Recent Advances in Underwater Acoustic Communications & Networking

Mandar Chitre[1], Shiraz Shahabudeen[1], Lee Freitag[2], Milica Stojanovic[3]

[1] Acoustic Research Laboratory, National University of Singapore
[2] Woods Hole Oceanographic Institution
[3] Massachusetts Institute of Technology

***Abstract*– The past three decades have seen a growing interest in underwater acoustic communications. Continued research over the years has resulted in improved performance and robustness as compared to the initial communication systems. Research has expanded from point-to-point communications to include underwater networks as well. A series of review papers provide an excellent history of the development of the field until the end of the last decade. In this paper, we aim to provide an overview of the key developments, both theoretical and applied, in the field in the past two decades. We also hope to provide an insight into some of the open problems and challenges facing researchers in this field in the near future.**

I. INTRODUCTION

As electromagnetic waves propagate poorly in sea water, acoustics provides the most obvious medium to enable underwater communications. High-speed communication in the underwater acoustic channel is challenging due to limited bandwidth, extended multi-path, refractive properties of the medium, severe fading, rapid time-variation and large Doppler shifts. Communication techniques originally developed for terrestrial wired and wireless channels need significant modifications to suit underwater channels.

A series of review papers provide an excellent history of the development of the field until the end of the last decade [1-4]. A recent review paper presents an overview of the development in the field from the start of the decade [5]. In this paper, we aim to provide a brief overview of the key developments, both theoretical and applied, in the field in the past two decades. We also hope to provide an insight into some of the open problems and challenges facing researchers in this field in the near future. We do not attempt to provide an exhaustive survey of all research in the field, but instead concentrate on ideas and developments that are likely to be the keystone of future underwater communication networks.

This paper is divided into three main sections – one on historical perspective, another on underwater communications and a final one on underwater networking.

II. HISTORICAL PERSPECTIVE

A. *Initial Efforts in Underwater Communications*

Undersea acoustic communications dates back to the development of manned submarines and the need to communicate with them. The "Gertude", or underwater telephone was developed for audio communication using analog modulation at carrier frequencies between 2 and 15 kHz, and this hardware is still in use on submarines around the world, both large military systems and small industrial or scientific submersibles such as Alvin. The design of these analog systems simply employ analog filters for the voice band plus spectral shaping and single-sideband modulation to the transmit carrier. On the receiver the signal is demodulated, filtered and then reproduced, sometimes with poor fidelity, depending upon the transmission path. However, the underwater telephone remains the standard for person-to-person communication, and it works well in part due to the ability of the human ear and brain to detect and process distorted speech.

The development of digital communications for undersea applications dates back to simple ping-based use of sonars that operate in the audible band. The use of "one ping only" in the fictional Hunt for Red October that was used to communicate from submarine to submarine is an example of digital communications, which while primitive, certainly is sufficient when only one bit is necessary.

The advent of digital communications in the 1960s brought about a general awareness of the principles of signaling and modulation for imperfect channels. In particular, the throughput in a non-compensated delay-spread channel is limited to be less than $1/Ts$, where Ts is the length of the delay spread. Thus, in the highly reverberant ocean acoustic channel the data rate can be very low, and it is natural that researchers in ocean propagation would consider how to increase throughput for communications.

An early effort to unravel ocean multipath to increase the data rate of potential communications system was reported by Ross Williams and Henry Battestin in 1971 [6]. Their paper is rarely cited, but it includes an actual example of multipath compensation that would allow faster than $1/Ts$ rate communication. Williams and Battestin were researching low frequency propagation over medium ranges, and used a 300 Hz carrier, processing signals sent 270 and 450 km in the Atlantic Ocean. The measured multipath structure at 270 km had distinct arrivals spanning six seconds, plus up to two seconds of late-arriving, non-resolvable energy. The distinct signals present in the six seconds included seven arrivals within 30 to 50% of the highest arrival. After "un-distorting" the channel using the signal estimate, only one peak was left, and while the resulting plot was not a perfect delta function (the processing was done using analog delay lines), the result demonstrated multipath compensation that made a dramatic reduction in the total spread in the channel.

The feature of the ocean acoustic channel that was exploited by Williams and Battestin is the temporal coherence that is high enough to allow channel estimation and subsequent compensation. In the nearly 40 years since their early work, other researchers have been able to use more sophisticated processing methods for channel estimation and implement algorithms on digital computers, but the principles that were demonstrated in this seminal work remain the same.

B. Incoherent and Coherent Modulation

Most early underwater acoustic communications systems used incoherent modulation methods for reasons of simplicity and reliability. However, there were a number of exceptions, in particular systems that were used in channels with little boundary action, for example vertical links in deep-water. Vertical links using directional transducers on unmanned underwater vehicles (UUVs) and ships are very clean, experiencing little or no delay spread, with the result that the biggest challenge is tracking the carrier phase that changes with respect to range.

Through the 1980s phase coherent communication was used almost exclusively for deep-water vertical links, but in the early 1990s phase coherent communication in multipath channels began to attract attention, as incoherent methods were limited to a bandwidth efficiency of approximately 0.5 bits per Hz. The desire for more throughput in a physical channel with little bandwidth naturally lead to interest in adaptive equalization to combat the effects of multipath, and these efforts are described in detail below.

Despite the incredible advances in methods for phase-coherent processing over the past 15 years, incoherent systems still have their place and are still in use. Their biggest advantage is algorithmic simplicity, requiring modest processors and thus reducing cost and power. A number of commercial systems are available, and while their bandwidth efficiency may be low, they are satisfactory for many applications where low bit rates (and perhaps low power efficiency levels) are acceptable. Incoherent methods generally include frequency-hopping (with single or multiple tones transmitted in a given time instant), and M-ary frequency-shift keying using symbol durations that are longer than the channel clearing time, and variations that employ alphabets of FM sweeps transmitted one at a time, or simultaneously in different bands.

C. Production Systems

Examples of commercial and low-volume production systems that have been developed and used in the field include the early modems developed by Datasonics in the US in the late 1980s that operated at low bit rates using binary FSK with analog electronics for detection. Typical data rates were 80 bps without any error correction. While not the only low-rate system, due to its availability this system was used in a number of applications. An early MFSK system that was commercialized through Datasonics was originally developed at Woods Hole in 1990 and included a simple transmitter based on an 8-bit processor and an early 32-bit floating-point processor for the receiver. This became the basis for the later Benthos ATM series modems, now part of Teledyne. Throughput the 1990s a number of additional systems were developed and commercialized using both coherent and incoherent modulation.

Today commercial acoustic communications systems are available from a number of manufacturers, including Teledyne and LinkQuest in the US and Evologics and Devologics in Europe. There are several others offering acoustic modems also, with many government and industry-funded efforts that have resulted in low-volume production systems for in-house applications.

A significant issue in selecting a system is establishing what the real range and data rate will be for a specific use. A system designed for deep-water may work poorly in shallow water (or when configured for too high a data rate when reverberation is present). Manufacturers specifications of maximum data rates are useful for establishing the upper performance bound, but often are not achievable, in particular in challenging acoustic environments. Users that are well-funded have resorted to purchasing multiple systems and testing them in specific environments to determine if they will meet their needs. An international effort that will standardize tests for acoustic communications systems is needed, but the costs to undertake this (and the value of the resulting information) means that an impartial body is difficult to establish and private organizations or governments that perform comprehensive tests tend not to publish the results.

III. Underwater Communication Techniques

A. Challenges posed by the Channel

High-speed communication in the underwater acoustic channel has been challenging due to a number of reasons. The bandwidth available for communication is severely limited due to the strong absorption of high frequency sounds by sea water. Extended multi-path, rapid time-variation and severe fading are also common in many underwater channels. The relatively slow signal propagation speed in water implies large Doppler shifts at moderate speeds of communicating platforms. A good understanding of the communications channel is important in the design and simulation of a communication system. A good review of early channel modeling work has been presented in [7].

At high frequencies appropriate for shallow water communications, ray theory provides the framework for determining the coarse multipath structure of the channel. As such a model does not capture the time-varying nature of the channel, efforts have been made to augment this model with a time-varying surface [8]. The primary limitation of this approach is the availability of an accurate and calibrated surface time-variation model. Moreover the time-variation in the channel is not limited to surface reflected arrivals.

Some researchers model the shallow water channel as a Rayleigh fading channel but others challenge that assumption, especially when discrete arrivals can clearly be seen in the channel response. There has been no consensus among researchers on the model applicable in shallow waters. Recently, a ray theory based multipath model where the individual multipath arrivals are modeled as Rayleigh stochastic processes has been shown to describe the medium range very shallow water channel accurately [9]. Studies of acoustic propagation through anisotropic shallow water environments in the presence of internal waves [10] may form the basis of future physics-based channel modeling research.

Modeling of the rapidly time-varying surface in a surf zone is especially difficult. The scattering of acoustic signals off shoaling surface gravity waves results in a time-varying channel impulse response and occasional caustics characterized by intense, rapidly fluctuating arrivals [11]. Hence most channel impulse response algorithms have difficulty coping with surf zones. Further work in this area is needed to help improve performance of communication systems in surf zones.

An additive Gaussian noise assumption is used commonly in the development of most signal processing and communication techniques. Although this assumption is valid in many environments, some underwater channels exhibit highly impulsive noise. Signal detection [12] and Viterbi decoding [13] techniques developed for impulsive noise models such as the symmetric α-stable noise have been shown to perform better in warm shallow waters dominated by snapping shrimp noise.

A. Channel Equalization

The shallow water acoustic communication channel is characterized by a long delay spread and a high Doppler spread. Coherent modulation schemes such as phase shift keying (PSK) along with adaptive decision feedback equalizers (DFE) and spatial diversity combining have been shown to be an effective but computationally complex way of communication in such channels [14].

Although the channel has a long delay spread, the multipath arrivals are often discrete. This presents the possibility of using a *sparse equalizer* with tap placement based on the actual channel response to reduce the number of required taps. This would lead to lower complexity, faster channel tracking and enhanced performance [15-17]. Sparse partial response equalizers (sPRE) exploit the sparse nature of the underwater channel to shorten the impulse response of the channel. When combined with a low-complexity belief propagation (BP) detector, the residual inter-symbol interference (ISI) from the sPRE can be used for multipath diversity [18].

Conventional equalization techniques require a training period during which the equalizer converges. However *blind equalization* techniques use only the statistical properties of the signal and do not require an explicit training sequence. They typically converge slower than training based methods and therefore their use has been limited to long or continuous data streams. In [19], the authors show that a blind DFE when combined with an appropriate iterative procedure provides good performance on short data bursts.

DFEs suffer from error propagation due to the feedback of erroneous decisions in the loop. Hence powerful forward error correction (FEC) codes are needed to ensure low bit error rate (BER) communication. Inspired by the iterative information exchange in Turbo decoders, researchers have developed *turbo equalization* techniques where iterative interactions between the equalizer and a decoder result in joint estimation, equalization and decoding [20]. Although experimental testing at 1 km range in very shallow waters with a vertical 8-hydrophone receiver array showed that the algorithm performed significantly better than DFE, the algorithm had some difficulty with sparse channels; future work combining sparse equalization techniques with turbo equalization may help address this difficulty.

The computational complexity of maximum a posteriori probability (MAP) equalization used in turbo equalizers increases exponentially with channel length. Even with per-survivor processing (PSP), this complexity can be too high for practical implementations. In [21], the authors propose a soft-input DFE structure to replace the MAP algorithm in the turbo equalizer. A joint DFE is optimal for multichannel combining, but is often too complex. The authors considered alternatives with separate DFE for each receiver and found that a set of DFE with a log-likelihood ratio (LLR) output yields good performance. To avoid error propagation problems with DFE, some researchers have successfully used a linear equalizer instead of the DFE in the turbo equalizer structure [22]. Most receivers have difficulty in shallow water channels due to the large Doppler spread induced by rapid channel variation. In a two-part paper [23, 24], the authors use a channel tracker with a linear decoder to combat large Doppler spread.

The use of direct sequence code division multiple access (DS-CDMA) has some benefits such as multi-user access and low probability of detection (LPD). DFE has been used to combat ISI in DS-CDMA systems [25]. A symbol decisions feedback (SDF) DFE uses the symbol decisions after de-spreading on the feedback path. As the symbols in a DS-

CDMA system are relatively long, a DFE using SDF is not able to track rapidly varying channels. For such channels, a chip hypothesis feedback (CHF) can help track the channel at the chip rate rather than the symbol rate.

B. Time Reversal Mirrors and Phase Conjugation

Due to the symmetry of the linear wave equation, sound transmitted from one location received at other locations, reversed and retransmitted, focuses back at the original source location. This is the principle behind time reversal mirrors (TRM) or its frequency domain equivalent – active phase conjugation. The temporal compression effect of TRM reduces the delay spread of the channel while the spatial focusing effect improves signal-to-noise ratio (SNR) and reduces fading. An experiment conducted in 1999 demonstrated such a TRM communication system in shallow waters [26]. The larger the number of transmitters, the better the TRM focus. TRM based communication systems effectively utilize spatial diversity at the transmitter rather than the receiver (spatial focusing does not allow the use of multiple receivers). This opens up the possibility of spatial multiplexing and low probability of intercept (LPI) communications. In a TRM based communication system, a probe signal has to be first transmitted from the receiver to the transmitter. The transmitter then uses a time-reversed version of this signal to convey information. As the channel changes over time, the probe signal has to be retransmitted to sample the channel but decoherence times up to several tens of minutes were observed at frequencies of 3.5 kHz during experiments.

Although TRM helps reduce delay spread of the channel, it does not eliminate ISI completely. Hence the communication performance can be improved through the use of a DFE [27]. Without equalization TRM is ISI-limited at high signal strengths. A detailed analysis of several solutions to deal with the ISI in a TRM system is presented in [28].

A closely related idea – passive phase conjugation (PPC) – uses the cross-correlation of two consecutive signals transmitted from the transmitter to the receiver to convey information. In one such system which uses pulse position modulation (PPM) with PPC for communication, the spacing between a linear frequency modulated (LFM) signal and its mirror image is used to encode the data [29]. Another PPC communication system uses a probe signal followed by several data-carrying PSK symbols [30]. In [31], the authors present results from an experiment to compare the performance of several methods including equalization, PPC and combinations of both methods. Adaptive equalization can be effectively combined with PPC to estimate and eliminate residual ISI [32]. In another experiment, it was found that continuous channel updates and Doppler tracking is required before time reversal in order to achieve acceptable performance in presence of ocean variability due to surface movement [33].

The computational simplicity of phase conjugation based communication systems is compelling. However, the use of such systems is limited by the quasi-static channel requirement. Rapidly changing channels due to moving communication nodes may pose a challenge to the use of phase conjugation in mobile applications.

C. Multi-carrier Modulation

Multi-carrier modulation offers an alternative to a broadband single-carrier communication. By dividing the available bandwidth into a number of narrower bands, orthogonal frequency division multiplexing (OFDM) systems can perform equalization in frequency domain and eliminate the need for complex time-domain equalizers. OFDM modulation and de-modulation can easily be accomplished using fast Fourier transforms (FFT). A shallow water experiment in the Mediterranean sea yielded good OFDM performance (BER $< 2\times10^{-3}$) at ranges by to 6 km [34]. At the same ranges, the DSSS performance was found to be significantly poorer.

OFDM systems often use a guard period (often implemented as a cyclic prefix or zero prefix) between consecutive OFDM symbols to avoid ISI. When the delay spread is long, the prefix length can significantly affect the bandwidth efficiency. Maximum likelihood sequence detection (MLSD) on individual sub-carriers using a low complexity PSP can combat ISI when the symbol period is smaller than the delay spread [35]. Other channel shortening techniques such as sPRE may also be used in future OFDM systems to reduce the prefix length and improve bandwidth efficiency.

When using coded OFDM, consecutive symbols are often striped across sub-carriers to reduce the error correlation due to fading. However, impulse noise present in some environments can affect multiple sub-carriers simultaneously and hence generate correlated errors. The use of a channel interleaver with coded OFDM allows symbols to be distributed over frequency-time plane thus allowing the code to make maximal use of frequency and time diversity offered by OFDM [36]. The knowledge of error correlation due to impulsive noise could be used in future decoding algorithms to improve decoding performance.

OFDM systems are very sensitive to Doppler shift due to the small bandwidth of each sub-carrier as compared to the Doppler shift. As the carrier frequency in underwater acoustic systems is typically low as compared to Doppler shift experienced due to movement, the communication systems have to cope with wideband Doppler which results in non-uniform Doppler shift across sub-carriers. In [37], the author presents an algorithm for non-uniform Doppler compensation in OFDM systems based on a single adaptively estimated parameter. In [38], the authors present a preprocessor that estimates Doppler shift by measuring the time between two known signals and removes the Doppler shift using a computationally efficient linear interpolator. Being a preprocessor, the technique can be used with any type of modulation and equalization.

D. *Spatial Modulation*

Information theoretic studies have shown that the capacity of a channel increases linearly with the minimum of the number of transmit and receive antennas. This increase in capacity translates to a corresponding increase in achievable data rate through the use of multiple input multiple output (MIMO) processing techniques and space-time coding.

Optimal detection techniques such as MAP and maximum likelihood sequence estimation (MLSE) exponentially grow in terms of complexity with the number of antennas. To address this problem, space-time trellis codes (STTC) and layered space-time codes (LSTC) can be used with sub-optimal decoding techniques [39]. The benefits of MIMO over single-input single-output (SISO) underwater communication systems were successfully demonstrated through an experiment in the Mediterranean Sea using 2 transmit projectors for STTC and 4 transmit projectors for LSTC. In another set of experiments with 6 transmit projectors, a spatial modulation scheme with an outer block code, interleaver and an inner trellis-coded modulation (TCM) was demonstrated [40]. The experiments demonstrated that with the proposed spatial modulation scheme offered increased bandwidth and power efficiency as compared to signals constrained to temporal modulation. For ISI-limited channels, spatial modulation offers the possibility of increasing data rates when simply increasing transmission power does not. In a MIMO-OFDM experiment, nearly error-free performance was achieved with a 2-transmitter 4-receiver setup at ranges up to 1.5 km using a ½-rate low-density parity check (LDPC) code at a coded data rate of 12 kbps [41].

The promise of increased throughput and spatial diversity in practical MIMO systems can only be achieved if the transducers in transmit and receive arrays are placed with spacing larger than the spatial coherence scale at the frequency of interest. In [42], the author theoretically and experimentally studies the gain due to spatial diversity given parameters such as the number of transducers and the spacing between them. Further research is required to better understand issues surrounding transducer locations, especially as their placement may be constrained in mobile systems such as autonomous underwater vehicles (AUV).

IV. Underwater Networking

There have been significant advances in underwater networking over the last few decades. In this section, we look at some of the key developments in datalink layer (DLL), media access control (MAC) and routing protocols.

A. *Media Access Control*

In static MAC protocols, nodes are allocated predetermined data channels, are contention-free (also referred to as scheduled or deterministic protocols). Static protocols are inherently non-scalable. In dynamic and ad-hoc schemes, nodes typically use a shared control channel over which data channels are requested. Two main MAC topologies used are centralized or distributed. In centralized topology (also referred to as clustered, cellular etc) a master node controls media access for nodes in its neighborhood. In a distributed topology, there are no controlling master nodes and all nodes asynchronously handles data transfers. Dynamic MAC protocols in distributed topology are contention-based. In centralized topology, they could also use polling methods with no contention.

1. *Static Protocols*

The traditional contention-free static MAC protocols include TDMA, FDMA, and CDMA. Space division multiple access (SDMA) is rarely used. Among these, a general consensus in underwater network research is that FDMA is inefficient for underwater applications [43]. TDMA has been reported to be better in some aspects [44] but requires good time synchronization in nodes. In some publications, CDMA is favored over TDMA and FDMA [45-47]. PCLS, a loosely synchronized form of TDMA with non-overlapping timeslots, has been proposed for low capacity sensor networks [48].

2. *Dynamic Contention-based MAC in a Distributed Topology*

Some of the simpler contention-based distributed protocols include half duplex ALOHA, carrier sense multiple access (CSMA) and medium access collision avoidance (MACA) using RTS/CTS handshaking [44]. A CSMA based contention protocol was described in [49]. MACA based protocols use RTS, CTS, DATA, ACK sequences and were shown to be effective for underwater use compared with scheduled protocols early on in the Seaweb project [43]. The authors observe that in the physical and MAC layers, adaptive modulation and power control are the keys to maximizing both channel capacity and channel efficiency and RTS/CTS handshaking permits that, along with addressing, ranging and channel estimation. MACA based protocols are found to be highly suited in many scenarios underwater where scalability is important and time-synchronization is not available [50-53]. However in some sensor networks, RTS/CTS mechanisms could perform poorly due to latency issues and inefficiency for small payload packets [48].

Protocol extensions and enhancements of MACA have been investigated to suit them better to underwater channel. For example, a WAIT command extension has been investigated in [54, 55]. A WAIT command is sent back by the receiver if it is currently busy and intends to send a CTS later on. In [43], instead of using ACK packets, selective ARQ is initiated by recipient should it not receive packets in a specified time. In [56], the authors proposed to counter the wasted bandwidth in handshaking due to the high propagation delay, using a variant called PCAP which pipelines other actions while waiting for CTS from receiver. Packet trains have been shown to greatly improve the performance of protocols such as MACA [51, 57, 58]. Analytical results for optimal packet size as a function of the acoustic link parameters (transmission rate, link distance, and error probability) and the train or group size have been presented in [59]. Floor acquisition multiple access (FAMA), a family of protocols of which MACA is a variant, was originally proposed for terrestrial networks. It uses carrier sensing (absent in MACA) and puts restrictions on RTS/CTS time durations. Time-slotting can also be implemented to enhance performance [60]. FAMA in its original form is quite unsuited to underwater networks, but with enhancements such as slotting, it can be used underwater effectively [51]. Distance aware-collision avoidance protocol (DACAP) is also based on MACA [61]. It adds a warning message if a RTS is overheard while waiting for a reply to its own RTS. While waiting for reply, if another CTS or a warning is heard, a random back off is used. Optimal power control for DACAP is studied in [62]. The optimal power is found to be that which minimizes connectivity.

3. *Dynamic Contention-based MAC in Centralized Topology*

We review one of the reported networks of this type, a deep-water acoustic local area network (ALAN) deployed in Monterey Canyon [63]. The sub-surface nodes send asynchronous requests via a shared channel (similar to MACA RTS) to send data packets to the master node. The master node sends an acknowledgement (similar to MACA CTS) via a different channel indicating the data channel to be used. The node transmits data immediately on the data channel. The request, ACK, data channels are different frequency bands. This protocol resembles MACA except that the RTS, CTS and DATA are sent on different channels. Since the transmit request happens on a shared contention channel, we classify this as a contention protocol. MAC topology is centralized as the MAC function of data channel allocation is performed by the central node.

4. *Dynamic Contention-free MAC in Centralized Topology*

The polling-based protocol called FAMA-CF in [50] uses request for RTS (RRTS), RTS, CTS, DATA, ACK handshaking to communicate with the central node. The central node initiates the RRTS to its peers. In [64], the authors look at one CDMA code per cluster and spatial re-use of codes. TDMA is used within each cluster. Nodes are assumed to be able to handle multiple CDMA codes simultaneously. Similar scheme in which clusters are allocated either different CDMA codes or FDMA bands is found in [65] where, within each cluster TDMA is used. Since cluster heads are tasked with TDMA slot allocation to ordinary nodes, we can classify the above as centralized MAC topology.

An underwater acoustic cellular network is an extension of centralized topology. Analysis of frequency re-use between adjacent clusters and optimal cell-radius selection criteria has been carried out recently [66]. A related work on channel allocation and scheduling protocol for cellular networks is presented in [67].

B. *Other Datalink Layer Aspects*

A key DLL/MAC aspect is energy conservation. PCLS as discussed earlier [48] incorporates a power control and sleep-wake up scheme. Another example on energy minimization [68] shows an ultra-low duty cycle MAC protocol focusing on energy conservation at low data rate. A sensor wakeup scheme – adaptive wakeup schedule function (AWSF), suitable for underwater sensor systems uses a time cyclic wakeup schedule for each node such that at any one time only a few nodes are active [69].

An novel approach to provide reliable data transfer uses rate-less codes, a class of erasure correcting codes where the source data packets are converted into virtually an infinite stream and can be reconstructed from received data, provided it contains a minimum number of packets [70].

C. *Network Layer and Routing*

Fully connected peer-to-peer topologies without the need for routing were commonly used earlier [45]. But such networks could suffer from near-far power problems and multi-hop routing is now preferred for large networks. In clustered network routing topology, only some nodes have routing (gateways) functionality and ordinary nodes within one-hop distance to gateways send data to them for routing. In fully distributed routing topology, all nodes are equal and perform routing to neighbors as required.

A good review of underwater network protocols until the year 2000 can be found in [44]. A store-and-forward protocol was proposed in [71] for shallow-water ALAN's, where they use a form of packet radio network (PRN) protocol [72] that matches the shallow-water acoustic channel characteristics. In [73], the authors presented a clustered topology assuming full-duplex modems. The gateway node manages route discovery through the use of probe messages to its neighbors. In [74] AODV based routing together with MACAW is proposed. The authors modify the standard reactive AODV protocol to use reverse link pointers by assuming bi-directionally symmetric links. In [75], the authors discuss location aware source routing for dynamic AUV networks, a modification from the terrestrial DSR protocol. It uses known TDMA frame timings to compute ranges based on propagation delay, and estimate local topology to determine routes. In [76], for delay-tolerant applications, the protocol chooses low packet error rate links, to maximize the probability of correct reception, and thus minimize retransmissions. For delay-sensitive applications, it tries to minimize the energy consumption, while limiting the end-to-end packet delay by estimating at each hop the time to reach the sink and unacknowledged packets are not retransmitted.

The idea of mixing data at intermediate nodes in a network is at the root of network coding, a technique introduced in a seminal paper in the year 2000 [77]. Such schemes for underwater networks are considered in [78]. In a concatenated relay network, the authors compare two routing schemes based on end-to-end acknowledgements, two based on link-by-link acknowledgements and two based on network coding. The use of network coding in underwater networks remains a promising open research area.

D. AUV Networking

Due to ever increasing applications, networking of mobile AUVs is currently a very active area of research. The mobility and ad-hoc requirements for such networks pose many challenges. In [79], the authors describe a TDMA protocol for AUVs. Exchanged packets contain position information for localization. Simulated results from a FAMA based MAC for an AUV network were presented in [51]. AUVs are sometimes equipped with multiple modems [80]. The effective use of multiple modems optimized for different ranges in an AUV network using random access protocols is explored in [57].

E. Standardization

Some of the existing standardization initiatives are reviewed here. The physical layer of the WHOI micro-modem was published as a standard [81] and a commercial modem maker Benthos implemented compatible modems [82]. Standardized communications to acoustic modems includes the WHOI micro-modem that supports a standard NMEA 0183 protocol [82]. At a higher layer, the command and control language (CCL) specifications for AUV networks outline a TCP/IP based protocol for access to a CCL gateway [83]. However, standardization in underwater networks is still in its infancy compared to terrestrial networks.

V. Summary

Although well-studied incoherent techniques still play a significant role in low data rate communication applications that demand robust and low-complexity solutions, most of the new advances in the past decade have been in the area of coherent communications. Advances in DFE algorithms have enabled underwater communication channels to be equalized, thus enabling coherent communications. Channel characteristics (such as sparseness) or channel models are sometimes used to reduce noise in channel estimates. When combined with error correction coding and iterative (turbo) algorithms, the performance of DFE algorithms can be further improved. Advances in OFDM systems include algorithms for equalization or partial equalization to reduce the effective channel delay spread and wideband Doppler compensation. Although phase conjugation provides an innovative low complexity solution to equalization problems, constraints on channel variation may limit its use. The use of multiple receivers for spatial diversity gains is becoming common in underwater communication systems. With gains from MIMO processing, we expect that more communication systems will include multiple transmitters in the future.

The past decades has significantly advanced underwater networking research. Static protocols such as TDMA or CDMA or dynamic protocols such as MACA have been used in a UW-LAN in either distributed or centralized topologies. AODV, DSR-based and many other lightweight routing protocols have been investigated for underwater use. Efficient multi-hop and ad-hoc packet routing protocols for AUV networks are promising research areas for the future. Time is fast approaching for IEEE 802.11 style standardization for underwater network protocols – this will lead to interoperable underwater communication devices that can be used in a plug-and-play fashion similar to terrestrial wireless systems today.

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