CHAPTER 23

ADVANCES IN UNDERWATER ACOUSTIC NETWORKING

Tommaso Melodia, Hovannes Kulhandjian, Li-Chung Kuo, and Emrecan Demirors

State University of New York at Buffalo

The field of underwater acoustic networking is growing rapidly thanks to the key role it plays in many military and commercial applications. Among these are disaster prevention, tactical surveillance, offshore exploration, pollution monitoring and oceanographic data collection. The underwater acoustic propagation channel presents formidable challenges, including slow propagation of acoustic waves, limited bandwidth, high and variable propagation delay. Furthermore, it is affected by fading, Doppler spread and multipath propagation. Therefore, efficient protocol design tailored for underwater acoustic sensor networks entails many challenges across different layers of the networking protocol stack. The objective of this chapter is to provide an overview of the recent advances in underwater acoustic communication and networking. We briefly describe the typical communication architecture of an underwater network followed by a discussion on the basics of underwater acoustic propagation and the state of the art in acoustic communication techniques at the physical layer. We then present an overview of the recent advances in protocol design at the medium access control and network layers as well as in cross-layer design. Finally, we provide a detailed discussion of the existing underwater acoustic platforms for experimental evaluation of underwater acoustic networks.

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23.1 INTRODUCTION

It has been argued that the recent disastrous spill that followed the oil-rig explosion in the Gulf of Mexico in the Summer of 2010 could have been prevented by acoustic sensing/actuating systems (recently mandated for example by Norway and Brazil) that can be triggered by acoustic control signals. This example is only one of many demonstrating the importance of underwater acoustic networked sensing, communication, and control systems, and the potential that this technology can offer in addressing major problems of our times such as climate change monitoring, pollution control and tracking, offshore exploration, study of marine life, disaster prevention, and tactical surveillance [126, 18].

Another example of recent initiatives is the joint IBM and Beacon Institute, Beacon, NY announcement of a $15M funding plan from state and corporate sources to create an environmental-monitoring system for New York's Hudson River by turning the 315 miles of the river into a distributed network of sensors that will collect biological, physical, and chemical information and transmit the data to a central location to be processed by IBM's data management center.

Unfortunately, radio frequency (RF) electromagnetic waves propagate over long distances through conductive salty water only at extra low frequencies $(30-300\,\mathrm{Hz})$, which require large antennas and high transmission power. Optical electromagnetic waves do not suffer from such high attenuation, but are affected by scattering and require high precision in pointing laser beams. Underwater optical communications have therefore ranges of a few tens of meters only and are typically directional.

Acoustic communication is therefore the transmission technology of choice for underwater networked systems [126]. Still, due to the physical properties of the propagation medium, underwater acoustic signals suffer from severe transmission loss, time-varying multipath propagation, Doppler spread, limited and distance-dependent bandwidth, and high propagation delay. For example, the slow propagation speed of sound underwater makes Doppler a significant effect when signals are scattered from moving ocean wave surfaces and from mobile vehicles. These formidable challenges limit the available bandwidth for underwater acoustic communications, while the rapidly varying channel causes communication links to be highly unreliable, ultimately hindering advancement in underwater networked communications. As a consequence, currently available underwater acoustic technology can support mostly point-to-point, low-data-rate, delay-tolerant applications. Current experimental point-to-point acoustic modems use signaling schemes that can achieve data rates lower than $20\,\mathrm{kbit/s}$ with a link distance of $1\,\mathrm{km}$ over horizontal links. Academic experimental research activities have demonstrated modems for low-cost, short range, and low data rate ($1\ \mathrm{kbit/s}$) sensor networks [67]. Data rates as high as $150\,\mathrm{kbit/s}$ have been reported, but only on very short-length ($\approx\ 10\,\mathrm{m}$) vertical links, which are unaffected by multipath [100]. Typical commercially available modems provide even lower data rate waveforms [1, 2, 3].

In addition to advances in transmission techniques, the last few years are seeing a surge in research to attack these technical challenges from the perspective of networking protocols. Architectures, protocols, and algorithms for underwater networking are being actively discussed [94, 109, 142, 110, 73, 105, 4, 22, 21, 31]. It is necessary, however, to state clearly upfront that *currently available underwater acoustic technology can support only low-data-rate and delay-tolerant applications.* Also, *underwater networking experiments are expensive and hard to reproduce, and the research community still lacks affordable infrastructure for rapid (and reproducible) experimental evaluation and prototyping of advanced underwater communications and networking methodologies*. As a consequence, underwater communications and networking are far from being well understood. In spite of significant theoretical research progress in the last decade, only limited experimental data are available to the scientific community at large to work with.

The objective of this chapter is to provide a comprehensive account of recent advances in underwater acoustic communications and networking. To do so, in Section 23.2, we briefly describe the typical communication architecture of an underwater network. In Section 23.3, we discuss key notions of underwater acoustic propagation. In Section 23.4, we discuss the state of the art in acoustic communication techniques at the physical layer. In Sections 23.5 and 23.6 we discuss recent advances in protocol design at the medium access and network layers of the protocol stack, respectively. In Section 23.7, we discuss advances in cross-layer design techniques. Finally, in Sections 23.8 and 23.9 we provide a detailed discussion of the existing underwater acoustic platforms for experimental evaluation of underwater networks.

23.2 COMMUNICATION ARCHITECTURE

In typical underwater networks, a group of sensor nodes are anchored to the bottom of the ocean, and possibly interconnected to one or more underwater gateways by means of wireless acoustic links. The sensor network, usually through multi-hop paths, relays data from the ocean bottom network to a surface station. Underwater gateways may be equipped with two acoustic transceivers, namely a *vertical* and a *horizontal* transceiver. The horizontal transceiver is used by the underwater gateways to communicate with the sensor nodes to send commands and configuration data to the sensors and/or collect monitored data [111]. The vertical link is used by the underwater gateways to relay data to a surface station. In deep water applications, vertical transceivers are usually long-range transceivers. The surface station may be equipped with an acoustic transceiver able to handle multiple parallel communications with the deployed underwater gateways and may communicate with an *onshore sink* and/or to a *surface sink* through a long-range radio transmitter and/or satellite transmitter (see Fig. 23.1). Sensor nodes may float at *different depths* to observe a given phenomenon. One possible solution is to attach each sensor node to a surface buoy, by means of wires whose length can be regulated to adjust the depth of each sensor node. Although this solution enables easy and quick deployment of the sensor network, floating buoys may obstruct ships navigating on the surface, or they can be easily detected and deactivated by enemies in military settings. Furthermore, floating buoys are vulnerable to weather and tampering or pilfering. Typically, sensing

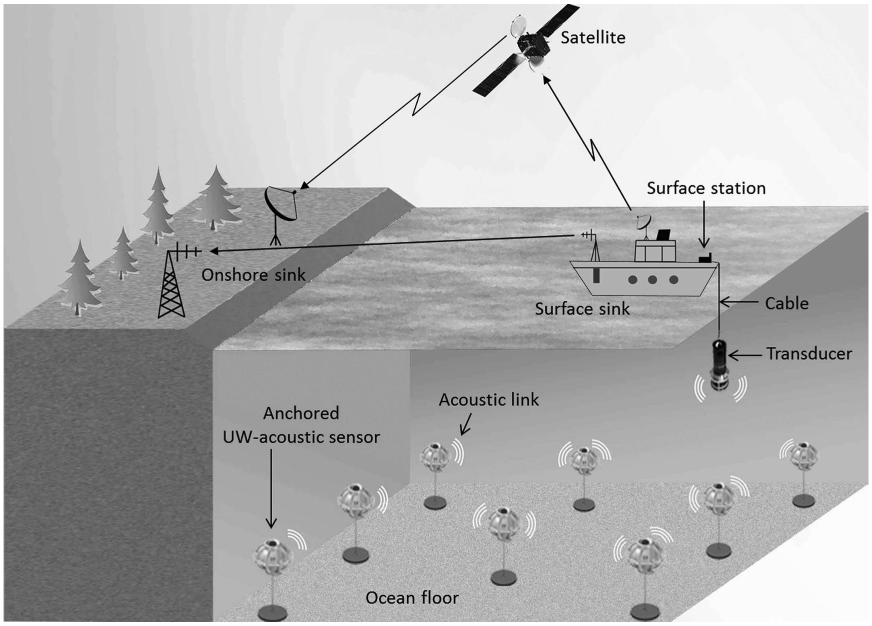


Figure 23.1 Architecture of an underwater acoustic sensor network.

devices are anchored to the bottom of the ocean, and are equipped with floatation capabilities.

23.3 BASICS OF UNDERWATER COMMUNICATIONS

Typical physical carriers for underwater communication signals are RF electromagnetic waves, optical waves and acoustic waves. RF waves are affected by high attenuation in water (especially at higher frequencies), thus requiring high transmission power and large antennas [16, 136, 61]. Therefore, RF waves are generally used for underwater communications over very short ranges (up to 10 meters) [34, 68]. Optical waves enable high data rate communications (in the order of a few $\mathrm{Gbit/s}$) [55], but are rapidly scattered and absorbed in water, leading again to short-range communications [41]. Acoustic waves, instead, may enable communications over long-range links since they suffer from relatively low absorption. This has contributed to making acoustic transmission the most common underwater communication technique since World War Two [17, 141, 126].

Still, Underwater Acoustic (UW-A) communications are severely affected by *high path loss*, *noise*, *multipath*, *high and variable propagation delay* and *Doppler spread*. The combined effect of these phenomena causes the UW-A channel to be *temporally* and *spatially variable*. This limits the available bandwidth and makes it dramatically dependent on both range and frequency. Short-range systems that operate over several tens of meters may have more than $100\ \mathrm{kHz}$ of bandwidth, while long-range systems that operate over several tens of kilometers may have bandwidths of only a few kHz. Therefore, UW-A communication system mostly have low bit rates, which are in the order of tens of $\mathrm{kbit/s}$ [32].

Depending on their range, UW-A communication links can be classified as *very long*, *long*, *medium*, *short* and *very short* [126]. Typical bandwidths of underwater links for various ranges are presented in Table 23.1. Acoustic links can also be roughly classified as *vertical* and *horizontal* according to the direction of the sound ray with respect to the ocean bottom. Propagation characteristics of the links vary considerably on multipath spreads, time dispersion and delay variance. The oceanic literature typically refers to *shallow water* as water with depth lower than $100\ \mathrm{m}$, while *deep water* is used for deeper oceans [18].

Table 23.1 Available bandwidth for different ranges in UW-A channels.

	Range [km]	Bandwidth [kHz]
Very long	1000	< 1
Long	10 - 100	2 - 5
Medium	1 - 10	$\approx$10
Short	0.1 - 1	20 - 50
Very Short	< 0.1	> 100

Below, we provide a detailed discussion of the factors that influence UW-A communications. These include:

- **Transmission (Path) Loss:**

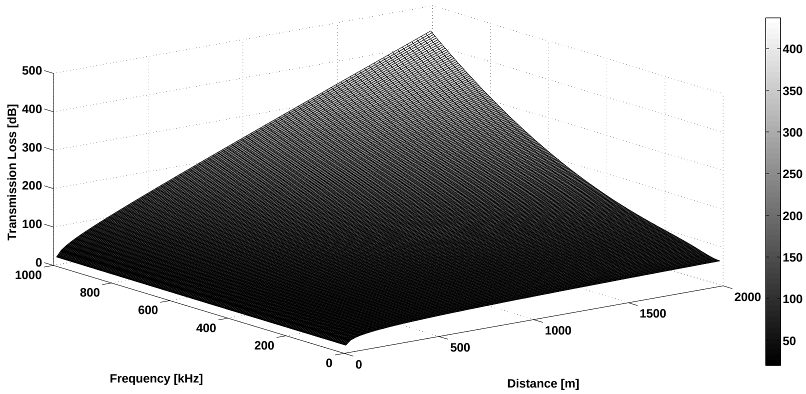
  Transmission loss is mainly caused by two phenomena: *geometric spreading loss* and *attenuation*. Transmission loss for a signal of frequency f $[\mathrm{kHz}]$ over a transmission distance d $[\mathrm{m}]$ can be expressed in [dB] as

  $$10 \log TL(d, f) = k \cdot 10 \log(d) + d \cdot \alpha(f) + A, \tag{23.1}$$

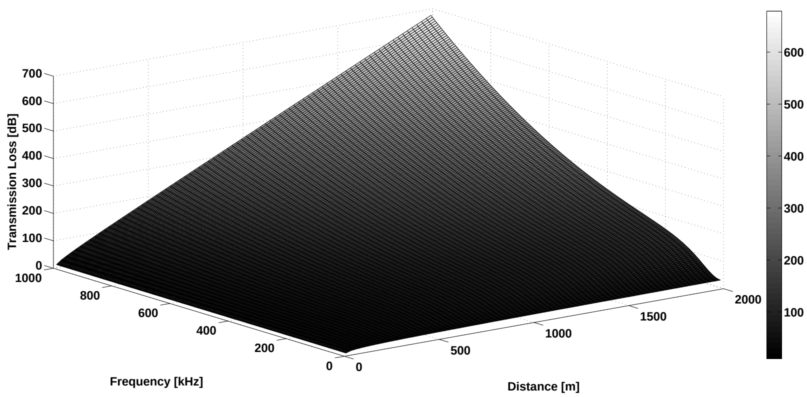
  where k is the *spreading factor*, which describes the geometry of propagation, $\alpha(f)$ $[\mathrm{dB/m}]$ is the *absorption coefficient* and A $[\mathrm{dB}]$ is the so-called *transmission anomaly* which accounts for factors other than absorption including multipath propagation, refraction, diffraction and scattering [141, 107]. Figure 23.2 shows the transmission loss with varying frequency and distance for shallow and deep water UW-A channels. The shallow water UW-A channel has higher values of attenuation than the deep water UW-A channel, while transmission loss increases with distance and frequency for both.

  – *Geometric Spreading Loss:*

    Geometric Spreading Loss is caused by the spreading of acoustic energy to a larger surface as a consequence of the expansion of acoustic waves.



(a) Deep water UW-A channel.



(b) Shallow water UW-A channel.

Figure 23.2 Transmission loss as a function of distance and frequency. In the sea water for $T = 15$ C, $pH = 8$ and $S = 35$ ppt.

Typically, spreading loss depends only on propagation range; hence, it is frequency independent. There are two common types of geometric spreading; *spherical* (which occurs when acoustic waves spread spherically outward from a source in an unbounded medium), which characterizes deep water communications, and *cylindrical* (which occurs when acoustic waves spread horizontally because of a medium which has parallel upper and lower bounds); the latter typically characterizes shallow water communications. The spreading factor, k is equal to 1 for cylindrical and 2 for spherical spreading. In practice, a spreading factor of $k = 1.5$ is often considered.

– *Attenuation:*

Attenuation can be mainly attributed to absorption, caused by conversion of energy of the propagating acoustic wave into heat (also referred to as *absorption loss*). The absorption coefficient for frequencies above a few hundred Hz can be expressed empirically using Thorp's formula [139], which defines $\alpha(f)$ $[\mathrm{dB/m}]$ as a function of f $[\mathrm{kHz}]$

$$\begin{aligned}\alpha(f) \quad &= \quad (0.11\frac{f^2}{f^2+1} + 44\frac{f^2}{f^2+4100} + 2.75 \cdot 10^{-4} f^2 + \\ &\quad + 0.003) \cdot 10^{-3}. \qquad (23.2)\end{aligned}$$

For lower frequencies, the absorption coefficient can be expressed as [128]

$$\alpha(f) = (0.002 + 0.11\frac{f^2}{f^2+1} + 0.011 f^2) \cdot 10^{-3}. \qquad (23.3)$$

An alternative expression for the absorption coefficient $\alpha(f)$ $[\mathrm{dB/m}]$ is given by the Fisher and Simmons formula [42]

$$\alpha(f) = (A_1 P_1 \frac{f^2}{f_1^2 + f^2} f_1 + A_2 P_2 \frac{f^2}{f_2^2 + f^2} f_2 + A_3 P_3 f^2) \cdot 10^{-3}, \qquad (23.4)$$

where the three terms account for the effects of boric acid, magnesium sulphate, and pure water, respectively. The terms A_1, A_2, A_3, f_1, and f_2 are somewhat complex functions of temperature, while P_1, P_2, and P_3 are functions of water pressure [141].

As seen in Fig. 23.3, the absorption coefficient is proportional to the operating frequency. Therefore, absorption loss is strongly dependent on frequency and distance. Moreover, water depth also plays a key role in determining the level of attenuation, as absorption is affected by water pressure [43]. This phenomenon can be modeled as

$$\alpha_d = \alpha_0 (1 - 1.93 \cdot 10^{-5} d), \qquad (23.5)$$

where α_0 and α_d are the absorption coefficients at depth zero ($d = 0$) and *d* meters respectively at a water temperature of $4\,^{\circ}\mathrm{C}$. Hence, the absorption loss decreases in deep water [118]. As mentioned earlier, attenuation is also provoked by multipath propagation, refraction, diffraction and scattering.

- **Noise:**

Acoustic noise in the underwater communication channel can be either *natural* or *man-made*. The latter is mainly caused by machinery noise (pumps, reduction gears, power plants), and shipping activities, while the former is produced by biological, seismic activities and hydrodynamics (waves, currents, tides, rain, and wind). The contributions of the major noise sources can be expressed through empirical formulae [38, 128], which provide power spectral densities of each source relative to frequency f $[\mathrm{kHz}]$ in $[\mathrm{dB\ re}\,\mu\,\mathrm{Pa\ per\ Hz}]$

$$10\log N_t(f) = 17 - 30\log f, \tag{23.6a}$$
$$10\log N_s(f) = 40 + 20(s-5) + 26\log f - 60\log(f+0.03), \tag{23.6b}$$
$$10\log N_w(f) = 50 + 7.5w^{1/2} + 20\log f - 40\log(f+0.4), \tag{23.6c}$$
$$10\log N_{th}(f) = -15 + 20\log f, \tag{23.6d}$$

where N_t, N_s, N_w, N_{th} stand for *turbulence*, *shipping*, *wind* and *thermal* noise, respectively. The total noise power spectral density for a given frequency f $[\mathrm{kHz}]$ is then

$$N(f) = N_t(f) + N_s(f) + N_w(f) + N_{th}(f). \tag{23.7}$$

Figure 23.4 depicts empirical noise power spectrum densities in deep water for different conditions of shipping and wind speeds. It can be observed that each noise source is dominant in specific frequency bands. Turbulence noise is dominant in the frequency band ($0.1\,\mathrm{Hz}$ - $10\,\mathrm{Hz}$), while *shipping activities* is

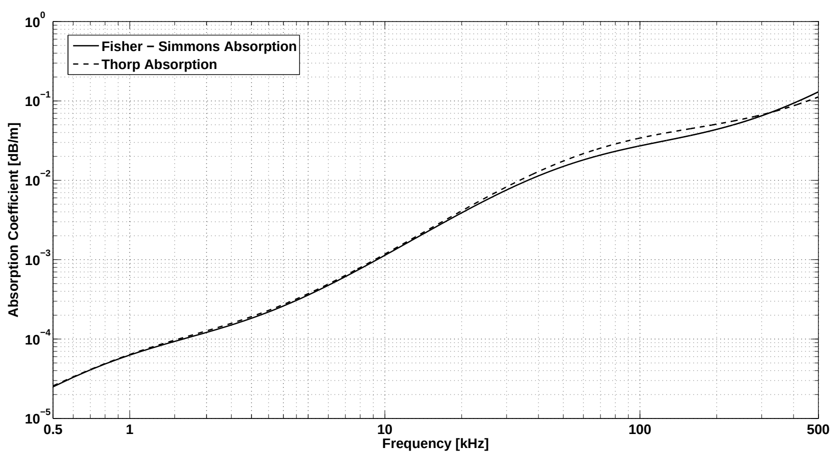


Figure 23.3 The Fisher and Simmons and Thorp's absorption coefficient.

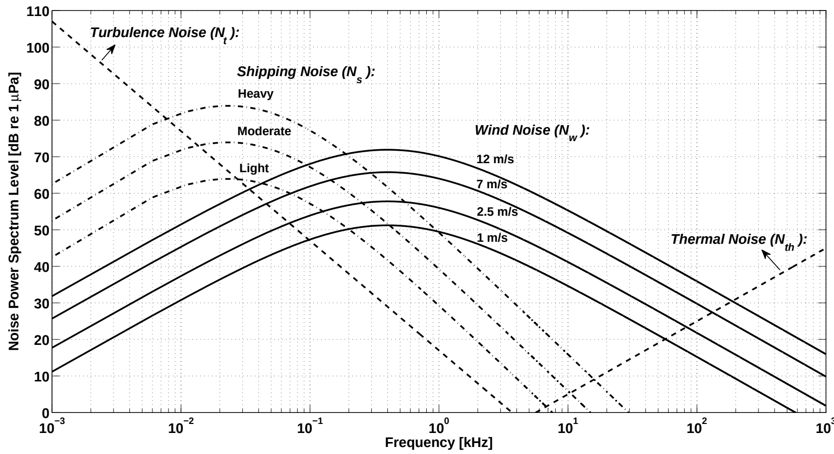


Figure 23.4 The noise power spectrum level in $\mathrm{dB\,re\,\mu\,Pa\,per\,Hz}$ based on empirical formulae. Shipping noise is presented for *high* (s $= 1$), *moderate* (s $= 0.5$), *light* (s $= 0$) shipping activities. Wind noise is shown for different wind speeds ($w =$ 1, 2.5, 7 and 12 m/s).

the major factor contributing to noise in the frequency region ($10\,\mathrm{Hz}$ - $200\,\mathrm{Hz}$). Shipping activities are typically weighted by a factor *s*, whose values range between 0 and 1 representing *low* and *high* activity, respectively. The frequency region ($0.2\,\mathrm{kHz}$ - $100\,\mathrm{kHz}$) is dominated by surface motion, which is mainly provoked by *wind* (w is the wind speed in m/s). For frequencies higher than ($100\,\mathrm{kHz}$) *thermal* noise is dominant. These noise sources depend on weather and other factors.

In shallow water, noise is difficult to model or predict compared to the deep water case, since it shows greater variability in both time and location. In [141], three major noise sources in shallow water environments are identified as wind noise, biological noise (especially noise created by snapping shrimp whose noise signature has a high amplitude and wide bandwidth) and shipping noise.

The signal-to-noise ratio (SNR) can be evaluated based on the transmission loss $TL(d, f)$ and the noise power spectral density $N(f)$. The narrowband SNR observed over a distance d when the transmitted signal has a frequency of f and power P, is given by [128]

$$SNR(d, f) = \frac{P/TL(d, f)}{N(f)\Delta f}, \tag{23.8}$$

where Δf is the receiver noise bandwidth (a narrow band around the frequency f). Figure 23.5 shows the factor $1/(TL(d,f)N(f))$, which defines the combined effect of transmission loss and noise in acoustic communication, for different transmission distances and frequency values. For a given transmission distance, the aforementioned factor is maximized corresponding to a specific frequency value f_p, which in practice indicates an optimal operating frequency for that specific transmission range. Consequently, f_p can be used as the center frequency and the transmission power can be adjusted accordingly to achieve the desired SNR level [128, 132].

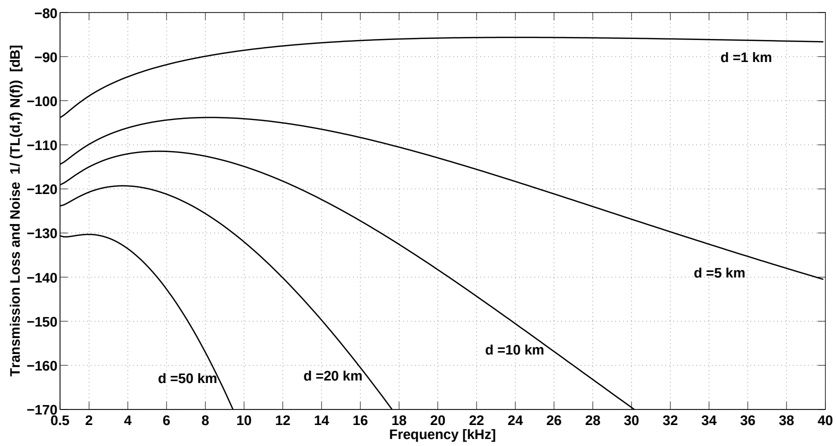


Figure 23.5 The factor that defines the combined effect of transmission loss and noise in dB. Practical spreading, k = 1.5, wind speed, w = 3 m/s and moderate shipping activity, s = 0.5.

- **Multipath:**

Multipath arises from either wave reflections from the surface, bottom and other objects, or wave refraction caused by sound speed variations with depth (acoustic waves always bend towards regions where the propagation speed is lower) [141, 129]. Multipath propagation can severely deteriorate the acoustic signal, as it generates inter-symbol interference (ISI) [68]. The multipath geometry depends on the link configuration. Vertical channels typically have little time dispersion, while horizontal channels may show long multipath spreads [18]. The extent of spreading is highly dependent on depth and distance between transmitter and receiver. The channel impulse response for a time-varying multipath underwater acoustic channel can be expressed as [79]

$$c(\tau, t) = \sum_p A_p(t)\delta(\tau - \tau_p(t)), \tag{23.9}$$

where $A_p(t)$ and $\tau_p(t)$ denote time-varying path amplitude and time-varying path delay respectively. This expression can be used in simulation studies and in developing receiver algorithms [79, 90].

- **High Delay and Delay Variance:**

  The propagation speed of an acoustic signal in water is five orders of magnitude lower than electromagnetic signal propagation in air. The high propagation delay can considerably reduce the throughput of the system [18], when typical networking protocols are used. The underwater acoustic propagation speed can be expressed empirically as [141]

$$\begin{aligned} c(z, S, t) \quad = \quad & 1449.05 + 45.7t - 5.21t^2 + 0.23t^3 + \\ & + (1.333 - 0.126t + 0.0009t^2) \cdot (S - 35) + \\ & + 16.3z + 0.18z^2, \end{aligned} \tag{23.10}$$

  where $t = 0.1 \times T$, T represents the temperature in ^oC, S is the salinity in ppt, and z is the depth in km. The propagation speed varies between ($1450\ \mathrm{m/s}$ - $1540\mathrm{m/s}$). The delay variance, caused by time-varying multipath propagation, may impact protocol design since it may prevent accurate estimation of the round trip time (RTT) [18].

- **Doppler Spread:**

  The range of frequencies over which the Doppler power spectrum of the channel is nonzero is called the Doppler spread of the channel, and is denoted as B_d [114]. The Doppler spread can be represented in time by the inverse of the coherence time of the channel, given by [114]

$$\Delta t_c \approx \frac{1}{B_d}. \tag{23.11}$$

  Doppler spread occurs as a result of Doppler shifts caused by motion at the source, receiver, and channel boundaries. Mobile nodes exhibit a Doppler shift proportional to their relative velocity, while currents and tides can also force moored nodes to move, introducing slight Doppler shifts. In addition to this, tidal and water currents can introduce Doppler shifts that create surface and volume scatterers relative to a fixed receiver [141]. When a channel experiences a Doppler spread with bandwidth B and if a transmitted signal has a symbol duration of T, then there will be BT uncorrelated samples of its complex envelope [18]. If BT is much less than unity, the channel is said to be *underspread*, and Doppler spread effects can be basically ignored. If greater than unity, it is said to be *overspread* [68]. The Doppler spread can be significant in UW-A channels [126], thus causing degradation in the performance of digital communications. ISI occurs at the receiver with high data rate transmission. Doppler spreading generates two different effects on signals: a simple frequency translation, which is relatively easy for a receiver to compensate for, and a continuous spreading of frequencies that creates a non-shifted signal.

23.4 PHYSICAL LAYER

The physical (PHY) layer encompasses functionalities like modulation, error correction and channel equalization for reliable transmission of digital bit streams. The key challenge underlying the PHY layer is to design spectrally efficient yet robust modulation schemes and receivers to exploit the limited bandwidth available in the underwater acoustic channel. This challenging objective has resulted in extensive research, whose developments we describe in this section. Specifically, in Section 23.4.1, we discuss non-coherent modulation techniques, which were initially used as a low-complexity, practical technique for underwater acoustic communications. In Section 23.4.2, we discuss coherent modulation methods, which are used to increase the spectral efficiency with respect to non-coherent methods. In Section 23.4.3, we discuss recent developments on channel equalization techniques. In Section 23.4.4, we look at the state of the art in direct-sequence spread-spectrum transmission schemes applied to underwater communications, while in Section 23.4.5, we discuss multi-carrier modulation schemes. Finally, in Section 23.4.6, we review advancements in spatial-modulation techniques.

23.4.1 Non-Coherent Modulation

In the early years of underwater acoustic communications researchers in the field mainly focused on non-coherent modulation methods due to their simplicity, reliability and robustness. In particular, frequency-shift keying (FSK) modulation schemes based on energy detection were favored since FSK modulation does not require carrier-phase tracking. Shallow water as well as long- and medium-range underwater acoustic channels show rapid phase variations mainly due to the Doppler spread caused by mobility of the acoustic medium and as a result phase tracking is very challenging [125, 18]. Multipath effects in underwater acoustic channel, which result in ISI, can be suppressed by inserting guard times between successive symbols to ensure that all the reverberations caused by the rough ocean surface and bottom vanish before the next symbol is received [18]. To adapt the communication to the Doppler spread of the underwater acoustic channel dynamic frequency guards with varying guard times may be used [18]. The insertion of guard intervals evidently diminishes the overall achievable data rate. Selection of an appropriate length of the guard interval is therefore very important to identify the right tradeoff between ISI suppression and achievable data rates. Moreover, since fading is correlated among frequencies separated by less than the coherence bandwidth, $B_c = 1/T_m$ (where T_m represents the multipath delay spread), frequency channels simultaneously in use need to be separated by at least a coherence bandwidth to avoid ISI [124]. This additional constraint impairs the efficiency of the modulation scheme unless a source coding method like multiple FSK (MFSK) is utilized in which symbols transmitted simultaneously on adjacent frequency channels belong to different codewords [124]. Even though non-coherent systems have bandwidth efficiency lower than 0.5 bit/s/Hz, they are characterized by high power efficiency and are ideal for applications that require moderate data rates with robust performance. The evolution of data rates achievable with non-coherent modulation techniques is shown in Table 23.2.

Table 23.2 Evolution of data rates for non-coherent modulation techniques.

Principal Investigator	Data Rate [kbit/s]	Band [kHz]	Bandwidth Efficiency	Range [km][a]	BER
Catipovic (1984) [33]	1.2	5	0.24	3_s	$\sim 10^{-2}$
Freitag (1990) [48]	2.5	20	0.13	3.7_d	10^{-4}
Freitag (1991) [50]	0.6	5	0.12	2.9_d	10^{-3}
Mackelburg (1991) [87]	1.25	10	0.13	2_d	N/A
Scussel (1997) [119]	0.6 - 2.4	5	0.47	10_d - 5_s	N/A

[a] The subscripts d and s stand for *deep* and *shallow* water respectively.
N/A indicates the data was not available in the published reference.

23.4.2 Coherent Modulation

To increase the spectral efficiency and communication range, research in underwater acoustic communications has shifted in recent years towards phase-coherent modulation techniques, such as phase-shift keying (PSK) and quadrature amplitude modulation (QAM) [18]. Phase-coherent systems were previously not considered feasible because of rapid phase variations in the underwater acoustic medium. However, with advancements in phase tracking algorithms, phase-coherent systems have become practical means for achieving high data rates over different underwater channels including severely time-spread horizontal shallow water channels [124, 131]. Interestingly, the raw data rates achievable on recently developed coherent underwater acoustic systems are an order of magnitude higher than those of the existing non-coherent systems [125].

Phase-coherent systems can be classified into two categories; *purely phase-coherent* and *differentially coherent*. Differential phase-shift keying (DPSK) encodes information relative to the previous symbol instead of using an arbitrary fixed reference. DPSK serves as an intermediate solution between non-coherent and purely coherent in terms of spectral efficiency [18]. The advantage of using DPSK is that it allows simple carrier recovery, while it suffers from higher bit error rates (BERs) compared to PSK at equivalent data rates [18]. Even though bandwidth-efficient methods have been extensively investigated in various underwater acoustic channels, real-time systems have primarily been employed for applications in *vertical* and *very* *short* range channels with stable phase and minimal multipath effects [125]. A selection of data rates achievable for DPSK modulation techniques is depicted in Table 23.3. To further enhance coherent modulation schemes researchers have utilized channel equalization techniques in underwater acoustic communication, which will be discussed next.

Table 23.3 Evolution of data rates for DPSK modulation techniques.

Principal Investigator	Data Rate [kbit/s]	Band [kHz]	Bandwidth Efficiency	Range [km][a]	BER
Mackelburg (1981) [88]	4.8	8/14	0.6	4.8_d	10^{-6}
Osen (1995) [98]	2	2/10	1.0	6_d	$< 10^{-3}$
Howe (1992) [58]	1.6	10/50	0.16	0.1_s	$< 10^{-3}$
Suzuki (1992) [135]	16	8/20	2.0	6.5_d	10^{-4}
Jones (1997) [64]	20	10/50	2.0	1.0_d	10^{-2}

[a] The subscripts d and s stand for *deep* and *shallow* water respectively.

23.4.3 Channel Equalization

Shallow water acoustic communications are characterized by the long delay spread caused by the multipath effects due to reflections from the surface and the bottom of the medium. Moreover, the dynamic channel environment caused by the motion of acoustic transducers, ocean floor, internal and surface waves results in long time variations and as a consequence leads to a high Doppler spread. Accordingly, channel equalization is essential for successful detection of coherent modulation schemes. Using PSK together with adaptive decision feedback equalizers (DFE) as well as spatial diversity combining is shown in [130] to be an effective solution for shallow water communications. Even though the underwater channel has long impulse response, the multipath arrivals are usually resolvable, which allows using a sparse equalizer with taps positioned according to the locations of the actual channel response [37]. In doing so one can effectively reduce the number of taps, and this may lead to lower complexity, faster channel tracking and improved performance [37]. In [133], an adaptive channel estimation-aided equalization algorithm is proposed in which spatial-diversity multi-channel combining is utilized to reduce the large number of input channels to fewer ones before equalization.

Underwater acoustic channels are generally considered sparse in nature since most of the channel energy is located at a few delay and/or Doppler values [25]. Lopez and Singer [86] have therefore proposed an algorithm that adaptively allocates DFE taps in sparse channels and alternates between updating feedback and feedforward filter tap placement for DFE. Unlike previous methods that either have a fixed or indirectly determine the number of sparse taps based on thresholding of impulse response estimate, their stopping criterion is based on estimated mean square error (EMSE). Experimental results conducted in the Narragasett Bay Operating Area using a four-hydrophone receive antenna array successfully demonstrated the effectiveness of the algorithm, which utilizes on average 10 feedforward taps per array element and 25 feedback taps. For shallow water environments, this number of taps is considerably smaller than the required taps for conventional DFE. More recently, Weichang and Preisig [84] developed a sparse channel estimation technique based on the delay-Doppler spread function representation of the channel to account for the time variation of the impulse response. The channel impulse response is consecutively estimated by selecting the dominant components that minimize the mean square error. The benefit of this method is that it captures the channel structure and its dynamics simultaneously without the need for explicit channel modeling. The proposed method is compared with non-sparse recursive least square (RLS) estimation and sparse channel impulse response estimation. Through experimental results the proposed method demonstrated a 3 dB reduction in signal prediction error.

Conventional equalization algorithms are supervised and require transmission of a training data sequence to enable the receiver to estimate the channel. In applications where long streams of data packets are transmitted over time invariant channel the overhead incurred by the pilot bits is insignificant. On the other hand, if short data packets are preferred for transmission or the channel is strongly time-varying, then the overhead from the training sequence could be significant. In such applications unsupervised (blind) equalization algorithms may be used. However, the latter normally converge slower than supervised ones and as a result their use is limited to transmission of long streams of data packets. In [76], the authors demonstrated that for short data record combining blind adaptive DFE with an iterative algorithm may reduce BER, hence performance may be improved.

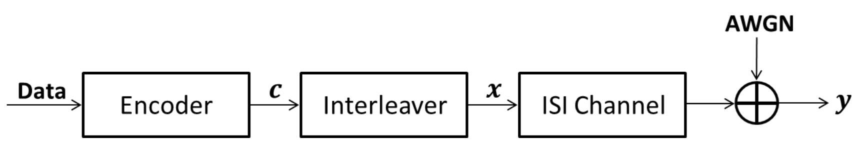


Figure 23.6 Transmission section of data transmitter system.

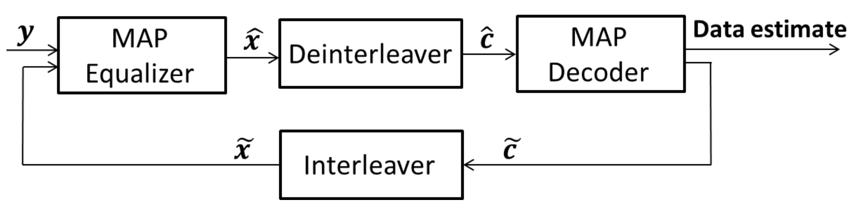


Figure 23.7 Receiver section with turbo equalization.

One of the drawbacks of DFE is that errors may propagate because of wrong decisions fed into the feedback loop. Strong forward error correction (FEC) codes may be used to combat the error propagation and as a result reduce the BER. Turbo codes, Reed-Solomon (RS) codes as well as low-density parity check codes (LDPC) are considered among the strongest FEC codes [95]. As a natural consequence, turbo equalizers were developed in which an iterative interaction between the equalizer and a decoder results in joint estimation, equalization and decoding [121]. As shown in Fig. 23.6, at the transmitter side the data is encoded, interleaved and transmitted through the channel. Figure 23.7 depicts the receiver structure with turbo equalization in which the received signal, $\mathbf{y}$, is first passed through a maximum *a posteriori* probability (MAP) equalizer, then it is de-interleaved and MAP decoded. After interleaving the estimated data bits are fed back into the MAP equalizer to reduce errors. However, the downside of MAP equalizers lies in the fact that the computational complexity increases exponentially with the channel memory. In [26], a soft-input DFE structure is proposed instead of the MAP algorithm in the turbo equalizer. By combining data from multiple receivers, spatial diversity is achieved. According to the authors, using a separate DFE for each receiver with log-likelihood ratio output provides good performance. A selection of achievable data rates for coherent modulation techniques is shown in Table 23.4.

Table 23.4 Evolution of data rates for coherent modulation techniques.

Principal Investigator	Modulation Method	Data Rate [kbit/s]	Band [kHz]	Range [km][a]	BER
Suzuki (1989) [134]	4, 8-PSK	20 - 30	10 / 25	3.5_d	10^{-4}
Kaya (1989) [66]	16-QAM	500	125 / 1000	0.06_d	10^{-7}
Stojanovic (1993) [130]	4, 8-PSK, 8-QAM	0.6 - 3.0	0.7 - 1.4	28 - 120_s, 74 - 259_d	10^{-2}
Labat (1994) [52]	QPSK	6	3 / 60	4_d	N/A
Capellano (1997) [29]	BPSK	0.2	0.2 / 7	50_d	10^{-4}
Freitag (1998) [47]	QPSK	1.67 - 6.7	2 - 10	4.0_s, 2.0_s	N/A
Kojima (2002) [71]	4, 8-PSK, 16-QAM	46, 96, 128	40	0.03_d	10^{-5}
Pelekanakis (2003) [100]	8-PSK, 16, 32, 64-QAM	75, 100, 125, 150	60 - 90	0.01_d	~ 0
Ochi (2010) [97]	QPSK, 8-PSK	80, 120	80	0.84_d, 0.62_d	~ 0

[a] The subscripts d and s stand for *deep* and *shallow* water respectively.
N/A indicates the data was not available in the published reference.

23.4.4 Direct-Sequence Spread-Spectrum

In direct-sequence spread-spectrum (DSSS) modulation, a narrowband signal of bandwidth B is spread over a wideband signal of bandwidth W before transmission. The spreading operation is done by multiplying each symbol with a pseudo-random or pseudo-noise (PN)-like code sequence with a spreading code length,

$L = W/B$ and transmitting the generated signal at a higher rate. At the receiver side, the received signal is de-spread, using the same spreading code, before decoding. Multiuser communication may be supported by assigning each user with a unique spreading sequence with good autocorrelation and cross-correlation properties that can resist interference from multiple users. DSSS, also known as direct-sequence code-division multiple-access (DS-CDMA), has many characteristics that make it an appealing modulation (and multiple access) scheme for underwater acoustic communications. One of the properties of DS-CDMA is that it is resilient to adversary jammer and can therefore enable covert communications. Besides, DS-CDMA has more relaxed synchronization requirements compared to Time Division Multiple Access (TDMA) schemes. Moreover, DS-CDMA combined with a RAKE receiver may be used to combat the multipath fading acoustic channel. In non-coherent DS-CDMA, each user detects the signal of interest by matched-filtering the received signal and performing energy detection. Coherent DS-CDMA is more involved as it may require channel estimation and phase tracking before de-spreading and decoding the information bits [49]. The spreading operation of DS-CDMA may affect the achievable data rates. For bandwidths of several kHz, the data rates are in the order of hundreds of $\mathrm{bit/s}$, which results in bandwidth efficiency lower than $0.5\ \mathrm{bit/s/Hz}$ [85].

Due to the highly-frequency selective distortion caused by multipath propagation, it would be useful, if not essential, to employ DFE in DS-CDMA receiver design. In [132], Stojanovic and Freitag propose two types of DFEs, a symbol decision feedback (SDF) receiver and a chip hypothesis feedback (CHF) receiver. SDF feedback equalization is adapted at the symbol level, which makes use of the symbol decisions after being de-spread on the feedback path. For highly time varying channels, CHF feedback equalization is utilized instead. The latter tracks the channel at the chip rate, R_c, at the price of an increase in computational complexity. In more recent work the authors in [19] proposed two iterative DFE receivers, DFE-IDMA (interleave-division multiple access) and DFE-CDMA. Both of the single-element receivers utilize chip-level adaptive DFE, carrier phase tracking together with iterative interference cancellation (IC) and channel coding. The experimental results show that the proposed adaptive receivers outperform channel estimation based RAKE receivers and maintain lower complexity. The achievable data rates of some DS-CDMA modulation techniques is shown in Table 23.5.

23.4.5 Multi-Carrier Modulation

A possible way to overcome the long delay-spread in underwater communication is to use multi-carrier modulation schemes such as orthogonal frequency-division multiplexing (OFDM) [120]. Multi-carrier processing maps the frequency selective channel into a set of flat-fading sub channels. Accordingly, equalization may be done by multiplying each flat-fading channel output by a single complex tap value. As a result, long equalization filters required to combat ISI may be avoided and hence the complexity of the receiver design may be reduced significantly [120]. However, the major challenge in applying multi-carrier modulation for underwater acoustic chan-

Table 23.5 Evolution of data rates for DS-CDMA modulation techniques.

Principal Investigator	Modulation Method	L	Data Rate per user [kbit/s]	R_c [kchip/s]	Range [km][a]	BER
Freitag (2000) [45]	BPSK	15, 31	0.12, 0.058	4	3_s	~ 0
Stojanovic (2006) [132]	QPSK	15, 63, 255	2.5, 0.6, 0.15	19.2	2.3_s	~ 0
Calvo (2008) [28]	QPSK	15, 63, 255	2.048, 0.487, 0.12	16	2.3_s	~ 0
He (2011) [56]	M-ary	31, 63, 127	0.129, 0.063, 0.031	2	5 - 15_s	~ 0

[a] The subscripts d and s stand for *deep* and *shallow* water respectively.
N/A indicates the data was not available in the published reference.

nel is the presence of large Doppler spread caused by time variation of the acoustic channel. As a consequence, the orthogonality principle among subcarriers may no longer hold and may result in inter-carrier interference (ICI). Early attempts at applying OFDM in underwater acoustic channels had limited success due to lack of effective ways to suppress the ICI [85].

Recently, however, OFDM schemes have actively been investigated for underwater acoustic communications, including [127] on a low-complexity adaptive OFDM receiver design, [51] on non-coherent OFDM based on on-off keying (OOK) and [79] on a pilot-tone based block-by-block receiver design. In [127] a non-uniform Doppler compensation algorithm is proposed that utilizes low-complexity post-FFT (Fast Fourier Transform) phase tracking. The receiver uses adaptive channel estimation and performs minimum mean square error (MMSE) combining of signals collected from an array of receivers to successfully correct Doppler shifts of about $7\ \mathrm{Hz}$. Experiments conducted through a shallow water channel over a distance of $2.5\ \mathrm{km}$ using quadrature phase-shift keying (QPSK) modulation in $24\ \mathrm{kHz}$ acoustic bandwidth data rate of $30\ \mathrm{kbit/s}$ was recorded. The experimental results reveal that to maximize the bandwidth efficiency an optimal number of carriers need to be selected. While non-coherent OFDM-OOK was designed using a low complexity receiver in mind with a potential of offering signaling rates close to binary phase-shift keying (BPSK). The block-by-block coherent receiver does not rely on channel dependence across OFDM blocks; hence it is suitable for fast varying underwater acoustic channels [82, 83]. In [80], a scalable OFDM design is proposed that adapts to a vast range of transmission bandwidths. Employing QPSK modulation with $1/2$ coding for bandwidth variation from $3\ \mathrm{kHz}$ to $50\ \mathrm{kHz}$ data rates of $1.5\ \mathrm{kbit/s}$ to $25\ \mathrm{kbit/s}$ were reported in [80]. Moreover, using a 16-QAM modulation with $1/2$ coding data rates of $12\ \mathrm{kbit/s}$, $25\ \mathrm{kbit/s}$ and $50\ \mathrm{kbit/s}$ were achieved again in [80] for bandwidths of $12\ \mathrm{kHz}$, $25\ \mathrm{kHz}$ and $50\ \mathrm{kHz}$ respectively. Recent studies indicate that OFDM modulation is a feasible and flexible means for underwater acoustic communications. A selection of achievable data rates for multi-carrier modulation techniques is shown in Table 23.6.

Table 23.6 Evolution of data rates for multi-carrier modulation techniques.

Principal Investigator	Modulation Method	Data Rate [kbit/s]	Band [kHz]	Range [km][a]	BER
Stojanovic (2006) [127]	QPSK	30	24	2.5_s	~ 0
Li (2008) [80]	QPSK	1.5 - 25	3 - 50	0.5_d	10^{-5}
Li (2008) [80]	16-QAM	12, 25, 50	12, 25, 50	0.5_d	10^{-5}
J.-Z. Huang (2010) [60]	QPSK, 16-QAM	5.2, 10.4	9.77	1_s	10^{-3}

[a] The subscripts d and s stand for *deep* and *shallow* water respectively.
N/A indicates the data was not available in the published reference.

23.4.6 Spatial Modulation

The underwater acoustic channel suffers from limited bandwidth availability and spectral efficiency. The success of techniques that leverage spatial diversity in the RF community has inspired researchers to explore spatial modulation schemes in underwater acoustic channels. A wireless system that utilizes multiple transmitters and multiple receivers is referred to as multiple-input-multiple-output (MIMO) system. By using multiple receive and transmit antennas, *diversity gain* may be explored by transmitting multiple copies of the same information through different independently fading channels. Multiple independent replicas of the received signal increase the probability of correct reception. On the other hand, by transmitting multiple independent streams of information through spatial channels, so-called *multiplexing gain* may be achieved, which may lead to increase in data rate [146]. However, there is a tradeoff since a higher spatial *multiplexing gain* comes at the price of sacrificing *diversity gain* and vice versa [146]. According to Shannon's theory, the theoretical MIMO channel capacity in a scattering-rich environment depends on the correlation between the channel gains on each antenna element and increases linearly with the minimum between the number of transmit and receive antennas [53].

MIMO modulation has been explored in both single-carrier and multi-carrier transmission in underwater acoustic channels. By applying spatial modulation on single carrier transmission with existing equalization techniques, a $5\ \mathrm{dB}$ space-time coding gain and about double capacity are reported in [69] compared to a temporal modulation scheme. Moreover, in [117] using four transmitters and QPSK modulation, data rates of $48\ \mathrm{kbit/s}$ over $23\ \mathrm{kHz}$ bandwidth over a range of $2\ \mathrm{km}$ were reported. In another experiment using six transmitters and QPSK modulation a data rate of $12\ \mathrm{kbit/s}$ over $3\ \mathrm{kHz}$ bandwidth over a range of $2\ \mathrm{km}$ was achieved, i.e., a spectral efficiency of $4\ \mathrm{bit/s/Hz}$. The combination of MIMO with OFDM is yet another attractive scheme to increase data rates in underwater acoustic channels. In [81], a MIMO-OFDM scheme is designed with two transmitters and four receivers, and almost errorless performance is observed. In the same work, using QPSK modulation after 1/2 rate LDPC coding, a data rate of $12.18\ \mathrm{kbit/s}$ was achieved with $12\ \mathrm{kHz}$ bandwidth leading to a spectral efficiency of $1\ \mathrm{bit/s/Hz}$, which is double the efficiency compared to single transmission in [83] with the same modulation and coding scheme.

The potential increase in data rates and spatial diversity in underwater acoustic communications may only be achieved if the transducers are spaced by more than the signal coherence length in transmit and receive antenna arrays. Based on experimental data in [144], Yang studied the spatial processing gain as a function of the number of receivers and the receiver separations. For a given number of receivers, the optimal output SNR may be obtained by separating the receivers by at least a signal coherence length. The achievable data rates of some MIMO modulation techniques are shown in Table 23.7.

Table 23.7 Evolution of data rates for MIMO modulation techniques.

Principal Investigator	Modulation Method	M_t	M_r	Data Rate [kbit/s]	Band [kHz]	Range [km][a]	BER
Roy (2007) [117]	QPSK	4	N/A	48	23	2_d	$\sim 10^{-2}$
Roy (2007) [117]	QPSK	6	N/A	12	3	2_d	$\sim 10^{-2}$
Li (2007) [81]	QPSK	2	4	12.18	12	2_d	10^{-5}
Li (2009) [78]	QPSK, 8, 16-QAM	2	N/A	31.4, 47.1, 62.8	31.25	0.45_s	~ 0
Li (2009) [78]	QPSK, 8, 16-QAM	2	N/A	62.8, 94.3, 125.7	62.5	0.45_s	~ 0
Huang (2010) [59]	QPSK, 16-QAM	2	4	10.4, 20.8	9.77	1_s	10^{-3}
Huang (2010) [59]	QPSK, 16-QAM	3	6	15.6, 31.2	9.77	1_s	10^{-3}

M_t and M_r are number of transmit and receive antennas respectively used in the experiment.
[a] The subscripts d and s stand for *deep* and *shallow* water respectively.
N/A indicates the data was not available in the published reference.

To summarize, non-coherent modulation methods, although with modest data rates, are still in use for applications that may be satisfied with low data rate but require robust and low-complexity system design. On the other hand, coherent modulation schemes were implemented to increase the data rates. Advancements in DFE combined with FEC schemes improved the performance of underwater acoustic communication links. Moreover, the emergence of multi-carrier and MIMO modulation schemes has further enhanced the data rate and spectral efficiency of underwater acoustic communications.

23.5 MEDIUM ACCESS CONTROL LAYER

In this section we review the state of the art in medium access control protocols for UnderWater Acoustic Sensor Networks (UW-ASNs). The unique characteristics of the propagation of acoustic waves underwater introduce specific challenges in the design of multiple access protocols. In particular,

- The available bandwidth is severely limited;
- The propagation delay is five orders of magnitude higher than in RF terrestrial channels, and possibly variable;
- High BERs and temporary losses of connectivity are frequently experienced.

Multiple access techniques can be broadly classified into two main categories: i) schedule-based, such as frequency-division multiple access (FDMA) and TDMA and ii) random-access based, such as ALOHA and carrier-sense multiple access (CSMA). Moreover, CDMA-based MAC protocols can be used in both scheduled and random-access based environments and possibly improve the system performance by allowing simultaneous code-division transmissions from multiple stations.

Table 23.8 illustrates some pros and cons of each category of MAC protocol for underwater communications. Due to the narrow bandwidth in UW-A channels and the vulnerability of limited band systems to fading and multipath, together with the often distributed nature of control in underwater networks, FDMA is rarely used. Pure TDMA schemes have also been proposed. For example, the Staggered TDMA Underwater MAC Protocol (STUMP) [72] is a TDMA-like protocol that uses propagation delay information to enable concurrent transmissions by multiple nodes and thus increase the channel utilization. However, TDMA shows a limited channel utilization efficiency in large-scale networks because of the long time guards and/or heavy signaling requirements in UW-A links. Therefore, current underwater MAC solutions are for the most part based on random access schemes such as ALOHA, CSMA or CDMA.

Table 23.8 Classification of MAC protocols in underwater communications.

	Pros	Cons
FDMA-based	Multiple users access simultaneously	Narrow bandwidth in UW-A channels and vulnerability of limited band systems.
TDMA-based	Avoiding collisions	Limited channel utilization efficiency in large-scale networks.
ALOHA-based	Easy to implement	Pure ALOHA has limited channel utilization.
CSMA-based	Prevents collisions with ongoing transmission	Channel may be sensed idle while a transmission is ongoing.
CDMA-based	Robust to frequency-selective fading caused by underwater multipaths	Near-far problem reduces the performance.

23.5.1 ALOHA-based MAC Protocols

In pure ALOHA, nodes transmit backlogged packets without performing channel sensing before accessing the medium. After receiving a packet, the receiver sends an acknowledgment to inform the transmitter that the data has been received successfully. If a collision happens, the transmitter will not receive the acknowledgment and instead it will retransmit the packet. However, the efficiency of Pure ALOHA is low [70]. Slotted ALOHA is an improved version of Pure ALOHA that introduces discrete time slots. A node can transmit data only at the beginning of a time slot. Collisions are consequently reduced, resulting in increased throughput.

In [36], two ALOHA-based protocols, called ALOHA with collision avoidance (ALOHA-CA) and ALOHA with advance notification (ALOHA-AN), are proposed for underwater acoustic networks. In ALOHA-CA, the sender-receiver information extracted from the overheard packet along with the propagation delay of the packet is used to estimate for how long the channel will be busy. Based on these calculations, each node decides the time for transmitting its packet to avoid collisions. Each packet is divided into two distinct segments, a header segment and a data segment. By overhearing a packet, each node monitors the states of every neighboring node and updates its local database table. A node checks its database table before transmitting a packet to ensure that the transmission would not result in a collision at any other node. ALOHA-AN is an improved version of ALOHA-CA; it transmits a small advance NoTiFication (NTF) packet prior to transmitting the data packet so that other nodes have prior information about the data packet arrival. The sender will then wait for a period of time, called the *lag time*, before sending the actual data packet. The main advantage of having a lag time between the NTF and the data packets is that a node extracts information from multiple NTF packets and makes better decisions in trying to avoid collisions. Small lag time prevents nodes from acquiring enough NTF packets from their neighbors, thus resulting in higher collisions and as a consequences lower throughput. Conversely, a long lag time results in nodes wasting a lot of time listening to NFT packets, hence bandwidth is underutilized. In conclusion, with a suitable selection of the lag time, ALOHA-AN offers better throughput than ALOHA-CA.

23.5.2 CSMA-based MAC Protocols

CSMA [39] prevents collisions with ongoing transmissions at the transmitter side. A node wishing to transmit data first listens to the medium for a certain amount of time. If it does not hear a transmission from another node, the node is allowed to begin its transmission. However, due to the high propagation delay of UW-A channels, when carrier sense is used, the channel may be sensed idle while a transmission is ongoing, since the signal may not have reached the receiver yet. Thus, collisions are more likely to occur.

In [94], slotted floor acquisition multiple access (Slotted FAMA) is proposed, which combines carrier sensing (CS) and a dialogue between the source and receiver prior to data transmission. During the initial dialogue, control packets are exchanged between the source node and the intended destination node to avoid multiple transmissions at the same time. A node wishing to transmit data waits until the next slot and transmits an request to send (RTS) packet. The RTS packet is received by the destination node and the neighboring nodes of the source node within the slot time.

Unlike IEEE 802.11 protocol, the destination node then sends a clear to send (CTS) packet at the beginning of the next time slot. The CTS packet will be received by the source node and the neighboring nodes of the destination node within the slot time. Once the source node has received the CTS packet, it knows that it is allowed to transmit. The source node waits until the beginning of the next slot and then starts transmitting the data packet. After the destination node has received the entire data packet, it sends an ACK packet to indicate that the transmission has ended successfully. Moreover, time slotting eliminates the asynchronous nature of the protocol and the need for excessively long control packets, thus saving energy.

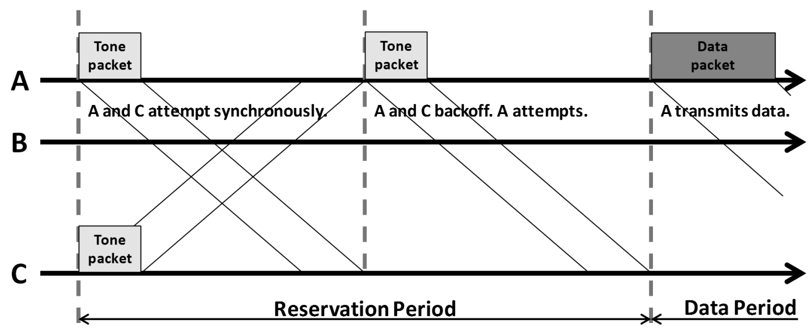


Figure 23.8 Illustration of the reservation procedure in ST-Lohi.

T-Lohi [137] is a tone-based contention mechanism that exploits space-time uncertainty and high latency to detect collisions and count contenders. Nodes send short reservation tones and then listen for the duration of the contention round (CR) to prevent data packet collisions. If they do not overhear tones sent by other nodes, the reservation is successful and then they transmit data at the end of the CR. If multiple nodes compete in a CR, each of them will hear the tones from other nodes, and thus will back off and try again in a later CR. T-Lohi uses a low-power wake-up tone receiver to reduce the energy consumption. The modem’s data receiver and the host central processing unit (CPU) are off as often as possible. They are activated when a tone is detected by the low-power wake-up receiver. The authors define three flavors of T-Lohi that vary the reservation mechanism with different implementation requirements and performance results. Synchronized T-Lohi (ST-Lohi), as shown in Fig. 23.8, assumes that all nodes are time synchronized. ST-Lohi exploits synchronization to estimate contender behavior, at the cost of requiring distribution of some reference time. In Conservative Unsynchronized T-Lohi (cUT-Lohi), nodes can start contending any time they know the channel is idle. cUT-Lohi avoids the complexity of synchronization but its long contention time reduces throughput. Aggressive unsynchronized T-Lohi (aUT-Lohi) follows cUT-Lohi, however cuts the duration of its contention round. The channel utilization of aUT-Lohi is better than cUT-Lohi, but the packet loss of aUT-Lohi is higher due to collisions.

A detailed comparison and performance evolution of CSMA-based protocols is presented in [103]. The throughput efficiency and the packet latency are compared.

The performance of these protocols is evaluated from traces recorded during extensive tests off Pianosa island. The authors investigated the impact on performance of different possible packet sizes. The results show that larger packet sizes can lead to significantly better system performance in terms of throughput efficiency, at a cost of increased packet latency, especially for low traffic loads. The authors also show how acoustic modem operations and limitations can strongly affect at-sea performance and how overcoming some of these limitations can strongly improve the network performance in terms of throughput efficiency and packet latency.

23.5.3 CDMA-based MAC Protocols

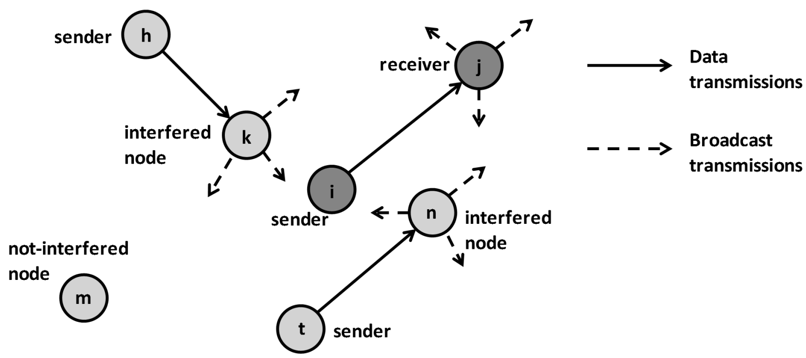


Figure 23.9 Message transmissions in UW-MAC.

CDMA transmission techniques, as discussed in Section 23.4.4, are robust to frequency-selective fading caused by underwater multipaths. In [110], a distributed MAC protocol named UW-MAC tailored for UW-ASNs is proposed. Extensive simulations demonstrate that UW-MAC achieves high network throughput, low channel access delay, and low energy consumption. UW-MAC simultaneously achieves these three objectives in deep water communications, which usually are not severely affected by multipath. In shallow water communications, which may be heavily influenced by multipath, it dynamically finds the optimal tradeoff among these objectives according to the application requirements. UW-MAC is a transmitter-based CDMA scheme that incorporates a novel closed-loop distributed algorithm to set the optimal transmit power and code length.

In UW-MAC, nodes randomly access the channel transmitting a short header called Extended Header (EH), which is sent using a common pseudo-random code known by all devices at the maximum rate (minimum code length). The EH contains information about the chosen next hop, and the subset of parameters that the sender will use to generate the chaotic spreading code for the actual data packet. Immediately after transmission of the EH, the sender transmits the data packet on the channel using the optimal transmit power and code length set by a power and code self-assignment algorithm. If no collision occurs during the reception of the

EH, the chosen next hop will be able to 1) synchronize to the signal from the sender, 2) despread the EH using the common code, and 3) acquire the carried information. At this point, if the EH is successfully decoded, the receiver will be able to locally generate the chaotic code that is used by the sender to send its data packet, and set its decoder according to this chaotic code. Once the receiver has correctly received the data packet from the sender, it acknowledges it by sending an ACK packet to the sender. For the distributed power and code self-assignment problem, UW-MAC periodically collects information on the state of the channel from the neighborhood and feeds the algorithm with the required information, as shown in Fig. 23.9. In order to set the transmit power and spreading factor, a node needs to leverage information on the multiple access interference (MAI) and normalized receiving spread signal of neighboring nodes. This information is broadcast periodically by active nodes.

MIMO techniques use multiple antennas at both the transmitter and receiver to improve communication performance. MIMO systems offer significant capacity improvement compared to single-input-single-output (SISO) systems. They may exploit the rich scattering and multipath fading to provide higher spectral efficiencies without increasing power and bandwidth. MIMO communications are characterized by i) the transmission rate increasing with the multiplexing gain, and ii) the BER decreasing with increasing diversity gain. In [73], a new medium access control protocol named UMIMO-MAC is proposed. UMIMO-MAC is designed to i) adaptively leverage the tradeoff between multiplexing and diversity gain according to channel conditions and application requirements, ii) select suitable transmit power to reduce energy consumption, and iii) efficiently exploit the UW-A channel, minimizing the impact of the long propagation delay on the channel utilization efficiency. In a cross-layer fashion, UMIMO-MAC jointly selects optimal transmit power and transmission mode through the cooperation of transmitter and receiver to achieve the desired level of reliability and data rate according to application needs and channel condition. In UMIMO-MAC, each transmitter is assumed to know the distance from itself to its neighbors. Each transmitter is also assumed to be capable of estimating the transmission loss. Moreover, each receiver is capable of estimating the MAI and noise power.

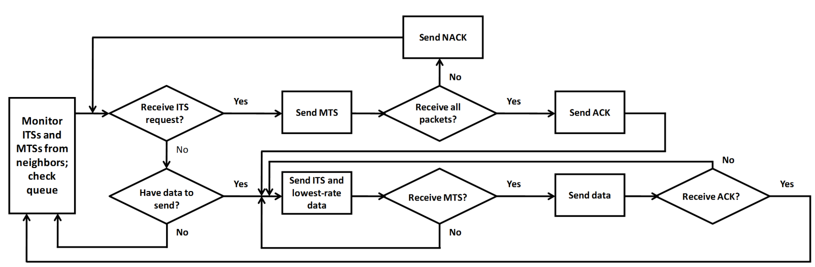


Figure 23.10 The flowchart of UMIMO-MAC.

Figure 23.10 depicts the flowchart of UMIMO-MAC, and Fig. 23.11 illustrates the basic operations and timing of the UMIMO-MAC protocol. The protocol em-

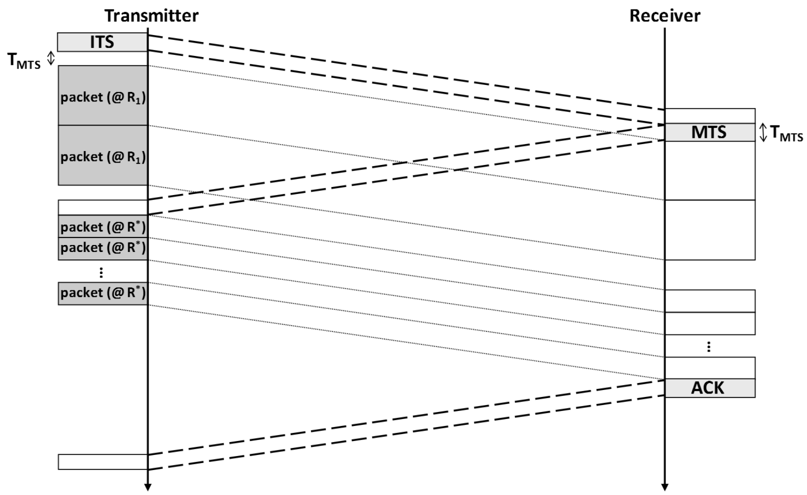


Figure 23.11 The UMIMO-MAC protocol, where R_1 is the lowest transmission rate and R^* is the assigned transmission rate.

ploys *Intent to Send* (ITS) and *Mode to Send* (MTS) control packets to negotiate and regulate channel access among competing nodes. Note that while this may seem to be analogous to the IEEE 802.11-like carrier sense multiple access with collision avoidance protocols (CSMA-CA), the analogy with CSMA-CA is limited to the two-way handshake - UMIMO-MAC does not employ carrier sense, and there is no collision avoidance mechanism. In addition, unlike IEEE 802.11-like protocols, a single ITS-MTS handshake is used to transmit a block of consecutive packets. This is done to improve the utilization efficiency of the underwater channel. ITS and MTS are transmitted using a common spreading code which is known by all nodes. The ITS contains i) the parameters that will be used by the transmitter to generate the spreading code for the data packet, ii) the upper bound on the transmit power, and iii) the total number of packets that will be transmitted back-to-back. Based on this information, the receiver will be able to locally generate the spreading code that the transmitter will use to send data packets. The receiver will calculate the appropriate transmission mode and transmit power for the transmitter. Besides, by overhearing the ITS, the transmitter's neighbors can become aware of the time when the transmitter will end its transmission. The MTS contains i) the chosen transmission mode, i.e., the multiplexing and diversity tradeoff, ii) the assigned transmit power, iii) the receiver's interference tolerance, and iv) the finish receive time. The chosen transmission mode and the assigned transmit power will be used by the transmitter to generate the signal. However, power and transmission mode are selected at the receiver, since the latter can be responsive to the dynamics of the channel based on local measurements and consequently control loss recovery and rate adaptation. With suitable transmission mode and transmit power obtained by ITS/MTS handshake, neither the transmitter will impair nor the receiver will be impaired by ongoing communications. Therefore, the retransmission probability is reduced, thus avoiding feedback overheads and latency. The receiver's interference tolerance and finish receive time are used by the neighbors of the receiver to determine their own upper bound on transmission power. DATA and ACK are then transmitted using the assigned spreading code.

23.6 NETWORK LAYER

Because of the unique nature of the underwater environment and applications, many existing RF routing solutions developed for ad hoc and sensor networks show poor performance in underwater networks. Existing routing protocols are usually divided into three categories, namely *proactive, reactive* and *geographical* routing protocols:

- *Proactive protocols* (e.g., destination-sequenced distance vector (DSDV) [102], optimized link state routing (OLSR) [62]). These protocols attempt to minimize the message latency by maintaining up-to-date routing information at all times from each node to every other node. This is obtained by broadcasting control packets that contain routing table information (e.g., distance vectors). These protocols provoke a large signaling overhead to establish routes for the first time and each time the network topology is modified because of mobility or node failures, since updated topology information has to be propagated to all the nodes in the network. Scalability and excessive use of bandwidth are major issues in these families of protocols, which make them unsuitable for dynamic underwater networks.

- *Reactive protocols* (e.g., ad hoc on-demand distance vector (AODV) [101], dynamic source routing (DSR) [63]). A node initiates a route discovery process only when a route to a destination is required. Once a route has been established, it is maintained by a route maintenance procedure until it is no longer desired. These protocols are more appropriate for dynamic environments but incur a higher latency and still require source-initiated flooding of control packets to establish paths. Reactive protocols are considered unsuitable for underwater networks because they cause a high latency in the establishment of paths, which is amplified by the slow propagation of acoustic signals underwater. Furthermore, links are likely to be asymmetrical, due to bottom characteristics and variability in sound speed channel. Hence, protocols that rely on symmetrical links, like most reactive protocols, may not be feasible.

- *Geographical routing protocols* (e.g., greedy-face-greedy (GFG) [27], partial-topology knowledge forwarding (PTKF) [91]). These protocols establish source-destination paths by leveraging localization information, i.e., each node selects its next hop based on the position of its neighbors and of the destination node. These techniques are very promising for their scalability and limited signaling requirements. However, global positioning system (GPS) radio receivers do not work underwater. Therefore, ad-hoc designed accurate localization techniques are essential. For example, in [93], the Sufficient Distance Map Estimation (SDME) scheme provides an energy efficient self-localization approach for underwater mobile networks. In [138], the Underwater Sensor Positioning (USP) scheme is proposed to improve localization capabilities in three-dimensional underwater sensor networks.

Table 23.9 Classification of routing protocols in underwater communications.

	Pros	Cons
Proactive	Routing protocol always tries to keep its routing data up-to-date	Scalability is a major issue
Reactive	Route is only determined when actually needed	A higher latency is amplified by the slow propagation of acoustic signals
Geographical	Very promising for their scalability and localized signaling	GPS radio receivers do not work underwater

Table 23.9 illustrates some pros and cons of each routing protocol in underwater communications. Recent work has proposed routing protocols specifically tailored for underwater acoustic networks. We classify underwater routing protocols as *location-based* and *non-location-based*, and discuss recently-proposed solutions in the following sections.

23.6.1 Location-based Routing Protocols

In [123], the authors provide a simple design example of a shallow water network, where routes are established by a central manager based on neighborhood information gathered from all nodes by means of poll packets. The nodes create neighbor tables, which contain a list of node's neighbors and the quality measure of their link, during initialization. The quality of link could be measured by the received SNR from the corresponding neighbor. Then, the master node collects the neighbor tables and forms a routing tree.

In [108], the problem of data gathering for three-dimensional underwater sensor networks is investigated at the network layer by considering the interactions between the routing functions and the characteristics of the underwater acoustic channel. A resilient routing solution tailored for long-term critical monitoring missions is proposed. The proposed routing solution follows a two-phase approach. In the first phase, the network manager determines optimal node-disjoint primary and backup multi-hop data paths such that the energy consumption of the nodes is minimized. In the second phase, an on-line distributed solution guarantees survivability of the network, by locally repairing paths in case of disconnections or failures, or by switching the data traffic on the backup paths in case of severe failures.

In [112], a new geographical routing algorithms designed to distributively meet the requirements of delay-insensitive and delay-sensitive sensor network applications for the 3D underwater environment is proposed. The proposed routing solutions allow each node to select the optimal next hop, transmit power, and strength of the forward error correction algorithm, with the objective of minimizing the energy consumption. The proposed routing solution allows a node to select the next hop that satisfies the following two requirements: 1) it is closer to the surface station than the sender, and 2) it minimizes the energy required to successfully transmit a payload bit from the sender to the sink. The proposed routing solutions are tailored for the characteristics of the 3D underwater environment, e.g., they take into account the very high propagation delay, which may vary in horizontal and vertical links, the different components of the transmission loss, the impairment of the physical channel, the limited bandwidth, and the high BER. These characteristics lead to a very low utilization of the underwater acoustic channel when communication protocols not specifically designed for this environment are adopted. The proposed routing solutions allow achieving two conflicting objectives, i.e., 1) increasing the efficiency of the acoustic channel and 2) limiting the packet error rate on each link. In other words, this conflict is between achieving high channel efficiency (which requires longer packets) and maintaining low packet error rate (which requires smaller packets). This problem is resolved by letting a sender transmit a train of short packets back-to-back without releasing the channel.

In [148], the authors propose a class of routing schemes designed to take into account all major effects that characterize underwater communications and study tradeoffs in the design of energy efficient routing protocols for underwater networks. The proposed routing scheme is a geographic forwarding approach that chooses the next hop toward the destination, and only requires local positioning information. The optimal per-hop distance can be calculated off-line according to different application requirements, and announced to all nodes at network setup. In dynamic scenarios, one or more specific nodes are in charge of periodically calculating the optimal per-hop distance information and broadcasting it to all nodes in the network.

In [20], the authors present a new distributed cross-layer Channel-Aware Routing Protocol (CARP) for multi-hop delivery of data in UW-ASNs. CARP exploits link quality information for cross-layer relay selection. Nodes are selected as relays if they have a history of successful transmissions to the sink through multi-hop paths. CARP combines link quality with simple topology information to find routes around connectivity voids and shadow zones. CARP is also designed to take advantage of modem power control for selecting robust and reliable links.

23.6.2 Non-location-based Routing Protocols

In [143], a depth-based routing protocol is developed, which does not require full-dimensional location information of sensor nodes and only needs local depth information. The depth of forwarding nodes decreases while a packet is delivered to the sink if no void zone is present. In the presence of a void zone a recovery algorithm is performed to route the packet around the void zone. A sensor node makes decisions on packet forwarding based on its own depth and the depth of the previous sender. After receiving a packet, a node checks if it is qualified to forward the packet based on the depth information. If the node is qualified and the packet is not in the packet history buffer, it calculates the sending time for the packet based on the current system time and the holding time.

In [74], the authors introduce a tier-based distributed routing algorithm. The objective of the proposed algorithm is to reduce the energy consumption through adequate selection of the next hop subject to requirements on the end-to-end packet error rate and delay. The protocol is based on lightweight message exchange, and the performance targets are achieved through the cooperation of transmitter and available next hops.

In particular, an analysis is conducted that shows the strong dependence of the available bandwidth on the transmission distance, which is a peculiar characteristic of the underwater environment. Two types of receivers that utilize multichannel processing of asynchronous multiuser signals are proposed in [132]. Both of the receivers proposed offer a realistic platform for a next generation system that needs to support wideband acoustic CDMA communications. Other significant recent studies consider delay-reliability tradeoff analysis [145], the benefits achievable with cooperative communications [30], multipath routing and pressure routing for underwater sensor networks.

In [147], a new multipath power-control transmission (MPT) scheme is proposed to guarantee certain end-to-end packet error rate while achieving a good balance between the overall energy efficiency and the end-to-end packet delay. MPT combines power control with multipath routing and packet combining at the destination. Through the proposed power-control strategies, MPT consumes less energy than the conventional one-path transmission scheme without retransmission. Moreover, MPT, for which retransmissions are not allowed, introduces shorter delays than the traditional one-path scheme with retransmission. MPT assumes that underwater sensor nodes with acoustic modems are densely distributed in a 3D underwater environment, and multiple gateway nodes with both acoustic and RF modems are deployed on the water surface. Each underwater sensor node monitors local events and reports the data to one or multiple surface gateway nodes through acoustic links, and the surface gateway nodes transmit the data to the destination through the RF modem. MPT can be divided into multipath routing, source initiated power-control transmission, and destination packet combining. First, the source node initiates a multipath routing process to find paths from the source to the surface gateway nodes. Through this routing process, the source node selects some paths and calculates the optimal transmit power for each node along the selected paths. Then, the source node sends the same packet along the selected paths. The relay nodes on these selected paths will read the packet header and obtain the specified transmit power parameters for relaying the packet. Finally, the destination receives all copies of the packet and performs packet combining to recover the original packet.

In [77], a hydraulic pressure based anycast routing protocol named HydroCast is proposed to report time-critical sensor data to the sonobuoys on the ocean surface using acoustic multi-hopping. The major challenges in this work are the ocean current and the limited bandwidth and energy in underwater acoustic communications. HydroCast is a 2D geographic route discovery method in a vertical direction to the ocean surface using the depth information from a pressure sensor. The path is from a mobile sensor to any one of the sonobuoys on the ocean surface. The tagging of the sensed data with its location can be performed when the data come to the surface monitoring center, and the off-line localization method is performed by local neighbor information collected from each node. An efficient recovery method with delivery guarantee is used in HydroCast to recover from a dead end. Instead of using expensive 3D flooding, the authors present a local lower-depth-first recovery method that guarantees the delivery using 2D surface flooding. The number of packet transmissions in underwater sensor deployments challenged by ocean currents, unreliable acoustic channels and voids is reduced.

The Void Aware Pressure Routing (VAPR) protocol [96] sets up the next hop direction with periodic beacons, which include sequence number, hop count and depth information. A directional trail to the closest sonobuoy is built, and the opportunistic directional forwarding can be efficiently performed even in the presence of voids. At the beginning, sonobuoys broadcast their reachability information to sensor nodes via periodic beacons. Each node updates the received beacon variables including minimal hop to the surface, sequence number, data forwarding direction, and next hop data forwarding direction. Then, the updated beacon is broadcasted to neighbors. After receiving multiple beacon messages from different nodes, a node chooses the node with minimal hop count as the next hop.

23.7 CROSS-LAYER DESIGN

In a traditional layered architecture, each layer interacts only with the adjacent layers in the protocol stack through well-defined interfaces. Although strictly layered architectures have served well the development of wired networks, they are known to be less than ideally suited for energy constrained wireless applications including UW-ASNs. While a layered architecture may achieve high performance in terms of metrics associated with each individual layer, it does not allow joint optimization of functionalities at different layers of the protocol to maximize the overall network throughput or minimize the energy consumption [92]. Cross-layer design breaks the barrier of rigid interaction only among neighboring layers, by allowing interactions among different layers that may lead to higher network efficiency and flexible Quality of Service (QoS) support. The highly dynamic nature of underwater acoustic channel calls for cross-layer design for efficient data delivery. Since underwater acoustic networks are power constrained and as routing and medium access decisions have strong impact on power consumption, joint decisions of both may lead to more efficient power usage for UW-ASNs.

In [65], the proposed Focused Beam Routing (FBR) protocol, based on location information, considers energy-efficient multi-hop communications in underwater acoustic networks. Data packets are routed with minimum energy in a cone-shaped region whose axis passes through the sender and the receiver. The transmission power is increased until an intermediate relay node is found. By coupling routing and MAC functionalities with power control, the next relay is selected at each step of the path. The proposed FBR protocol is suitable for underwater networks containing both static and mobile nodes.

In [106], the authors explore cross-layer design techniques to make efficient use of the bandwidth-limited acoustic channel. The objective of their work is: 1) study the interactions of key underwater communication functionalities such as modulation, forward error correction, medium access control, and routing; and 2) develop a distributed cross-layer communication solution that allows multiple devices to efficiently and fairly share the bandwidth-limited high-delay underwater acoustic medium. The authors develop a resource allocation framework that accurately models every aspect of the layered network architecture. Efficient underwater communication is achieved by a distributed optimization problem to jointly control the routing, MAC, and physical functionalities. The proposed solution combines a 3D geographical routing algorithm (routing functionality), a novel hybrid distributed CDMA/ALOHA-based scheme to access the bandwidth-limited high-delay shared acoustic medium (MAC functionality), and an optimized solution for the joint selection of modulation, FEC, and transmit power (physical functionalities). The authors group underwater multimedia applications into four traffic classes and highlight their different requirements. The authors integrate the CDMA/ALOHA-based MAC and location-based routing functionalities and control different communication functionalities in a distributed manner.

Multimedia underwater sensor networks would enable new applications for underwater multimedia surveillance, undersea explorations, video-assisted navigation and environmental monitoring. However, these applications require much higher data rates than currently available with acoustic technology, and more flexible protocol design to accommodate heterogeneous traffic demands in terms of bandwidth, delay, and end-to-end reliability. To accommodate such traffic demands, UMIMO-Routing [75] is proposed to leverage the potential of MIMO transmission techniques on acoustic links, leverage the potential of OFDM to reduce inter-carrier interference, and develop a new cross-layer routing protocol to flexibly exploit the potential performance increase offered by MIMO-OFDM links under the unique challenges posed by the underwater environment. For these reasons, the objective of UMIMO-Routing is to explore the capabilities of underwater MIMO-OFDM links, and to leverage these from the perspective of higher layer protocols, and in particular at the routing layer, with a cross-layer design approach.

UMIMO-Routing considers multimedia underwater monitoring applications with heterogeneous traffic demands in terms of bandwidth and end-to-end reliability. Distributed routing algorithms are introduced for delay-insensitive and delay-sensitive applications, with the objective of reducing the energy consumption by i) leveraging the tradeoff between multiplexing and diversity gain that characterizes MIMO links, and ii) allocating transmit power on suitable subcarriers according to channel conditions and application requirements. To achieve the above objective, each node jointly i) selects the next hop, ii) chooses a suitable transmission mode, and iii) assigns optimal transmit power on different subcarriers to achieve a target level of QoS in a cross-layer fashion.

23.8 EXPERIMENTAL PLATFORMS

In addition to simulation studies, extensive field experimentation is needed to validate underwater transmission schemes and networking protocols. Unfortunately, setting up an experimental platform for underwater acoustic networks is very expensive compared to establishing an RF wireless sensor network testbed. Not only are acoustic modems expensive, but also the deployment and maintenance of the testbed itself are costly. As a natural consequence, deployment of underwater acoustic sensors in general are less dense, fewer sensors are utilized and with longer communication range compared to deployments in terrestrial wireless sensor networks [57]. A limited number of experimental platforms have been deployed so far. In Section 23.8.1 we discuss some of the available commercial acoustic modems, while in Section 23.8.2 we discuss some of the available experimental acoustic modems. Finally, in Section 23.8.3 we review recent progress in developing underwater acoustic testbeds.

23.8.1 Commercial Acoustic Modems

There are only a handful of companies involved in manufacturing of commercial acoustic modems. Some of the leading companies include Teledyne Benthos, LinkQuest, EvoLogics, DSPComm and Tritech; as well as a few platforms developed within the research community, most notably the WHOI Micro-Modem. In the following section, we review the state-of-the-art in commercial acoustic modems in terms of modulation schemes, transmission capacity, power efficiency, operating depth and range, and networking capabilities.

Teledyne Benthos. Teledyne Benthos [5] is a leading manufacturer of underwater acoustic modems located in the United States. Benthos offers a wide variety of underwater acoustic equipments; ranging from acoustic modems, acoustic releases and Smart Modem Acoustic Release Technology (SMART) products. We focus on some of their acoustic modems including ATM-900 series, SMART modems and surface unit UDB-9000. ATM-900 series acoustic telemetry modems provide high data capacity logging capability through data storage and user command line interfaces to real-time clock integration. The SMART modem series provides release functionalities and enables real-time communication with subsea devices. The SM-75 product in the line of SMART modem series is an all-in-one design that provides float and release capabilities. The RS-232 serial interface enables modem connection to an attached sensors. The Universal Deck Box, UDB-9000 is a multi-receive deck box that operates with Teledyne Benthos acoustic modems and releases. The acoustic data modulation methods provided by the modems are PSK and MFSK. Table 23.10 summarizes some of the important characteristics of both conventional and SMART acoustic modems provided by

Teledyne Benthos. In addition, Teledyne Benthos modems may allow playing and recording an arbitrary waveform, and provide substantial support for networked operations - see also discussion in Section 23.9.

Table 23.10 A selection of commercial acoustic modems offered by Teledyne Benthos [5].

Product	Depth $[m]$	Data Rate $[\mathrm{bit/s}]$	Range $[\mathrm{km}]$	BER
ATM-920	2000	140 - 15, 360	2 - 6	$< 10^{-7}$
ATM-960	6000	140 - 15, 360	2 - 6	$< 10^{-7}$
SR-100	6700	140 - 15, 360	max. 10	$< 10^{-7}$
SR-50	305	140 - 15, 360	max. 10	$< 10^{-7}$
SM-75	6700	140 - 15, 360	max. 10	$< 10^{-7}$

LinkQuest. LinkQuest Inc. [3] is another manufacturer of precision acoustic instruments including underwater acoustic modems and tracking systems. LinkQuest produces a number of acoustic modems ranging from short range, low power modems (UWM 1000) for shallow water communications to long range, high power modems (UWM 10000) for deep ocean communications. Each of their acoustic modems is tailored for a specific application. Data rates vary depending on the range of communication and power mode. LinkQuest acoustic modems may be used for near-vertical, horizontal and extreme horizontal underwater environments. In addition, the acoustic modems are equipped with RS-232 connections that may be used to connect to underwater sensors. Table 23.11 summarizes some of the acoustic products characteristics provided by LinkQuest.

Table 23.11 A selection of commercial acoustic modems offered by LinkQuest [3].

Product	Depth $[m]$	Data Rate $[\mathrm{bit/s}]$	Range $[\mathrm{km}]$	BER
UWM 1000	2000	960 - 19200	0.35	$< 10^{-9}$
UWM 2000	2000/4000	1960 - 19200	1.2/1.5	$< 10^{-9}$
UWM 3000	2000/4000/7000	2500 - 5000	3/5	$< 10^{-9}$
UWM 4000	3000/7000	4800 - 9600	3/6	$< 10^{-9}$
UWM 10000	2000/4000/7000	2500 - 5000	7/10	$< 10^{-9}$

EvoLogics. EvoLogics [6] is a manufacturer of underwater modems based in Germany. EvoLogics provides advanced underwater acoustic solutions including underwater acoustic modems, sonobots, subsea gliders and bionik robotics. We focus on the underwater acoustic modems. The R-series are software-configurable underwater acoustic modems that offer full-duplex acoustic transmission utilizing S2C (Sweep-Spread Carrier) scheme. The R-series modems provide solutions for short-medium- and long-range communications in shallow or deep water environments. A serial RS-232 interface provides connection to underwater sensors. Table 23.12 summarizes some of the acoustic products characteristics provided by EvoLogics.

Table 23.12 A selection of commercial acoustic modems offered by EvoLogics [6].

Product	Depth [m]	Band [kHz]	Data Rate [bit/s]	Range [km]	BER
S2C R 48/78 USBL	500/1000/2000	48 - 78	up to 31200	1	$< 10^{-10}$
S2C R 40/80 USBL	500/1000/2000	38 - 64	up to 27700	2	$< 10^{-10}$
S2C R 18/34 USBL	500/1000/2000	18 - 34	up to 13900	3.5	$< 10^{-10}$
S2C R 12/24 USBL	500/1000/2000/6000	13 - 24	up to 9200	6	$< 10^{-10}$
S2C R 7/17 USBL	500/1000/3500/6000	7 - 17	up to 6900	8	$< 10^{-10}$

DSPComm. DSPComm [2] is a manufacturer of underwater wireless communication systems located in Australia. DSPComm offers two types of wireless acoustic modems:

- **AquaComm:** Underwater wireless modem ideal for highly reliable applications [2]. AquaComm is available in 100 bit/s and 480 bit/s versions.

- **AquaNetwork:** Underwater wireless modem that provides networking capability and includes all the features of AquaComm. It provides a various networking capabilities, such as setting up parallel links using CDMA, broadcast and unicast, store and forward and broadcast wake up [7].

Table 23.13 summarizes the main parameters of DSPComm product.

Table 23.13 Commercial acoustic modem offered by DSPComm [2].

Product	Depth [m]	Band [kHz]	Data Rate [bit/s]	Range [km]	BER
AquaComm	200	16 to 30	100, 480	3	$< 10^{-6}$

Tritech. Tritech [8] specializes in the design and production of high performance acoustic sensors, sonars, video cameras and mechanical tooling equipment for the professional underwater markets including defence, energy, engineering, recreation, survey and underwater vehicles. Tritech is a leading supplier of sensors and tools for remotely operated vehicles (ROVs) and autonomous underwater vehicles (AUVs) markets. The Micron Data Modem by Tritech is a low-cost and very compact acoustic modem that accommodates robust spread-spectrum communication capabilities. Moreover, the Micron Data Modem may be utilized as a responder or transponder for AUV and ROV tracking applications. The power consumption is very low and it has an option for remote battery powering. In addition, it has multipath and noise rejection functionalities, which is ideal for shallow water communications. Table 23.14 summarizes the main parameters of Micron Data Modem.

Table 23.14 Commercial acoustic modem offered by Tritech [8].

Product	Depth [m]	Band [kHz]	Data Rate [bit/s]	Range [km][a]	BER
Micron Data Modem	750	20 - 24	40	$0.5_h, 0.15_v$	N/A

[a] The subscripts h and v stand for *horizontal* and *vertical*, respectively.
N/A indicates the data was not available in the published reference.

23.8.2 Experimental Acoustic Modems

Reconfigurable underwater acoustic modems should allow flexible implementation of different protocols and algorithms. Flexible modems range from reconfigurable modems, which allow users to select the modulation method from a finite set of schemes, to fully reprogrammable modems, which permit the user to implement any modulation and demodulation scheme in addition to flexible networking protocol in software [99]. However, currently most of the available off-the-shelf acoustic modems are not flexible enough to test new emerging ideas. As a result, there is a strong need for flexible acoustic modems to be able to conduct more accurate experiments. Several experimental acoustic modems have been developed by different research groups. In this section, we discuss some of the existing experimental modems.

Micro-Modem. The Micro-Modem [46] is a compact, low-power acoustic transceiver developed at the Woods Hole Oceanographic Institute (WHOI). It is a user-programable open alternative solution to the available commercial modems. Currently, it is used for navigation and communication of AUVs, autonomous surface vehicles (ASVs), buoy sensor telemetry, and deep water ocean observatories. The modulation schemes supported by the Micro-Modem are low-power, low-rate frequency-hopping frequency-shift keying (FH-FSK) and high-power, variable rate PSK. The user may configure the modem to transmit in four different frequency bands from 3 to $30\,\mathrm{kHz}$ range. Moreover, the modem supports data rates in the range from $80\,\mathrm{bit/s}$ to $5300\,\mathrm{bit/s}$. Micro-modem's robust FH-FSK modulation along with error correction coding (ECC) capability allows long range communication (2 to $4\ \mathrm{km}$), in very shallow water channels. The Micro-Modem provides RS-232 serial port user interface. It supports two different forms of packets; mini-packet, which may be used to transmit very short commands and long-packet, used for data packet transmission. A built-in floating point processor board enables the user to run computationally complex algorithms. It also supports four and eight channel receive hydrophone arrays and a flash memory board allowing large raw data capture. The power consumption of the Micro-Modem is very low. Moreover, it includes some basic built-in networking capabilities, which supports up to 16 units in a polled or random-access mode and its acknowledgement scheme may be used to guarantee successful packet delivery.

rModem. rModem [122] is a reconfigurable acoustic modem developed at the Massachusetts Institute of Technology (MIT). rModem is designed to allow the user to reconfigure functionalities across different layers of protocol stack with possibility of cross-layer optimization. It contains a digital signal processor, (DSP) and a field-programmable gate array (FPGA). The FPGA allows the user to operate at any carrier frequency and bandwidth within the $1\,\mathrm{kHz}$ to $100\,\mathrm{kHz}$ range, while the DSP running at $255\ \mathrm{MHz}$ enables floating point arithmetic computation. Moreover, it has $32\ \mathrm{Mbytes}$ of internal flash RAM for persistent program and data storage and $32\ \mathrm{Mbytes}$ of SD-RAM for program and memory storage. rModem allows MIMO transmission schemes to be implemented using the four configurable input and output channels. The embedded analog anti-aliasing filter with $1\ \mathrm{kHz}$ to $100\ \mathrm{kHz}$ bandwidth may be used for various applications while the 56 pin daughter card port accommodates future expansions. rModem provides a graphical user interface (GUI), which may be used to control the rModem's hardware, send and receive packets, and log events and data.

UANT Platform. The Underwater Acoustic Networking plaTform (UANT) [140] is a software-defined research platform designed at the University of California, Los Angeles (UCLA). The objective is to provide a flexible software-defined reconfigurable platform for researchers to experiment new protocols and modulation schemes on a fully functional underwater network. UANT uses GNU Radio, a software-defined framework, for physical layer design configurations and TinyOS for network protocol stack design. UANT allows real time configuration of the acoustic modem. Hence, it may adapt to constantly changing underwater acoustic environment. UANT provides a Gaussian Minimum Shift Keying (GMSK) modulation scheme and allows data rate configuration from $244\ \mathrm{bit/s}$ to $500\ \mathrm{kbit/s}$, while the central frequency may be varied from $0.1\ \mathrm{Hz}$ to $30\ \mathrm{MHz}$. UANT may be reconfigured at the physical, MAC, and application layers. However, one of the drawbacks of UANT platform is that it needs to run on a personal computer.

SWDAM Project. UW SWDAM [54] is a Software Defined Acoustic Modem project developed at the University of Washington. The general idea is to get the software as close to the antennas as possible so that researchers can implement the entire modem stack in software using general purpose processors. To achieve this, an Intel D945GCLF2 mini-ITX motherboard and an Avnet Memec's Spartan-II 200 PCI development kit board in cooperation with Avnet Memec's P160 Analog Module daughter-board are utilized. A linear amplifier and a projector are used for the transmitter, and a hydrophone and a preamplifier are used for the receiver. Moreover, common operating systems such as Linux or Microsoft Windows can be implemented on the ITX platforms, which enables researchers to port algorithms from their desktops.

23.8.3 Experimental Testbeds

Building real experimental systems and conducting actual experiments in undersea is very expensive. Although simulations may be considered as an alternative solution, it is very difficult to accurately model the underwater acoustic channel. Consequently, simulations may lead to inaccurate results. An intermediate solution that overcomes the limitations of simulations is using experimental testbeds to adequately evaluate algorithms and protocols in real-world scenarios. In this section we present some of the existing experimental testbed platforms as well as ongoing projects.

Seaweb Project. Seaweb [116] is among the first experimental platforms primarily designed for military applications. Seaweb is funded by Office of Naval Research (ONR) and it is run by Spawar Systems Center (SSC) San Diego and Naval Postgraduate School (NPS) with Teledyne Benthos as the main contractor. Seaweb is a wide-area network with DSP-based telesonar underwater acoustic modems that connects autonomous and fixed nodes together. Backbone nodes are autonomous, stationary sensors and telesonar repeaters. Peripheral nodes include unmanned undersea vehicles (UUVs) and specialized devices such as low-frequency sonar projectors. Gateway nodes provide interfaces with command centers afloat, submerged, ashore, and aloft, including access to terrestrial, airborne, and space-based networks. Seaweb is an organized network for command, control, communications, and navigation (C^3N) of deployable autonomous undersea systems [116]. Throughout the years many networking protocols have been developed and using Seaweb platform numerous field tests have been carried out to validate the protocols.

CMRE NATO Facility. The Centre for Maritime Research and experimentation (CMRE) [9], formerly known as the NATO Undersea Research Centre (NURC) [113, 115, 23] is a scientific research and experimentation NATO facility. Among other research areas, CMRE is engaged in conducting research on off-board Low Frequency Active (LFA) sensors that could be used in Cooperative distributed Anti-Submarine Warfare (CASW) [23] to create a scalable and autonomous system that would potentially remove vulnerable personnel from high risk areas such as deep oceans. Moreover, CMRE is involved in standardizing channel modeling schemes and networking architecture design that supports cross-layer interactions [113]. CMRE also runs and maintains an underwater networking testbed with heterogeneous modems [24].

Ocean-TUNE Testbed. A community Ocean Testbed for Underwater Networks Experiments (Ocean-TUNE) is presented in [40]. Ocean-TUNE is a collaborative work from four institutions namely, University of Connecticut, University of Washington, University of California, Los Angeles, and Texas A&M

University. Ocean-TUNE is an open testbed suite comprised of four testbeds remotely accessible to the public at four different sites that will enable advancement of research in the areas of underwater communications, networking, engineering, and marine science communities. The testbeds provide flexible choices of surface nodes, bottom nodes, and mobile nodes (gliders and drifters). Three of the testbeds include reconfigurable modems with MIMO capabilities that may allow the user to experiment various acoustic communication strategies. The network nodes in each testbed are equipped with OFDM acoustic modems that could provide high data rates and strong networking support.

SUNSET Framework. The Sapienza University Networking framework for underwater Simulation Emulation and real-life Testing (SUNSET), developed by the UWSN Group [10], is a collaborative effort between the WHOI, the NATO Undersea Research Centre (NURC) and the University of "Sapienza". SUNSET provides a framework based on open source network simulator ns-2 [11] software, for simulating and testing at sea underwater acoustic communication protocols. The framework contains a number of commercial acoustic modems models that allows simulation and emulation of actual underwater acoustic channel conditions. Moreover, the simulator code written in ns-2 may be ported onto a small computer-on-module hardware device like Gumstix [12], which may be embedded inside an acoustic modem or AUV's housing to control their functionalities. In addition to that the framework allows interfacing software communication modules with various hardware and commercial acoustic modems, and at the same time having an open architecture to allow integration with different acoustic modems and AUV's. The framework is a powerful tool that may be used to validate, test and implement new algorithms and protocols [104].

DESERT Underwater. DESERT Underwater is an NS-Miracle based framework to DEsign, Simulate, Emulate and Realize Test-beds for Underwater network protocols [89] developed at the University of Padova. The objective of this framework is to realize a complete set of public C/C++ libraries to support the design and implementation of underwater network protocols. DESERT Underwater extends the NS-Miracle [13] simulation software library, an ns2-based simulation platform also developed at the University of Padova, to accommodate a number of protocol stacks for underwater networks, and to support routines essential for the development of new protocols.

WHOI UAN Testbed. The WHOI is developing an underwater acoustic network (UAN) testbed [44], which will provide a valuable infrastructure for evaluating and developing network protocols for shallow and deep water communications. The testbed can be made available for collaborative experiments with the UAN research community. The acoustic nodes in the testbed can remotely be controlled through the serial port over the Internet for most of the experimental configurations. Each testbed node includes a WHOI Micro-Modem, which is controlled by a Gumstix, an embedded computer, on which network protocols are implemented and executed.

The center frequency of the transducer is $25\,\mathrm{kHz}$ with $5\,\mathrm{kHz}$ bandwidth and the data rates range from $80\,\mathrm{bit/s}$ to $5300\,\mathrm{bit/s}$. Moreover, the testbed includes buoy nodes that operate at both $10\,\mathrm{kHz}$ and $25\,\mathrm{kHz}$, and are equipped with GPS receivers and Freewave radios to provide gateway routing capabilities.

CPS Lab Project. The Cyber Physical Systems (CPS) Laboratory [14] at Rutgers University is developing an acoustic communication substrate to support cross-layer underwater communication strategies for AUV inter-communications while supporting traffic with different QoS requirements. A demonstration of underwater vehicle team formation and steering algorithms using CPS underwater testbed are described in [35]. The testbed allows the user to configure ocean currents and underwater communication parameters through a GUI. With a multi-input multi-output audio interface installed on a Personal Computer (PC), the user can adjust the signal gains, introduce propagation delay, mix the acoustic signals, and add ambient and man-made noise as well as interference in real time.

23.9 UW-BUFFALO: AN UNDERWATER ACOUSTIC TESTBED AT THE UNIVERSITY AT BUFFALO

The underwater acoustic networking testbed at the University at Buffalo (UW-Buffalo) [15] is designed to bridge the gap between experimentation and theoretical developments in underwater communications and networking, and is the result of a joint venture between the University at Buffalo and Teledyne Benthos. The objective of the project is to provide the research community with a versatile and shared reconfigurable platform to enable experimental evaluation of underwater communications and networking protocols.

The testbed, which is being developed under sponsorship of the US National Science Foundation, is based on the Teledyne Benthos Telesonar SM-75 modem, which, in its many configurations, is also a key component in multiple U.S. Navy programs and of many wireless tsunami warning systems worldwide.

In the commercial implementation of the SM-75 Benthos modem, all networking functionalities, including channel access negotiation, selective repeat request (SRQ), and waveform selection, reside within the core DSP of the individual modem, and cannot be reconfigured by the end-user. Similarly, the existing network layer implements static routing tables at each node in the network within the main modem board, and is not separable from it. Therefore, in the current on-board networking implementation, all packet processing occurs completely within the modem CPU and firmware. This does not allow for external implementation of alternate networking and MAC schemes, and this logic is only accessible by Teledyne Benthos personnel.

The SM-75 has been modified to allow the research community to perform advanced networking and communication experiments as follows. First, a programmable Gumstix network processor is being interfaced with the SM-75 modem through a newly designed interface that defines communication primitives between the modem board and the external processor. A reconfigurable, software-defined protocol stack, including medium access control, IP network layer with reconfigurable ad hoc routing, network self-configuration primitives (e.g., neighbor discovery, DHCP), is being implemented on the Gumstix board to enable the definition of complex networking experiments with reconfigurable, cross-layer designed protocol stacks. Second, the modified platform allows playing and recording custom defined acoustic waveforms to allow reconfigurable physical-layer experimentation with arbitrary transmission schemes. The testbed architecture is modeled after the architecture illustrated in Fig. 1.1. The modems are based on SM-75 with embedded Gumstix inside the housing, while the surface station is based on UDB-9000 (also from Teledyne Benthos).

23.10 CONCLUSIONS

In this chapter, we provided a comprehensive account of recent advances in underwater acoustic communications and networking. We described the typical communication architecture of an underwater network. We discussed key notions of underwater acoustic propagation and the state of the art in acoustic communication techniques at the physical layer. We described the challenges posed by the peculiarities of the underwater channel with particular reference to monitoring applications for the ocean environment. We presented an overview of the recent advances in protocol design at the medium access control and network layers in addition to cross-layer design. Finally, we provided a detailed discussion of the existing underwater acoustic platforms for experimental evaluation of underwater networks. The objective of this chapter is to encourage research efforts to lay down fundamental basis for the development of new advanced communication techniques for efficient underwater communication and networking for enhanced ocean monitoring and exploration applications.

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