OFDM for Underwater Acoustic Communications
OFDM FOR UNDERWATER ACOUSTIC COMMUNICATIONS
OFDM FOR UNDERWATER ACOUSTIC COMMUNICATIONS

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To Juanjuan, Daniel, Joyce, and my parents Heting and Caiyun
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To my parents Yongcheng and Jiuqin
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Preface

Underwater acoustic (UWA) channels have been regarded significantly different from wireless radio channels, due to their unique characteristics, such as large temporal variations, abundance of transmission paths, and wideband property in nature. Although there are a plethora of digital and wireless communication textbooks, most of them are tailored towards wireless radio channels, where simplified channel models are usually adopted to streamline presentation. Following standard receiver designs in textbooks, a practitioner might often be frustrated by the receiver performance in real underwater acoustic environments. This book is written to unfold and to address the challenges in UWA communications particularly for the multicarrier modulation in the form of orthogonal frequency-division multiplexing (OFDM).

The last decade has witnessed the tremendous development and revolutionary impact of OFDM on high data-rate radio communications. It is the workhorse of many wireless communication standards, such as WiFi (IEEE 802.11 a/g/n), WiMAX (IEEE 802.16), digital audio and video broadcasting (DAB/DVB), and the fourth generation (4G) cellular systems. The popularity of OFDM stems from its capability to convert a long multipath channel in the time domain into multiple parallel single-tap channels in the frequency domain, thus considerably simplifying receiver design. Such a feature makes OFDM an attractive choice for UWA channels. However, the feasibility of underwater acoustic OFDM had not been validated with experimental data sets until the mid 2000s, although OFDM has been tested in UWA environments since the 1990s. Considerable progress for OFDM has been observed in the UWA community since the late 2000s.

This book is dedicated to the techniques for OFDM in UWA channels, and different chapters are focused on addressing different challenges. Readers are expected to have certain signal processing and communication background. For readers within the UWA community, this book could deepen their understanding in the design aspects specific to underwater systems. For readers outside the UWA community, this book will help them to appreciate the distinctions of system design in different domains.

The technical content of this book mainly originates from the research performed within the UnderWater Sensor Network (UWSN) lab at the University of Connecticut (UCONN), which is co-directed by Dr. Jun-Hong Cui and the first author Dr. Shengli Zhou. The past and existing members who have contributed to the content of the book include: postdoctoral researchers: Drs. Jie Huang, Hao Zhou, and Xiaoka Xu; past Ph.D. students: Drs. Baosheng Li, Christian Berger, Jianzhong Huang; current Ph.D. students: Patrick Carroll, Lei Wan, Yi Huang; past M.S. students: Sean Mason, Weian Chen, Wei Zhou; and visiting scholars: Yougan Chen,
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Shengli Zhou  
University of Connecticut

Zhaohui Wang  
Michigan Technological University
**Acronyms**

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>AF</td>
<td>Amplify and Forward</td>
</tr>
<tr>
<td>ANC</td>
<td>Analogy Network Coding</td>
</tr>
<tr>
<td>AoA</td>
<td>Angle of Arrival</td>
</tr>
<tr>
<td>ARQ</td>
<td>Automatic Repeat Request</td>
</tr>
<tr>
<td>AUTEC</td>
<td>Atlantic Undersea Test and Evaluation Center</td>
</tr>
<tr>
<td>AUV</td>
<td>Autonomous Underwater Vehicle</td>
</tr>
<tr>
<td>BCJR</td>
<td>The Bahl-Cocke-Jelinek-Raviv Algorithm</td>
</tr>
<tr>
<td>BICM</td>
<td>Bit Interleaved Coded Modulation</td>
</tr>
<tr>
<td>BP</td>
<td>Basis Pursuit</td>
</tr>
<tr>
<td>BPSK</td>
<td>Binary Phase-Shift Keying</td>
</tr>
<tr>
<td>BER</td>
<td>Bit Error Rate</td>
</tr>
<tr>
<td>BLER</td>
<td>Block Error Rate</td>
</tr>
<tr>
<td>CC</td>
<td>Convolutional Code</td>
</tr>
<tr>
<td>CCDF</td>
<td>Complementary Cumulative Distribution Function</td>
</tr>
<tr>
<td>CCI</td>
<td>Cochannel Interference</td>
</tr>
<tr>
<td>CDF</td>
<td>Cumulative Distribution Function</td>
</tr>
<tr>
<td>CDMA</td>
<td>Coded-Division Multiple Access</td>
</tr>
<tr>
<td>CF</td>
<td>Compress and Forward</td>
</tr>
<tr>
<td>CFO</td>
<td>Carrier Frequency Offset</td>
</tr>
<tr>
<td>CP</td>
<td>Cyclic Prefix</td>
</tr>
<tr>
<td>CRLB</td>
<td>Cramer-Rao Lower Bound</td>
</tr>
<tr>
<td>CS</td>
<td>Compressive Sensing</td>
</tr>
<tr>
<td>CSI</td>
<td>Channel State Information</td>
</tr>
<tr>
<td>CZT</td>
<td>Chirp Z-Transform</td>
</tr>
<tr>
<td>DBC</td>
<td>Dynamic Block-Cycling</td>
</tr>
<tr>
<td>DCC</td>
<td>Dynamic Coded Cooperation</td>
</tr>
<tr>
<td>DF</td>
<td>Decode and Forward</td>
</tr>
<tr>
<td>DFE</td>
<td>Decision-Feedback Equalization</td>
</tr>
<tr>
<td>DFT</td>
<td>Discrete Fourier Transform</td>
</tr>
<tr>
<td>DSSS</td>
<td>Direct Sequence Spread Spectrum</td>
</tr>
<tr>
<td>FDM</td>
<td>Frequency Division Multiplexing</td>
</tr>
<tr>
<td>FFT</td>
<td>Fast Fourier Transform</td>
</tr>
<tr>
<td>FH</td>
<td>Frequency Hopping</td>
</tr>
<tr>
<td>FG</td>
<td>Factor Graph</td>
</tr>
<tr>
<td>Acronyms</td>
<td>Definitions</td>
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<tr>
<td>----------</td>
<td>-------------</td>
</tr>
<tr>
<td>FSK</td>
<td>Frequency Shift Keying</td>
</tr>
<tr>
<td>GIB</td>
<td>GPS Intelligent Buoy</td>
</tr>
<tr>
<td>GLRT</td>
<td>Generalized Log-Likelihood Test</td>
</tr>
<tr>
<td>GMP</td>
<td>Gaussian Message Passing</td>
</tr>
<tr>
<td>GPS</td>
<td>Globe Positioning System</td>
</tr>
<tr>
<td>HFM</td>
<td>Hyperbolic-Frequency Modulation</td>
</tr>
<tr>
<td>IBI</td>
<td>Interblock Interference</td>
</tr>
<tr>
<td>ICI</td>
<td>Intercarrier Interference</td>
</tr>
<tr>
<td>i.i.d.</td>
<td>Independent and Identically Distributed</td>
</tr>
<tr>
<td>IMM</td>
<td>Interacting Multiple Model</td>
</tr>
<tr>
<td>ISI</td>
<td>Intersymbol Interference</td>
</tr>
<tr>
<td>LASSO</td>
<td>Least Absolute Shrinkage and Selection Operator</td>
</tr>
<tr>
<td>LBL</td>
<td>Long Baseline</td>
</tr>
<tr>
<td>LDPC</td>
<td>Low Density Parity Check Code</td>
</tr>
<tr>
<td>LFM</td>
<td>Linear-Frequency Modulation</td>
</tr>
<tr>
<td>LLR</td>
<td>Log-Likelihood Ratio</td>
</tr>
<tr>
<td>LLRV</td>
<td>Log-Likelihood Ratio Vector</td>
</tr>
<tr>
<td>LMMSE</td>
<td>Linear Minimum Mean-Square Error</td>
</tr>
<tr>
<td>LPF</td>
<td>Low Bandpass Filtering</td>
</tr>
<tr>
<td>LPM</td>
<td>Linear-Period Modulation</td>
</tr>
<tr>
<td>LS</td>
<td>Least Squares</td>
</tr>
<tr>
<td>MAC</td>
<td>Medium-Access Control</td>
</tr>
<tr>
<td>MACE10</td>
<td>Mobile Acoustic Communication Experiment in 2010</td>
</tr>
<tr>
<td>MAP</td>
<td>Maximum A Posteriori Probability</td>
</tr>
<tr>
<td>MCMC</td>
<td>Markov Chain Monte Carlo</td>
</tr>
<tr>
<td>MIMO</td>
<td>Multi-Input Multi-Output</td>
</tr>
<tr>
<td>ML</td>
<td>Maximum Likelihood</td>
</tr>
<tr>
<td>MP</td>
<td>Matching Pursuit</td>
</tr>
<tr>
<td>MSE</td>
<td>Mean Square Error</td>
</tr>
<tr>
<td>MMSE</td>
<td>Minimum Mean Square Error</td>
</tr>
<tr>
<td>MRC</td>
<td>Maximum Ratio Combining</td>
</tr>
<tr>
<td>MUD</td>
<td>Multiuser Detection</td>
</tr>
<tr>
<td>MUI</td>
<td>Multiuser Interference</td>
</tr>
<tr>
<td>NC</td>
<td>Network Coding</td>
</tr>
<tr>
<td>NCM</td>
<td>Nonbinary Coded Modulation</td>
</tr>
<tr>
<td>NLNC</td>
<td>Network-Layer Network Coding</td>
</tr>
<tr>
<td>OFDM</td>
<td>Orthogonal Frequency-Division Multiplexing</td>
</tr>
<tr>
<td>OMP</td>
<td>Orthogonal Matching Pursuit</td>
</tr>
<tr>
<td>PAM</td>
<td>Pulse Amplitude Modulation</td>
</tr>
<tr>
<td>PAPR</td>
<td>Peak-To-Average-Power Ratio</td>
</tr>
<tr>
<td>PDA</td>
<td>Probabilistic Data Association</td>
</tr>
<tr>
<td>PER</td>
<td>Packet Error Rate</td>
</tr>
<tr>
<td>PLNC</td>
<td>Physical-Layer Network Coding</td>
</tr>
<tr>
<td>PSNR</td>
<td>Pilot Signal-To-Noise Ratio</td>
</tr>
<tr>
<td>QAM</td>
<td>Quadrature Amplitude Modulation</td>
</tr>
<tr>
<td>QC</td>
<td>Quasi-Cyclic</td>
</tr>
<tr>
<td>Acronym</td>
<td>Description</td>
</tr>
<tr>
<td>---------</td>
<td>-------------</td>
</tr>
<tr>
<td>QMF</td>
<td>Quantize, Map and Forward</td>
</tr>
<tr>
<td>QPSK</td>
<td>Quadrature Phase Shift Keying</td>
</tr>
<tr>
<td>RIP</td>
<td>Restricted Isometry Property</td>
</tr>
<tr>
<td>RMSE</td>
<td>Root Mean-Squared Error</td>
</tr>
<tr>
<td>S2C</td>
<td>Sweep-Spread Carrier</td>
</tr>
<tr>
<td>SBL</td>
<td>Short Baseline</td>
</tr>
<tr>
<td>SDA</td>
<td>Sphere Decoding Algorithm</td>
</tr>
<tr>
<td>SIMO</td>
<td>Single-Input Multi-Output</td>
</tr>
<tr>
<td>SINR</td>
<td>Signal-to-Interference-and-Noise Ratio</td>
</tr>
<tr>
<td>SIR</td>
<td>Signal-to-Interference Ratio</td>
</tr>
<tr>
<td>SISO</td>
<td>Single-Input Single-Output</td>
</tr>
<tr>
<td>SNR</td>
<td>Signal-to-Noise Ratio</td>
</tr>
<tr>
<td>SOFAR</td>
<td>Sound Fixing and Ranging</td>
</tr>
<tr>
<td>SONAR</td>
<td>Sound Navigation and Ranging</td>
</tr>
<tr>
<td>SPA</td>
<td>Sum Product Algorithm</td>
</tr>
<tr>
<td>SPACE08</td>
<td>Surface Processes and Acoustic Communication Experiment in 2008</td>
</tr>
<tr>
<td>SPRT</td>
<td>Sequential Probability Ratio Test</td>
</tr>
<tr>
<td>SUD</td>
<td>Single-User Detection</td>
</tr>
<tr>
<td>TCM</td>
<td>Trellis Coded Modulation</td>
</tr>
<tr>
<td>TDOA</td>
<td>Time Difference of Arrival</td>
</tr>
<tr>
<td>TVR</td>
<td>Transmitter Voltage Response</td>
</tr>
<tr>
<td>USBL</td>
<td>Ultra-Short Baseline</td>
</tr>
<tr>
<td>UUV</td>
<td>Unmanned Underwater Vehicle</td>
</tr>
<tr>
<td>UWA</td>
<td>Underwater Acoustic</td>
</tr>
<tr>
<td>VA</td>
<td>Viterbi Algorithm</td>
</tr>
<tr>
<td>ZF</td>
<td>Zero Forcing</td>
</tr>
<tr>
<td>ZP</td>
<td>Zero Padding</td>
</tr>
</tbody>
</table>
Notation

Scalars

$K$  Number of subcarriers in one OFDM symbol
$B$  Frequency bandwidth of one OFDM symbol
$\Delta f$  Subcarrier spacing in one OFDM symbol, $:= B/K$
$T$  Time-duration of one OFDM symbol, $:= 1/\Delta f$
$T_g$  Time-duration of guard interval for one OFDM symbol
$T_{bl}$  Time-duration of one OFDM block, $:= T + T_g$
$f_c$  Center frequency of communication system
$f_k$  Frequency of the $k$th subcarrier, $:= f_c + k/T$
$S_N$  The set of null subcarriers in one OFDM symbol
$S_P$  The set of pilot subcarriers in one OFDM symbol
$S_D$  The set of data subcarriers in one OFDM symbol
$S_A$  The set of active subcarriers in one OFDM symbol $:= S_P \cup S_D$
$h(t; \tau)$  Time-varying channel impulse response
$A_p(t)$  Time-varying amplitude of the $p$th path
$A_p$  Time-invariant amplitude of the $p$th path
$\tau_p(t)$  Time-varying delay of the $p$th path
$\tau_p$  Initial delay of the $p$th path
$a_p$  Doppler rate of the $p$th path
$N_{pa}$  Number of paths in the channel
$a$  The main Doppler scaling factor in the UWA channel
$\epsilon$  The residual Doppler shift after removing the main Doppler effect
$\xi_p$  The equivalent amplitude of the $p$th path in the baseband
$\tilde{\tau}_p$  The equivalent scaled delay of the $p$th path in the baseband
$b_p$  The equivalent residual Doppler rate of the $p$th path in the baseband
$D$  ICI depth
$\mathcal{N}(\mu, \sigma^2)$  Real Gaussian distribution with mean $\mu$ and variance $\sigma^2$
$\mathcal{CN}(0, \sigma^2)$  Circularly symmetric complex Gaussian distribution with zero mean and variance $\sigma^2$
$\tilde{x}(t)$  The waveform in passband
$x(t)$  The waveform in baseband; Conversion between $\tilde{x}(t)$ and $x(t)$:
\[ \hat{x}(t) = 2\Re\{x(t)e^{j2\pi f_c t}\} \]
\[ x(t) = \text{LPF}[\hat{x}(t)e^{-j2\pi f_c t}] \]

**Vectors and Matrices**

- **z**: Measurement vector formed by frequency samples at all the OFDM subcarriers
- **s**: Transmitted symbol vector formed by symbols at all the OFDM subcarriers
- **w**: Ambient noise vector formed by the ambient noise at all the OFDM subcarriers
- **η**: Equivalent noise vector formed by the equivalent noise at all the OFDM subcarriers
- **H**: Channel mixing matrix
- **C, N(0, Σ)**: Circularly symmetric complex Gaussian random vector with zero mean and covariance matrix Σ

**Operations**

- **∞**: Equality of functions up to a scaling factor
- **|S|**: Cardinality of set S
- **[a]_m**: The mth entry of vector a
- **[A]_{m,k}**: The (m, k)th entry of matrix A
- **{a}_{i}^{j}$$_{r=i}$$**: A set formed by elements \{[a]_i, [a]_{i+1}, \ldots, [a]_j\}
- **\hat{a}**: The estimate of scale a
- **\hat{A}**: The estimate of matrix A
- **A^T**: The transpose of matrix A
- **A^H**: The complex conjugate transpose of matrix A
- **A^†**: The pseudo-inverse of matrix A
- **tr(A)**: Trace of matrix A
- **Pr\{A\}**: Probability of an event A
- **𝔼(X)**: Expectation of random variable X
- **𝔼(x)**: Expectation of random vector x
- **Cov(X, Y)**: Covariance of two random variables
- **Cov(x, y)**: Covariance matrix of two random vectors
- **ℜ\{x\}**: Real part of a complex number x
- **ℑ\{x\}**: Imaginary part of a complex number x
1

Introduction

1.1 Background and Context

1.1.1 Early Exploration of Underwater Acoustics

The Earth is a water planet, with two-thirds of the surface covered by water. Exploration of the mysterious underwater world has never ceased in human history. As early as 400 BC, Aristotle had noted that sound could be heard in water as well as in air. In AD 1490, Leonardo da Vinci wrote: “If you cause your ship to stop and place the head of a long tube in the water and place the other extremity to your ear, you will hear ships at great distances” [268]. In 1826, Charles Sturm and Daniel Colladon made the first accurate measurement of sound speed in water at Lake Geneva, Switzerland. The first practical application of underwater sound appeared in the 1900s: the underwater bells equipped on lightships were simultaneously sounded with a fog horn to measure the offshore distance based on the difference of the airborne and waterborne arrivals, and meanwhile the stereo headphones were also used for directions [397]. With the sinking of Titanic in 1912, L. F. Richardson successively filed a patent of echo ranging with sound in air and a patent application of echo ranging in water.

Along with the application of submarine and underwater mines in World War I (1914–1918), considerable progress has been made in underwater acoustics, especially on the underwater echo ranging for submarine and mine detection. In 1914, Constantin and Chilowski conceived the idea of submarine detection by underwater echo ranging. Based on the discovery of the piezoelectric effect by Jacques Curie and Pierre Curie in 1880, Paul Langevin in 1918 used quartz (piezoelectric) transducers as source and receiver to extend one-way sound transmission to 8 km, and for the first time observed clear echoes from a submarine at distances as large as 1500 m. Between World War I and World War II, scientists started to understand some fundamental concepts of sound in water, such as sound refraction due to changes of water temperature, salinity and pressure. Development of underwater sound applications during this period can be found in echo ranging for commercial use, underwater tomography and fisheries acoustics. The research effort on underwater acoustics during World War II (1941–1945) was mainly focused on improving echo ranging systems which were later coined as “sonar” (for SOund Navigation And Ranging). During this period, topics relative to sonar system performance were extensively investigated, including the high-frequency acoustics, low-frequency sound propagation, ambient noise, etc. By the end of World War II, the underwater sound had
been primarily used for navigation and threat-finding. In 1945, an underwater telephone, which was developed by the Navy Underwater Sound Laboratory in the United States for the purpose of communication with submerged submarines, was the first application of underwater sound for communications [321]. Since then, development on underwater acoustic communications has been made in various underwater acoustic applications.

### 1.1.2 Underwater Communication Media

To establish communications among underwater assets and systems floating on the surface, four different communication media have been used.

- **Cables.** There have been many cabled observatories established over the years. Cables provide robust communication performance; however, the deployment and maintenance cost is very high. This motivates the use of wireless data transmission.
- **Acoustic waves.** For underwater wireless communication systems, acoustic waves are used as the primary carrier due to their relatively low absorption in underwater environments. However, acoustic waves have low propagation speed and a very limited frequency band.
- **Electromagnetic (EM) waves.** The use of EM waves in the radio frequency band has several advantages over acoustic waves, mainly faster velocity and high operating frequency (resulting in higher bandwidth). The key limitation of using EM waves for underwater communication is the high attenuation due to the conductive nature of seawater [255].
- **Optical waves.** Using optical waves for communication obviously has a big advantage in data rate. However, there are a couple of disadvantages for optical communication in water. Firstly, optical signals are rapidly absorbed in water. Secondly, optical scattering caused by suspended particles and plankton is significant. Thirdly, the high level of ambient light in the upper part of the water column is another adverse effect for using optical communication.

Apparently, each of the three physical waves as wireless information carrier has its own advantages and disadvantages. For a more intuitive comprehension, we summarize the major characteristics of acoustic, electromagnetic and optical carriers in Table 1.1. Acoustic waves propagate well in seawater and can reach a far distance. This justifies using acoustic waves for most underwater wireless communications.

<table>
<thead>
<tr>
<th>Table 1.1</th>
<th>Comparison of acoustic, EM and optical waves in seawater environments</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Acoustic</strong></td>
<td><strong>Electromagnetic</strong></td>
</tr>
<tr>
<td>Nominal speed (m/s)</td>
<td>$\sim 1500$</td>
</tr>
<tr>
<td>Power loss</td>
<td>relatively small</td>
</tr>
<tr>
<td>Bandwidth</td>
<td>$\sim$ kHz</td>
</tr>
<tr>
<td>Frequency band</td>
<td>$\sim$ kHz</td>
</tr>
<tr>
<td>Antenna size</td>
<td>$\sim 0.1$ m</td>
</tr>
<tr>
<td>Effective range</td>
<td>$\sim$ km</td>
</tr>
</tbody>
</table>

Source: Liu 2008 [255], Table 2, p. 984. Reproduced with permission of Wiley.
1.1.3 Underwater Systems and Networks

Along with the tremendous scientific and technology advances in last several decades, a wide range of underwater exploration and applications have emerged. The scientific exploration spans across multiple disciplines, such as physical oceanography, marine biology, and deep sea archaeology (e.g., discovery of the wreck of the Titanic). Environmental applications involve studies in pollution monitoring, climate change, and global warming. Commercial applications of underwater technologies can be found in, e.g., offshore oil/gas field monitoring, fishery industries, and treasure discovery. Military applications of underwater technologies include tactical surveillance in coastal areas, harbors and ports etc.

In recent years, development of underwater vehicles of various sizes and capabilities, such as sea gliders and autonomous underwater vehicles (AUVs), has enabled underwater applications without human interaction. For example, sea gliders can be deployed in lakes or oceans to collect data samples of water over a large time period, and then send the data back to a control center for scientific studies. A fleet of underwater vehicles can form an underwater network, in which vehicles can collaborate to accomplish predetermined tasks. As more intelligent systems are deployed in underwater applications, the need of communications and networking keeps growing.

1.2 UWA Channel Characteristics

Given the complexity of underwater acoustic medium and the low propagation speed of sound in water, the underwater acoustic channel is commonly regarded as one of the most challenging channels for communication. Next we will look into several distinguishing characteristics of underwater acoustic channels. Comparisons between the underwater acoustic channel and the terrestrial radio channel are made along with the descriptions of underwater acoustic channel characteristics.

1.2.1 Sound Velocity

The extremely slow propagation speed of sound through seawater is an important factor that differentiates it from electromagnetic propagation. The speed of sound in water depends on the water properties of temperature, salinity and pressure; illustrative plots of the three parameters as functions of water depth are shown in Figure 1.1 [305, Chap. 9]. A typical speed of sound in water near the ocean surface is about 1520 m/s, which is more than 4 times faster than the speed of sound in air, but five orders of magnitude smaller than the speed of light. The speed of sound in water grows with increasing water temperature, increasing salinity and increasing depth. Approximately, the sound speed increases 4.0 m/s for water temperature rising 1°C. When salinity increases one practical salinity unit (PSU), the sound speed in water increases to 1.4 m/s. As the depth of water (therefore also the pressure) increases to 1 km, the sound speed increases roughly to 17 m/s. It is noteworthy to point out the above assessments are only for rough quantitative or qualitative discussions, and the variations in sound speed for a given property are not linear in general.

A typical sound speed profile as a function of depth in deep water, is shown in Figure 1.2 [305, Chap. 9]. Depending on the depth, the profile can be divided into four layers.
• **Surface layer.** The surface layer usually has a water depth of a few tens of meters. Due to the mixing effect of wind, both temperature and salinity in this layer tend to be homogeneous, which leads to a constant sound velocity. This layer is also called a *mixed layer*.

• **Seasonal and permanent thermocline layers.** In the *thermocline* layers, the water temperature decreases as the water depth grows; as illustrated in Figure 1.1. In these two layers, the effect of increases in pressure and salinity cannot compensate the effect of temperature decrease. Therefore, there is a negative gradient of the sound speed profile in depth. In the seasonal thermocline layer, the negative gradient varies with seasons, while it is less seasonal in the permanent thermocline layer.