PAPER

Underwater Acoustic Communications and Networking: Recent Advances and Future Challenges

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ABSTRACT

The past 30 years have seen a growing interest in underwater acoustic communications because of its applications in marine research, oceanography, marine commercial operations, the offshore oil industry and defense. Continued research over the years has resulted in improved performance and robustness as compared to the initial communication systems. In this paper, we aim to provide an overview of the key developments in point-to-point communication techniques as well as underwater networking protocols since the beginning of this decade. We also provide an insight into some of the open problems and challenges facing researchers in this field in the near future.

I. Introduction

The past three decades have seen a growing interest in underwater acoustic communications because of its applications in marine research, oceanography, marine commercial operations, the offshore oil industry and defense. Continued research over the years has resulted in improved performance and robustness as compared to the initial communication systems. A series of review papers provides an excellent history of the development of the field until the end of the last decade (Baggeroer, 1984; Catipovic, 1990; Stojanovic, 1996; Kilfoyle and Baggeroer, 2000). In this paper, we aim to provide an overview of the key developments in the field since the beginning of this decade. We also hope to provide an insight into some of the open problems and challenges facing researchers in this field in the near future.

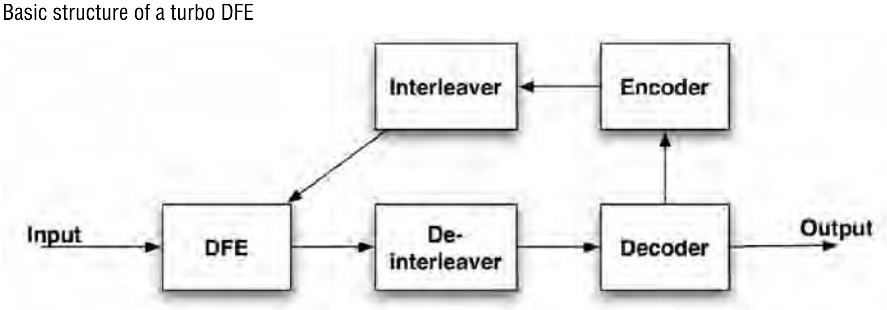
This paper is divided into two main sections—one on underwater communications and another on underwater networking. Section II concentrates on research on point-to-point communication issues such as channel modeling, modulation, coding and equalization. Key advances in these areas have enabled us to establish reliable high-speed underwater communication links. Using these links as a foundation, underwater networks can be established. Section III focuses on research on algorithms and protocols for such networks. In this paper, 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.

II. Underwater Communications

High-speed communication in the underwater acoustic channel has been challenging because of limited bandwidth, extended multipath, refractive properties of the medium, severe fading, rapid time variation and large Doppler shifts. In the initial years, rapid progress was made in deep water communication, but the shallow water channel was considered difficult. In the past decade, significant advances have been made in shallow water communication.

FIGURE 1

Basic structure of a turbo DFE



A. Channel Equalization

The shallow water acoustic communication channel exhibits a long delay spread because of numerous multipath arrivals resulting from surface and bottom interactions. Movement of transducers, ocean surface, and internal waves lead to rapid time variation and, consequently, a high Doppler spread in the channel. 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 way of communication in such channels (Stojanovic et al., 1993). However, the long delay spread (often hundreds of symbols) and rapid time variation of the channel often makes this approach computationally too complex for real-time implementations.

Although the underwater channel has a long impulse response, the multipath arrivals are often discrete. This opens up the possibility of using a *sparse equalizer* with tap placement based on the actual channel response. This can potentially dramatically reduce the number of required taps and hence lead to a lower complexity, faster channel tracking and an enhanced performance. In Stojanovic et al. (1999), the authors proposed an algorithm to track the channel explicitly and determine the tap placement for the DFE based on this channel estimate. The equalizer and the channel estimator are separately updated throughout the packet. The channel estimator can update either the whole estimate or a set of selected channel coefficients at one time, depending on computational and channel considerations. The algorithm uses spatial diversity by multi-channel combining before equalization.

Another algorithm for robust automated DFE tap placement in sparse channels is presented in Lopez and Singer (2001). The algorithm alternates between tap placement for the feedforward and feedback filters in the DFE. A stopping criterion is defined in terms of the estimated mean square error (MSE) rather than a fixed number of taps. As increased model order leads to increased estimation noise, a model order penalty is imposed in the optimization. When used with multiple receivers for exploiting spatial diversity, the algorithm uses the same number of taps in each receiver. An empirically tuned version of the algorithm was successfully demonstrated in an experiment using a 4-hydrophone receiver array. The algorithm placed an average of 10 feedforward taps and 25 feedback taps; this is a significantly smaller number than the number of taps required in a conventional DFE for shallow water communication.

In Weichang and Preisig (2007), the authors develop a sparse channel estimation technique based on the delay-Doppler-spread function representation of the channel. As this representation is an approximation of a rapidly time-varying channel, it captures the channel structure and its dynamics simultaneously. In the paper, the authors compare the performance of recursive least square (RLS) estimation, spare channel impulse response estimation and the proposed method.

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. Data collected during an experiment in Kauai was used to demonstrate a communication scheme based on a sPRE with a BP detector (Roy et al., 2006).

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 Labat et al. (2003), the authors show that a blind DFE, when combined with an appropriate iterative procedure, provides good performance on short data bursts.

DFE structures 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. Turbo codes are a class of powerful codes that utilize iterative information exchange between two decoders to correct errors. Inspired by this idea, researchers have developed *turbo equalization* techniques where iterative interactions between the equalizer and a decoder result in joint estimation, equalization and decoding (Sozer et al., 2001). The data to be transmitted is encoded, interleaved and transmitted. The receiver treats the combination of the encoder, interleaver and channel as a serial concatenated code. A maximum *a posteriori* probability (MAP) equalizer is used along with a decoder as the two components of the turbo decoder. The turbo decoder's output is used in the feedback loop of the DFE to reduce errors. Although MAP equalization is computationally intensive, per-survivor processing (PSP) helps reduce the number of trellis states used in channel equalization. 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 however had some difficulty with sparse channels; future work combining sparse equalization techniques with turbo equalization may help address this difficulty.

The computational complexity of MAP equalization increases exponentially with channel length. Even with PSP, this complexity can be too high for practical implementation. In Blackmon et al. (2002), the authors propose a soft-input DFE structure to replace the MAP algorithm in the turbo equalizer. The data from multiple receivers can be combined to gain spatial diversity. A joint DFE is optimal for such 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 (Oberg et al., 2006).

Many conventional receivers have difficulty in shallow water channels due to the large Doppler spread induced by rapid channel variation. In a two-part paper, Eggen et al. (2000, 2001) use a channel tracker with a linear decoder to combat large Doppler spread. The tracker uses a modified RLS algorithm and frequency domain filters known as Doppler lines to estimate channel coefficients. The decoder makes use of the channel tracker coefficients in order to perform minimum mean square error (MMSE) decoding.

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). In Stojanovic and Freitag (2006), the authors explored the use of a DFE to combat ISI in DS-CDMA systems. 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. For M-ary signal constellations, the complexity of the CHF is at least M times higher than the SFD as M different hypotheses have to be tracked. However, the advantage of a CHF was clearly demonstrated at high spreading factors during a shallow water experiment in Italy. The authors expect that the performance difference would be more apparent in a mobile environment as one would expect the channel to change more rapidly.

If the statistics of the errors in channel estimation are known, DFE or linear equalizer performance can be estimated (Preisig, 2005). The error estimate can be split into the minimum achievable error and the excess error. The excess error component is strongly affected by rough sea conditions. Through a scattering function analysis, it was also shown that the rate of change of propagation path length for the surface bounced arrival is a primary contributor to the error. This suggests that the ability to effectively track the surface bounced arrival may provide an improved equalizer performance.

B. Phase Conjugation

Due to the symmetry of the linear wave equation, if the sound transmitted from one location is received at other locations, reversed and retransmitted, it 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 (Edelmann et al., 2002). The larger the number of transmitters, the better the TRM focus. Thus, TRM based communication systems effectively utilize spatial diversity at the transmitter rather than the receiver. In fact, the spatial focusing precludes the use of multiple receivers for spatial diversity, but opens up the possibility of spatial multiplexing and low probability of intercept (LPI) communications. Although TRM helps reduce delay spread of the channel, it does not eliminate ISI completely. By implementing a DFE at a TRM receiver, the communication performance can be further improved (Edelmann et al., 2005). 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.

Since TRM does not eliminate ISI completely, it is ISI-limited at high signal strengths. In Stojanovic (2005), the author presents a detailed analysis of several solutions to deal with the ISI in a TRM system if the channel response is known. By introducing optimal filters at the transmitter and receiver, ISI can be completely eliminated. However, this is prohibitively complex and requires channel knowledge at both ends. An excellent trade-off between complexity and performance can be found by limiting filter adjustment to the array-side of the communication system. The paper presents strong analytical results and upper bounds on system performance, but the ideas have yet to be experimentally tested. Imperfect channel estimation resulting from noise may limit the performance of the algorithms described in the paper.

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 Hursky et al. (2001), the authors describe 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. PPC requires that the spacing between signals is more than the delay spread of the channel. Although this results in relatively low symbol rates, the use of PPM allows many bits to be packed in each symbol. The use of LFM signals also enables low-complexity Doppler correction. The authors present results from a successful PPC communication experiment at ranges of up to 10 km using a single transmitter and receiver. Another communication system using PPC is described in Rouseff et al. (2001). This system uses a probe signal followed by several data-carrying PSK symbols. The system was successfully demonstrated at ranges up to 5 km using a single transmitter and a 14-hydrophone receiver-array. More recently, Gomes et al. (2006) presents results from an experiment off the west coast of Portugal where the authors compare the performance of several methods including equalization, PPC and combinations of both methods. In Song et al. (2006), the authors study the benefits of spatial diversity in PPC communications. They also show that adaptive equalization can be effectively combined with PPC to estimate and eliminate residual ISI. In the experimental results presented, gains of up to 5 dB were obtained through equalization in the case of a fixed transmitter/receiver. When the transmitter was moving, the channel varied more rapidly and the gain from equalization increased to 13 dB. In another experiment, it was found that continuous channel updates and Doppler tracking are required before time reversal in order to achieve acceptable performance in the presence of ocean variability (Song et al., 2008). This ocean variability was shown to be primarily a result of interaction of the acoustic field with the dynamic ocean surface.

The computational simplicity of phase conjugation-based communication systems makes them extremely attractive. However, the use of such systems is constrained by the quasi-static channel requirement that is fundamental to the idea. The quasi-static constraint may be somewhat relaxed in cases where an adaptive equalizer is used in conjunction with a phase conjugation scheme. Rapidly changing channels resulting from moving communication nodes may limit the use of phase conjugation in mobile applications.

C. Channel Modeling

A good understanding of the communications channel is important in the design and simulation of a communication system. A good review of channel modeling work prior to the year 2000 has been presented in Bjerrum-Niese and Lutzen (2000).

At high frequencies appropriate for shallow water communications, ray theory provides the framework for determining the coarse multipath structure of the channel. However, such a model does not encapsulate the time-varying nature of the channel. By augmenting this model with a time-varying surface model, a shallow water channel can be simulated (Bjerrum-Niese et al., 1996). As acknowledged by the authors, the primary limitation of such a channel model 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.

If the received signal is a sum of a large number of multipath arrivals, each of which are modeled as a complex Gaussian stochastic processes, the resulting model is the well-known Rayleigh fading channel. 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 (Chitre, 2007). The physics resulting in the time-variation of each arrival is not fully understood, but it may result from micro-multipath or internal waves. Theoretical and experimental studies of acoustic propagation through anisotropic shallow water environments in the presence of internal waves (Badiey et al., 2007) may form the basis of further physics-based channel modeling research in the future.

Channel modeling in the surf zone is especially difficult because of the large impact of the rapidly time-varying surface on the acoustics. 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 (Preisig and Deane, 2004). Through a combination of experimental measurements and propagation modeling, the authors showed that the high intensity arrivals were often due to focusing by surface gravity waves and caustic formation. 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 (Chitre et al., 2006) and Viterbi decoding (Chitre et al., 2007) 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.

D. Multi-carrier Modulation

Multi-carrier modulation is an attractive alternative to a broadband single-carrier communication system. By dividing the available bandwidth into a number of narrower bands, orthogonal frequency division multiplexing (OFDM) systems can perform equalization in frequency domain, thus eliminating the need for complex time-domain equalizers. OFDM modulation and de-modulation can easily be implemented using fast Fourier transforms (FFT). In shallow waters in the Mediterranean sea, an experiment was conducted to compare the performance of OFDM with direct sequence spread spectrum (DSSS), both using differential PSK modulation (Frassati et al., 2005). The authors reported good OFDM performance (BER $< 2\times10^{-3}$) at ranges up to 6 km. At the same ranges, the DSSS performance was found to be significantly poorer.

OFDM equalization is simplified greatly if a guard interval longer than the delay spread is allowed between consecutive OFDM symbols. This guard period is usually implemented as a cyclic prefix to maintain orthogonality of the sub-carriers. However, when the delay spread is long, the prefix length can become undesirably long and affect the efficiency of transmission significantly. In Morozov and Preisig (2006), the authors explore the use of maximum likelihood sequence detection (MLSD) on individual sub-carriers when the symbol period is smaller than the delay spread. An algorithm to perform joint channel estimation and MLSD using a low complexity PSP was proposed and experimentally demonstrated in the paper. Channel shortening techniques such as sPRE may also be used in future OFDM systems to reduce the prefix length and improve bandwidth efficiency.

To conserve energy, the cyclic prefix can be replaced by a zero prefix (ZP). Optimal de-modulation of ZP-OFDM requires a computationally intensive matrix inversion operation. In Li et al. (2006), the authors use pilot-based channel estimation with a low complexity overlap-add de-modulation to implement an OFDM system. By using maximum-ratio combining over the data from multiple receivers, the authors utilize the spatial diversity available to further increase the robustness of the system.

When using coded OFDM, consecutive symbols are often striped across sub-carriers to reduce the error correlation resulting from 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 a frequency-time plane, thus allowing the code to make maximal use of frequency and time diversity offered by OFDM (Chitre et al., 2005). The knowledge of error correlation resulting from impulsive noise could be used in future decoding algorithms to improve decoding performance.

The narrowband sub-carriers in an OFDM system make the system very sensitive to Doppler shift. As the carrier frequency in underwater acoustic systems is low as compared to typical Doppler shift experienced as a result of movement, the communication systems have to cope with wideband Doppler. In the case of OFDM, this results in non-uniform Doppler shift across sub-carriers. As a maximum likelihood solution for Doppler compensation is computationally far too expensive to be practical, a simpler solution is needed. In Stojanovic (2006), the author presents an algorithm for non-uniform Doppler compensation in OFDM systems based on a single adaptively estimated parameter. The algorithm was tested on experimental data from a ZP-OFDM system with multiple receivers to correct a Doppler shift of about 7 Hz (0.02%). By adaptive MMSE combining of data from a minimum of 3 receivers, the author was able to successfully demonstrate the proposed algorithm. In Sharif et al. (2000), 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. The technique was tested in the North Sea using a prototype communication system and demonstrated to work well at speeds of 2.6 m/s and accelerations of 0.9 m/s^2. The authors expect the technique to work at higher speeds and accelerations.

E. 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. The computational complexity of optimal detection techniques such as MAP and maximum likelihood sequence estimation (MLSE) grows exponentially with the number of transmit antennas. In Roy et al. (2004), the authors explore the use of space-time trellis codes (STTC) and layered space-time codes (LSTC) with various sub-optimal decoding techniques. For STTC, the proposed receiver consists of explicit phase tracking and timing recovery loops which are jointly optimized with a MIMO DFE. The equalization and decoding is jointly performed using the powerful trellis structure of STTC. This limits the error propagation that is inherent in DFE. For LSTC, the equalization is performed iteratively (turbo equalization). The authors demonstrated the benefits of MIMO over single-input single-output (SISO) underwater communication systems through a successful 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 (Kilfoyle et al., 2005). A joint DFE and phase-locked loop (PLL) was used for each data stream at the receiver. Low latency soft decisions were released to support the DFE. 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 a unique and effective means to increase data rates when simply increasing transmission power does not. Recently, results from a MIMO-OFDM experimental data obtained during the AUV Fest in Panama City, Florida in 2007 have been presented (Li et al., 2007). 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) codes at a coded data rate of 12 kbps.

In Nordenvaad and Oberg (2006), the authors consider the channel as a 1-rate code and use turbo decoding framework to decode the MIMO signals. A widely linear model of the Alamouti code was used for joint equalization and decoding, with a linear equalizer chosen for its low complexity. The Alamouti code uses two transmit antennas and multiple receive antennas to achieve spatial diversity gains without a direct increase in data throughput. Although this algorithm was successfully tested in a trial in the Baltic Sea, the gains resulting from MIMO processing were questionable in the trial as a single dominant path with very slow fading was observed in most of the data.

To achieve the promise of increased throughput and spatial diversity in practical MIMO systems, the transducers in transmit and receive arrays must be placed with spacing larger than the spatial coherence scale at the frequency of interest. In Yang (2007), the author theoretically and experimentally studies the gain from spatial diversity given parameters such as the number of transducers and the spacing between them. Further research is needs to be conducted to better understand issues surrounding transducer locations, especially as their placement may be constrained in mobile systems such as autonomous underwater vehicles (AUV).

F. Summary

Robust incoherent techniques have been well studied in the past. Although they 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 resulted in robust algorithms that can be used to equalize underwater communication channels. Channel characteristics (such as sparseness) or channel models may be used to reduce noise in channel estimates. When combined with error correction coding and iterative (turbo) algorithms, DFE algorithms can benefit from the higher reliability of the feedback loop. In OFDM systems, equalization or partial equalization may be used to reduce the effective channel delay spread and improve performance. OFDM systems suffer from high sensitivity to Doppler shift. As new algorithms for wideband Doppler compensation for OFDM systems develop, we expect that success of OFDM in wireless networks could be replicated in underwater networks. Although phase conjugation provides an innovative low complexity solution to equalization problems, constraints on channel variation may limit the use of algorithms based on phase conjugation. The use of multiple receivers for spatial diversity gains is becoming common in underwater communication systems. With MIMO processing techniques, we expect that more communication systems will include multiple transmitters as well and derive benefits from the increased theoretical channel capacity. As researchers master the techniques required for point-to-point communication links in the next 5-10 years, we expect that the research emphasis on underwater networking will increase.

III. Underwater Networking

A recent survey on research in underwater protocol development presents a good overview of the subject (Akyildiz et al., 2006). The state of the art in current underwater networking technology is oriented towards a setup as shown in Figure 2. The network consists of a set of underwater local area networks (UW-LAN, also known as *clusters* or *cells*), connected to each other via *gateway nodes*. A gateway node provides administration, security and routing between multiple UW-LANs and other wireless or wired networks.

In a cluster, the exact choice of physical layer protocol may depend on factors such as specific channel conditions, security reasons, processing capability, data rate requirements and energy efficiency. In view of the limited bandwidth underwater, a high level of cross layer optimizations or transcending of traditional layer boundaries may be needed to provide high data rates. We now review some of the recent work and future challenges. The key focus of our review will be on the data link layer (DLL) and network topology.

G. Datalink Layer

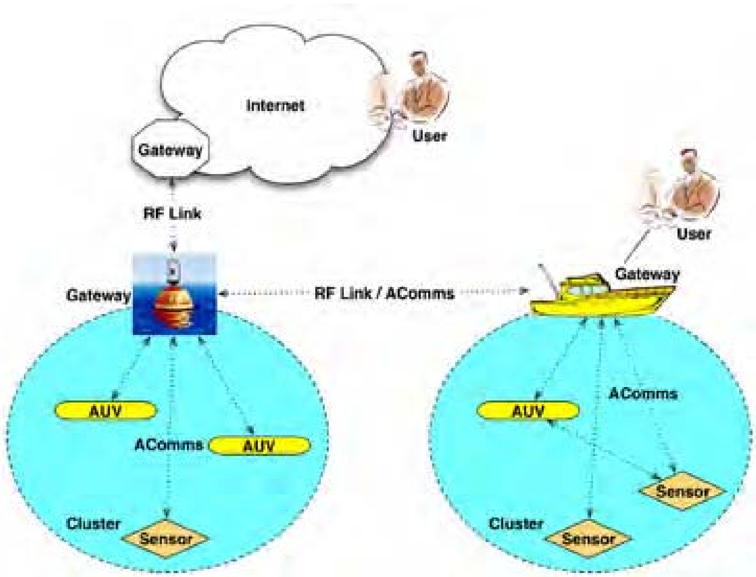
Key differences between terrestrial radio wireless networking and underwater acoustic networking are the large propagation delay of sound, extremely low point-to-point data rates and high raw BER. Thus it is often proposed that media access control (MAC) protocols for underwater networks be developed ground up and not directly adopt existing terrestrial protocols (Jiejun et al., 2005; Heidemann et al., 2006). MAC protocols can be typically be classified into contention-based (non-orthogonal) and contention-free (scheduled, orthogonal or deterministic) protocols. Some of the simpler contention-based protocols include half duplex ALOHA, ALOHA with acknowledgements (ACK) and retries, medium access collision avoidance (MACA)-based half duplex protocol using RTS/CTS handshaking (Sozer et al., 2000). The traditional contention-free MAC protocols include time division multiple access (TDMA), frequency division multiple access (FDMA), CDMA and space division multiple access (SDMA).

In contention-based protocols the key protocol family is based on MACA originally proposed for terrestrial networks (Karn, 1990). Such protocols use RTS, CTS, DATA, ACK sequences, as illustrated in Figure 3. These protocols were shown to be effective for underwater use compared with scheduled protocols early on in the Seaweb project (Rice et al., 2000). 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. Handshaking permits addressing, ranging, channel estimation, adaptive modulation, and power control. RTS/CTS exchanges channel measurement so that the DATA frame can be sent using optimal parameters. In Sozer et al. (2000), the authors review MAC protocols such as ALOHA and MACA and present results on throughput and delay performance. MACA-based protocols are found to be highly suited in many scenarios underwater where scalability is important and time-synchronization is not available (Kebkal et al., 2005; Heidemann et al., 2006; Molins and Stojanovic, 2006; Xie and Cui, 2006). However in some sensor networks, RTS/CTS mechanisms could perform poorly due to latency issues and inefficiency for small payload packets (Turgay and Erdal, 2006).

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 Sozer et al. (2000) and

FIGURE 2

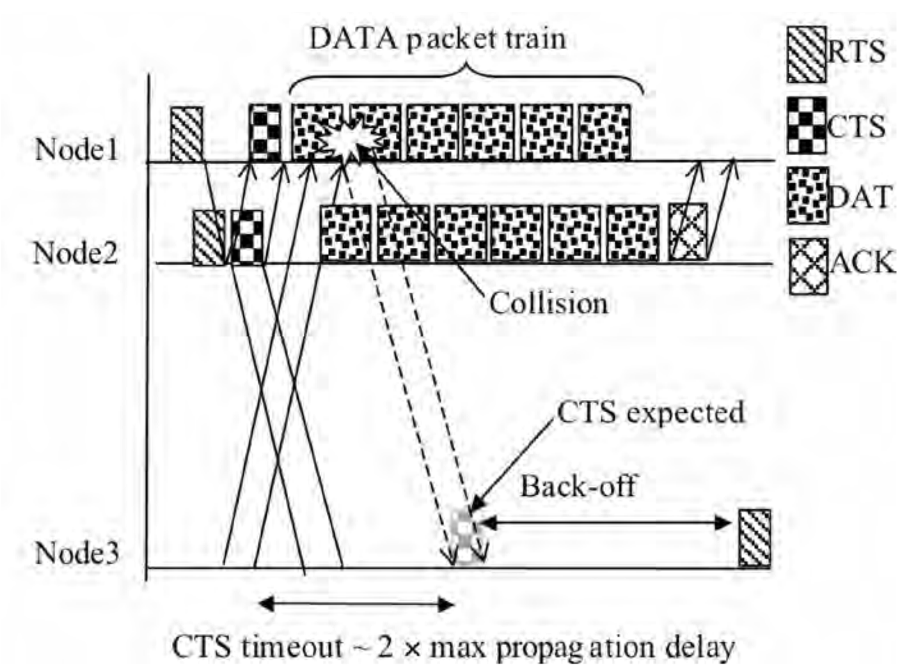
A topology for underwater networks



Doukkali et al. (2006). A WAIT command is send back by the receiver if it is currently busy and intends to send a CTS later on. In Rice et al. (2000), instead of using ACK packets, selective ARQ is initiated by recipient should it not receive packets in a specified time. Guo et al. (2006) proposed to counter the wasted bandwidth of using RTS, CTS, DATA, ACK resulting from the high propagation delay, through a new protocol called PCAP. It requires accurate time synchronization. They propose to pipeline other actions while waiting for CTS from receiver. Packet trains can greatly improve the performance of protocols such as MACA (Garcia-Luna-Aceves and Fullmer, 1998; Molins and Stojanovic, 2006; Shahabudeen et al., 2007). By dividing the DATA segment into packets, RTS/CTS collisions only affects a small number of packets and do not result in complete retransmission of the DATA, as shown in Figure 3. Floor acquisition multiple access (FAMA), a family of protocols of which MACA is a variant, was originally proposed for terrestrial networks. Control of the channel is assigned to at most one station in the network at any given time and uses carrier sensing (absent in MACA) and puts restrictions on RTS/CTS time durations.

FIGURE 3

Packet trains in MACA protocol



Although the effectiveness of carrier sensing is limited by long propagation delays in underwater networks, it can nevertheless provide some collision avoidance against nearby nodes. Time-slotting can also be implemented to enhance performance (Fullmer and Garcia-Luna-Aceves, 1995). FAMA in its original form is quite unsuited to underwater networks, but with enhancements such as slotting, it can be used underwater effectively (Molins and Stojanovic, 2006). Distance aware-collision avoidance protocol (DACAP) is based on MACA (Peleato and Stojanovic, 2006). 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 Dolc and Stojanovic (2007). The optimal power is found to be that which minimizes connectivity. A RTS/CTS-based handshaking scheme can be expected to perform well in dynamic mobile AUV networks too, since during the delay of at most a few seconds between RTS and CTS, typical AUV velocities and distances imply little change in geometry and consequently appropriate power levels. However, DATA packet trains long enough for the AUVs to travel significant distances may render the power setting inappropriate.

Among contention-free protocols, there seems to be general consensus that FDMA is inefficient for underwater applications (Rice et al., 2000). TDMA is better than FDMA but requires good time synchronization in nodes. In some publications CDMA is favored over TDMA and FDMA (Proakis et al., 2001), and over MACA based protocols (Jun-Hong et al., 2006; Chan and Motani, 2007). PCLS, a loosely synchronized form of TDMA with non-overlapping timeslots, has been proposed for low capacity sensor networks (Turgay and Erdal, 2006).

Some analytical results are presented for a variant called FAMA-CF (Collision Free) that applies only to a centralized topology in (Kebkal et al., 2005). Mathematical analysis for slotted-FAMA is presented in Molins and Stojanovic (2006). Xie and Cui (2006) compare random access protocols such as ALOHA with collision avoidance handshaking scheme such as MACA and present some mathematical analysis. Gibson et al. (2007) present one of the first analyses of contention-based protocols in a multi-hop string network.

Contention-based and contention-free protocols are both being used in many underwater networks today. The choice is driven by the exact constraints and requirements such as time synchronization, delay-tolerance, time criticality and reliability in messaging, ad-hoc network establishment, number of expected nodes, nature of traffic (continuous or bursty), sleep-wake schedules in sensors and mobility. In the future, more rigorous analytical results and accurate simulations are needed to further verify the many ideas put forward for underwater DLL and MAC.

DLL/MAC aspects such as energy conservation have also been looked into recently. PCLS as discussed earlier (Turgay and Erdal, 2006) incorporates a power control and sleep-wakeup scheme. Another example on energy minimization (Rodoplu and Min Kyoung, 2005) shows an ultra-low duty cycle MAC protocol focusing on energy conservation and not data rate.

The paper makes some over-simplifying assumptions that the propagation delay is constant and there is no clock drift. Nodes transmit sporadically and each transmission includes a preamble that specifies the next intended transmission. Listeners decide their wakeup times based on this preamble and sleep till packets are expected from transmitters. The objective is to minimize the fraction of energy wasted in collisions. For a transmit duty cycle of 0.4%, a 3% loss due to collisions is obtained. Assuming no loss due to bit errors, a physical layer data rate of 5 kbps only yields an effective data rate per node of $5 \times 0.4\% \times 97\% = 19.4$ bps. 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. Time asynchronous situations also work with AWSF except for a loss and change in neighborhood connectivity (Wong et al., 2006). In general, sleep and wakeup schemes focus on energy savings at the cost of bandwidth efficiency due to the usage of wakeup preamble signals and time delays required to switch modes. The improvements in energy efficiency are therefore at the expense of data rate. Such schemes are meant for long term underwater deployments that can cope with extremely low data rates and very long latencies.

One essential service choice offered by DLL to higher layers is reliability. In protocols such as MACA with packet trains, this involves ACKs and negative ACKs (NACK) that indicate received or lost data and retries for lost data. Packet size or train/group size adaptation is required to optimize performance. 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 Stojanovic (2005). An alternative 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 (Chitre and Motani, 2007). This allows a file transfer protocol to be designed where the individual packets do not have to be acknowledged and is suited for large file transfers. The sender can stop transmitting after it has decided that the probability that the receiver has not received enough packets is smaller than a preset threshold or the receiver can acknowledge complete delivery.

For optimal performance, the DLL needs to adapt packet size, batch size and timers based on measured link metrics. Reply timeout can be adapted for MACA RTS based on inter-node distance (Doukkali et al., 2006). Inter-node distances can be known through direct exchange of position information or through acoustic ranging techniques implemented in many modems. For optimal performance, the DLL could help adapt the FEC code rate at the physical layer.

H. Clustered and Cellular Topologies

Fully connected peer-to-peer topologies without the need for routing were commonly used earlier (Proakis et al., 2001), but such networks suffer from near-far power problems. A clustered network topology helps extend and scale the network and easily accommodates connectivity to other networks. One CDMA code per cluster and spatial re-use of codes is considered in Salva-Garau and Stojanovic (2003). 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 Casari et al. (2007). Within each cluster TDMA is used but it is not clear how the inter-cluster communications are handled. The protocol called FAMA-CF in Kebkal et al. (2005) uses MACA-like RRTS, RTS, CTS, DATA, ACK handshaking to communicate with the central node. The central node initiates the request for RTS (RRTS) to its peer nodes. Both analytical and experimental results are presented in the paper. Algorithms for cluster formation and dynamic changes are presented in Salva-Garau and Stojanovic (2003).

An underwater acoustic cellular network is an extension of the cluster topology and analysis of frequency re-use between adjacent clusters and optimal cell-radius selection criteria has been carried out recently (Stojanovic, 2007). A related work on channel allocation and scheduling protocol for cellular networks is presented in Peleato and Stojanovic (2007). An interesting example of a gateway node is the smart buoy where a surface raft that can maintain its position is equipped with global positioning system (GPS), surface radio and acoustic modems (Curcio et al., 2006).

I. Network Layer and Routing

A review of underwater network protocols until the year 2000 can be found in Sozer et al. (2000). Routing overheads for underwater networks should be kept as minimal as possible due to the extremely low data rates. In a typical clustered topology, the nodes communicate to a gateway node using a single hop while the gateway node handles all routing. In Xie and Gibson (2001), the authors present a similar topology assuming full-duplex modems. The gateway node manages route discovery through the use of probe messages to its neighbors. Route information is cached unless errors are reported in future relaying. In Foo et al. (2004) AODV-based routing together with MACAW is proposed. AODV is reactive and routing is initiated only when requested. The authors modify the standard AODV to use reverse link pointers by assuming bi-directionally symmetric links. Carlson et al. (2006) discuss location aware source routing for dynamic AUV networks, a modification from the DSR protocol originally designed for terrestrial networks. It uses TDMA and known TDMA frame timings to compute ranges based on propagation delay. Ranges are used to estimate local topology to determine routes. The authors suggest the use of a recursive state-estimation filter algorithm, but have not implemented it in their study.

Cross layer optimization of the routing algorithms with the DLL is required for optimal performance; much work remains to be done in this area. The Delay Tolerant Networking Research Group (http://www.dtnrg.org) has developed an architecture (known as DTN) that focuses on unreliable networks that uses store and forward techniques and future developments in underwater network layer can benefit from this. In Pompili et al. (2006), the authors propose routing algorithms for delay-sensitive and delay-tolerant networks. In the delay-tolerant case links are chosen based on energy minimization. In the delay-sensitive case, the algorithm is further constrained by avoiding retransmissions of corrupted packets at the DLL. Thus effectively implements cross-layer optimization by involving the DLL in the networking problem.

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 and gaining popularity since (Ahlswede et al., 2000). In a recent paper, network coding schemes for underwater networks are considered (Lucani et al., 2007). In a concatenated relay network, the authors compare via simulation two routing schemes based on end-to-end acknowledgements, two based on link-by-link acknowledgements and two based on network coding. At high loads, the transmission delays in network-coded schemes were much better than in the other schemes. At low loads, the transmission delays in all schemes were similar; however, the network-coded schemes had lower power consumption as compared to the other schemes. Network coding with implicit acknowledgements has the lowest power consumption per node while providing low transmission delays. The use of network coding in underwater networks is being explored only recently and remains a promising open research area.

J. AUV Networking

As a result of the increasing applications of AUVs, networking of mobile assets is currently a very active area of research. The mobility and ad-hoc requirements for such networks pose many challenges. Stojanovic et al. (2002) 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 Molins and Stojanovic (2006).

AUVs are sometimes equipped with multiple modems or a single modem with multiple frequency band transducers (Freitag et al., 2005). The effective use of multiple modems optimized for different ranges in an AUV network using random access protocols is explored in Shahabudeen et al. (2007). As AUVs move around during a collaborative mission, the inter-node separations may vary from few tens of meters to several kilometers and different modems are used at different ranges based on exchanged position information. Such multi-channel or multi-modem nodes will also be needed in clustered or cellular topologies (to act as gateway nodes) and this is an exciting area for future research. Efficient multi-hop and ad-hoc packet routing protocols for AUV networks also are in their infancy and a potential research area for the future (Jiejun et al., 2005).

K. Simulation Studies

Simulations using appropriate software have been norm in underwater network research even more so than in terrestrial networks, because of the difficulty and cost in setting up sea trials and lack of direct access to the physical layers of commercial modems. Simulations provide a quick assessment of performance for new and modified protocols before an actual implementation. Mathematical analysis often offers limited and very loose bounds on complex network performance measures. The network simulator needs a base software platform, an appropriate channel simulator and a physical layer simulator.

Base software platforms include commercial network software such as Opnet used in Xie et al. (2006), open-source network software such as NS2 used in Harris and Zorzi (2007), discrete event simulation packages such as Omnet++ used in Shahabudeen et al. (2007), or custom simulation software written in languages such as C++ (Carlson et al., 2004). The simulated channel needs to account for propagation delay and path loss. Spherical spreading model provides a first level approximation. More complicated models could be implemented depending on the accuracy needed (Raysin et al., 1999; Chitre, 2007). Computationally efficient physics-based underwater channel models have been developed (Xie et al., 2006). The physical layer is typically assumed to be a half duplex system as it is usually the case in many commercial acoustic modems. A simple physical layer model that computes BER and packet loss using received SNR can be used. Direct BER against range curves could be used if empirical data for a channel is available. Packets may also be lost due to collisions. AUV networking studies requires motion modeling (Carlson et al., 2004).

Some authors explicitly state the limitations of the simulators they used (Carlson and Beaujean et al., 2004) but often none are reported. The accuracy of simulations has to be addressed in the future. It is important to move towards standardized open-source simulation frameworks in the underwater network research community.

L. Standardization

The underwater networking research community can benefit hugely from standardization. Standardized protocols for gateway access from external networks and routing would allow applications to access underwater nodes easily. As a first step towards this goal, the common control language (CCL) specifications for AUV networks outline a TCP/IP based protocol for access to a CCL gateway (Stokey et al., 2005). Landline and GSM modems typically use the "AT" command set to allow applications to communicate with them. The WHOI micro-modem supports a NMEA 0183 protocol (Freitag et al., 2005). Most other commercial modems today provide support only for proprietary protocols. Standardization on communications to acoustic modems would enable applications to be easily integrated with various modems.

Modems' internal stacks can be developed adhering to standardized inter-layer interfaces that allows interoperability and portability of stack software from different researchers. These can be used in real implementations as well as simulation studies. The inter-layer interfaces may expose optional settings such as FEC code-rates, power control, etc to enable interoperable cross-layer optimization. Modem vendors may choose to expose some of these application programming interfaces (APIs) to the user to enable them to access lower layer functionality directly. Some initiatives towards this goal have started. In one initiative an underwater network architecture (UNA) for modem network layers was proposed to standardize inter-layer messages (Chitre et al., 2006). Figure 4 shows the recommended interfaces for each layer, with request, response and notification messages between layers. The UNA specifications include an optional framework application programming interface (FAPI) to eliminate direct coupling between layers though the use of a messaging framework, to abstract hardware and operating system functionality and to help make layers easily portable. The CCL specifications also propose an application layer protocol for AUV networks (Stokey et al., 2005).

The use of standardized open-source simulation frameworks in the underwater network research community will help provide results that can easily be reproduced by others. Simulations from various research groups can run on common simulation platforms, if the simulation frameworks are written conforming to standard layer interfaces. This will also enable the use of the software used in simulation to be plugged in directly to the actual modem hardware that uses the same standard interfaces.

An important aspect of standardization is the physical layer implementation to enable greater interoperability between modems made by different vendors. The standards should allow for the existence of different technology families such as CDMA, OFDM, PSK, etc, with the option of using control information to convey which modulation scheme is being used. The physical layer of the WHOI micro-modem was published as a standard (Freitag and Singh, 2000) and a commercial modem maker Benthos implemented compatible modems (Freitag et al., 2005). A related body of work on software radio, a structured and modular concept for modem implementation, has been proposed for use in underwater modems (Jones, 2007). In software radio, the bulk of the signal processing happens in software on DSPs and FPGAs. A software communications architecture (SCA) initiated by U.S. Department of Defense allows defining software components descriptors in extensible markup language (XML). The components are mapped on to hardware through device package and device configuration descriptor files.

Standardization in underwater networking is still very much in its infancy. A summary of interfaces and protocols that could be standardized is shown in Figure 5. Lack of technology is not the bottleneck for standardization, as most of the architectural components have proprietary implementations in many projects around the world. Setting up an underwater network will be just as easy as setting up a terrestrial WiFi network once standardization takes place and users have choice of alternative components from different vendors.

FIGURE 4

UNA layer interfaces

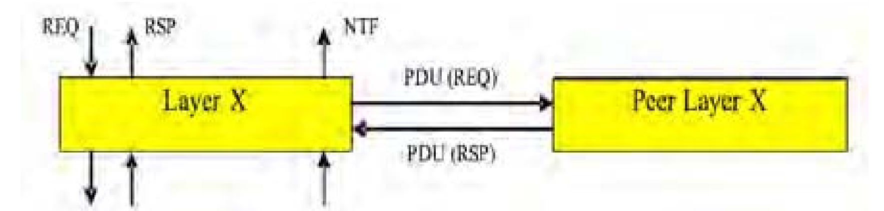
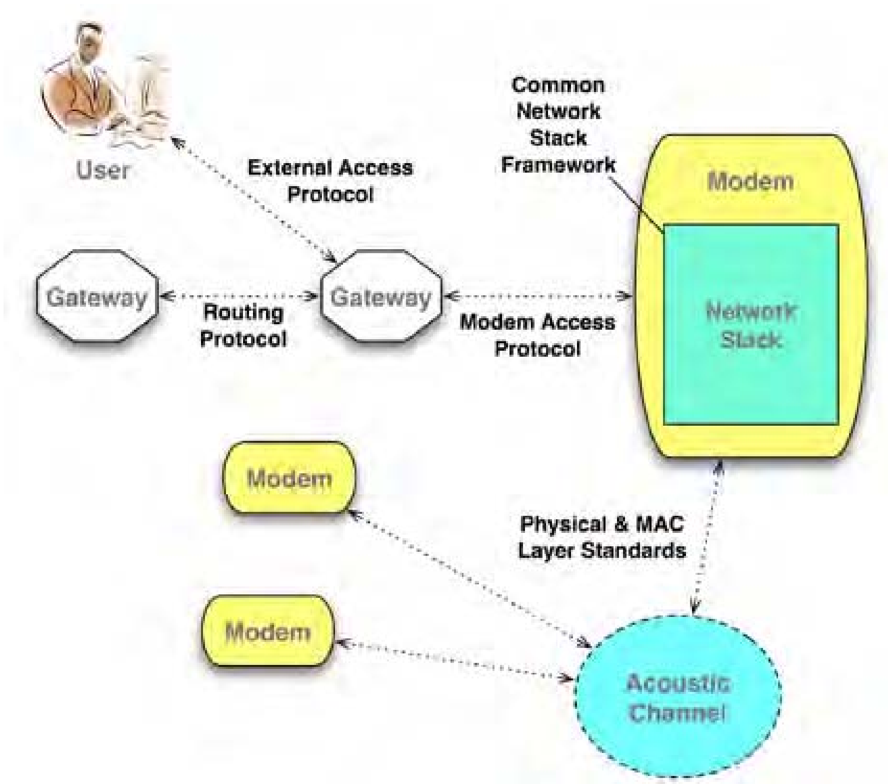


FIGURE 5

Target interfaces for standardization



M. Summary

MACA-based contention protocols and TDMA or CDMA-based contention-free protocols can be used in a UW-LAN depending on the exact requirements and constraints. Multi-modem adaptive MAC protocols for AUV networks have been proposed to provide a unified interface to higher layers. AODV and DSR-based lightweight routing protocols have been proposed for underwater use. Efficient routing for ad-hoc mobile underwater networks still remains an open research challenge. Standardization for underwater networking is required to provide interoperability and ease of operation and help accelerate the research in the field.

List of Abbreviations

API	Application programming interface
AUV	Autonomous underwater vehicle
AWSF	Adaptive wakeup schedule function
BER	Bit error rate
BP	Belief propagation
CCL	Common control language
CHF	Chip hypothesis feedback
CTS	Clear to send
DACAP	Distance aware-collision avoidance protocol
DFE	Decision feedback equalizers
DLL	Data link layer
DS-CDMA	Direct sequence code division multiple access
DSSS	Direct sequence spread spectrum
DTN	Delay tolerant network
FAMA	Floor acquisition multiple access
FAMA-CF	Floor acquisition multiple access (collision free)
FAPI	Framework application programming interface
FDMA	Frequency division multiple access
FEC	Forward error correction
FFT	Fast Fourier transform
GPS	Global positioning system
GSM	Global system for mobile communications
ISI	Inter-symbol interference
LDPC	Low-density parity check
LFM	Linear frequency modulated
LLR	Log-likelihood ratio
LPD	Low probability of detection
LPI	Low probability of intercept
LSTC	Layered space-time codes
MAC	Media access control
MACA	Medium access collision avoidance
MAP	Maximum a posteriori probability
MIMO	Multiple input multiple output
MLSD	Maximum likelihood sequence detection
MLSE	Maximum likelihood sequence estimation
MMSE	Minimum mean square error
MSE	Mean square error
OFDM	Orthogonal frequency division multiplexing
PCM	Phase-locked loop
PPC	Passive phase conjugation
PPM	Pulse position modulation
PSK	Phase shift keying
PSP	Per-survivor processing
RLS	Recursive least square
RTS	Request to send
SCA	Software communications architecture
SDF	Symbol decisions feedback
SDMA	Space division multiple access
SISO	Single-input single-output
SNR	Signal-to-noise ratio
sPRE	Sparse partial response equalizers
SSTC	Space-time trellis codes
TCM	Trellis-coded modulation
TCP/IP	Transmission control protocol/Internet protocol
TDMA	Time division multiple access
TRM	Time reversal mirror
UNA	Underwater network architecture
UW-LAN	Underwater local area network
XML	Extensible markup language
ZP	Zero prefix

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