Multicarrier Spread Spectrum Communication Scheme for Cruising Sensor Network in Confined Underwater Space

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Received 28 February 2014; Revised 5 June 2014; Accepted 5 June 2014; Published 1 July 2014

1. Introduction

The research of this paper is based on cruising sensor network which takes charge of large oil storage tank online detection. Cruising sensor network consists of several actuated wireless sensor nodes. These wireless sensor nodes are ball-shaped, carry various types of sensors, and could independently move about in the large oil storage tanks. The advantage is that the sensors could get more detail messages by “cruising” to a specified place when monitoring the industrial process. The sketch map of the working cruising sensor network is shown in Figure 1. Cruising sensor network has promising applications in the online multiparameter detection and supervision of industrial liquid environments such as oil tanks, industrial ponds, and reservoirs.

Data exchange between the nodes and the control station necessitates a reliable and high-speed underwater acoustic (UWA) communication scheme. Underwater acoustic communication has always been considered to be difficult but research has made great progress in combating the negative effects of the underwater channel [1]. Most existing research concentrates on spacious environments such as seas and lakes; however, many of the industrial reservoirs such as large oil tanks and nuclear storage ponds are confined. The main difficulty to realize robust underwater communication in such limited space is the presence of strong multipath arrivals reflected by the boundaries, which can cause more severe intersymbol interference (ISI). We propose a communication scheme which applies spread spectrum in orthogonal frequency-division multiplexing (OFDM) to address severe frequency selective fading channels. This scheme can be robust in confined underwater channels when coupled with turbo code. The simulation and experimental results prove the feasibility and reliability of this scheme. It is demonstrated that significantly better performance is achieved than that of the conventional OFDM method.
Direct sequence spread spectrum (DSSS) technique has been demonstrated to be reliable in UWA communication [7–11]. The DSSS technique not only features a low probability of interception but also is immune to multipath interference. In DSS modulation, the spread spectrum process is achieved by multiplying the information signal with a spreading code. Due to the strong autocorrelation property of the spreading sequence, multiple arrivals can be separated via the despreading operation which suppresses the multipath interference. Researchers have done a great deal of work to enhance the performance of a DSSS system. Stojanovic and Freitag applied adaptive channel equalization to suppress ISI [8]. Sozer et al. applied a RAKE receiver to combine multipath arrivals [9]. In T. C. Yang and W. Yang's research, DSSS was coupled with passive-phase conjugation to achieve communication with low SNR input signals [10]. However, due to the conflict between the spread spectrum process and a limited available bandwidth of UWA channels, the main drawback of DSSS technique is the bandwidth efficiency, which is lower than 0.5 bit/s/Hz [12]. Therefore, DSSS systems are most commonly used in low-speed UWA communication where the data rates are often in the order of hundreds of bps.

Orthogonal frequency-division multiplexing (OFDM) is a prevailing technique used in wireless communication [13, 14]. The main idea of OFDM is to divide the bandwidth into many subchannels and transmit relatively low-speed data streams in a parallel way over these subchannels, each of which experiences frequency-flat fading. Therefore OFDM performs robustly in multipath environments with a high spectral efficiency [15]. Another advantage of OFDM systems is low complexity. OFDM modulation and demodulation can be easily implemented using fast Fourier transforms (FFT). In Frassati et al.'s research, an experiment was conducted to compare the performances of OFDM and DSSS in shallow waters of the Mediterranean Sea, and the result showed that OFDM outperforms DSSS [16].

In order to decrease ISI, one method is to split the bandwidth into more subchannels in the OFDM system. However, this method also introduces some negative effects, for example, a larger implementation complexity and more sensitivity to phase noise and frequency offset, as well as an increased peak-to-average power ratio. Another method is to insert a cyclic prefix (CP) in front of each OFDM block. Although using a cyclic prefix (CP) can cancel out most ISI and intercarrier interference (ICI), the cyclic prefix may be undesirably long where there is a long time spread [4]. In addition, the attenuation of multipath arrivals is very weak in confined underwater space. The strong multipath interference calls for a more powerful antimultipath scheme.

In this study, we propose an SS-OFDM scheme, which combines spread spectrum and OFDM, to overcome the severe interference of ISI in confined underwater channels. In the proposed scheme, the data sequence undergoes the procedure of spectrum spreading before OFDM modulation; thus, the residual multipath interference is significantly suppressed. The working process and principle of SS-OFDM are addressed. We compare the proposed scheme with conventional OFDM schemes and demonstrate superior antimultipath performance based on the simulation analysis and experimental results.

This paper is organized as follows. Section 2 introduces the system model and the mathematical description of the antimultipath performance of OFDM and SS-OFDM. Section 3 presents the simulation results. Section 4 shows the experimental design and results. Section 5 summarizes the paper.

2. System Description and Analysis

In this section, we develop an SS-OFDM system model for communication in confined underwater channels. Then, we introduce the transmitter structure in detail and analyze the antimultipath performance of an SS-OFDM system.

2.1. System Description. In our proposed scheme, turbo code, which is known as a strong channel code, is adopted to enhance the system performance. The basic principle and procedure of SS-COFDM (coded OFDM) are given in Figure 2.

The source signal is turbo-encoded, interleaved, and then mapped into a QPSK constellation (the most commonly used modulation mode in OFDM). The data sequence is then converted into \( M \) parallel data streams, as for conventional OFDM systems. For SS-OFDM, the next step is to replicate each stream to \( N \) copies. The signal will enter the spread spectrum process which is shown in Figure 3. \( N \) is equal to the length of the spreading code—a pseudonoise (PN) sequence, which is multiplied with each of these copies. Now there are \( M \times N \) subcarriers; that is, the SS-OFDM symbol length is \( M \times N \). The following procedure is the same as a conventional OFDM system.

Let \( f_k = f_c + k/T_b \) for \( k = 0, \ldots, M \times N - 1 \) be the \( M \times N \) subcarrier frequencies, where \( f_c \) is the carrier frequency and \( T_b \) is the SS-OFDM block duration.
The orthogonal basis functions are

\[ \phi_k(t) = \begin{cases} e^{j2\pi f_k t} & 0 \leq t \leq T_b, \\ 0 & \text{otherwise.} \end{cases} \]  

(1)

And the time domain of the \( r \)th block of an SS-OFDM signal can be written as

\[ x(t) = \sum_{k=0}^{N-1} X_{r,k} \phi_k(t) + \sum_{k=0}^{N-1} X_{r,r_1} \phi_{k+N}(t) + \cdots + \sum_{k=0}^{N-1} X_{r,M-1} \phi_{k+(M-1)N}(t), \]  

(2)
where \([x_{r,0}, \ldots, x_{r,M-1}]\) are the QPSK symbols transmitted on the \(m\)th subcarrier in the \(r\)th block and \([c_0, \ldots, c_{N-1}]\) are the symbols of the spread spectrum sequence.

In the demodulation process, based on the orthogonality between the subcarriers, the result for the \(l\)th subcarrier for the \(r\)th block (assuming \(0 \leq l \leq N - 1\)) is as follows:

\[
\tilde{d}_{r,l} = \frac{1}{T_b} \int_0^{T_b} x(t) \phi_l^* (t) \, dt
\]

\[
= \frac{1}{T_b} \int_0^{T_b} e^{-j2\pi f_l t} \sum_{k=0}^{N-1} x_{r,k} c_k e^{j2\pi f_k t} \, dt
+ \cdots + \frac{1}{T_b} \int_0^{T_b} e^{-j2\pi f_l t} \sum_{k=0}^{N-1} x_{r,m-1} c_k e^{j2\pi f_k t} \, dt
\]

\[
= \frac{1}{T_b} \sum_{k=0}^{N-1} c_k \int_0^{T_b} e^{j2\pi (f_k - f_l) t} \, dt
+ \cdots + \frac{1}{T_b} \sum_{k=0}^{N-1} c_k \int_0^{T_b} e^{j2\pi (f_k - f_l) t} \, dt
\]

\[
= x_{r,0} c_l.
\]

The demodulation process in (3) can be extended to all the subcarriers. After demodulation, the received array is

\[
\begin{bmatrix}
x_{r,0} c_0, x_{r,1} c_1, \ldots, x_{r,M-1} c_{N-1}, \\
x_{r,1} c_0, x_{r,1} c_1, \ldots, x_{r,1} c_{N-1}, \\
\cdots \\
x_{r,M-1} c_0, x_{r,M-1} c_1, \ldots, x_{r,M-1} c_{N-1}
\end{bmatrix}.
\]

Then, after the despreading process, we obtain the data sequence \([x_{r,1}, x_{r,2}, \ldots, x_{r,M}]\) which is transmitted by the \(r\)th block of the SS-OFDM signal.

2.2. Antimultipath Performance Analysis. In this section, we provide the antimultipath performance analysis of the proposed SS-OFDM scheme. In (2), without loss of generality, we only consider the first term. The transmitted symbol sequence is \([c_0, c_1, \ldots, c_{N-1}]\). The time domain expression can be written as

\[
s_{r,0}(t) = x_{r,0} \sum_{k=0}^{N-1} c_k \exp \left( j2\pi f_k t \right) \quad 0 \leq t \leq T_b.
\]

where \(\tau, A, \) and \(T_g\) are time delay, attenuation, and duration of the guard interval, respectively. Consider the following:

\[
y(t) = x_{r,0} \sum_{k=0}^{N-1} c_k \exp \left( j2\pi f_k t \right) \\
+ A x_{r,0} \sum_{k=0}^{N-1} c_k \exp \left( j2\pi f_k (t - \tau) \right)
+ A x_{r-1,0} \sum_{k=0}^{N-1} c_k \exp \left( j2\pi f_k (t + T_b + T_g - \tau) \right).
\]

In (7), the latter two terms represent the two types of multipath interferences mentioned above. In the receiver, the output of the \(l\)th subcarrier of the \(r\)th block can be written as

\[
y_{r,l} = x_{r,0} c_l + A x_{r,0} \sum_{k=0}^{N-1} c_k e^{-j2\pi f_k \tau} \int_0^T e^{j2\pi (f_k - f_l) t} \, dt
+ A x_{r-1,0} \sum_{k=0}^{N-1} c_k e^{-j2\pi f_k (T_b + T_g - \tau)} \int_0^T e^{j2\pi (f_k - f_l) t} \, dt.
\]

In this case, orthogonality between the subcarriers is not valid, so the latter two interference terms are included in the expression of \(y_{r,l}\) which can be simplified to

\[
y_{r,l} = x_{r,0} c_l + A x_{r,0} \sum_{k=0}^{N-1} c_k \lambda_{k,l}(\tau) + A x_{r-1,0} \sum_{k=0}^{N-1} c_k \mu_{k,l}(\tau)
\]

\[
= x_{r,0} c_l + \sum_{k=0}^{N-1} c_k \omega_{k,l}(\tau).
\]

We obtain the received sequence

\[
\begin{bmatrix}
x_{r,0} c_0 + \sum_{k=0}^{N-1} c_k \omega_{k,0}(\tau), x_{r,0} c_1 + \sum_{k=0}^{N-1} c_k \omega_{k,1}(\tau), \ldots, x_{r,0} c_{N-1}
+ \sum_{k=0}^{N-1} c_k \omega_{k,0}(\tau)
\end{bmatrix}.
\]

The receiver then multiplies the received sequence by the spreading sequence \([c_0, c_1, \ldots, c_{N-1}]\) and since there is good autocorrelation, the interference terms can be minimized.

By analyzing the antimultipath performance of SS-OFDM, we can conclude that the spread spectrum process eliminates the residual ISI that a conventional OFDM system is not able to address.

3. Simulation Results

In this section, we present simulation results in order to validate the performance of OFDM and SS-OFDM in the theoretical analysis.
Table 1: The system parameters of OFDM and SS-OFDM in the simulation.

| Communication mode | Effective subcarrier number | Length of PN sequence | Guard interval | Data rate (kbps) |
|--------------------|------------------------------|-----------------------|---------------|-----------------|
| OFDM               | 512                          | ×                     | $T_g = 41$ ms | 11.36           |
| OFDM               | 512                          | ×                     | $T_g = 82$ ms | 7.58            |
| OFDM               | 512                          | ×                     | $T_g = 102.5$ ms | 6.49         |
| SS-OFDM            | 170                          | 3                     | $T_g = 8.2$ ms | 6.29            |
| SS-OFDM            | 72                           | 7                     | $T_g = 8.2$ ms | 2.66            |

3.1. Channel Model. We begin by establishing an acoustic channel suitable for confined underwater space. Usually, UWA channel simulation studies are modeled on the sea. In such a UWA channel, complex time-varying oceanographic processes and ocean surface waves often produce a channel with short coherence time [17], so channel variation is an important issue which must be taken into account. However in oil storage tanks, the liquid is in a stationary state. Thus we refer to a time-invariant response acoustic channel proposed in [18].

In the model, each multipath acts as a low-pass filter. The transfer function of the $p$th propagation path is

$$H_p(f) = \frac{\Gamma_p}{\sqrt{A(l_p, f)}},$$

where $\Gamma_p$ is the cumulative reflection coefficient along the $p$th path, $l_p$ is the length of the $p$th path, and $f$ is the frequency of the signal. Consider

$$A(l, f) = A_0k^l a(f)^l,$$

where $A_0$ is a scaling constant, $k$ is the spreading factor, and $a(f)$ is the absorption coefficient.

The overall channel response is

$$h(t) = \sum_p e^{j(\theta_p + 2\pi f_D t_p)}h_p(t - \tau_p),$$

where $h_p(t)$ is the inverse Fourier transform of $H_p(f)$ and $\tau_p$, $\theta_p$, and $f_D$ are delay, phase rotation, and Doppler frequency of each path, respectively.

3.2. Simulation Results. Our considered channel for the simulation does not include the Doppler shift, and the lengths and relative delays of multiple propagation paths in the model are calculated from the geometry of the oil tank. There are totally 130 paths in the channel. The maximum time delay of the channel we propose is 45 ms.

We provide the BER analysis of OFDM and SS-OFDM in the channel. We set the number of effective subcarriers to 512 in OFDM, the carrier frequency is 10 kHz, and sample frequency is 50 kHz. QPSK modulation is used on each carrier. The IFFT size is 2048, the block duration is 41 ms, and each subcarrier is spaced by 24.4 Hz. In SS-OFDM, the number of effective subcarriers decreases because of the spread spectrum process. We adopt different lengths of cyclic prefix in OFDM and different lengths of PN sequence in SS-OFDM to analyze the system performance. The parameters are shown in Table 1.

Figure 4 shows performance results of the SS-OFDM and OFDM system. We can see the BER decreases as the cyclic prefix elongates in OFDM system. To address the long time delay of the channel, the length of the cyclic prefix could be longer than 100 ms. Correspondingly, SS-OFDM shows better performance in this multipath fading channel with the cyclic prefix length only 8.2 ms. The BER decreases as the length of PN sequence increases in SS-OFDM; however, the data rate also decreases.

4. The Experiment

4.1. Experimental Environment. The experiment was conducted in the quadrate tank in the laboratory, and the side length of the tank is 1.5 m. Since no sound absorption measure is adopted, this is a typical confined underwater channel with severe multipath fading. The transmitter and receiver were deployed in opposite corners of the tank.

To test the channel, a sine signal of 50 kHz frequency lasting 20 cycles was sent, and the received signal is shown in Figure 5. The direct signal is enclosed by the rectangle and the amplitude in the picture is a relative value. We can see that the channel condition is particularly harsh in the test, the multipath arrivals decay slightly in the first 20 ms we
intercept, and the multipath signal next to the direct signal nearly has the same amplitude with the direct signal. We can see more details in Figure 6 which displays a 10 ms capture. The multipath arrivals are numerous and intensive with large amplitudes.

Then we measured the channel impulse response by transmitting a 100 ms LFM signal with frequency swept from 30 kHz to 80 kHz. By calculating the cross-correlation functions between the received signal and the original LFM signal, the measured channel response can be shown in Figure 7. The maximum time delay is more than 50 ms.

4.2. Experimental Results and Analysis. At the transmitter, we set the sample frequency 500 KHz to make the carrier frequency 50 kHz, which is also the resonant frequency of the transducers. The OFDM modulation is realized by an IFFT with a size \(N = 2^{14}\); thus, the symbol duration of OFDM is 
\[ T_{\text{OFDM}} = 32.8 \text{ ms}. \]

The subcarrier spacing is 
\[ \Delta f = 1/T_{\text{OFDM}} = 30.5 \text{ Hz}. \]

The number of effective subcarriers is 160, and the bandwidth of OFDM signal is \( B = 4.9 \text{ kHz}. \)

We evaluate the OFDM system performance with different lengths of cyclic prefix and the results are shown in Table 2. The BER reduces as the guard interval length is increased, but the system performance is unsatisfactory even with a guard interval of 32.8 ms, the same length as the symbol duration of OFDM.

We can enhance the IFFT size of the OFDM system in order to increase the time duration of each subcarrier. The length of the guard interval \( T_g \) is always equal to \( T_{\text{OFDM}} \). In this set of experiments, the effective subcarrier is unchanged because we are only concerned about the performance of multipath resistance and take no account of data rate. Three sets of data are compared in Table 3. The system performance improves when the bandwidth is split into more channels and the length of cyclic prefix is increased beyond the maximum time delay. However, the transmission efficiency is becoming unacceptably low. Moreover, the sensitivity to Doppler shift interference increases as the subcarrier spacing decreases.

The SS-OFDM scheme has similar parameters to the experiments in Table 2. The difference is that the bandwidth is widened by the spread spectrum sequence. We use \( M \) sequence with length of 15 as the spread spectrum sequence. We compare the performance of the SS-OFDM with different...
Table 2: Performance of OFDM scheme with different lengths of guard interval.

| Communication mode | Subcarrier number | Guard interval | Data rate (kbps) | BER (%) |
|-------------------|------------------|---------------|-----------------|--------|
| OFDM              | 160              | \( T_g = T_{OFDM}/4 = 8.2 \text{ ms} \) | 6.79 | 16.68 |
| OFDM              | 160              | \( T_g = T_{OFDM}/2 = 16.4 \text{ ms} \) | 5.66 | 10.9 |
| OFDM              | 160              | \( T_g = T_{OFDM} = 32.8 \text{ ms} \) | 4.24 | 6.28 |

Table 3: Performance of OFDM scheme with different IFFT sizes.

| Communication mode | IFFT size | Guard interval | Subcarrier spacing (Hz) | BER (%) |
|-------------------|-----------|---------------|-------------------------|--------|
| OFDM              | \( 2^{14} \) | \( T_g = T_{OFDM} = 32.8 \text{ ms} \) | 30.5 | 6.28 |
| OFDM              | \( 2^{15} \) | \( T_g = T_{OFDM} = 65.6 \text{ ms} \) | 15.2 | 5.34 |
| OFDM              | \( 2^{16} \) | \( T_g = T_{OFDM} = 131.2 \text{ ms} \) | 7.6  | 3.13 |

Table 4: Performance of SS-OFDM scheme with different lengths of guard interval.

| Communication mode | Subcarrier number | Length of \( M \) sequence | Guard interval | Data rate (kbps) | BER (%) |
|-------------------|------------------|-----------------------------|---------------|-----------------|--------|
| SS-OFDM           | 160              | 15                          | \( T_g = T_{OFDM}/4 = 8.2 \text{ ms} \) | 6.79 | 4.27 |
| SS-OFDM           | 160              | 15                          | \( T_g = T_{OFDM}/2 = 16.4 \text{ ms} \) | 5.66 | 2.73 |
| SS-OFDM           | 160              | 15                          | \( T_g = 3T_{OFDM}/4 = 24.6 \text{ ms} \) | 4.86 | 2.45 |
| SS-OFDM           | 160              | 15                          | \( T_g = T_{OFDM} = 32.8 \text{ ms} \) | 4.24 | 2.51 |
| SS-OFDM           | 160              | 7                           | \( T_g = T_{OFDM}/2 = 16.4 \text{ ms} \) | 5.66 | 3.84 |
| SS-OFDM           | 320              | 7                           | \( T_g = T_{OFDM}/2 = 16.4 \text{ ms} \) | 11.32 | 4.9 |

Table 5: Performance of SS-COFDM scheme with different subcarrier numbers.

| Communication mode | Subcarrier number | Guard interval | Data rate (kbps) | BER (%) |
|-------------------|------------------|---------------|-----------------|--------|
| SS-COFDM          | 160              | \( T_g = T_{OFDM}/2 = 16.4 \text{ ms} \) | 2.83 | 0 |
| SS-COFDM          | 320              | \( T_g = T_{OFDM}/2 = 16.4 \text{ ms} \) | 5.66 | 0 |
| SS-COFDM          | 640              | \( T_g = T_{OFDM}/2 = 16.4 \text{ ms} \) | 11.32 | 0.016 |

lengths of cyclic prefix. The experimental result is shown in Table 4.

We can compare the experimental results with Table 2 and notice that much better performance is achieved with the same parameter settings in the SS-OFDM system. When \( T_g \) is equal to \( T_{OFDM}/2, 3T_{OFDM}/4 \), and \( T_{OFDM} \), the BER performance is nearly the same. We can consider that the guard interval \( T_{OFDM}/2 \) is enough for SS-OFDM in the experiment, which saves the transmission efficiency greatly compared to the OFDM scheme. At the end of Table 4, the SS-OFDM system performance degrades as the length of \( M \) sequence shortens and the number of effective subcarriers increases.

In order to further improve the system performance, turbo code, which is a strong channel coding method, is adopted to construct SS-COFDM scheme and compared with the last two schemes. In a turbo coding system, the data rate is halved because the coding rate is 1/2. The IFFT size is \( 2^{14} \), and the length of \( M \) sequence is 7. The experimental results are shown in Table 5. The system is error-free when the data rates are 2.83 and 5.66 kbps, although the length of cyclic prefix is only 16.4 ms which is much shorter than the maximum time delay of the channel. An acceptably small BER around \( 10^{-4} \) emerges when data rate reaches 11.32 kbps.

5. Conclusions

In this paper, we focused on building a reliable and high-speed communication scheme in confined underwater environments due to the need for application of cruising sensors network in online detection of oil tanks. Conventional OFDM scheme performs inferiorly in this environment, and we investigated SS-OFDM, the combination of DSSS and OFDM, and better performance was achieved when turbo code was employed simultaneously. We were able to demonstrate error-free transmission at data rate up to 5.66 kbps and low BER at 11.32 kbps in the experiment. In addition, this scheme offers convenient method for multiple users to access the channel simultaneously and asynchronously, an important research direction for the future.

Conflict of Interests

The authors declare that they do not have any commercial or associative interest that represents a conflict of interests in connection with the paper they submitted.

Acknowledgment

This work has been supported by the National Natural Science Foundation of China under Grant no. 61074181 and
References

[1] S. J. Hwang and P. Schniter, “Efficient multicarrier communication for highly spread underwater acoustic channels,” IEEE Journal on Selected Areas in Communications, vol. 26, no. 9, pp. 1674–1683, 2008.

[2] J. W. Jung and K. M. Kim, “Optimizing of iterative turbo equalizer for underwater sensor communication,” International Journal of Distributed Sensor Networks, vol. 2013, Article ID 129781, 6 pages, 2013.

[3] M. Stojanovic, J. G. Proakis, and J. A. Catipovic, “Analysis of the impact of channel estimation errors on the performance of a decision-feedback equalizer in fading multipath channels,” IEEE Transactions on Communications, vol. 43, no. 2, pp. 877–886, 1995.

[4] M. Chitre, S. Shahabudeen, and M. Stojanovic, “Underwater acoustic communications and networking: recent advances and future challenges,” Marine Technology Society Journal, vol. 42, no. 1, pp. 103–116, 2008.

[5] T. C. Yang, “Temporal resolutions of time-reversal and passive-phase conjugation for underwater acoustic communications,” IEEE Journal of Oceanic Engineering, vol. 28, no. 2, pp. 229–245, 2003.

[6] G. Zhang and H. Dong, “Underwater communications in time-varying sparse channels using passive-phase conjugation,” Applied Acoustics, vol. 74, no. 3, pp. 421–424, 2013.

[7] M. Stojanovic, J. G. Proakis, J. A. Rice, and M. D. Green, “Spread spectrum underwater acoustic telemetry,” in Proceedings of the 1998 Oceans Conference (OCEANS ’98), pp. 650–654, Nice, France, October 1998.

[8] M. Stojanovic and L. Freitag, “Hypothesis-feedback equalization for direct-sequence spread-spectrum underwater communications,” in Proceedings of the OCEANS MTS/IEEE Conference and Exhibition, vol. 1, pp. 123–128, Providence, RI, USA, September 2000.

[9] E. M. Sozer, J. G. Proakis, M. Stojanovic, and J. A. Rice, “Direct sequence spread spectrum based modem for underwater acoustic communication and channel measurements,” in Proceedings of the MTS/IEEE: Riding the Crest into the 21st Century (Oceans ’99), pp. 228–233, Seattle, Wash, USA, 1999.

[10] T. C. Yang and W. Yang, “Performance analysis of direct-sequence spread-spectrum underwater acoustic communications with low signal-to-noise-ratio input signals,” The Journal of the Acoustical Society of America, vol. 123, no. 2, pp. 842–855, 2008.

[11] G. Zhang and H. Dong, “Experimental demonstration of spread spectrum communication over long range multipath channels,” Applied Acoustics, vol. 73, no. 9, pp. 872–876, 2012.

[12] S. Climent, A. Sanchez, J. V. Capella, N. Meratnia, and J. J. Serrano, “Underwater acoustic wireless sensor networks: advances and future trends in physical, MAC and routing layers,” Sensors, vol. 14, no. 1, pp. 795–833, 2014.

[13] M. Stojanovic and L. Freitag, “Recent trends in underwater acoustic communications,” Marine Technology Society Journal, vol. 47, no. 5, pp. 45–50, 2013.

[14] B. Li, S. Zhou, M. Stojanovic, and L. Freitag, “Pilot-tone based ZP-OFDM demodulation for an underwater acoustic channel,” in Proceedings of the OCEANS 2006, Boston, Mass, USA, September 2006.
