

Underwater Acoustic Communication Modems: Recent Trends in Technology

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Underwater communication is critical for various applications e.g. oceanographic research, underwater biological monitoring, military operations, seismic survey and offshore oil and gas exploration. Over the past few years, there have been significant advancements in underwater communication modems, enhancing their reliability, range, data rate, and adaptability to the challenging underwater environments. This article provides a technical overview of these recent developments and serves as a valuable reference for researchers in the field. The paper is focused on previous research and surveys in the field of designing underwater modems according to modulation techniques and signal processing methods. It reviews the state-of-the-art underwater acoustic (UWA) communication modems into two categories, namely Software-defined UWA modems and Digital-signal-processor-based UWA modems. The advanced networking techniques associated with underwater modems are being implemented for high-end applications. Underwater signal transmission is integrated by machine learning with highly developed signal-processing techniques nowadays. The study discusses various modem designs, including those for a small autonomous unmanned vehicle (AUV), hybrid optical-acoustic modem, a reconfigurable/flexible UWA modem, and a real-time UWA modem. Additionally, the challenges faced by the researchers from academia as well as from industry in designing the UWA communication modem are also highlighted.

Keywords: Software-defined UWA modem, Digital-signal-processor-based UWA modem, Machine learning, Hybrid optical-acoustic modem, Reconfigurable/flexible UWA modem

1 Introduction

The undersea flora and fauna, since their inception, have demonstrated the ability to detect sound waves in rivers and seas, providing evidence that sound waves can travel underwater. The study of underwater acoustics can be traced back to 1490 when Leonardo da Vinci noted that placing the head of a long tube in water and listening at the outer end would allow one to hear distant ships. This was likely the first recorded recognition that sounds propagate underwater, though cetaceans (marine mammals) have been doing it successfully for many years. Since then, research in underwater communication has significantly advanced through the application of science and technology. The Titanic disaster marked a pivotal moment, spurring serious efforts to develop communication techniques even at the ocean's depths.

World War I and then World War II accelerated investments in underwater communication technologies, primarily for security purposes. Underwater researchers, scientists, and engineers have been rigorously investigating the ways to implement modern technology to underwater applications.

A theory of classification, design issues, capabilities, taxonomy, and future trends in modem design have been presented¹⁻⁵. The propagation models for underwater acoustic (UWA) communication channels have been demonstrated in the article⁶. Researchers have presented classification, and design challenges and also proposed cost-effective and energy-efficient techniques for modem design^{1,7}. The different parameters of acoustic, optical, and electromagnetic modems have been compared⁸⁻¹⁰. However, to put the recent works together it is important to explore and analyse. The literature on UWA communication reveals a wide range of approaches aimed at achieving high speed and high data rates. Previous research has also demonstrated the possibilities of creating new ways to advance the UWA communication system. To provide a comprehensive understanding of recent advancements, this article synthesizes and analyses current research, categorizing modern technology into software-defined modems and digital-signal-processor-based modems.

2 Key Technologies in UWA Modems

Underwater communication modems primarily utilize acoustic, optical, and electromagnetic (EM) waves to transmit data¹⁰. Table 1 compares different

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Table 1 — Comparison of acoustic, optical and EM modems on the basis of physical parameters

Type of Modem	Communicating signal	Signal Speed (ms ⁻¹)	Cost	Bandwidth	Data Rate	Range (m)
Acoustic Modem	Sound signal	1500	Low	1kHz-100kHz	kbps	Medium-to-long range
Optical Modem	Optical signal	2.3x10 ⁸	High	150MHz	Gbps	Short range (10-150)
Electromagnetic Modem	Radio frequency signal	2.3x10 ⁸	High	MHz	Mbps	Very short (≤ 10)

modems and the communicating signals. Each technology has its working principle, advantages, and challenges.

2.1 Acoustic Modems

An acoustic modem facilitates underwater data transmission in a manner analogous to how telephone modems transmit data over phone lines. Adaptation from digital data into special underwater sound signals is done by acoustic modems⁵⁻⁷. These signals are then received by a second acoustic modem and converted back into digital data. Acoustic waves are the most widely used medium for underwater communication due to their ability to travel long distances through water. Recent improvements include higher data rates, better signal processing algorithms, adaptive modulation schemes, and more robust error correction techniques. Acoustic communication is limited by issues such as low bandwidth, multipath propagation, and high latency. The modulation techniques and networking protocols perform indispensably.

2.1.1 Adaptive Modulation and Coding

Adaptive modulation and coding schemes allow modems to dynamically adjust their transmission parameters based on the current underwater channel conditions¹¹⁻¹³. This enhances the robustness and efficiency of acoustic communication, enabling higher data rates and more reliable connections in varying underwater environments. An adaptive modulation based on reinforced learning provides better network throughput. The channel state information (CSI) is predicted using a long short-term memory (LSTM) neural network with the ϵ -greedy algorithm and the Dyna-Q algorithm¹⁴⁻¹⁶. Deep Q-network (DQN) based amplitude-modulated UWA communication system processes channel previous information and accordingly maps state-action pairs and records¹⁷. In a dynamic UWA environment, reinforced learning selects the modulation and coding policy for reduction in bit error rate (BER) and energy consumption¹⁸. Recently, an online learning algorithm “Multi-Armed Bandit (MAB) algorithm” has

contributed to Adaptive Modulation in Underwater acouStic nEtworks (AMUSE)¹⁹⁻²⁰. The action-value function in a MAB problem determines the average reward of each action. It concentrates on exploitation and selects the highest estimated reward action. To achieve optimum results, the researchers have adopted both adaptive and predictive techniques so that data retransmission can be avoided²¹. These advancements highlight the growing importance of adaptive modulation in addressing underwater communication challenges, ensuring efficient and robust data exchange.

2.1.2 Multi-Carrier Modulation

Multi-Carrier Modulation technique i.e. Orthogonal Frequency Division Multiplexing (OFDM) has been adopted to improve the data throughput and resilience of acoustic modems²²⁻²⁹. OFDM allows for better handling of multipath propagation and frequency-selective fading, the two common issues in underwater channels.

2.1.3 Networking Protocols

Development of sophisticated networking protocols such as Underwater Wireless Sensor Networks (UWSNs) and Delay Tolerant Networks (DTNs) have improved the scalability and reliability of underwater communication systems^{1,2}. These protocols facilitate efficient data routing and error handling in complex underwater environments. Various aspects of network design such as i) optimal node placement, routing and scheduling in UWA network, ii) topology control by means of low-power wakeup modes, and iii) optimal hop distance over a multihop path have been thought of to handle protocol design issues in UWA networks³⁰.

2.2 Optical Modems

Optical communication utilizes light waves for high-speed data transmission over short distances. Recent innovations include the development of blue and green lasers, which have better water penetration, and the integration of advanced modulation techniques to improve data rates and reliability^{3,9}. Optical modems are limited by water clarity and

require line-of-sight between the transmitter and receiver. A new concept has been introduced, where a low-power system for underwater data collection using sensors on individuals or robots has been proposed. Data is transmitted via an LED, received by a photodiode, and demodulated for real-time monitoring on a computer. It supports applications like biometric monitoring and aquatic environmental data collection³¹.

2.3 Electromagnetic (EM) Modems

Permeability (μ), ionic conductivity (σ) and permittivity (ϵ) of seawater vary as the salinity and temperature of seawater have diverse variations with respect to depth. Viscosity and density of seawater also have variation based on the ocean depth. All these factors adversely affect underwater electromagnetic wave propagation. EM waves can be used for very short-range communication due to their rapid attenuation in water. Improvements in antenna design and signal processing have enhanced the performance of EM modems for niche applications requiring high data rates over short distances. EM communication is typically restricted to very short ranges and high energy consumption⁸.

An enhanced underwater communication system that uses electromagnetic waves for long-range transmission with digital data compression to reduce bit rate has been proposed. A modulator encodes the compressed data onto a carrier signal, which is transmitted via an electrically insulated, magnetically coupled antenna³².

3 System Description

The UWA modem converts digital data into underwater sound signals, as opposed to optical

signals, which are heavily absorbed and scattered by water, limiting their use for underwater communication. The underwater acoustic communication as shown in Fig. 1 is established among the autonomous unmanned vehicles (AUV), divers, remotely operated vehicles (ROV), tethered projectors, and hydrophones (access point transducers).

Data transmission using a single transmitter-receiver pair in a typical underwater environment i.e. point-to-point communication link with two UW modems namely Projector and Hydrophone²³ are shown in Fig. 2. The three main factors affecting underwater acoustics are temperature, salinity, and depth (or pressure). These factors influence the density of seawater, which in turn affects the speed of sound. In comparison with acoustic propagation, optical and EM waves are not helpful in the harshness of underwater environments when applied in distances of the order of several kilometres. Typically, the UWA modem design combines hardware

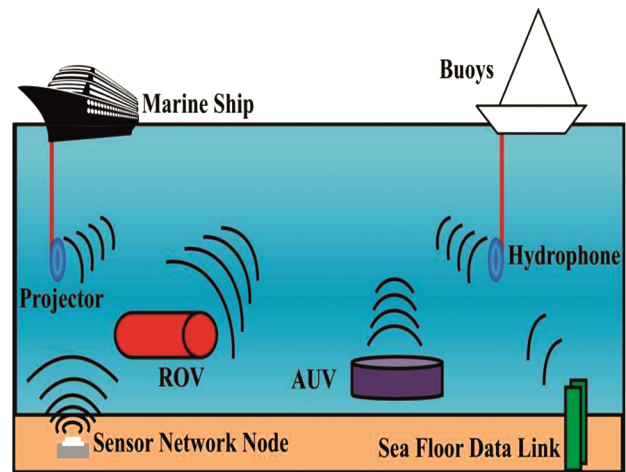


Fig. 1 — Schematic diagram of underwater communication through sound waves

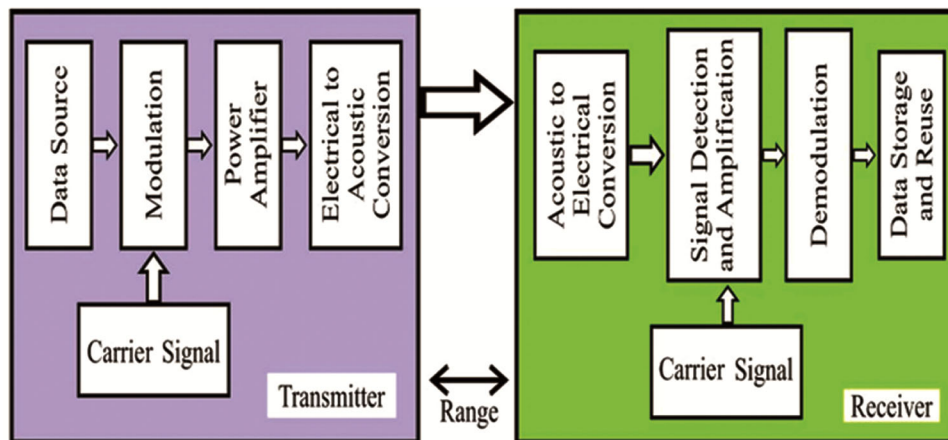


Fig. 2 — Block Diagram of Projector and Hydrophone of an acoustic modem

platforms, e.g., microprocessor/microcontroller unit (MCU), digital signal processor (DSP), field programmable gate array (FPGA), etc. It is imperative to utilize the spectrum resources efficiently with significant features of acoustic modems and UW channels. For more efficient transmission of information between UW acoustic equipment, a flexible and configurable UWA modem is required. The performance of proposed UWA modems is judged based on metrics like the range of communication, data transfer rate, modulation technique used, frequency spectrum, power requirement, and outage probability³³. Operating temperature, working depth, and weight are some exclusive parameters for designing commercial modems, while hardware platforms are mostly considered major parameters for designing research modems.

Absorption loss and multipath propagation adversely affect acoustic wave propagation³⁴⁻³⁵. Figure 3 shows the empirical models for different frequency ranges³⁴. In addition to the direct path, the signal propagates via reflections from the surface and bottom. Multipath gets attenuated because of repeated reflection loss and increased path length. In shallow seas, as shown in Fig. 4 the sound speed does not change significantly. In deep water, a multipath

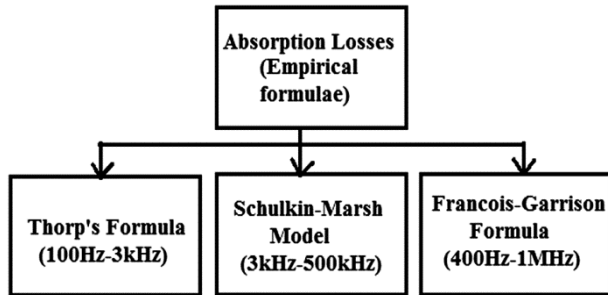


Fig. 3 — Empirical formulae for reducing absorption loss

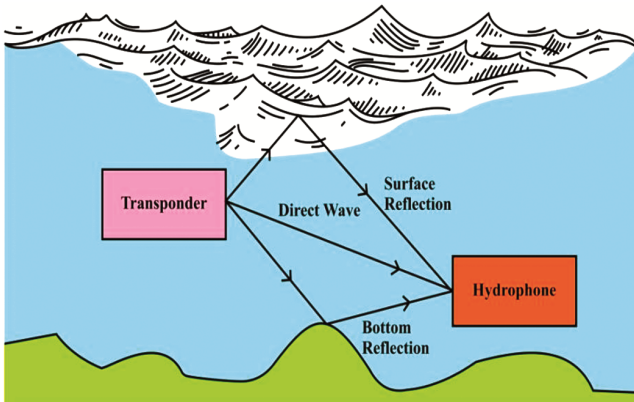


Fig. 4 — Shallow water multipath propagation

propagation ray launched at some angle bends towards the region of lower sound speed. In deep water communication we find application of Snell's law. There is no loss due to reflections.

There are a few most distinguishing factors of acoustic channels to be considered in the modem design³⁶:

i. Attenuation and Noise

The overall path loss is

$$A(l, f) = (l/l_r)^k a(f)^{l-l_r} \dots (1)$$

where $f =$ signal frequency,

$l =$ transmission distance taken

in reference to some l_r ,

$k =$ path loss constant which models the spreading loss

$a(f) =$ absorption coefficient

For frequencies up to about 50kHz, the overall path loss is

$$10 \log a(f) \approx \alpha_0 + \alpha_1 f + \alpha_2 f^2 \dots (2)$$

ii. Signal-to-Noise Ratio (SNR) in a Narrowband

$$SNR(l, f) = S_l(f)/A(l, f)N(f) \dots (3)$$

where $S_l(f) =$ Power spectral Density of the transmitted signal whose power may be adjusted according to the distance, $N(f) =$ Noise Power spectral Density

iii. Multipath Propagation

The overall channel response in the frequency domain:

$$H(f) = \sum_p H_p(f) e^{-j2\pi f \tau_p} \dots (4)$$

where $H_p(f) =$ frequency response of p-th path,

$\tau_p =$ relative path loss $= \frac{l_p}{c} - t_0$

$l_p =$ length of the p-th propagation

$\frac{l_p}{c} =$ path delays

and the corresponding impulse response:

$$h(t) = \sum_p h_p(t - \tau_p) \dots (5)$$

$$h(t) = \text{inverse Fourier transform of } H_p(f)$$

3 Received Signal Power

For a directional transmission (direct propagation path from transmitter to receiver), if a signal is

transmitted with a power P_{tx} , then the received signal power is

$$P_{rx} = \frac{P_{tx}}{A(l,d,t,f)} \quad \dots (6)$$

where $A(l, d, t, f)$ = Attenuation in dB that occurs over a transmission range l for a signal frequency f obtained from the Fisher and Simmons model.

t = ambient temperature in °C

The transmitted signal $s(t)$ is expressed as

$$s(t) = Re\{u(t)e^{j2\pi f_c t}\} \quad \dots (7)$$

The received signal $r(t)$ is expressed as

$$r(t) = Re\{v(t)e^{j2\pi f_c t}\}, \quad \dots (8)$$

where baseband signal $u(t)$ is modulated onto carrier frequency f_c .

4 Modem Design Considerations

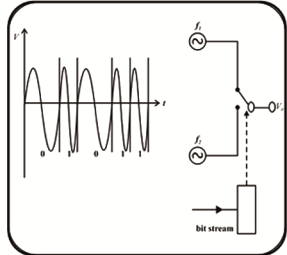
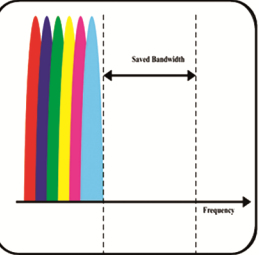
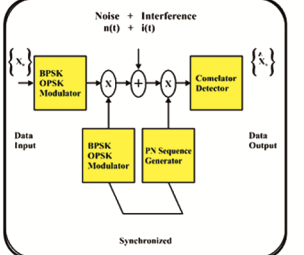
The UWA modem is designed based on the following considerations: i) Modulation scheme, ii) Underwater transducer, iii) Corresponding analog electronics, iv) Sensors interfacing with higher level networking devices, and v) Suitable hardware platform.

4.1 Modulation Scheme

Amplitude Shift Keying (ASK) and Frequency Shift Keying (FSK) modulation methods were used in

early UWA modems. ASK performs well in vertical transmission for low reverberation and straight path. FSK is suitable in shallow water with rapid phase variation in long and medium range channels. Phase Shift Keying (PSK) is also used for better SNR. Binary Phase Shift Keying (BPSK) modulation and demodulation are integrated in high frequency UWA modem design followed by carrier recovery and detection using low pass filter. These modulation schemes are compared in Table 2. Error correction schemes are implemented in noisy channels which decrease data rates. OFDM has been applied in most of the modem designs in the last few decades. In the frequency domain, OFDM performs channel equalisation, frequency synchronization and time-base (Doppler) correction³⁷. A new time-domain channel estimation (CE) technique for OFDM-based UWA communication with Rician fading is used to exploit the channel sparsity and offers significant performance enhancement³⁸. Two System-on-chip (SoC) based OFDM devices via advanced extensible interface (AXI) successfully transmit and decode data³⁹. In multipath propagation, Direct Sequence Spread Spectrum (DSSS) based Code Division Multiple Access (CDMA) reduces Signal-to-noise ratio (SNR) with decreased data rate. Sea experiments using an adaptive acoustic modem show that DSSS modulation constantly outperforms FSK¹².

Table 2 — Modulation schemes used in UWA modems

		
<p>Shift Keying methods</p> <ul style="list-style-type: none"> ➤ ASK ➤ FSK- Low power, Low Data rate, low cost ➤ PSK- Better SNR ➤ BPSK ➤ Multiple Frequency Shift Keying (MFSK) ➤ Offset Quadrature PSK (OQPSK) 	<p>OFDM</p> <ul style="list-style-type: none"> ➤ Resistance to Multipath fading ➤ Higher data rate ➤ High bandwidth efficiency <p>MIMO-OFDM</p> <ul style="list-style-type: none"> ➤ Increased opto-acoustic modem performance ➤ Quadrature Amplitude Modulation (QAM) 	<p>FHSS</p> <ul style="list-style-type: none"> ➤ Robust transmission path <p>DSSS</p> <ul style="list-style-type: none"> ➤ Lower SNR ➤ Decreased data rate ➤ Larger bandwidth ➤ Increased speed of transmission ➤ Error-resistant modulation scheme

4.2 Underwater Transducer

Acoustic waves follow cylindrical wave propagation into a homogeneous water medium. Seawater diverse properties impose challenges even in acoustic wave propagation. Electromagnetic acoustic transducers, acousto-optic devices and piezoelectric acoustic transducers are readily used in UWA communications⁴⁰. Piezoelectric acoustic transducers play a vital role in surveillance and other specialized marine purposes. Sound navigation and ranging (SoNaR, generally written as Sonar) technique has been used in both active and passive modes for many decades for navigating underwater

and to map things in the ocean. The naturally occurring Sound Fixing and Ranging (SOFAR) channel carries sound to great distances. Low propagation speed and small frequency band of UWA waves are main challenges to be diminished. A large number of UWA sensors with different frequency values/ranges⁴¹ are listed in Table 3. With advances in sensing, underwater stations now use cutting-edge technologies like underwater vision and synthetic aperture sonar (SAS), generating vast data for remote supervision. Real-time video enables remote intervention, but data rates exceed commercial acoustic modem capacity, making high-bandwidth

Table 3 — UWA sensors ordered by frequency and detection range⁴¹

Acoustic sensor	Manufacturer	Frequency (kHz)	Range (m)
Single-Beam Echo-Sounder (SBES)			Target Detection Range (m)
1.1. ^F EK60	SIMRAD	18-20	270-1170
1.2 EA600	KONGSBERG	12-200	280-850
1.3 Ping	BlueRobotics	115	-
1.4 ^{SW} EA MCU	KONGSBERG	15-200	-
Multi-Beam Echo-Sounder (MBES)			Maximum Range (m)
2.1. WBMS	NORBIT	200-700	160
2.2. Sonic 2026	R2SONIC	100/200/450	800
2.3. Sonic 2024	R2SONIC	200/450/700	400
2.4. Sonic 2020	R2SONIC	200/400/700	200
2.5. EM304	KONGSBERG	26-36	8000
2.6. EM712	KONGSBERG	40-100	3600
2.7. EM712S	KONGSBERG	40-100	1800
2.8. EM2040-04 MKII	KONGSBERG	200/300/400	635/480/315
2.9. Seabat T50-S	TELEDYNE MARINE	200/400	400/225
2.10. Seabat T20-S	TELEDYNE MARINE	200/400	400/225
Side-Scan Sonar (SSS)			Max swath width (m)
3.1. Shark-S900U	Icocean	900	75
3.2. S-150D	SonarTech	100/400/900/1250	-
3.3. ARC Scout MKII	Marine Sonic Technology	150-1800	500-25
3.4. Geoswath Plus	KONGSBERG	125/250/500	200/100/50
3.5. UUV-3500	KLEIN	75/100/400	1500/750/200
3.6. Solstice	Sonardyne	725-775	-
3.7. 2205	EdgeTech	75-1600	1000-35
3.8. SYSTEM 5900	KLEIN	600	150
Synthetic Aperture Sonar (SAS)			Max Range per side (m)
4.1. AquaPix INSAS	KRAKEN	337	220
4.2. ProSAS-60	SL Hydrospheric	60	1200
4.3. HISAS 1030	KONGSBERG	60-120	260
Sub-Bottom Profiler (SBP)			Range (m)
5.1. SES-2000 Standard	Innomar	100/4-15	500
5.2. SES-2000 AUV	Innomar	115/4-15	400
5.3. Topas PS-18	KONGSBERG	15-21/0.5-6	11000
5.4. Topas PS-120	KONGSBERG	70-100/2-30	400
5.5. Topas PS-40	KONGSBERG	35-45/1-10	2000
5.6. K-Chirp 3310	KLEIN	5	-
5.7. SeaKing	Tritech	20/200	-
5.8. 2205	EdgeTech	4-24/2-16/1-10	-

(Contd.)

Table 3 — UWA sensors ordered by frequency and detection range⁴¹ — (Contd.)

Acoustic sensor	Manufacturer	Frequency (kHz)	Range (m)
Obstacle Avoidance Sonar (OAS)			Range (m)
6.1. Dolphin 6201	MARINE ELECTRONICS	250	200
6.2. SA9520	KONGSBERG	70-100	1000
6.3. NOAS	Sonardyne	70	1500
6.4. Seabat F50	TELEDYNE MARINE	200-400	300-600
6.5. WBMS-FLS	NORBIT	400	250
6.6. MRS 900	EcoLogger	900	60
6.7. Gemini 720is	Tritech	720	120
Diver Detection Sonar (DDS)			Detection range radius (m)
7.1. Sentinel	Sonardyne	70	900
7.2. Aquashield	DSIT	60	700/1000
7.3. Cerberus Mod2	ATLAS ELEKTRONIC	70-130	700/900
7.4. Echorium	Koc	70	800
Variable Depth Sonar (VDS)			Detection Range (m)
ST2400	KONGSBERG	22-29	6000@22kHz
CAPTAS-4	THALES	<2	Up to second oceanic coverage zone
Towed Array Sonar (TAS)			Acoustic aperture (m)
Passive sensor			
TAS	ATLAS ELECTRONIC	50-10,000	-
Krait Array	sea	10-20,000	150
Hull Mounted Sonar (HMS)			Range (m)
Passive/Active Sonar			
ASO 713/723	ATLAS ELECTRONIC	6-9	-
SS2030	KONGSBERG	20-30	16000
BLACKFISH	DSIT	5-11	-
Hydrophones			Operating depth (m)
Passive sensors			
AQ-17	TELEDYNE MARINE	5-10	1732
AQ-18	TELEDYNE MARINE	7-10	1732
AQ-25 Broadband	TELEDYNE MARINE	2-90,000	1500
TAH-1	TELEDYNE MARINE	1-40,000	1000
T-5B	TELEDYNE MARINE	1-5,000	300
Dipping Sonar			Range (m)
SD9500	KONGSBERG	70-110	5000
AN/AQS	L3HARRIS	9.23/10/10.77	18288
Acoustic Doppler Current Profiler			Maximum Range (m)
TELEDYNE MARINE			
Ocean Surveyor	TELEDYNE MARINE	38/75/150	1000/700/400
Workhorse Quartermaster	TELEDYNE MARINE	150	210-270
Pinnacle	TELEDYNE MARINE	45	450/550
Workhorse Monitor	TELEDYNE MARINE	300/600/1200	110/50/12
NORTEK			
Signature 1000	NORTEK	1MHz	30
Signature 250	NORTEK	250	200
Signature 55	NORTEK	55/75	1000/600
Son Teck			
ADP	Son Teck	1500/1000/500/250	25/35/120/180
ROWE			
Sea PROFILER	ROWE	300/600/1200	150/75/30
Sea SEVEN	ROWE	300/600/1200	150/75/30
Sea WATCH	ROWE	300/600/1200	150/75/30
Alimeter			Maximum Range (m)
ISA500	Impact Subsea	500	120
PA200	Tritech	200	100
PA500	Tritech	500	50
VA500	VALEPORT	500	100
1007D	KONGSBERG	120/200/675	600/600/125

solutions essential, especially for demanding technologies like SAS⁴².

4.3 Corresponding Analog Electronics

Pre-amplifier, power amplifier and transmit/receive switch are basic components which transmit/receive electrical signals and produce a suitable power level. Analog processing modules work on analog signals to execute amplification and bandwidth limitation of received signals. On the other hand, digital processing modules implement a physical layer in the UWA communication system. Digital processing modules may consist of a fixed point processor or floating type processor or combination of both⁴³. Microphone, transducer, speaker, headphone, transmit/reception key, telegraph key, recorder/ generator, monitor, keyboard are the external supporting devices to accomplish the complete setup.

4.4 Sensors Interfacing with Higher Level Networking Devices

Many technologies are used in submarines and underwater vehicles for UWA communication. A wireless sensor node interfaces between the physical underwater parameters and in the wireless sensor network⁴⁴. Underwater non-stationary multipath environments limit the performance of traditional equalizers and Phase Locked Loop (PLL) based methods. In UWA communication, prefix based channel estimation may be approached for extracting the entire packet even in Doppler and multipath environments⁴⁵.

4.5 Suitable Hardware Platform

Application-specific integrated circuit (ASIC), microcontroller, digital signal processor (DSP), Field Programmable Gate Array (FPGA) and general purpose processor (GPP) are suitably used as hardware platforms. ActUP V2.2L, an UWA propagation modelling software is used to get steadiness in a menu-driven user interface where

numerous UWA propagation codes are used. Software based modem using FPGA acoustic design is preferable to reduce hardware cost. A Reconfigurable FPGA platform is a better choice for a robust communication system. FPGA is implemented in FSK demodulator with two different schemes: 1) conventional matched-filter coherent detection and 2) CORDIC non-coherent zero-crossing detection. Better bit error rate is achieved in coherent schemes as compared to non-coherent schemes⁴⁶.

5 UWA Communication Codes and Algorithms

5.1 Error Control Coding (ECC)

Coding techniques significantly improve the performance of digital communication systems. A block diagram for ECC is shown in Fig. 5. Barker codes in the receiver are useful in UWA networks for slower data rates i.e. 0-100kbps⁴⁷. Error control codes combat the transmission and storage errors and the digital information is protected by a signal processing scheme known as error control coding⁴⁸. Parity checking is the simplest form of ECC. Linear block code corrects one error and detects multiples of errors. Cyclic codes are the main linear block codes. The two subclasses of ECC are block codes and convolution codes. Random error correcting codes, burst- error correcting codes, bit-oriented codes and word-oriented codes lie in the different categories of ECC. Reed-Soloman (R-S) codes are used for correcting burst errors. To ensure errorless communication in adverse channels, an efficient error resistant modulation scheme should be acquainted with optimum error control coding scheme⁴⁹.

An efficient linear block code named as Polar code has been applied in OFDM UWA communication system⁵⁰. Turbo codes are also implemented in UWA modem design. Trellis coding and higher level signal constellation are being considered for use in the UWA communication system⁵¹.

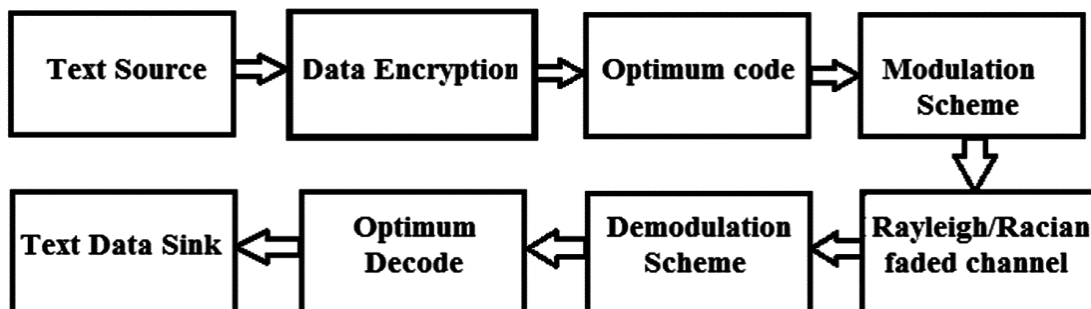


Fig. 5 — Optimum Error Control Coding scheme in UWA modem

5.2 Support Vector Machine (SVM) Algorithm

Adaptive modulation systems use SVM algorithms for classification (pattern recognition) tasks. The algorithm is based on Statistical learning theory. SVM evolved from sound theory. If $y = f(x)$ is some indefinite and non-linear dependency (mapping, function). x is a high-dimensional input vector and y is scalar or vector (in case of multiclass SVMs) output. The only available training data set $D = \{(x_i, y_i) \in X \times Y\}$, $i = 1, l$. The number of training data set pairs l equals to the size of the training data set D . y_i is also denoted as d_i , desired (target) value. SVM is a supervised learning technique. The basic risk functional applied in SVM statistical model¹³ is

$$R = \underbrace{\sum_{i=1}^l L\mathcal{E}}_{\text{closeness of data}} + \underbrace{\Omega(l, h)}_{\text{capacity of a machine}}, \quad \dots (9)$$

where $L\mathcal{E}$ denotes the loss function of SVMs' SVM algorithm develops fitting function for support vector regression algorithm. Ω function bounds the learning machine capacity and h is a VC dimension introduced by Vapnik and Chervonenkis.

5.3 Support Vector Regression (SVR) Algorithm

Adaptive modulation systems use the SVR algorithm for regression (function approximation) tasks. Statistical learning theory based SVR algorithm has been used in non-linear system modelling⁵². Underwater vehicles implement SVR based integrated navigation methods⁵³. SVR is a straightforward method in which pattern recognition is applied for high-dimensions. The non-linear regression problems are usually dealt with by the SVR method through a kernel function where a low-dimensional sample space is mapped to high-dimensional feature space⁵⁴. Let a sample set is taken as $\{(x_1, y_1), \dots, (x_m, y_m)\}$ with a capacity of m , where $x_i \in \mathbb{R}^n$ is n -dimension input space and output space is denoted as $y_i \in \mathbb{R}$. The SVR fitting function for nonlinear problems can be written as

$$g(x) = \omega^T \cdot \phi(x) + b, \quad \dots (10)$$

where $\phi(x)$ = mapping function which maps nonlinear samples of low dimension to feature space of high-dimension. ω is the regression coefficient and $b \in \mathbb{R}$ is an intercept term.

5.4 Algorithm for Encryption and Decryption

As far as the security of data or information is concerned in UWA communication cryptography is

the cheapest solution in terms of power and cost⁵⁵. RSA (Ronald Rivest, Adi Shamir, Leonard Adleman) algorithm is a popular method for encryption and decryption which is based on an associated private key that cannot be accessed by anyone else. A message is transformed into a ciphertext using mathematical operations for encryption. One way functions of complicated nature are used in the RSA system. Key generation, encryption and decryption are the three steps that perform modular exponentiation operation. We need algorithms and security mechanisms in underwater acoustic networks (UAN) to sustain integrity and data secrecy. An ultra-lightweight encryption scheme secures UAN architecture by creating a good swap between security and overhead⁵⁶. Ciphertext expansion phenomenon is implemented in cryptography where the modification identification codes (MICs) and message authentication codes (MACs) increase the message length. It causes transmission delay and increases energy consumption. To protect the integrity and confidentiality, a secure UWA communication suite has been described⁵⁷. The suite consists of a secure routing protocol and a set of cipher, digest and re-keying i.e. cryptographic primitives.

6 Classification of Currently Available Modems

This article reviews the state-of-the-art UWA communication, to develop a hardware UWA modem with lower power consumption and cost, and to experiment with new communication algorithms to increase bit-rate and counter harsh environmental effects. Researchers have applied different methodologies to attain underwater communication goals i.e. long-distance data transmission with high bit-rate, high bandwidth, low cost, low power, and small-size UW receivers. Researchers are utilizing advanced techniques for signal processing and adopting machine learning in integration with a processor that finds new ways to improve system accuracy. Here are the brief notes on different types of currently available modems.

6.1 Software-defined UWA modem

Doppler effect and multi-path propagation cause signal distortion. Deep Belief Network (DBN) explores the machine learning technique that has been proposed to combat the challenge of signal distortion⁵⁸. The receiver system is based on DBN denoising which classifies the received signal. A novel pixelation algorithm pre-processes after the

segmentation of the received signal into frames. DBN-based classification reconstructs the received signal when a de-noising algorithm based on DBN and features are extracted from the frames. The channels face problems like the Multipath Propagation and Doppler Effect. DBN solves the problem and the performance improves at 10^{-3} Bit Error Rate (BER) provided by 13.2dB.

The advanced networking techniques associated with underwater modems are being used for high-end applications. The underwater acoustic networking testbed is a key component in Navy programs and tsunami warning systems in many countries that use the Telesonar modem⁵⁹. To monitor the UWA communications the testbed consists of a sonar SM-975 modem, many Telesonar modems, and a universal deck box equipped with an acoustic transducer as shown in Fig. 6. The modems are interfaced with the UWA channel emulator which resides in a personal computer (PC). Interfacing through serial port links can direct the transmission and recording of custom-defined acoustic waveforms.

The Janus standard, developed by the military sector, specifies the physical and link layer design for underwater acoustic (UWA) modems operating within the frequency band of 9,440-13,600Hz⁶. A JANUS-compatible multiple-input multiple-output (MIMO) acoustic communication link utilizes a software-defined acoustic modem. It provides a 20kbps maximum transmission rate in a 5-kHz bandwidth in shallow water conditions⁶⁰. The spatial diversity is significantly degraded for the space-time block code or continuous-phase frequency-shift keying (FSK) which causes high spatial correlation. While single carrier modulation by space-time block code improves the bit error rate. The implementation of a MIMO

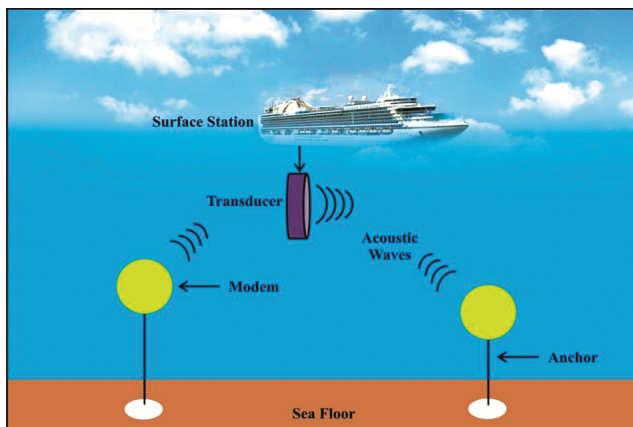


Fig. 6 — UWA modem networking testbed

acoustic communication link is dependent on the software-defined acoustic modem transmission mode in shallow water conditions. In a Channel-Aware Adaptive Modem, the prefix length and sub-carrier numbers are dynamically adjusted to utilize OFDM modulations, while fall-back modulation is used in harsher environments¹¹. Keeping in mind the constraints of long propagation delays, severe attenuation, extended multipath, large Doppler shifts and rapid time variation a software-defined modem has been designed that dynamically calculates approximately the acoustic channel. The OFDM modulator parameter as a function of the environment is tuned. The channel behaviour has temporal variability which allows switching to a more robust modulator in ruthless propagation conditions¹¹. Doppler scale estimation in UWA modem is performed with one of two methods; either zero-padded (ZP) OFDM or cyclic-prefixed (CP) waveforms²³.

Coherent Acoustic Modem predicts *in situ* performance in a Reverberant environment⁶¹ using measured Channel Impulse Response (CIR) is a realistic option that is useful on modelled or measured CIRs. Eight units of bottom-mounted instruments were deployed in a network configuration to perform channel sounding and communications experiments. A software-defined acoustic modem was programmed to pass on probe signals and packets in a round-robin fashion. Communication channel theory has been linked to UWA expressions. Calibration of channel measurements and channel knowledge, have been used to foresee the phase coherent acoustic modem performance. The signal-to-noise ratio (SNR) in a receiver over a certain signalling period has been predicted by employing delay-Doppler spread functions and power-delay profiles. The prediction of output SNR is relevant as it illustrates the relationship between output SNR and the probabilities of bit and packet error. A low-cost design of a software-defined acoustic modem has been developed with off-the-shelf components. The simple integration has been chosen to perform One-way travel-time (OWTT) in a Morphing Distributed Autonomous Underwater Vehicle (MODA)⁶². A prototype has obtained results which proved the modem design an effective one. The installed high-precision oscillator accomplishes one-way travel-time (OWTT) in the modem processing unit to halve the latency. A Software-defined UWA modem has been proposed with the modular software design to simply configure parameters e.g. modulation scheme,

coding schemes, carrier frequency, scheduling algorithm, bandwidth, and source power. This low-cost software-defined acoustic modem has been developed with only off-the-rack components. Packet detection ratio, packet delivery ratio, and ranging for one-way travel time are improved specifically in shallow water environments. The authors have presented the detailed study of low cost UWA modems required in affordable AOVs and ROVs for civil applications⁶³.

Digital-to-analog converter (DAC), analog-to-digital converter (ADC), power amplifier (PA), low noise amplifier (LNA), and MC protocol (Ethernet) communications jointly form communication modules as depicted in Fig. 7. The latest research on software-defined UWA modems introduces a new modem system utilizing machine learning for signal classification. The improved reliability of underwater transmissions is integrated by the use of machine learning with highly developed signal-processing techniques which provide increased clarity. The signals are modulated in a Lattice Semiconductors Field Programmable Gate Array (FPGA) and the underwater environment is emulated in a half-pipe waveguide. Signals are classified using Support vector machines (SVMs) strengthened with the continuous wavelet transform (CWT). Features are extracted from acoustic signals employed in an SVM-Powered UWA Modem⁶⁴. This modem design has significantly enhanced the accuracy and eliminated the need for further dimensionality reduction in the model.

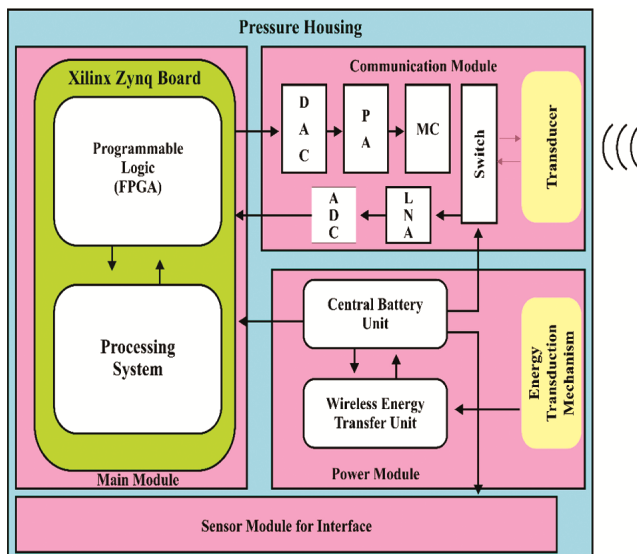


Fig. 7 — Block diagram of Software-defined UWA networking platform

The data mining methodologies can play a vital role in increasing transmission reliability and clarity of signals in marine environments. With the advancement of software-defined UWA modem design, there is rapid growth in underwater wireless communication technology. Improved high-data-rate, mobile, IP-compatible software-defined UWA networking platform as shown in Fig. 7 has been introduced with characteristics in terms of spectrum agility and hardware/software flexibility to support distributed networked monitoring operations⁶⁵.

6.2 Digital-Signal-Processor-based UWA Modem

A digital signal processing chip is embedded in an acoustic modem. The appropriate modular algorithm processes the collected data to achieve real-time data transmission. Advanced modulation and multiplexing techniques yield single-input single-output (SISO) as well as multi-input multi-output (MIMO) signal processing and transmission. Orthogonal frequency division multiplexing (OFDM) performs signal transmission in multipath environments. It supports a high data rate with reasonable spectral efficiency. Researchers explored different OFDM variants contributing high resilience to frequency selective channels⁶⁶. Implementation of OFDM for multi-carrier acoustic communication has been demonstrated in²⁴.

We have categorized the recent five-year modem designs as follows:

6.2.1 Modem for a Small AUV

Designing a Small Autonomous Unmanned Vehicle (AUV) for underwater applications is always constrained by physical parameters. A modem using Direct Sequence Spread Spectrum (DSSS) has been proposed for a lower cost, and small-sized AUV⁶⁷. In this article, researchers have adopted an adaptable analog-to-digital (A/D) sampling rate and also approached Doppler compensation to decrease the complexity of hardware implementation. The acoustic modem performance has been evaluated for robustness upon AUV integration and unstable Doppler.

UWA modem using synchronous chip-scale atomic clocks (CSAC) for upgradable tasks of AUV positioning⁶⁸ has been presented with the experimental results. Researchers have addressed the sensor time synchronization challenge on mobile carriers and clock synchronization on mobile nodes to perform synchronized and cooperated operations by Automatic Underwater Vehicles (AUV) in UWA networks. The

experiment results have provided the phase synchronization of CSACs with a source of timekeeping signals. It has been recommended that CSACs be 'disciplined' (steered). Another UW modem uses a Cesium atomic clock with an exceptional ranging capability⁶⁹. Researchers have tried to overcome the system clock drift where the traditional UW-ranging system depends on the time accuracy of the local system. High-precision Cesium atomic clocks are incorporated with vigorous spread spectrum technology and have a high precision ranging capability.

6.2.2 Hybrid Optical-Acoustic Modem

A novel hybrid opto-acoustic modem transmits and receives optical as well as acoustic signals³⁰. A hybrid opto-acoustic modem has been proposed and simulated with the integration of optical and acoustic signals. It has communicated over long distances with smaller power consumption and data transmission is efficiently achieved³⁰. The system uses the basic principle of Orthogonal Frequency Division Multiplexing (OFDM) and the single data stream of combined optical and acoustic signals has been converted as multi narrowband channels. These different frequency ranges have been transmitted simultaneously over several subcarriers. The hybrid opto-acoustic modem has also been proposed in⁴ to overcome the limitations of underwater acoustic communication i.e. short range of communication, very low bandwidth, frequency-dependent attenuation, and lower data rates. The development of opto-acoustic modem has been aimed at the growth of underwater communication using fifth-generation (5G) communication techniques. MIMO in conjunction with OFDM has been proposed to improve hybrid opto-acoustic modem²⁵. Green Underwater Wireless Communication (GUWC), a new technology using a hybrid MIMO-OFDM-based opto-acoustic modem has been emerging²⁶.

6.2.3 Cost-effective and Miniaturized UWA Modem

The use of a single-board computer, a microcontroller, and amplifiers with discrete components has revealed the design of a cost-efficient acoustic modem for underwater communications covering short-range⁷. The PSK modulator is integrated with a power amplifier in one module. A web-based testbed along with a simulation platform has been designed for testing modems. A prototype of a miniaturized size, low-cost, and low-power UWA

Modem using multipath spread-spectrum techniques⁷⁰ has been investigated by Spread-spectrum M-ary orthogonal signaling (MOS). The symbols are constructed from long pseudorandom code subsequences. It is a miniaturized prototype for a 24kHz-32kHz band with transmit power lesser than 1w and low receive power consumption (12.5mw). The point-to-point communication has been successfully achieved at ranges greater than 3km (lakes) and ranges greater than 2km in the sea. The experimental prototype has enabled long-term, large-scale future Internet of Underwater Things (IoUT).

UWA Micromodem with ambient features of economical, low-power consumption and miniaturization has used a convolutional code-block interleaving-frequency hopping-MFSK UWA scheme with underwater Internet of Things (IoT)⁷¹. For fast digital signal processing, the processor has been fixed in the Micromodem. The model design has overcome interference in the aquatic environment and has achieved steady UWA communication with the reduced modem size. The hardware design is in an integrated package. Small-size underwater acoustic modems have been proposed using a compact vector transmitter with a physics-based particle velocity modulation method over co-located underwater vector field components⁷². It has been demonstrated that there is no need for extra bandwidth to transmit multiple data streams concurrently. Micromodems can be deployed on a mass level to connect buoy nodes at the bottom of the sea.

6.2.4 Reconfigurable/Flexible UWA Modem

An innovative OFDM MODEM design for shallow water acoustic communication has been proposed, specifically to address Doppler estimation. Many pilot subcarriers and channel estimation algorithms estimate the Doppler Effect²⁷. The system design has acquired a balance between data rate and bit error rate under the constraints of Doppler channels, long delay channels, and frequency selective channels. The proposed OFDM MODEM design has shown results with configurable parameters including different channel estimation methods, various received channels, a range of pilot subcarriers, and different null subcarriers. The maximum raw data rate (4387.5bps after channel decoding) of the OFDM MODEM has obtained 0 BER. The OFDM MODEM has obtained a BER of 10^{-4} under mobile channels. The Doppler Effect is high and a raw data rate of 2662.6bps is acquired after channel decoding. An

OFDM Transceiver for the UWA channel has proposed a MATLAB model to implement different OFDM modulation methods. Monte Carlo simulations are performed to compare bit error rates and to tune multiple UWA channel parameters to approach flexibility²⁸. Rician shadowing model for the multipath channel has been assumed. The flexible transceiver has simulated MPSK-OFDM and other mapping schemes such as QAM and DPSK, etc. Self-interference (SI) channel modeling is introduced for the In-band full duplex (IBFD) UWA modem⁴⁷ which shows SI cancellation. The IBFD UWA communication is simulated using a simple and finite model. A more intensive scattering component has been found in the nearby receiver.

6.2.5 Real-Time UWA System

Single-carrier communication and multiple-carrier communication both can be thought of using a Real-time Orthogonal signal-division multiplexing (OSDM) MODEM⁷³. OSDM yields a reduced peak-to-average power ratio (PAPR) which is yet to recover in multipath propagation and Doppler shift. This limitation has been addressed in the research including hardware and software. The research continues with a Minimum-mean-square-error (MMSE) equalizer and polar decoding in a slow time-varying channel. The OSDM MODEM has achieved an improved data rate at a range larger than 5km. A transmitter and receiver module implemented on Xilinx’s FPGA and prepared on MATLAB with System Generator blocks has combined the telecommunication techniques based on RF and UWA communication to provide a real time complete functional UWA system⁷⁴.

7 Recent Trends in UWA Modems

Research modems do not fulfil industrial requirements. Different modulation schemes like amplitude shift keying (ASK)/on-off keying (OOK), frequency shift keying (FSK)/multiple frequency shift keying (MFSK), OFDM, multiple phase shift keying (MPSK)/quadrature phase shift keying (QPSK), and spread spectrum modulation have been adopted in modem design. Microcontroller unit (MCU), ARM processor, Raspberry Pi, Laptop, Digital signal processor (DSP), and FPGA are connected to design research modems. Power consumption, data rate, center frequency, and bandwidth are also features to be considered while designing research modems.

Acoustic modems are extensively used for underwater monitoring, telemetry, data logging, command and control of remotely operated vehicles (ROV) and autonomous underwater vehicles (AUV), and diver communications. The comparison among different UWA commercial modems with their specifications has been detailed¹.

Low-frequency modems provide long-range communication with limited channel bandwidth while high-frequency modems deliver restricted use due to absorption of high-frequency signals in water. AquaSeNT provides high data rate communications. Commercial modems like Link quest provide a 38.4kbps data rate. Modem classification based on the usage of frequencies is presented⁵. The Popoto modem PMM6081⁷⁵ shown in Fig. 8 is a new standard in underwater research and communication. Various design parameters for available commercial modems have been compared explicitly in Fig. 9-15.

Popoto Modem has special features: 1) Simultaneous 8-channel Hydrophone Input, 2) High-Speed Quad-Core ARM Processor, and 3) Low Power Wake-Up. The advanced version Popoto 2000, a JANUS-compliant version delivers exceptional performance featuring 80bps to 10240bps multiple modulation schemes, data analysis through MATLAB application programming interface, and on-board programming through PYTHON application programming interface. The

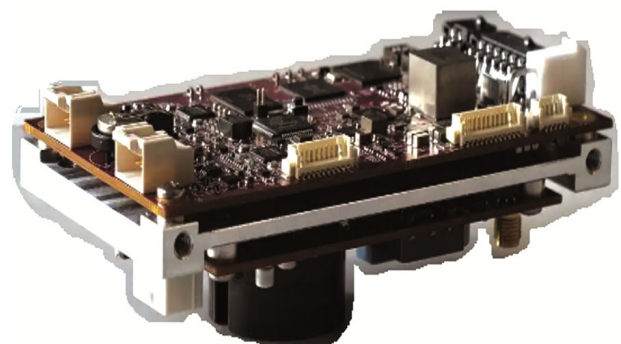
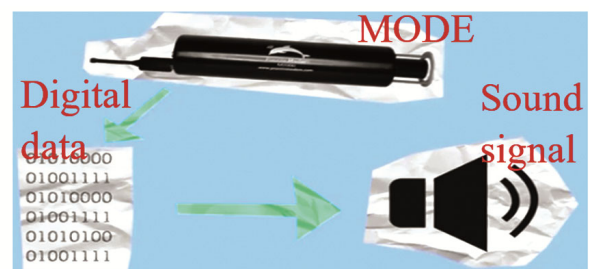


Fig. 8 — (a) Conversion of digital signal into acoustic signal, and (b) Internal Integrated circuit board⁶³

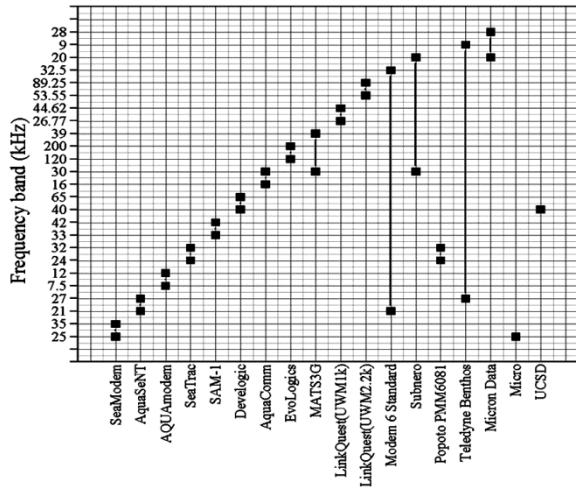


Fig. 9 — Frequency bands of commercial UWA modems

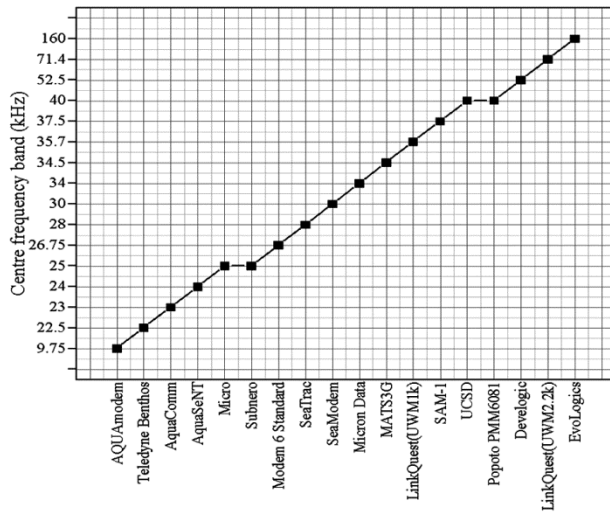


Fig. 10 — Centre frequencies of commercial UWA modems

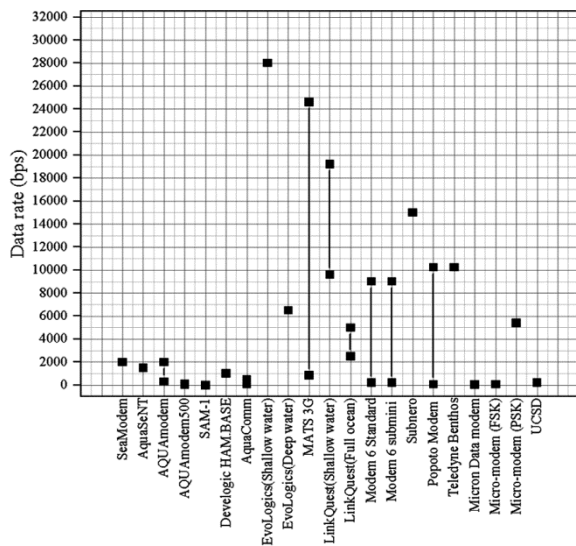


Fig. 11 — Data rates of commercial UWA modems

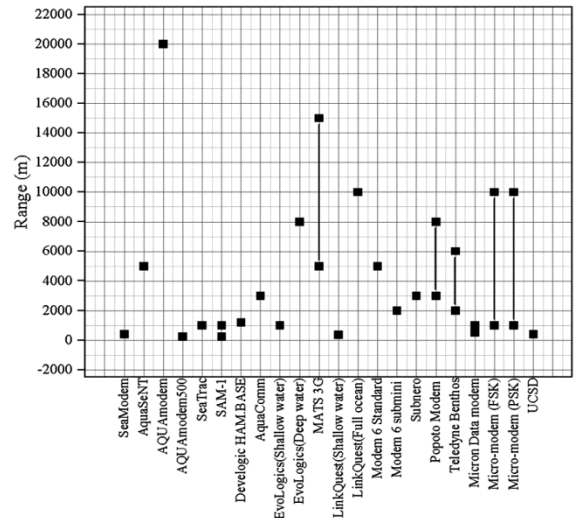


Fig. 12 — Operating ranges of commercial UWA modems

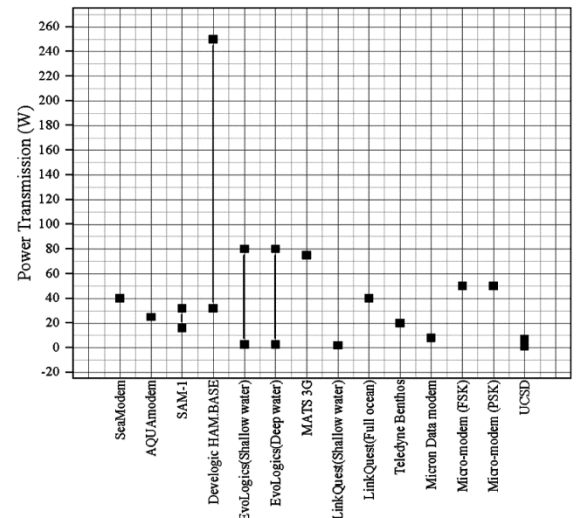


Fig. 13 — Transmission powers of commercial modems

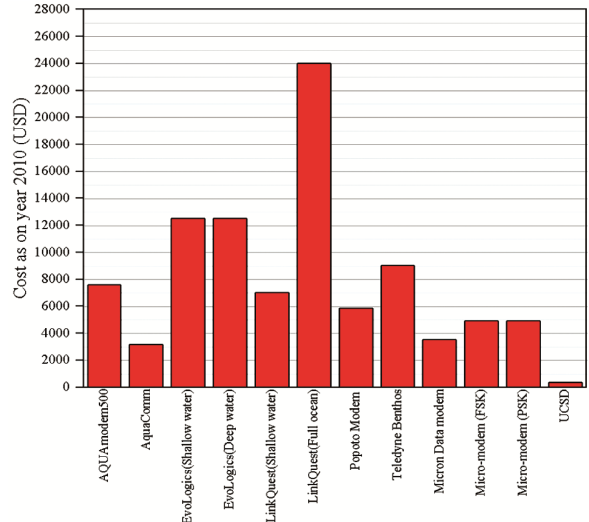


Fig. 14 — Cost of commercial UWA modems (Year 2010)

popular commercial modems are listed in Tables 4 and 5 with their specifications^{1,5,62}.

The key differences between currently available commercial and research UWA modems are listed in

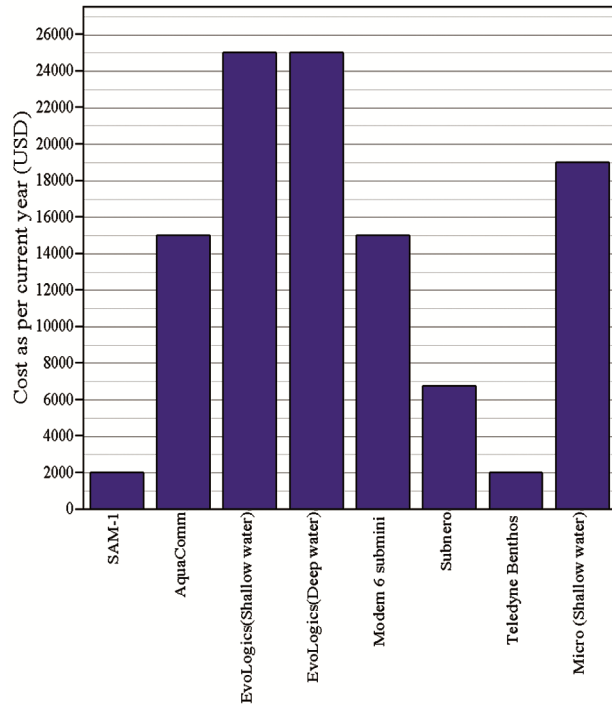


Fig. 15 — Cost of commercial UWA modems (Year 2023)

Table 6. Research UWA modems are based on academic approaches, while commercial UWA modems work on real harsh aquatic environments. They differ in design priorities, performance, and intended use. For example, deep learning and kernel-based algorithms suit better than linear algorithms in the context of data-fitting ability. But LSTM and SVR deviate from their ideal performance in calm ocean conditions. Commercial modems implicitly enhanced historical channel data with greater training time. Utilizing the underwater Internet of Things, the demand for commercial modems is increasing day by day.

8 Current Challenges in UWA Modem Design

The primary challenge in designing acoustic modems lies in the inherent capacity constraints of underwater acoustic communication channels⁴. The operation of acoustic modems is affected not only by fundamental limitations of acoustic propagation but also by system constraints such as bandwidth limitation of acoustic transducers, differences in transmitter power and receiver power requirements, and the energy consumption that matters⁶.

The three significant factors that characterize acoustic propagation are attenuation that increases with signal frequency, time-varying multipath propagation, and low speed of sound (1500ms⁻¹). Bandwidth-distance

Table 4 — Commercial modems and their specifications-1

Name	Manufacturer	Hardware	Frequency Band (kHz)	Modulation Scheme
SeaModem ⁷⁶	AppliCon	DSP	25-35	Multiple Frequency Shift Keying (MFSK)
AquaSeNT ^{1,5,29}	AquaSeNT	DSP	21-27	OFDM
AQUAmodem ⁷⁷	Aquatec	DSP	7.5-12	FSK and DPSK Spread Spectrum (SS)
SeaTrac ¹	Blueprint Subsea	DSP	24-32	SS modulation
SAM-1 ¹	Desert Star Systems	DSP	33-42	Pulse Position Modulation (PPM)
Develogic ^{1,78}	Develogic	DSP	40-65	OFDM and MFSK
Aqua Comm ^{71,77}	DSPComm	DSP	16-30	Direct Sequence Spread Spectrum and OFDM
EvoLogics ^{1,71,77}	Evo Logics	DSP	120-200	Sweep Spread Carrier (S2C)
MATS3G ¹	Sercel	DSP	30 -39	FSK/PSK
Link Quest ^{71,77}	Link Quest Inc.	DSP	26.77-44.62 (UWM1000) 53.55-89.25 (UWM2200)	Broadband acoustic spread spectrum
Modem 6 Standard ¹	Sonardyne	DSP	21-32.5	QPSK
Subnero ¹	Subnero	DSP & FPGA	20-30	QPSK
Popoto Modem PMM6081 ⁷⁵	OEM acoustic modems	High-Speed Quad-Core ARM Processor	24-32	JANUS standardization and an intuitive Python API
Teledyne Benthos ⁷⁸	Teledyne Benthos	High-Speed Quad-Core ARM Processor	9-27	MFSK and PSK
Micron Data modem ⁷¹	Subsea Technologies	multi-core x86-64 μ-processor	20-28	Tritech spread spectrum
Micro modem ⁷⁷	WHOI	DSP	25	FSK/PSK
UCSD ⁷⁷	UCSD	DSP & FPGA	40	FSK

Table 5 — Commercial modems and their specifications-2

Name	Area	Cost (\$)	Data rate (bps)	Transmission Power (watt)	Range (m)
SeaModem ⁷⁶	Shallow water	Low	2000	Upto 40	400
AquaSeNT ^{1,5,29}	Deep water	-	1500	-	5000
AM-D2000					
AQUAmodem (long range series) ⁷⁷	Wireless subsea data connectivity	-	300-2000	25	20000
AQUAmodem500 ⁷⁷	(subsea optical modem)	7600 (as on year 2010)	25-100	-	250
SeaTrac ¹	Small to medium AUV & ROV		100	6	1000
SAM-1 ¹	Intensive harbor basins, reefs, shallow water and deep water	1995 (recent)	150	8V-16V@2A peak power supply	250-1000
Develogic HAM.BASE ¹	Deep water	-	10000	30-250	1200
AquaComm ^{71,77}	-	2800- 3500 (as on year 2010) 15000 (recent)	100-480	-	3000
EvoLogics ^{1,71,77}	Shallow water	12500 (as on year 2010)	28000	2.5-80	1000
	Deep water	25000 (recent)	6500		8000
MATS 3G ¹	Low noise environment	-	850-24600	75	5000-15000
Link Quest UWM1000 ^{71,77}	Shallow water	7000 (as on year 2010)	9600-19200	2	350
Link Quest UWM10000 ^{71,77}	Full ocean	-	2500-5000	40	10000
Link Quest UWM10000 ^{71,77}		24000			
Modem 6 Standard ¹	Subsea-to-surface applications	-	200-9000	-	5000
Modem 6 submini ^{1,71}	Subsea applications	15000 (recent)	200-9000	-	2000
Subnero ¹	-	6750 (recent)	15000	-	3000
Popoto Modem ⁷⁸	Offshore applications	< 3000(5,850.00 USD)	80-10240		3000-8000
Teledyne Benthos ^{1,77}	Subsea networks	7200- 11000 (as on year 2010) 2000 (recent)	10240	20	2000-6000
Micron Data modem ⁷¹	Small AUV & ROV	3500 (as on year 2010)	40	7.92	500-1000
Micro-modem ⁷⁷	Shallow water	4900 (as on year 2010)	80 (FH/FSK)	< 50	1000-10000
		19000 (recent)	5400 (PSK)		
UCSD ⁷⁷	-	350	200	1.3-7	400

Table 6 — Commercial modems vs research modems

Feature	Commercial Modems	Research Modems
Approach	Practical deployment	Academic/theoretical
Environment	Unpredictable/varying	Predictable in ideal conditions
Reliability	High, field-tested	Experimental, variable
Data Rates	Moderate (few kbps)	Potentially higher
Power Efficiency	Optimized for long-term use	Often secondary to performance
Customization	Limited	High
Cost	Expensive (\$1000s–\$10,000s)	Lower, but not mass-produced
Priority	reliability, robustness, and ease of deployment	innovation, flexibility, and performance optimization, often at the cost of commercial viability
Interfacing	User-friendly interfaces for quick deployment	Greater flexibility for experimental protocol design
Power consumption	Optimized for long-term operations	Preferred higher data rates at the cost of power consumption
Applications	Real-world applications such as underwater vehicle communication, environmental monitoring, seismic survey and offshore industries	Innovative techniques may later be integrated into commercial products

dependence, transmission power, and the Doppler Effect bound the performance of UWA communication. The cumbersome design of the ultrasonic underwater projector has highly reactive impedance⁶⁷. The ultrasonic transducer in the projector and a low-noise amplifier (LNA) in the hydrophone, have poor impedance matching at lower frequencies. Due to the

limited lifetime of the battery and scarcity of allocable frequencies, the selection of adaptive techniques suitable to the communication requirement must be carefully considered. Multi-hop networks require a mechanism for adaptive power control to determine the appropriate transmission range. Standardization of UWA communication is a critical task as the different

manufacturers are providing modems that are not interoperable¹. The fading problem with Doppler spread is a compromise with modem performance when operated on a packet-by-packet basis. The reverberation limits the modem performance as a fraction of the signal power that cannot be neglected⁶¹. The reverberation as a function of the link becomes severe. The modems at different depths have been related to the Sound-speed profile (SSP). It finally results in propagation loss.

9 Deployment of UWA Modems in Underwater Networks

Routing is essential for deploying UWA modems in underwater networks to ensure efficient data transmission, minimize energy consumption, and overcome challenges like high latency and limited bandwidth. It enables reliable communication, enhances network lifetime, and supports real-time applications such as environmental monitoring, underwater surveillance, and marine research. Embedding routing protocols in underwater modems is essential for enhancing the efficiency, reliability, and longevity of underwater sensor networks. Given the challenges of high latency, limited bandwidth, and energy constraints in underwater acoustic communication, integrated routing mechanisms enable adaptive data transmission, reduce energy consumption, and improve network lifetime. By embedding optimized routing protocols directly into modems, real-time decision-making and seamless network operations are achieved, ensuring robust connectivity for critical applications such as environmental monitoring, underwater surveillance, and deep-sea exploration.

9.1 Routing in Underwater Acoustic Communication Networks

A balanced routing protocol utilizing machine learning to enhance network performance has been introduced⁷⁹. Machine learning-based routing to optimize energy efficiency in UACNs has been further explored⁸⁰. Recent advancements have focused on optimization-based routing. The BOUNCE protocol, leveraging multi-armed bandit algorithms to balance network costs, has been proposed⁸¹. Cluster-dragonfly optimization has been applied to improve the energy efficiency⁸². These studies highlight the growing trend of applying optimization techniques to underwater routing. A comprehensive analysis of routing protocols and machine learning approaches, identifying key challenges and future research directions, has been provided⁸³. Around the same

time, a cluster-based routing mechanism using the gravitational search algorithm, improving network lifetime was also introduced⁸⁴. Concurrently, a new hybrid localization and communication framework integrating blockchain with IoT-enabled UACNs, enhancing security and reliability, was also proposed⁸⁵.

9.2 Handshaking for Enhanced Efficiency

In underwater acoustic networks, the RTS-CTS handshake improves channel efficiency and reduces collisions by requiring sender permission before transmission. It mitigates long propagation delays and high collision rates through a two-way handshake. Researchers are enhancing RTS-CTS for better underwater communication performance⁸⁶. These studies collectively underscore the importance of routing in UACNs, demonstrating the shift from traditional methods to AI-driven and optimization-based approaches, ensuring energy efficiency, security, and longevity in underwater sensor networks.

9.3 Large-Scale Deployment

For large-scale deployment of underwater nodes in underwater sensor networks supposed to cover vast regions, the cost of the modem should be very low. Deploying underwater acoustic modems on a large scale presents several challenges due to the challenging underwater environment. These include limited bandwidth and low data rates, high power consumption, signal interference and noise, scalability and network coordination, cost, and deployment complexity. UWA channels support only a few kilobits per second due to signal attenuation, multipath propagation, and Doppler effects, limiting real-time data exchange. Acoustic communication requires significant power, making it challenging for battery-operated devices to sustain long-term operations, especially in deep-sea environments. Natural and anthropogenic noise (e.g., marine life, ship traffic) degrades signal quality, leading to reduced reliability and increased transmission errors. Synchronizing multiple modems over large distances is difficult due to high latency (propagation delays in the order of seconds), which complicates network protocol design and data scheduling. Large-scale networks require numerous expensive modems, along with robust deployment strategies, maintenance, and retrieval processes, increasing operational costs. These challenges can be addressed with advanced

energy-efficient hardware, adaptive signal processing, and improved networking protocols to enhance reliability and scalability in real-world underwater applications⁸⁷. An interference-aware and collision-free MAC protocol is under progress for the demand of large-scale deployment of UWA Wireless Sensor Networks⁸⁸. Blockchain technology in a hybrid underwater localization communication framework has been proposed for geometric distance-based localization routing⁸⁹.

To address dynamic topology high delay, energy limitations, and unstable links in underwater sensor networks, QLACO integrates Q-learning with the ant colony algorithm. Unlike traditional methods, QLACO offers faster convergence and greater robustness, leveraging reinforcement learning to adapt to underwater network dynamics effectively⁹⁰.

10 Future perspectives

Since there is a lack of interoperable modems from various manufacturers, we need to standardize the UWA communication. The robustness and efficiency of UWA systems can be enhanced by Solomon-Reed encoding. The conventional *clock* or *reference* signal can be replaced with a chirp signal for signal detection and synchronization in multipath underwater environments⁶². In underwater 5G communication, the parameters for the proposed system such as the type of Quadrature Phase Shift Keying (QPSK) modulation, guard Band timing, Barker Code length, FFT length for OFDM, etc. have to be adjusted²⁸. A novel hybrid Opto-acoustic modem is to achieve efficient data transmission with reduced power consumption and long-distance underwater communication. It can be implemented on terrestrial and underwater to attain better underwater wireless networks¹¹. A configurable network protocol explained in⁷¹ has to be designed for networking in shallow-water acoustic communication. In UWA micromodems for IoT, bit errors are often caused by the frequency hopping scheme used in the receiver. The impact of multipath on demodulation must be addressed to improve performance. Practically sensor data can be transferred at the data rate lesser than 100kbps. Many laboratories are investigating pathways to achieve 6G mobile communication which may enhance the speed, coverage distance and stability of UWA communication⁹¹. Many laboratories are developing testbed software as an emulator and simulator to deploy in a real world

environment⁹². Aqua-Sim is a network simulator which can simulate 3-dimensional network deployment⁵. The existing conventional modems need to adopt the emerging technology to achieve longer distance transmission at higher data rate.

11 Conclusion

The comprehensive study of the work in UWA communication is focused on leveraging modern technology e.g. machine learning, IoUT, JANUS compliant version, Lattice Semiconductor FPGA, hybrid MIMO-OFDM, etc. to acquire high data rate, reliable and efficient acoustic communication. Underwater wireless communications can be made more energy-efficient by adopting IoUT both in physical layer and upper layers⁹³. While designing UWA modem for adverse channels, the underlying underwater telemetry physics must be explicitly incorporated⁹⁴. Now-a-days the focus is on programming the modems to interface with each other and thereby developing UWA modem's network⁹⁵. Researchers and scientists are trying to mitigate effects caused by noise, Inter-symbol-interference, multipath propagation, and Doppler shift of sound signals. With the increasing use of deep learning, data-driven modems are being developed⁹⁶. Military applications involve diver-to-diver and diver-to-surface platform communications, border monitoring and control, underwater reconnaissance and surveillance, and submarine communications. Scientific and research work includes studying water properties (e.g., temperature, pH, salinity, pressure, and oxygen), aquatic life forms, marine ecology, tectonic plate movement, underwater volcanoes, and tsunami dynamics. Industrial and commercial ventures explore oil and gas reservoirs, search for extraction of natural resources, monitor underwater pipelines, and aquaculture. To our knowledge, software-defined UWA modems are deployed in industrial and commercial ventures. This paper presents a pilot study on digital-signal-processor-based UWA modems. The focus of attention is first to understand and then apply the predominantly compelling communication techniques in UWA modem design. We have addressed not only UWA modem design considerations and the empirical models but also design challenges such as fading problem with Doppler spread, propagation loss, transmission power, and bandwidth-distance dependence have been thought of with design considerations.

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