Research Article

Research on Improvement of Spectrum Efficiency of Spread Spectrum OFDM Communication Scheme for Cruising Sensor Network

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Cruising sensor nodes have an attractive application in monitoring liquid-based industrial environments. A cruising sensor node, equipped with various sensors, is self-propelled so that they can “cruise” to specified area to gather scientific data. The cruising sensor network consists of an array of such cruising nodes to perform collaborative monitoring task over a given area. A reliable and high-speed underwater acoustic (UWA) communication scheme is necessary for node-to-node communication. Most of the industrial liquid reservoirs are confined spaces, including large oil tanks and nuclear storage ponds. The communication in confined underwater space will suffer more severe multipath interference caused by numerous reflections from boundaries. Conventional orthogonal frequency-division multiplexing (OFDM) technique has poor performance in this channel. Instead, spread spectrum orthogonal frequency-division multiplexing (SS-OFDM), which applies spread spectrum technique into OFDM, has better performance in such severely multipath fading underwater channels. However, the spread spectrum process causes a huge waste in the spectrum efficiency. In order to enhance the transmission efficiency, a mapping sequence spread spectrum OFDM (MSSS-OFDM) method is proposed in this paper. The simulation and experimental results show that our scheme is a robust and spectrum efficient communication method for confined underwater space.

1. Introduction

A cruising sensor network takes charge of monitoring liquid-based industrial environments such as large oil tanks, nuclear storage ponds, and drinking water reservoirs. The cruising sensor network consists of an array of submerged nodes equipped with sensors to gather scientific data in collaborative monitoring missions. The nodes are self-propelled so that they are able to “cruise” to specified area for more detailed message. When executing the task, the cruising sensor nodes need to communicate with each other to cowork together and send data to central station back. Therefore, a robust and high-speed underwater acoustic (UWA) communication scheme is needed.

UWA communication is widely used in many applications of underwater exploration activities [1]. Almost all the existing research on UWA communication concentrates on spacious areas such as seas and lakes. However, most of the industrial liquid environments in practice are confined. Unlike the multipath interference generated from surface and floor reflections in the sea, the reflections are from all directions in confined underwater space. Therefore, the confined underwater channel is characterized by a long delay spread with slight attenuation.

The researchers have made huge efforts to eliminate the intersymbol interference (ISI) caused by multipath arrivals. Direct sequence spread spectrum (DSSS) technique has gained considerable attention in UWA communication not only for its low interception probability and inherent interference rejection, but also for its relative immunity from multipath interference [2–4]. In DSSS modulation, the original signal is multiplied by a pseudo-noise (PN) code to perform spread spectrum process. The received signal is despread using the same spreading code. Due to the strong autocorrelation property of the spreading code, the multipath arrivals longer than one chip of the spreading code can be suppressed greatly.
Orthogonal frequency-division multiplexing (OFDM) has been drawing the attention recently, featuring its strong anti-multipath and low complexity properties [5–7]. In OFDM modulation, a high-speed transmitted data stream is divided into a number of low rate ones which are transmitted over a certain number of subcarriers. Moreover, the OFDM structure is simple due to modulation and demodulation process can be implemented by fast Fourier transform (FFT).

Both DSSS and OFDM have great potential to combat multipath interference in UWA communication. We have proposed applying spread spectrum OFDM (SS-OFDM) scheme, which combines spread spectrum and OFDM technique, to address the severe frequency selective fading in confined UWA channels [8]. The simulation and experimental results show that the bit error rate (BER) performance of SS-OFDM has significantly better outcome than OFDM scheme. SS-OFDM requires much fewer subcarriers and significantly shorter cyclic prefix (CP) to eliminate the ISI. Therefore, SS-OFDM shows a robust communication scheme in confined UWA channels. Although the shorter CP in SS-OFDM contributes to enhancing the data rate, the spread spectrum process jeopardizes the system bandwidth and reduces spectrum efficiency [9]. A PN code with length \( N \) will cause the bandwidth efficiency dropping to \( 1/N \) times of the original OFDM system.

Our research aims at enhancing the bandwidth efficiency of SS-OFDM scheme. M-ary spread spectrum is widely used to improve the data rate of spread spectrum scheme [10, 11]. M-ary-SS-OFDM system can be constructed when M-ary spread spectrum modulation is applied in SS-OFDM. In the system, \( M = 2^k \) orthogonal PN sequences compose a PN sequence set. Every \( k \) bits of the original message formed one group and the resulting decimal value acts as an index to select the corresponding PN sequence in the set. The receiver correlates the received signal with each item in the PN sequence set and determines the transmitted symbol with the highest correlation. Therefore, the data rate is enhanced by \( k = \log_2 M \) times. However, the PN sequence we adopt in SS-OFDM scheme is quite short. Hence the inferior orthogonality of the PN sequence hinders the application of M-ary modulation in our scheme.

In this paper, we adopt mapping sequence spread spectrum (MSSS) scheme in SS-OFDM system to construct MSSS-OFDM system. In an MSSS system, three bits can be transmitted at the same time by transforming the three DSSS signals into one mapping sequence [12]. The mapping sequence has good correlation property with the DSSS signals. In the receiver, each transmitted signal can be demodulated with its own spread spectrum sequence. Thus the system data rate is tripled compared to DSSS system. We evaluate the performance of our proposed MSSS-OFDM scheme both in experiment and simulation with a heavy reverberation channel. Results show that the proposed scheme can provide a spectrum efficient and robust UWA link.

This paper is organized as follows. After the introduction in Section 1, Section 2 introduces and analyzes the MSSS-OFDM structure. The simulation and experimental results are demonstrated in Section 3 and Section 4, respectively. At last Section 5 leads us to the conclusions of this paper.

2. System Description

The system structure of DSSS-OFDM has been described in detail in [8]. In this section, firstly, the proposed MSSS-OFDM scheme will be introduced and analyzed in detail. Then, we compare the anti-multipath performance of DSSS-OFDM and MSSS-OFDM.

2.1. Mapping Sequence SS-OFDM. The transmitter block diagram of MSSS-OFDM system is shown in Figure 1. The source data stream is firstly converted to \( M \) parallel data streams. Then the parallel data are divided into \( M/3 \) groups. Each group has 3 bits. In every group, each bit is multiplied with its own spread spectrum sequence. Thus the system correlation functions between the MS and \( P_i \) are

\[
P_1 = x_0 PN_1 = x_0 \{a_0, a_1, \ldots, a_{N-1}\},
\]

\[
P_2 = x_1 PN_2 = x_1 \{b_0, b_1, \ldots, b_{N-1}\},
\]

\[
P_3 = x_2 PN_3 = x_2 \{c_0, c_1, \ldots, c_{N-1}\}.
\]

Then these three sequences are transformed into one mapping sequence as follows:

\[
m_i = \text{sign} (x_0 a_i + x_1 b_i + x_2 c_i) \quad (i = 0, 1, \ldots, N-1),
\]

where

\[
\text{sign} (u) = \begin{cases} +1, & (u > 0) \\ -1, & (u < 0). \end{cases}
\]

The mapping sequence \( MS = \{m_0, m_1, \ldots, m_{N-1}\} \) has strong correlation with the three original sequences. The correlation functions between the MS and \( P_i \) can be written as

\[
R_i = \sum_{i=1}^{L} m_i x_0 a_i = \sum_{i=1}^{L} x_0 a_i \text{sign} (a_i + b_i + c_i),
\]

\[
\text{sign} (a_i + b_i + c_i) = \begin{cases} a_i, & (b_i \neq c_i \text{ or } a_i = b_i = c_i) \\ -a_i, & (b_i = c_i \neq a_i). \end{cases}
\]

For three PN sequences, the probabilities that \( b_i \neq c_i, b_i = c_i = a_i, \) and \( b_i = c_i \neq a_i \) are 1/2, 1/4, and 1/4, respectively. Therefore, the correlation between the MS and \( P_i \) is \( R_i = 1/2 \).

Let \( T \) denote the MSSS-OFDM symbol duration and \( f_c \) for the carrier frequency. The \( k \) th subcarrier is at the frequency

\[
f_k = f_c + \frac{k}{T}, \quad k = 0, 1, \ldots, \frac{M \times N}{3} - 1.
\]

Define the orthogonal basis function for the \( k \) th subcarrier as

\[
\phi_k (t) = \begin{cases} e^{j2\pi f_c t}, & 0 \leq t \leq T, \\ 0, & \text{otherwise}. \end{cases}
\]
The time domain of the transmitted signal is

\[ s(t) = \sum_{k=0}^{N-1} \text{sign}(x_0a_k + x_1b_k + x_2c_k) \phi_k(t) \]

\[ + \cdots + \sum_{k=0}^{N-1} \text{sign}(x_{M-3}a_k + x_{M-2}b_k + x_{M-1}c_k) \times \phi_{k+(M/3-1)N}(t). \]

In the receiver, the demodulated symbol of the \(l\)th (assuming \(0 \leq l \leq N-1\)) subcarrier can be written as

\[ \hat{d}_l = \frac{1}{T} \int_0^T s(t) \phi^*_l(t) \, dt \]

\[ = \frac{1}{T} \left( \int_0^T \sum_{k=0}^{N-1} \text{sign}(x_0a_k + x_1b_k + x_2c_k) e^{j2\pi(f_k-f_l) t} \right) dt \]

\[ + \cdots + \int_0^T \sum_{k=0}^{N-1} \text{sign}(x_{M-3}a_k + x_{M-2}b_k + x_{M-1}c_k) \times e^{j2\pi(f_{k+(M/3-1)N}f_l)} dt \]

\[ = \text{sign}(x_0a_l + x_1b_l + x_2c_l) \]

\[ = m_l. \]  

(9)

For simplicity, only the first group \(\{x_0, x_1, x_2\}\) will be taken into consideration in the despreading process, which can be further expanded to all the groups. The demodulated mapping sequence of the first group is \(\{m_0, m_1, \ldots, m_{N-1}\}\). Multiply this sequence by \(PN_1, PN_2, \) and \(PN_3\) to perform the despreading process. On the output of the demodulator for \(PN_1\), we have

\[ y_0 = \sum_{k=0}^{N-1} \text{sign}(x_0a_k + x_1b_k + x_2c_k) \times a_k. \]

(10)

From the result in (5) we can obtain

\[ \text{sign}(x_0a_k + x_1b_k + x_2c_k) \times a_k \]

\[ = \begin{cases} x_0a_k = x_0, & x_1b_k \neq x_2c_k \text{ or } x_1b_k \neq x_2c_k = x_0a_k \\ -x_0a_k = -x_0, & x_1b_k = x_2c_k \neq x_0a_k. \end{cases} \]

(11)

Then the demodulated signal can be written as

\[ y_0 = \frac{N}{2} x_0. \]

(12)

Therefore, the transmitted signal will be demodulated correctly.

From the structure of MSSS-OFDM, we can conclude that the system data rate is tripled compared to DSSS-OFDM by transforming three parallel modulated signals into one mapping sequence. Moreover, comparing the structure of MSSS-OFDM with DSSS-OFDM, the receiver structure remains the same and the mapping process in the transmitter does not complicate the system.
2.2. Antimultipath Performance Analysis. We have analyzed the antimultipath performance of DSSS-OFDM system in [8]. Now we review this process briefly. The time domain expression of a DSSS-OFDM signal is given by

\[ S(t) = \sum_{k=0}^{N-1} x_0 c_k \exp(j2\pi f_k t) \]

\[ + \sum_{k=0}^{N-1} x_1 c_k \exp(j2\pi f_{k+N} t) \]

\[ + \cdots + \sum_{k=0}^{N-1} x_{M-1} c_k \exp(j2\pi f_{k+(M-1)N} t) . \]  

(13)

Without loss of generality, we only consider the first item in (13). After going through a multipath channel, the demodulated output of the \( l \)th subcarrier is

\[ y_l = x_0 c_l + \sum_{k=0}^{N-1} c_k \omega_{k,l}(\tau) , \]

where the latter is the interference item and \( \tau \) is the multipath delay. The received sequence is

\[ \left\{ x_0 c_l + \sum_{k=0}^{N-1} c_k \omega_{k,0}(\tau), x_0 c_1 + \sum_{k=0}^{N-1} c_k \omega_{k,1}(\tau), \ldots, x_0 c_{N-1} \right\} + \sum_{k=0}^{N-1} c_k \omega_{k,N-1}(\tau) . \]

(15)

Then the received sequence is multiplied by the spreading sequence \( \{c_0,c_1,\ldots,c_{N-1}\} \). The despreading output is

\[ \sum_{k=0}^{N-1} x_0 + \mu, \]

where \( \mu \) is the interference item. Due to the strong autocorrelation property of spreading sequence, the interference item is greatly suppressed. Moreover, the interference item reduces as the length of spreading sequence increases.

In MSSS-OFDM system, we also consider the first item in (8). The demodulated sequence of the multipath influenced signal is

\[ \left\{ m_0 + \sum_{k=0}^{N-1} m_k \omega_{k,0}(\tau), \ldots, m_{N-1} + \sum_{k=0}^{N-1} m_k \omega_{k,N-1}(\tau) \right\} . \]

(17)

Then the receiver multiplies the demodulated sequence by the three original PN sequence. Take sequence \( P_N \) as example; the despreading result can be obtained from the result in (12) as follows:

\[ \frac{1}{2} \sum_{k=0}^{N-1} x_0 + \mu. \]

(18)

MSSS-OFDM can suppress the multipath interference which the OFDM system is not able to eliminate because mapping sequence MS has strong correlation with PN. However, the correlation between MS and PN equals half of the PN autocorrelation; its antimultipath ability is inferior compared to DSSS-OFDM system, which could be compensated by using longer m-sequence or cyclic prefix.

So far we can conclude the advantages of the proposed MSSS-OFDM scheme.

(1) Compared to DSSS-OFDM system, MSSS-OFDM can merge every three parallel data streams into one stream. Although longer cyclic prefix is needed, the total data rate can be greatly enhanced without increasing the computational burden.

(2) Compared to M-ary-SS-OFDM system, MSSS-OFDM is more suitable for spectrum efficiency improvement of SS-OFDM system with short PN sequences.

3. Simulation Studies

In this section, we introduce the self-designed channel model for confined underwater space at first. Then relevant simulation has been done to evaluate our proposed scheme with different parameter settings.

3.1. Channel Model. Usually, in an UWA channel, a physical discrete multipath channel can be modeled as

\[ h(t) = \sum_p h_p \delta(t - \tau_p), \]

(19)

where \( h_p \) and \( \tau_p \) represent the gain and time delay of the \( p \)th propagation path, respectively [13, 14].

The simulation concerns a typical confined underwater channel. Random channel variation is not taken into account because most confined underwater spaces are static without surface wave disturbance. Sound speed can be taken as a constant \( c \) in confined underwater space. For underwater spaces with regular shape, path lengths can be calculated using plain geometry. Let \( l_p \) denote the length of the \( p \)th propagation path; the path delay can be obtained as

\[ \tau_p = \frac{l_p}{c}. \]

(20)

The propagation loss of the \( p \)th path is

\[ A_p = A_0 |k a(f)|^p, \]

(21)

where \( A_0 \) is a scaling constant, \( k \) is the spreading factor, and \( a(f) \) is the absorption coefficient. The gain of the \( p \)th path is given by

\[ h_p = \frac{\Gamma_p}{\sqrt{A_p}}, \]

(22)

where \( \Gamma_p \) is the cumulative reflection coefficient along the \( p \)th propagation path.
Table 1: The system parameters for simulation.

| Parameter                              | Value                  |
|----------------------------------------|------------------------|
| Effective subcarriers                  | 32 (DSSS-OFDM)         |
| Length of m-sequence                   | 15                     |
| IFFT size                              | 2048                   |
| Sampling frequency                     | 50 kHz                 |
| Carrier frequency                      | 10 kHz                 |
| Subcarrier spacing                     | 24.4 Hz                |
| Length of cyclic prefix                | 20.5 ms                |
| Pilot type                             | Block                  |

Table 2: Performances of three schemes with different length of m-sequence.

| Communication mode | Subcarrier number | Length of m-sequence | Data rate (kbps) | BER (%) |
|--------------------|-------------------|----------------------|------------------|---------|
| DSSS-OFDM          | 360               | 7                    | 12.74            | 4.25    |
| MSSS-OFDM          | 1080              | 7                    | 38.21            | 11.02   |
| M-ary-SS-OFDM      | 720               | 15                   | 25.48            | 27.56   |
| DSSS-OFDM          | 180               | 15                   | 6.37             | 2.21    |
| MSSS-OFDM          | 540               | 15                   | 19.11            | 6.56    |
| M-ary-SS-OFDM      | 540               | 15                   | 19.11            | 15.92   |
| DSSS-OFDM          | 90                | 31                   | 3.18             | 0.71    |
| MSSS-OFDM          | 270               | 31                   | 9.45             | 4       |
| M-ary-SS-OFDM      | 360               | 31                   | 12.74            | 8.02    |

Figure 2: BER performance of OFDM, DSSS-OFDM, and MSSS-OFDM.

We can develop the channel model by using ray theory for a given geometry and signal frequency. Image-source method is adopted to calculate the channel parameters of a 15 m cubic underwater space in this simulation. In our proposed model, there are more than 140 paths and the maximum time delay is more than 50 ms.

3.2. Simulation Results. The performances of three schemes including OFDM, DSSS-OFDM, and MSSS-OFDM in the channel described above are tested. The main parameters of the system are listed in Table 1. QPSK is used for mapping the data and m-sequence is adopted as the spreading code. Figure 2 shows the bit error ratio (BER) performance of OFDM, DSSS-OFDM, and MSSS-OFDM. We can see that MSSS-OFDM can greatly improve the system performance in confined UWA channels compared to OFDM. Although the BER performance is slightly poorer than DSSS-OFDM, MSSS-OFDM can enhance the system data rate by three times.

Figure 3 shows the system performance of MSSS-OFDM with different lengths of m-sequence. The system performance increases as the length of m-sequence elongates. The MSSS-OFDM system with 31-chip m-sequence has nearly the same BER performance as DSSS-OFDM system with 15-chip m-sequence. Although the m-sequence is twice the length of that in DSSS-OFDM, in MSSS-OFDM the overall data rate can be enhanced by 1.5 times.

4. Pool Experiment

4.1. Experimental Environment. For the experiment, we use a cube-shaped test tank with side length of 1.5 m. The transmitter and receiver are deployed in opposite corners of the tank, which is a typical confined underwater space. The channel condition is very harsh because no sound absorption approach is adopted. An LFM signal of 100 ms with frequency swept from 30 kHz to 80 kHz is transmitted to measure the channel. By calculating the crosscorrelation functions between the transmitted and received signal, the channel response can be shown in Figure 4. As evident, the channel...
Table 3: Performance of MSSS-OFDM with different length of cyclic prefix.

| Communication mode | Subcarrier number | Length of m-sequence | Cyclic prefix | Data rate (kbps) | BER (%) |
|--------------------|-------------------|----------------------|---------------|----------------|---------|
| MSSS-OFDM          | 540               | 15                   | $T_g = T_b/2 = 16.4$ ms | 19.11         | 6.56    |
| MSSS-OFDM          | 540               | 15                   | $T_g = 3 \times T_b/4 = 24.6$ ms | 16.38         | 4.27    |
| MSSS-OFDM          | 540               | 15                   | $T_g = T_b = 32.8$ ms | 14.3          | 3.16    |

Table 4: Performance of DSSS-COFDM and MSSS-COFDM with different length of m-sequence.

| Communication mode | Subcarrier number | Length of m-sequence | Cyclic prefix | Data rate (kbps) | BER (%) |
|--------------------|-------------------|----------------------|---------------|----------------|---------|
| DSSS-COFDM         | 180               | 15                   | $T_g = T_b/2 = 16.4$ ms | 3.18          | 0       |
| DSSS-COFDM         | 360               | 7                    | $T_g = T_b/2 = 16.4$ ms | 6.37          | 0.078   |
| MSSS-COFDM         | 540               | 15                   | $T_g = T_b = 32.8$ ms | 7.17          | 0       |
| MSSS-COFDM         | 1080              | 7                    | $T_g = T_b = 32.8$ ms | 14.3          | 0.57    |
| MSSS-COFDM         | 1080              | 7                    | $T_g = 3T_b/2 = 49.2$ ms | 11.5          | 0.024   |

Figure 4: The channel response of the test tank.

is characterized by strong multipath interference. The maximum multipath delay is more than 50 ms.

4.2. Experimental Results. We compare three schemes including DSSS-OFDM, MSSS-OFDM, and M-ary-SS-OFDM. The parameter settings are the same in all schemes. The carrier frequency is 50 kHz and sampling frequency is 500 kHz. The modulation is implemented using IFFT with size of $2^{14}$. Thus the block duration is $T_b = 32.8$ ms and the subcarrier spacing is $\Delta f = 1/T_b = 30.5$ Hz. Due to the strong anti-multipath capability of SS-OFDM, we use a guard interval of $T_g = 16.4$ ms which is greatly shorter than the maximum time delay to address the multipath interference. The modulation method is QPSK. We evaluate the performances of three schemes with a varying length of m-sequence. The experimental results are shown in Table 2. With the same parameter setting, MSSS-OFDM scheme allows triple subcarrier number as that of DSSS-OFDM and M-ary-SS-OFDM allows $k = \lfloor \log_2 M \rfloor$ times, where $M$ is the length of m-sequence. As predicted, the BER performance of MSSS-OFDM is worse than that of DSSS-OFDM with the same length of m-sequence. The system performance is getting better as the length of m-sequence is increased. The performance of M-ary-SS-OFDM is inferior to the other two schemes. Although the BER significantly reduces as the length of m-sequence elongates, the performance is still unsatisfying. The reason is that short m-sequence is adequate for SS-OFDM; the orthogonality of m-sequence is not good enough to make the performance of M-ary-SS-OFDM system satisfying.

Compared to the original m-sequence, the mapping sequence losses 1/4 message. Therefore the antimultipath performance degrades. With this in mind, we enhance the length of cyclic prefix in MSSS-OFDM scheme. The experimental results listed in Table 3 show that the BER performance is obviously enhanced as the length of cyclic prefix elongates. When the BER performance is nearly the same as DSSS-OFDM, the data rate is higher in MSSS-OFDM system.

In order to further improve the system performance, turbo code is adopted as the error correcting code in both schemes to construct DSSS-COFDM and MSSS-COFDM. The coding rate is 1/2, so the system data rate is halved. The experimental results of DSSS-COFDM and MSSS-COFDM with different length of m-sequence are shown in Table 4. The BER can be controlled in acceptable range when the turbo code is added. When the length of m-sequence is 15, both schemes show error-free performance. Although the MSSS-OFDM needs longer cyclic prefix to address the same multipath channel, the system data rate can be enhanced by about twice when the BER performances are very close.

5. Conclusions and Future Work

The DSSS-OFDM method, which combines direct sequence spread spectrum and OFDM, is a robust communication scheme for cruising sensor network in confined underwater space. However, the spread spectrum process decreases the bandwidth efficiency of the system. In order to build a spectrum efficient communication scheme, we investigated the application of mapping sequence spread spectrum scheme as the spreading process to construct an MSSS-OFDM scheme.
The MSSS-OFDM scheme can transmit three data signals at same time by transforming three spreading signals into one mapping sequence. There is no need to change the receiver structure and computational complexity is not increased in the proposed scheme. The simulation and experimental results show that it is a robust and spectrum efficient communication scheme in confined underwater channels.

As the point-to-point communication technique is well studied, the future research will focus on building an underwater network in confined space. One of the basic DSSS techniques known as code division multiple access (CDMA) allows several users to share a band of frequencies, which will be the starting point of our future work.

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.

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