W of radiated acoustic power creates a sound field of roughly 170.8 dB referenced to micropascal intensity 1 m away from the acoustic centre of an omnidirectional source. The absorption loss increases with the signal frequency, thus limiting the bandwidth that is available for transmission over a given distance.

Noise in acoustic systems comes from multiple sources in addition to the usual thermal noise. Ambient noise, which is present even in the 'quiet deep ocean', comes from distant shipping activity, breaking waves and turbulence. This noise is often characterized as Gaussian; however, it is not white. Its power spectral density increases up to 1 kHz, decreasing thereafter at approximately 17 dB per decade up to several tens of kilohertz (ref. 10). In addition to this noise, there is site-specific noise, such as ice cracking in polar regions[11–13], snapping shrimp in warm regions[14] or man-made noise coming from nearby machinery. Man-made noise is typically non-Gaussian and often consists of narrowband tonal signals.

The noise, whose power spectral density $N(f)$ decays with frequency, and the attenuation $A(d,f)$, which increases with both the distance d and the frequency f, result in a nominal signal-to-noise ratio (SNR) that varies over the signal bandwidth. Fig. 2a shows the factor $1/A(d,f)N(f)$, which determines the SNR in a narrowband around the frequency f. Several curves shown in the figure correspond to different distances d. The frequency at which the SNR is maximized represents the optimal centre frequency to be used for a given distance. Allowing for some tolerable SNR loss around the optimal frequency, for instance 3 dB, the viable frequency bands are shown in Fig. 2b. We note that longer distances support lower bandwidths. This fact speaks in favour of relaying as a way of conserving not only power but bandwidth as well. For example, a 100 km link consisting of a single hop admits transmission in about 1 kHz of bandwidth, whereas transmitting over 10 relay hops, each 10 km long, admits about 10 kHz of bandwidth.

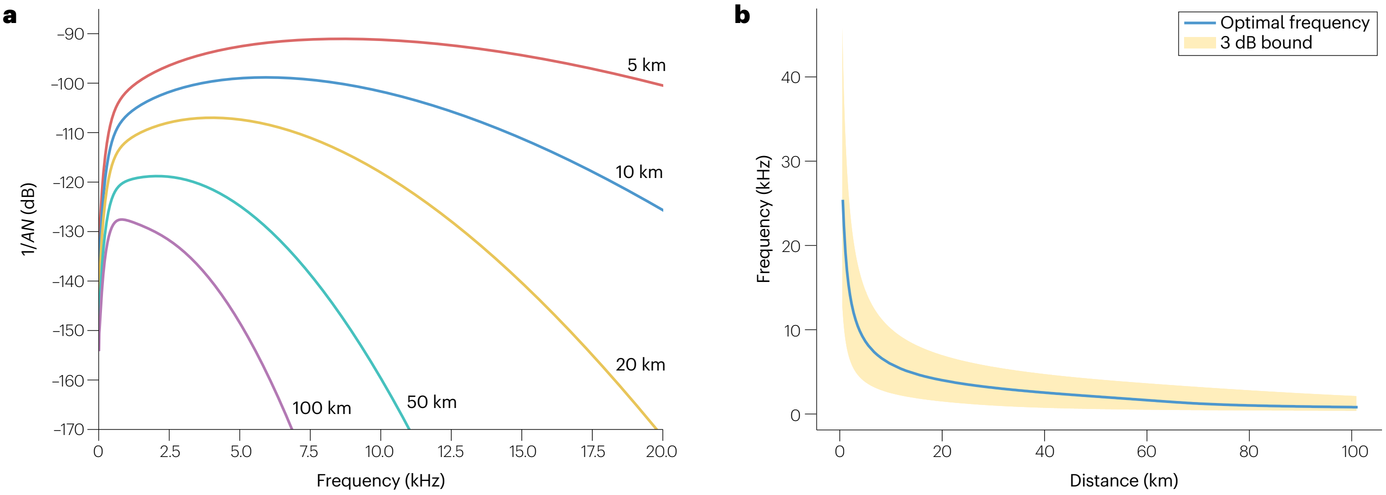

Fig. 2 | Signal-to-noise ratio in an underwater acoustic channel depends on both the frequency and the distance. a,b, Signal-to-noise ratio (SNR) in a narrowband around frequency f points to the best centre frequency (**a**) as well as to the available bandwidth (3 dB bandwidth, shaded in **b**), both of which vary with transmission distance d. Data in **b** are derived from **a**. A, attenuation; N, noise. Part **a** is adapted with permission from ref. 10, IEEE.

Regardless of the transmission distance, an important observation to make is that the acoustic bandwidth is not negligible with respect to the centre frequency. This situation is in stark contrast to the majority of radio systems, where the bandwidth, even if large in absolute terms, is still negligible with respect to the centre frequency (for instance, several megahertz of bandwidth centred in a gigahertz region). Although such systems are sometimes referred to as broadband, they in fact satisfy the basic narrowband assumption as their bandwidth is much smaller than the centre frequency, that is, $B \ll f_c$. Acoustic communication systems, even though band-limited in absolute terms, clearly do not satisfy this assumption. Their broadband nature has substantial implications on the applicability of many standard signal processing algorithms, notably in the domain of frequency synchronization and array processing.

Although the nominal SNR considerations provide an insight into the top-level link budget analysis, signal processing for acoustic communications is influenced by finer mechanisms of acoustic propagation. Multipath propagation notably contributes to delay spreading, which occurs due to repeated surface–bottom reflections or due to ray bending. Computational tools are available for acoustic ray tracing, including the classical BELLHOP[15], which provides a range-depth map of acoustic signal intensity for a given channel geometry, signal frequency and source location. The model can also be coupled with digital databases of bathymetry and sound speed profiles. Fig. 3 shows the sound speed profile collected during an underwater experiment, and the corresponding transmission loss computed by the BELLHOP ray tracer, expressed in decibels.

Although ray tracing provides an accurate image of the nominal signal strength in space, such an image pertains to a given channel geometry frozen in time. As the geometry changes ever so slightly, deviations from the nominal multipath profile will occur. Such deviations are perceived in practice as random fluctuations in the received signal. On longer timescales, drifting in and out of partial shadow zones can occur, causing fluctuations in the locally averaged SNR. On shorter timescales, corresponding to second or sub-second intervals, surface scattering causes fluctuations in the instantaneous signal level which contribute to small-scale fading. A time-varying impulse response of a shallow-water mobile underwater acoustic channel is illustrated in Fig. 4.

Unlike radio propagation, where statistical models of channel fading have been standardized for universal use in computer simulation and testing, there are no models that have been standardized for underwater acoustic communication system design. Part of the reason for this is the sheer variety of channels, which exhibit different types of fading[16]. Two types of approaches have been pursued by different authors: those that involve utilizing the estimated channel response to replay arbitrary waveforms[17–19], offering the opportunity to test signal processing algorithms under realistic and reproducible conditions; and those that involve purely statistical modelling[20–22]. At the time of writing, an effort is underway to build a repository of channel models corresponding to several typical scenarios and make these models freely available to researchers around the world.

Statistical analyses of these random phenomena include an array of publications[10,20–23]. These analyses pertain to various channel types such as deep or shallow, or fixed or mobile, and are supported by different datasets. For example, Chitre[20] offers an experimentally calibrated model of a high-frequency warm water channel. Qarabaqi and Stojanovic[22] introduced a statistical model that describes a class of shallow-water acoustic channels, exhibiting complex Gaussian statistics. Channel variations, such as small-scale and large-scale fading, are modelled theoretically and verified by experimental recordings. Note that an underwater channel is inherently non-stationary and that the available statistical models hold only for given intervals of time during which the model parameters do not change. For example, a small-scale model of the instantaneous channel response might include surface height variance as its parameter, and thus represents a model that is conditioned on a given surface height variance. The variance might be changing, albeit at a much lower rate than the instantaneous response.

Signal processing for communications

As acoustic communication channels impose a severe bandwidth limitation (Fig. 2), signal processing for communications is largely driven by the quest for bandwidth efficiency. Meanwhile, distortions imposed by multipath propagation and motion-induced Doppler frequency offsets pose serious challenges to the design of reliable and efficient transmission and reception techniques. When reliability is of more importance than the information throughput, system designers often resort to modulation methods that admit non-coherent (energy) detection, such as frequency-shift keying. In its simplest form, frequency-shift keying utilizes several frequencies within the available bandwidth, and transmits on one of the frequencies in each transmission interval. A transmission interval is then followed by a guard time that allows the multipath to die out before the next symbol is transmitted. In practice, improved performance is achieved through channel coding and simultaneous transmission on more than one frequency in each transmission interval[24,25].

Achieving a high information rate necessitates bandwidth-efficient modulation techniques, such as phase-shift keying and quadrature amplitude modulation. As these methods require phase-coherent detection, accurate synchronization is essential, which is challenged by the Doppler frequency shifts. Meanwhile, delay spreading typically occurs over tens of symbol intervals, if not hundreds in some channels, much higher than in typical terrestrial radio systems. In addition, the underwater acoustic channel typically exhibits a short coherence time, for example, around 100 ms (ref. 10). These characteristics necessitate the application of long adaptive equalizers to alleviate the resulting inter-symbol interference.

The block diagram of an adaptive multichannel decision-feedback equalizer (DFE) is shown in Fig. 5. The adaptive multichannel DFE was used as the first proof of concept for bandwidth-efficient underwater acoustic communications[9,26]. This structure has also become a de facto standard, forming the basis of the first high-speed acoustic modem developed at the Woods Hole Oceanographic Institution[27]. Now in its second generation, the modem is routinely deployed in ocean-going missions. Two concepts that are essential to successful operation of this type of receiver are the joint adaptation of the equalizer and the phase-locked loop which tracks the time-varying phase of the incoming signal, and the use of a multichannel (array) combiner. The latter is essential in the majority of underwater acoustic applications, as it extracts the spatial diversity. More sophisticated receiver structures have also been developed from the original DFE, such as those that capitalize on channel sparseness in the impulse response domain[28], as well as those that use turbo equalization[29–32]. Other notable advancements in underwater acoustic communications include the application of multiple-input multiple-output techniques, as a means of achieving either higher information rates by spatial multiplexing of independent data streams or improved performance by exploiting spatial diversity[33–37], and vector sensors[38]. Achieving high information rates has been of particular interest to applications targeting video transmission, which has been demonstrated over deep-water vertical channels that have little multipath distortion, as well as short-range channels that support high bandwidths[39,40].

An alternative to single-carrier broadband modulation is multi-carrier modulation. Multi-carrier modulation has been considered in the form of multiband signalling, where the total bandwidth is divided into several sub-bands, such that each sub-band can be treated on the receiver side by a shorter equalizer, and in the form of orthogonal frequency-division multiplexing (OFDM)[41,42]. OFDM adopts a pre-emptive approach to overcoming the multipath-induced frequency selectivity by dividing the total available bandwidth into many narrow sub-bands and assigning a symbol to each. At the receiver, each carrier is demodulated, subsequently requiring only a single-coefficient equalizer to compensate for the corresponding narrowband channel. Modulation/demodulation is implemented in a computationally efficient manner using fast Fourier transform (FFT), whereas parallelization across frequencies affords bandwidth scalability and ease of software-defined implementation. In underwater acoustic channels, however, OFDM becomes prone to Doppler frequency shifts. If untreated, these shifts result in inter-carrier interference, whereby the signal observed on one carrier contains contributions of the data symbols transmitted not only on that carrier but on adjacent carriers

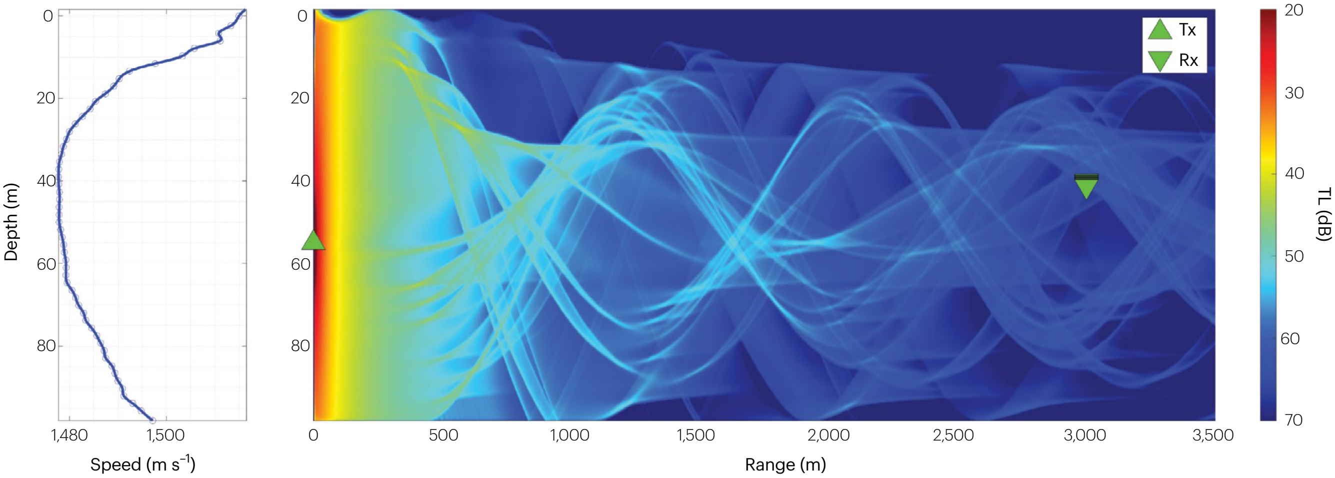

Fig. 3 | Sound speed profile and BELLHOP ray tracing. Sound speed profile collected during an underwater acoustic communication experiment (left) and BELLHOP ray tracing results (right). Multipath propagation in shallow water occurs mainly due to repeated surface–bottom reflections. In deep water, ray bending occurs because the speed of sound varies with depth, and multiple rays, with or without surface reflections, reach the receiver with different delays. The transmission loss (TL) was obtained through a single value of frequency, 13 kHz. Rx, location of the receiver; Tx, location of the transmitter. Reprinted with permission from ref. 51, IEEE.

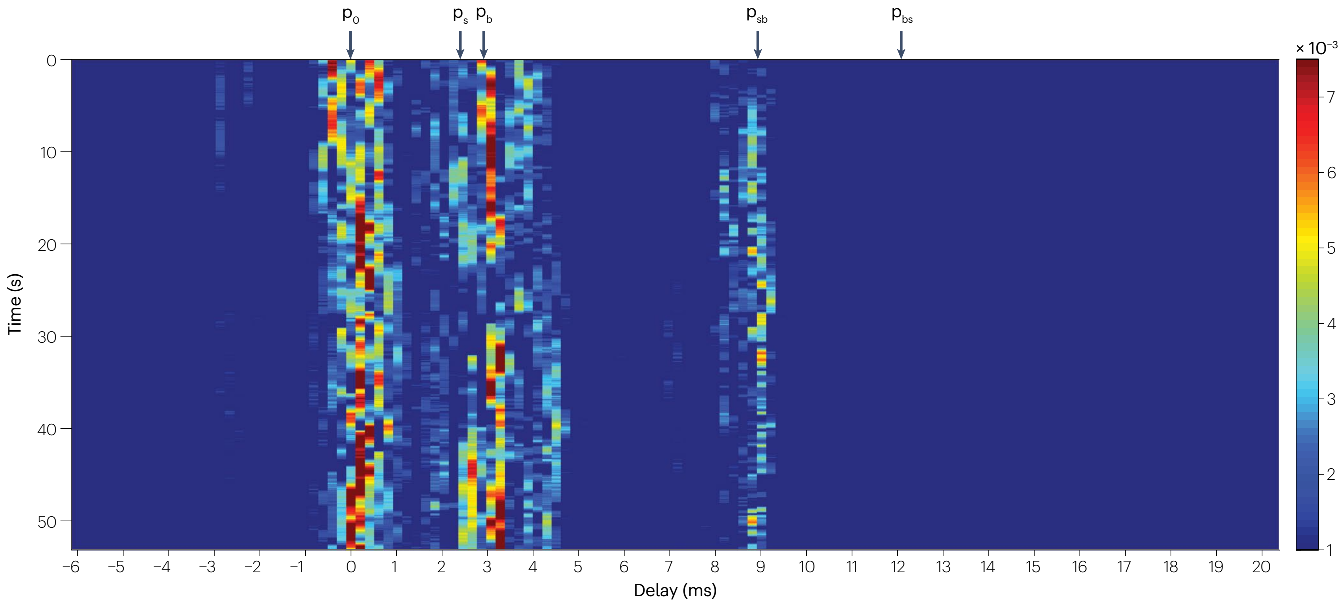

Fig. 4 | Channel response (amplitude in decibels) over a time period of 50 s collected during the Mobile Acoustic Communications Experiment 2010. A response extracted from the data recorded at sea in the North Atlantic near the shore of Rhode Island, USA. Acoustic signals were transmitted in the 10.5–15.5 kHz band over a few kilometres. A fixed receiver and a mobile transmitter were used. The colour indicates the signal strength, as shown in the key. A horizontal slice through the figure, taken at a fixed time, corresponds to the multipath intensity observed at that time. Multiple paths are present, each exhibiting micro-dispersion (intra-path dispersion). p_0, direct reflection; p_s, surface reflection; p_b, bottom reflection; p_{sb}, surface–bottom reflection; p_{bs}, bottom–surface reflection. Reprinted with permission from ref. 22, IEEE.

as well. Unlike in radio channels — where inter-carrier interference, if present at all, can be treated through simple equalization[43] — acoustic channels demand a dedicated, and often more intricate, approach to compensate for the frequency shifting before FFT demodulation can take place. Consider, for instance, the situation illustrated in Fig. 6. Shown in this figure are several OFDM blocks and the effect that Doppler shifting can have on them. If Doppler shifting is constant throughout a frame of blocks, each block will be lengthened in time by the same amount (middle row). However, if Doppler shifting changes throughout the frame duration, which could happen if the receiver first moves away from the transmitter and then towards it, one would observe time dilation followed by time compression (bottom row). Conventional front-end synchronization, which measures the length of the received frame and compares it with the known length of the transmitted frame to deduce the amount of time compression/dilation and resample the incoming signal accordingly, would fail in such a case[44]. This fact necessitates block by block Doppler frequency offset compensation in which the frequency offset is estimated in each block individually. A method that performs this task in an iterative manner by closing the pre/post FFT loop is described elsewhere[45]. This technique was shown to provide excellent results in real-data tests.

Any residual Doppler shifting, as well as general random time variation of the channel, will result in inter-carrier interference which might in some cases be strong enough to require a dedicated compensation method. An example of such a method is the so-called partial FFT demodulation, described elsewhere[46,47]. In this method, the signal is projected onto a set of basis functions which are chosen to preserve time invariance. Each projection is then processed by a separate FFT demodulator, and the results are combined in an adaptive manner. Several FFTs are now required instead of one, but the price paid in increased computations is small compared with the benefits gained in performance.

Another advantage of OFDM is the fact that it supports differentially coherent detection. In this context, differential encoding is performed in the frequency domain over carriers, on the grounds that in an OFDM system the channel transfer function does not change much from one carrier to the next. Differentially coherent detection eliminates the need for explicit channel estimation, which not only is challenging but also requires a potentially important pilot overhead for training. Moreover, the use of tightly packed carriers promotes the data throughput, resulting in better bandwidth efficiency than systems that require coherent detection. Differentially coherent detection has been addressed elsewhere[47] along with experimental results that testify to its performance using real underwater recordings.

Both single-carrier and multi-carrier techniques have been investigated for use in networked systems where multiple nodes need to access a common base station. Although more will be said about networks in 'Network architecture and protocols', here we comment on several interesting aspects of signal processing for multi-user communications based on code division. Typically implemented through direct sequence spread spectrum modulation, these methods assign a pseudo-random code to each user, which the base station uses to extract each user's signal from the arriving mixture (superpositioned signal in time). The related process of de-spreading involves correlating the incoming signal with the desired user's code to suppress the interference before data detection. The challenge encountered on acoustic channels is that the channel can change over the duration of the code, causing conventional de-spreading to fail. Shortening the spreading

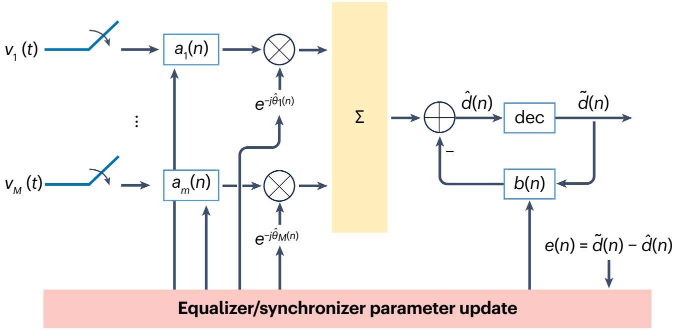

Fig. 5 | An adaptive multichannel decision-feedback equalizer. An adaptive multichannel decision-feedback equalizer incorporates a bank of fractionally spaced feed-forward filters $a_m(n)$, feedback equalizers $b(n)$ and a phase-locked loop. The filter coefficients are adapted jointly with the phase estimate $\hat{\theta}_m(n)$ to simultaneously compensate for inter-symbol interference and phase/frequency distortion. In the training stage, the error $e(n)$ is driven by the actual data symbols $d(n)$ and the estimated data symbols $\tilde{d}(n)$. In the decision-directed mode, the error is driven by the decisions $\tilde{d}(n)$ and $\hat{d}(n)$. Reprinted with permission from ref. 26, AIP.

code might not be an option as the length of the code determines the processing gain – the ability to suppress interference. A possible remedy for this situation is to integrate the process of de-spreading with adaptive channel estimation and data detection. Stojanovic and Freitag[48] report on a method that uses chip-level decision-feedback equalization, where the chips of the spreading code are modulated using hypothesized values of data symbols and processed by an adaptive DFE before making the final symbol decisions. In the context of multi-carrier code-division multiple access, direct sequence coding is performed over carriers, and this too can be done in a way that promotes coupling of channel estimation with the process of de-spreading. In particular, Li and Stojanovic[49] describe such an approach, along with experimental results.

An open frontier in underwater acoustic communications is transmit beamforming. In single-user scenarios, transmit beamforming focuses the total available power in a region of space, thus preventing it from dissipating in space and providing efficient system design and improved performance. It also offers security from unintended listeners positioned outside the desired direction. In multi-user settings, transmit beamforming offers the promise of spatial-division multiple access, in which the users are distinguished based on the direction of their signal arrivals, provided that they are spatially separable, and the available time-frequency resources do not have to be shared at the detriment of information throughput. In 'Outlook', we provide a discussion of both transmit beamforming and retrofocusing techniques.

Beyond signal processing techniques, channel coding is a critical component in an underwater acoustic communications system. The community has witnessed many practical performance evaluations of different channel codes, including low-density parity-check codes[50,51] and Polar codes[8,37,49]. Recent advances in universal decoding, such as guessing random additive Gaussian noise decoding (GRAND), provide excellent decoding performance for different classes of codes with modest complexity[52].

A large body of research is dedicated to predicting the communication system performance in different types of channels and environmental conditions. Efficient and accurate communications performance prediction is crucial to various feedback-based applications, such as in adaptive bit loading[53] and packet coding[54]. Performance prediction methods can be broadly categorized as channel quality prediction and communication system performance prediction. The latter includes reliability metrics such as the bit error rate, packet error rate and end-to-end latency[55–58]. Accurate performance prediction aids in identifying features that can withstand environmental changes, contributing to the development of intelligent modems and underwater acoustic networks. For instance, van Walree and Colin[57] calibrated the estimated channel impulse responses, and utilized impulse responses to predict the output SNR of a phase-coherent single-carrier modem equipped with an adaptive equalizer. Their predictions showed excellent agreement with experimental measurements.

Network architecture and protocols

Although it is essential for the physical layer signal processing algorithms to accurately deliver information, these algorithms alone are insufficient for most practical applications. The network layer protocols that are built upon the physical layer processing are critical to many aspects of the underwater acoustic communication architecture, including transmit and receive scheduling of an underwater node, error detection and correction, retransmissions, packet routing through multiple hops, packet queue management and quality of service. The network layer protocols are also expected to cater to the need of different applications, ranging from request–response-style transactions to file transfers. Although various protocols are designed to address such needs for terrestrial networks, many such protocols fail catastrophically if they are deployed unaltered in an underwater setting. This behaviour is due to several reasons.

Firstly, data rates of a terrestrial link, whether via wired or wireless medium, are orders of magnitude higher than those available via underwater links. Internet protocols can afford to trade efficient use of bandwidth for simplicity and modularity of design, robustness and computational load. In addition, the design considerations are very different in underwater networks, where energy per bit is substantially higher than their terrestrial counterpart.

Secondly, one of the most prominent characteristics of the underwater network lies in the propagation delay, which is not to be neglected, owing to the slow speed of acoustic wave propagation (a full second over 1.5 km, or 2 s for a round trip). The propagation delay has a profound impact on the performance of network layer protocols that employ carrier sensing, acknowledgements and feedback. Most terrestrial network protocols are not suited to deal with such a substantial propagation delay.

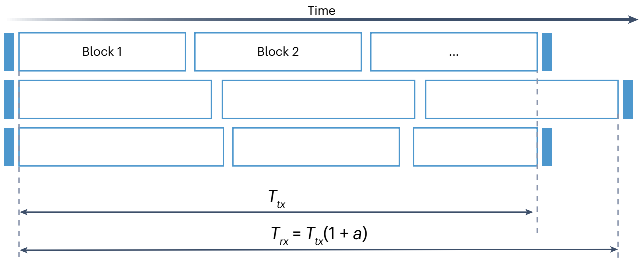

Fig. 6 | Time compression/dilation effects on orthogonal frequency-division multiplexing blocks. Motion induces time compression/dilation, which can cause different Doppler effects in different orthogonal frequency-division multiplexing blocks. a, Doppler factor; T_{tx}, duration of the transmitted signal; T_{rx}, duration of the received signal.

Lastly, outage statistics of underwater links are very different when compared with terrestrial wired or wireless links. Effects such as tidal changes, bubble clouds, noise generated by passing ships, and wind and rain-induced surface scattering can result in link outages that might last several tens of minutes, if not hours. Protocols that cannot deal with extended outage events often fail in underwater scenarios.

Dealing with these challenges often involves more than just adjusting parameters such as timeouts and retries. At the very least, characteristics of the underwater channel necessitate protocol redesign to reduce packet sizes, adjust the frequency of acknowledgements and improve robustness to outages. For example, careful alignment of transmission time slots and application of packet and network coding[54,59] with the aim of reducing possible feedback have been shown to improve throughput and reliability[60]. To address the challenges effectively, one has to understand application demands and carefully design protocols throughout all layers of the network stack. Understanding interactions between protocols at different layers and sharing information across layers are vital to the performance of underwater acoustic networks.

Naïve use of terrestrial protocols underwater led to poor user experience in the past; oceanic engineers, therefore, tend to design systems that can avoid or minimize the reliance on underwater communication. However, underwater communication technologies have matured over the last few decades, and the confidence in successful deployment of underwater networks has increased. Although commercially available underwater networks today rarely consist of more than a handful of underwater nodes, their performance critically depends on the choice of network architecture and protocol suite. As our understanding of the design of performant underwater networks deepens, we expect that the size and demand for underwater networks will grow in the future.

Network stacks and simulators

Many successful underwater communication systems employ application-specific monolithic software that implements custom and specialized protocols. Although this approach functions well for simple applications, the lack of modularity, interoperability and generalizability renders it too intricate for a wide range of distinct applications. Furthermore, such design methodology offers little or no software reuse across applications.

Terrestrial networks utilize layered network stacks (often variants of the Open Systems Interconnection layered architecture[61]) to reduce complexity. Typically, the layered architectures, including the physical layer and the medium access control layer, were also adopted for underwater networks[62], but the modularity they offer comes at a cost of inefficient use of bandwidth as information is not always effectively shared across layers. This shortcoming has been widely recognized even outside the domain of underwater networks, and researchers have developed cross-layer optimization extensions to traditional layered network stacks[63]. Layered network stacks with such extensions have been successfully deployed in some underwater applications[64,65]. Agent-based network stacks, however, share a different mindset – they retain modularity and software reuse while adopting a more flexible architecture for information sharing[66]. Such network stacks enable users to operate well under bandwidth constraints by employing techniques such as short-circuiting, where protocol headers might be automatically dropped when the functionality of a specific layer in the stack is not required. Potter et al.[7] proposed a multiple-access underwater communications signalling method, JANUS, that is widely adopted in many commercial modems. JANUS uses a frequency hopping scheme for spread spectrum modulation.

Network simulators are critical to the research and development of network protocols, notably refs. 64,65,67–70. Previous large-scale at-sea experiments[71–73] offer valuable insights into the performance of several network layer protocols. Some underwater network stacks such as SUNSET[64], DESERT[65] and UnetStack[66] provide two modes of operation – a real-time mode and a discrete event simulation mode. The real-time mode is suitable for actual underwater modem deployments, whereas the discrete event mode is designed for network simulation and performance prediction: hours of network traffic can be simulated in the matter of minutes. Having both modes supported by the same network stack implementation enables system developers to reuse their design for both protocol performance evaluation via simulation and at-sea deployment without significant porting efforts. Such a design is invaluable for underwater network research where at-sea experiments can be expensive and logistically challenging, and the ability to iterate between simulation and experiments is appreciable.

Medium access control

Underwater modems available today are mostly half-duplex, that is, they are unable to receive while they transmit. Even an underwater communication system with a single link requires coordination between two nodes on the timing of transmission and reception. As the number of nodes in a network increases, the need for coordination increases. The problem of medium access control layer design has received attention from researchers over the years[74–77].

Broadly speaking, multiple-access schemes can be categorized into two distinct methods: random access[78–89] and deterministic access[90–92]. The latter can be further dissected as time-division, frequency-division and code-division multiple access, where the resource is divided and shared among nodes. Although none of these approaches is fundamentally superior to others, the half-duplex nature of the modems and the long propagation delays favour time division, due to the asymmetry introduced in half-duplex communication[93]. When the network traffic is moderate and stochastic, handshaking-based random access protocols are preferable[78,79]. For low and sporadic traffic, random access protocols that are equipped with collision detection and back-off mechanisms are suitable[73,94], although the long propagation delays deteriorate the carrier sensing and handshaking procedure performance when compared with their radio counterpart. Finally, multimode medium access control protocols that are capable of switching between random and deterministic access have also been evaluated and assessed elsewhere[87]. As terrible as it might seem, long propagation delay, in turn, can be exploited and engineered to one's advantage[95]. This fact offers a unique opportunity to system designers to increase network capacity beyond what is offered by radio networks. The key to this increased capacity is that multiple acoustic transmissions can overlap in time without interfering and can be successfully received as long as they do not collide at the receiver. Although extensions to the idea have been theoretically explored[91,96–101] and experimentally demonstrated[71], practical application of such protocols in large-scale networks remains an open challenge.

Network architectures

Numerous protocols in ad hoc underwater networks have been explored[97,102–104], although practical applications of such protocols remain limited. However, there is a growing interest in permanent network infrastructure installations around coastal areas to support underwater vehicle operations and long-term environmental monitoring. Such an infrastructure is likely to use cellular-type architecture with cabled or radio backhaul and underwater acoustic last-mile links. However, protocols to support such cellular networks underwater have only received limited attention[90,105,106].

Underwater networks rarely operate in isolation. They typically connect to an on-ship or terrestrial network through a gateway node with a surface expression. The connecting links might be wired, terrestrial wireless or via satellite, and might have very different characteristics from the underwater links in terms of bandwidth, latency and outage statistics. Consequently, many challenges arrive in implementing a practical air–water interface[107]. The community awaits comprehensive research and development of routing protocols and network architectures that intelligently direct traffic across a combination of available underwater and above water links, addressing different traffic pattern and timing requirements.

Long-term variability leads to underwater links that might be down for extended periods of time[108–110]. Most data transfer protocols fail when such breakdowns occur and partially transferred data might be lost. Delay-tolerant or disruption-tolerant network protocols explicitly handle route breakages and ensure delivery of data when links are re-established. Several delay-tolerant or disruption-tolerant network protocols have been explored and demonstrated[111–113].

In a network where some nodes are mobile and can be controlled, delay-tolerant or disruption-tolerant network protocols offer some interesting and unique possibilities. For example, one might envision a data-muling application where an underwater vehicle is directed to approach an underwater sensor to collect data from it on a regular basis. The data could be transferred wirelessly via a gateway buoy that the vehicle approaches later in its mission, or physically downloaded from the vehicle after it returns to its home location. Doniec et al.[114] demonstrated that an underwater robot could locate and approach an underwater sensor using a long-range low-speed acoustic link and hand over to a high-speed optical link to transfer large amounts of data. We anticipate innovative solutions in designing the next-generation network layer protocols that are more resilient to environmental changes while maintaining high availability throughout the entire lifecycle of a network of underwater nodes.

Outlook

Although challenging, researchers and engineers have explored new frontiers of the next-generation underwater acoustic communications and networking system. Driven by the recent advancements in artificial intelligence, applying machine learning, especially physics-driven machine learning, approaches to underwater acoustic communications is a trending topic. In this section, we comment on a few specific areas, including channel model standardization, physical layer abstraction, feedback-based acoustic communications, new modulation and coding schemes, and data-driven solutions.

Channel model standardization

Acoustic communication channels encompass a wide variety of propagation environments, such as deep/shallow, long/short, warm/cold and mobile/fixed. These channels are known to impose extreme distortions onto communication signals, ranging from an extended multipath (frequency selectivity) to severe Doppler (high time variability). Propagation modelling tools such as ray tracers[15] are favoured among engineers, as they offer a first glimpse into the channel behaviour in the form of nominal propagation conditions. However, it is well known that the actual channel might deviate considerably from its nominal state, exhibiting both temporal and spatial variation on different time–space scales[20–22]. For this reason, experimental evaluation of candidate processing techniques remains a preferred choice among many researchers. However, at-sea experiments are costly, and not available to all. This fact is emphasized in recent work on data dithering, a method that enables reuse of an experimental recording on signals different from those that were used in the actual experiment[19].

Crucial to the design of any communication system is the availability of models that accurately capture the channel behaviour, both on the large and small scales. Such models provide a way to evaluate candidate signal processing and networking techniques prior to experimental testing and deployment. At this time, however, standardized acoustic channel models do not exist, despite the fact that they are sorely needed. Although several channel modelling tools have been developed[18,22,64–66], a consensus on a set of standard channel models has not yet been reached[115]. This situation is in stark contrast to terrestrial radio communications, where standard channel models have existed for decades. These models are not only standard in practice but are also standardized by international bodies such as the International Telecommunications Union, the Institute of Electrical and Electronics Engineers and others. Widespread adoption of common models notably enables a democratization of research, making it possible for those without extensive experimental facilities to participate in the advancement of the field. As already mentioned in 'Propagation channel', an effort is currently underway to remedy this situation and build a universally accessible repository of standard channel models.

Physical layer abstraction

Current network simulators, such as those in refs. 64,67,69,70,116,117, are often designed with simplified channel models and physical layer abstractions. Specifically, Guerra et al.[67] use BELLHOP[15] to ray trace the nominal channels, whereas Masiero et al.[117] incorporate mobility models. Although these simulators are of great interest in creating a fair and reproducible benchmark to evaluate physical layer algorithms and network layer protocols, they cannot accurately and adequately capture many effects and phenomena, such as frequency-selective fading and motion-induced frequency offsets, which have been observed abundantly in underwater experiments. Network layer simulators, therefore, often face trade-offs between accuracy and efficiency in simulations. In other words, achieving both accurate simulations of physical layer signal processing and overall simulation speed can be challenging. With the assistance of a class of standardized channel models, simulators can more accurately emulate the real experimental conditions.

Physical layer abstraction, or link-to-system mapping, is a highly efficient and accurate method for simulating wireless networks. Within the radio communication community, various models have been developed. Two models of particular interest are the exponential effective signal-to-interference-plus-noise ratio mapping and received bit information rate. The physical layer abstraction method, however, is scarce in underwater acoustic communications[118]. The community awaits comprehensive studies on the efficient physical layer abstraction for the next-generation network layer simulators, highlighting the unique characteristics of the underwater acoustic channels and their impacts on the signals in case of collisions and interferences. Beyond the channel standardization efforts, by carefully considering various unique effects posed by the underwater acoustic channel, physical layer abstraction stands to become a crucial component in enabling the next generation of network layer simulators.

Feedback-based acoustic communication

One of the major challenges in building the next-generation acoustic communication systems is the inclusion of an adaptive feedback link through which a receiver can inform the transmitter of the channel conditions, and the transmitter can, in response, adjust its parameters to best suit the current conditions. The challenge lies in the long delay, which can cause a potentially devastating discrepancy between the channel estimate and the actual channel, resulting in the subsequent failure of the conventional transmit-adaptation techniques. In other words, acoustic feedback, be it in the form of the full channel state information or precoding metrics, might become obsolete by the time the information is delivered to the remote site. Liu et al.[119] studied the channel reciprocity, and concluded that although the impulse responses were not fully reciprocal between the uplink and the downlink, the channels were partially reciprocal in terms of arrival time of the dominant paths at a high probability. This observation, in fact, encourages the system designers to re-evaluate the set of channel parameters that are stable and sustainable in a long round-trip feedback link and to implement the feedback in an informative and efficient manner.

Feedback is perceived as one of the enablers of the next-generation smart acoustic communication systems, and is seen in many forms, such as adaptive power control[54,120,121] and adaptive modulation[53,122–126]. Two studies[53,122] address the issue of adaptive (spatial) modulation in the context of single-carrier and multi-carrier modulation, respectively. These references also provide experimental results. In another study[127], the authors propose a Markov chain-based method that is capable of predicting some channel characteristics, and demonstrated the method using underwater acoustic experiments.

A larger body of work that touches on the topic of acoustic feedback and transmit arrays is that of time-reversal mirrors or phase-conjugate arrays, which have mainly been considered within the framework of single-carrier broadband modulation. In these systems, the transmitter array actively time-reverses a reference signal sent by the receiver (or equivalently, phase conjugates it in the frequency domain), effectively adjusting its weights in this manner. In a passive time-reversal system, the transmitter array uses the time-reversed probe as the front-end shaping filter. Retrofocusing techniques in the form of time reversal have been explored and experimentally verified by many researchers[128–134]. Kida et al.[134] experimentally demonstrate a data rate of up to 20 kbps over a 13.5 km link, and more than 98% of the frames are bit error-free.

As discussed in 'Signal processing for communications', another frontier of research is the directive communication, or, in other words, beamforming. The basic idea of transmit beamforming is a simple one, and rests on the notion that multiple transmit elements should apply different weights such that the signals transmitted from the array add constructively at the receiver. However, this idea relies on the assumption that the transmitter knows the channel to the receiver and uses that knowledge to determine the weights. The problem that arises in practice is that the assumption of complete channel knowledge might not be sufficiently accurate, as the transmitter has to learn the channel via the feedback from the receiver. The problem is particularly pronounced in time-varying underwater acoustic channels, as the feedback delay is long due to the low speed of sound propagation.

Directive transmission and reception have been explored[122,135–138]. In a single-user point-to-point system, directive transmission can re-direct energy towards the directions that have less dissipation, in addition to its applications in security. It can also serve multiple users simultaneously, promising spatial-division multiplexing. Although such a system is in active use in cellular systems, adaptive directive transmission still awaits fully fledged demonstration in oceans. Cuji and Stojanovic[137] and Li et al.[138] explored the possibility of using angles as one of the stable components that can resist long feedback delay. In the former study[137], the transmitter adjusts its weights to point the signal only in the direction of the principal coherent path, while nulling the unstable multipath. A similar approach is investigated in the context of spatial-division multiple access[138]. The technique is demonstrated in an over-the-air acoustic channel, showing good results. At this time, however, there have been no underwater experimental demonstrations of such a system.

Modulation and coding schemes

As discussed in 'Signal processing for communications', in a single-carrier communication scheme both adaptive equalizers and phase tracking mechanisms are essential to effectively counteract the channel impairments. Analogously, in multi-carrier schemes, such as OFDM, algorithms have been designed to estimate and compensate for motion-induced frequency offsets[45,139]. In light of the nature of the underwater acoustic channel, recent work[140–142] suggests that orthogonal signal-division multiplexing (OSDM) is a viable option to achieve high-speed and high-reliability communications in high-mobility scenarios. In addition, OSDM enjoys a lower peak to average power ratio when compared with OFDM, granting further advantages in practical implementations and deployments. Multi-carrier modulations in the form of orthogonal chirp division multiplexing[143] and orthogonal time-frequency space[144,145] and/or OSDM can also combat severe motion-induced frequency shifts and frequency-selective fading. Extensive comparative studies in conjunction with large-scale underwater experiments are yet to confirm the efficacy and performance of these methods.

Data-driven solutions

Advances made in machine learning in the past decade impact all scientific domains. Applying machine learning techniques to various aspects of underwater acoustic communication systems is no exception[146]. Examples include channel modelling[147], physical layer signal processing[145,148–150], power allocation[151], adaptive modulation[124,152,153] and routing[154,155].

Data-driven techniques allow researchers to model complicated processes without the need for explicit closed-form solutions and environmental knowledge. However, these techniques are often data-hungry, requiring extensive data collection. Transfer learning and data augmentation using simulators permit researchers to train the neural networks on smaller datasets, but the complexities and intricacies of actual underwater channels are often not fully captured by simulation models and tools.

A physics-based, scientific machine learning approach seeks to exploit domain-specific scientific knowledge to aid the data-driven methods, requiring substantially fewer data recordings, and is believed to be an emerging field of research[156–158]. Physics-based machine learning techniques have been successfully applied to underwater acoustic modelling and proved to improve underwater communication system performance[58,159,160]. Li and Chitre[159] incorporated the physical propagation models in conjunction with the neural networks to estimate the acoustic wave propagation, necessitating fewer training data and, more importantly, providing interpretability to the trained model parameters. The idea of amalgamating knowledge of underwater acoustics with data-driven machine learning to overcome model limitations, including lack of environmental knowledge, is ripe for further research.

We therefore anticipate more innovative applications of the data-driven approaches in the underwater acoustic communication context.

In addition to the applications in underwater acoustic modelling, the physics-driven machine learning approaches can be used to develop autonomous underwater vehicle navigation and communication systems. By employing physics-driven machine learning techniques, it is possible to predict the acoustic field accurately with limited environmental knowledge, utilizing field measurements made by the vehicle along its path[58]. An underwater vehicle could potentially choose to modify its course to follow a path that ensures good acoustic signal strength, avoiding shadow zones, as described elsewhere[161]. Route planning was demonstrated in an under-ice mission by Schmidt and Schneider[12], who used a physics-based acoustic propagation model to predict the acoustic field to aid path planning. These successful experiments demonstrate the applicability of the physics-driven approaches, thus opening exciting new research opportunities to develop techniques for underwater vehicles to adapt their route to guarantee good acoustic performance for navigation and communication during critical sections of their mission.

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Acknowledgements

The authors thank Z.L.'s grandmother, Z. Xu, for the initial drawing of the network diagram which inspired the final version of Fig. 1.

Author contributions

All authors contributed equally to this manuscript. Z.L., M.C. and M.S. researched data for this article, substantially contributed to discussion of content, wrote the manuscript, and reviewed and edited the manuscript before submission.

Competing interests

The authors declare no competing interests.

Additional information

Peer review information *Nature Reviews Electrical Engineering* thanks James C. Preisig and the other, anonymous, reviewer(s) for their contribution to the peer review of this work.