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Research Article

An Underwater Acoustic Implementation of DFT-Spread OFDM

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This paper presents a design of DFT-spread OFDM system applied to an underwater acoustic channel. It does not only combine all the advantages of a conventional OFDM system but also reduces the peak-to-average power ratio of the transmit signal. Besides, the scheme spreads the information over several subcarriers as a result of the application of an additional DFT operation and leads to a diversity gain in a frequency-selective fading channel, which is one of the many challenges of communicating data through an underwater acoustic channel. Simulation results show that our proposal possesses good bit-error-rate performance. The system has been tested in a real underwater acoustic channel—the experimental pool in Xiamen University. The experimental results show that the DFT-spread OFDM system can achieve better results than a simple OFDM system in a benign underwater channel.

1. Introduction

Underwater acoustic channels are considered to be “quite possibly nature’s most unforgiving wireless medium” [1]. The complexity of underwater acoustic channels is driven by the ocean environment characteristics which include large delay, Doubly-spread, Doppler-spreads, frequency-selective fading, and limited bandwidth [2]. However, since the beginning of the 20th century, underwater communication has been used [3] and there is a pressing demand for higher data rate systems that can cope with the highly scattered underwater channel.

Multicarrier modulation is an alternative to overcoming the long delay spread inherent in underwater acoustic channels. It increases the symbol interval and thereby decreases the intersymbol interference (ISI) [4]. The most popular method of multicarrier modulation for underwater acoustic communication is orthogonal frequency division multiplexing (OFDM), which has been widely studied. However, the OFDM system suffers a number of drawbacks, one of them is high peak-to-average power ratio, since the OFDM systems transmit signal resulting from the superposition of a large number of independent data symbols [5, 6].

In order to transmit a signal without distortion, the OFDM system requires a more expensive power amplifier with high linearity and a wide dynamic range. Besides, the nonlinear distortions due to clipping and amplification effects in the transmitted signal will lead to both in-band and out-of-band emissions [7]. In-band distortions will only degrade the performance of the OFDM system whereas out-of-band emissions will also disturb services in adjacent transmission bands. Normally, out-of-band emissions have therefore to be reduced below specified power levels to comply with a given spectrum mask [8].

There have been many studies on the reduction of peak-to-average power ratio, such as the clipping method, the pre-coding method, the partial-transmit sequence method, the selective mapping method, and so on [9–12]. But all methods have drawbacks. These drawbacks are associated with a high computational complexity, large memory requirements, or distortion of the transmitted signal. However, Discrete Fourier Transform-Spread Orthogonal Frequency Division Multiplexing (DFT-spread OFDM) is one outcome of such investigations [13].

The DFT-spread OFDM scheme was first proposed in [14]. In this scheme, data symbols are spread over several subcarriers by DFT, and this is followed by ordinary OFDM

processing. Compared with conventional OFDM systems, the DFT-spread OFDM leads to a diversity gain in frequency-selective channel, and it combines the advantages of single-carrier transmission, like constant signal envelope, simple clock, and frequency synchronization [15]. As such it has already been selected as the uplink modulation scheme for the upcoming Long-Term Evolution of 3G systems under the work item of Evolved-UTRA by 3GPP [16]. In [17], Nisar et al. analyzed the error probabilities of the DFT-spread OFDM and derived their analytical closed-form expressions for the additive white Gaussian noise (AWGN), fading AWGN, and multipath and fading multipath channel scenarios.

Underwater acoustic communication is an important challenge due to the presence of fading, multipath, and refractive properties of the sound channel [18]. Low peak-to-average power ratio and a diversity gain in frequency-selective channel are just two reasons why we chose a DFT-spread OFDM system to transmit data over an underwater acoustic channel. The former advantage can improve the power efficiency of the transmitter and the later advantage reduces the bit-error rate of the system.

The rest of this paper is organized as follows. In Section 2, the signal processing operations in DFT-spread OFDM system are described. As channel estimation is not the most important purpose in this study, we use a simple least squares channel estimation method, our system, as described in Section 3. Simulation results of the DFT-spread OFDM and OFDM systems under Rayleigh fading channel conditions are given in Section 4, as well as the experiment results in experimental pool of Xiamen University, China.

2. System Model

In DFT-spread OFDM, data symbols are spread by DFT, and this is followed by ordinary OFDM processing. Figure 1 shows the block diagram of the DFT-spread OFDM system. The input data is first mapped into a QPSK constellation. Then the data sequence is converted in parallel and entered the FFT to perform spreading. Pilot signals are inserted before the IFFT operation which is used to implement OFDM modulation. A cyclic prefix is also appended to the data sequence as guard interval. The complex base-band signal is then upconverted to the transmission frequency and sent out to the underwater acoustic channel by the transducer.

Suppose that the input data, $\{d_i, 0 \leq i \leq 2M-1\}$, is then the symbol mapping $\{x_l = d_{2(i-1)} + jd_{2i-1}, 0 \leq l \leq M-1\}$ and is then spread by DFT.

$$S_k = \text{FFT}(x_l) = \sum_{l=0}^{M-1} x_l e^{-j2\pi lk/M}. \quad (1)$$

The DFT spread symbols $\{S_k, 0 \leq k \leq M-1\}$ are mapped onto M subcarriers out of a total of $N = QM$ points by zero padding. The operation can be described as follows:

$$X_k = \begin{cases} S_k, & 0 \leq k \leq M-1 \\ 0, & M \leq k \leq N-1, \end{cases} \quad (2)$$

k denotes the k th subcarrier symbol. The resulting frequency-domain symbols X_k are then transformed to the time-domain symbol sequence $\{\hat{x}_n, 0 \leq n \leq N-1\}$ by an IFFT operation:

$$\begin{aligned} \hat{x}_n &= \text{IFFT}(X_k) \\ &= \frac{1}{N} \sum_{k=0}^{N-1} X_k e^{j2\pi(nk/N)} \\ &= \frac{1}{N} \sum_{k=0}^{M-1} S_k e^{j2\pi(nk/N)} \\ &= \frac{1}{N} \sum_{k=0}^{M-1} \sum_{l=0}^{M-1} x_l e^{-j2\pi(lk/M)} e^{j2\pi(nk/N)} \\ &= \frac{1}{N} \sum_{k=0}^{M-1} \sum_{l=0}^{M-1} x_l e^{j2\pi((n-Ql)k/N)}. \end{aligned} \quad (3)$$

Let $n = Qp + q$, where $0 \leq p \leq M-1$ and $0 \leq q \leq Q-1$. Then,

$$\begin{aligned} \hat{x}_n &= \hat{x}_{Ql+q} = \frac{1}{N} \sum_{k=0}^{M-1} \sum_{l=0}^{M-1} x_l e^{j2\pi((n-Ql)k/N)} \\ &= \frac{1}{N} \sum_{k=0}^{M-1} \sum_{l=0}^{M-1} x_l e^{j2\pi((Qp-lQ+q)/N)k}. \end{aligned} \quad (4)$$

If $q = 0$, then

$$\begin{aligned} \hat{x}_n &= \frac{1}{N} \sum_{k=0}^{M-1} \sum_{l=0}^{M-1} x_l e^{j2\pi((Qp-lQ+q)/N)k} \\ &= \frac{1}{N} \sum_{k=0}^{M-1} \sum_{l=0}^{M-1} x_l e^{j2\pi((p-l)/M)k} \\ &= \frac{1}{Q} x_p = \frac{1}{Q} x_{(n/Q)}. \end{aligned} \quad (5)$$

If $q \neq 0$, then

$$\begin{aligned} \hat{x}_n &= \frac{1}{N} \sum_{k=0}^{M-1} \sum_{l=0}^{M-1} x_l e^{j2\pi((Qp-lQ+q)/N)k} \\ &= \frac{1}{N} \sum_{l=0}^{M-1} x_l \sum_{k=0}^{M-1} e^{j2\pi((Qp-lQ+q)/N)k} \\ &= \frac{1}{N} \left(1 - e^{j2\pi(q/Q)}\right) \sum_{l=0}^{M-1} \frac{x_l}{1 - e^{j2\pi((Qp+q-Ql)/N)}}. \end{aligned} \quad (6)$$

As we have seen from the previous discussion, DFT-spread OFDM have exact copies of input time symbols with a scaling factor of $1/Q$ in the (Ql) th multiple sample positions, both of Q and l are integer, and in-between values are the sum of all the time input symbols in the input block with different complex weighting [19].

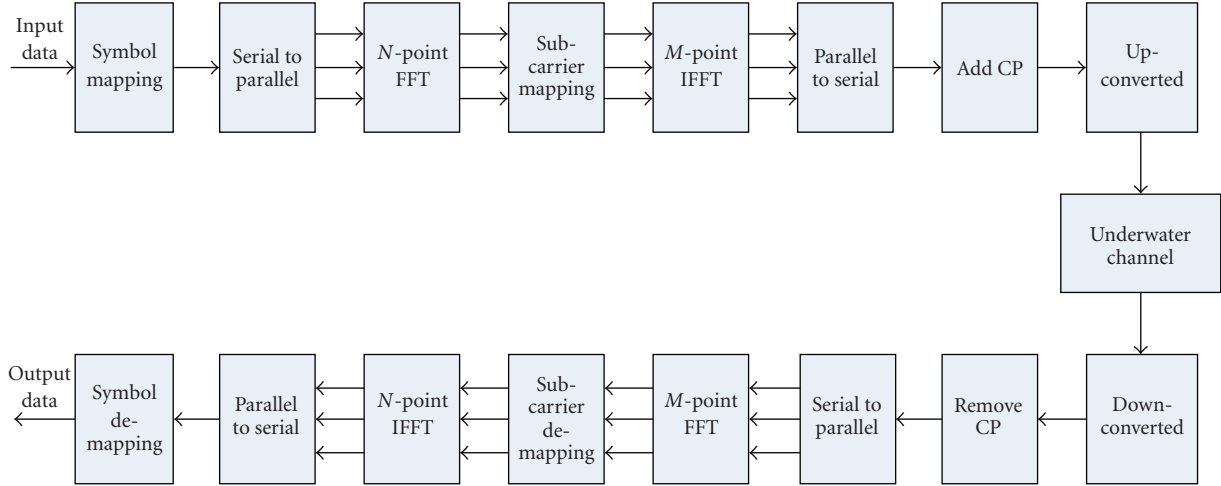


FIGURE 1: A block diagram of a DFT-spread OFDM system.

The structured mapping between the DFT spread symbols and sub-carriers enables the transmitted signal to have a low peak-to-average power ratio. Except for the DFT spreading and the structured symbol to subcarrier mapping, it is identical to OFDM [20].

A cyclic prefix is employed in order to avoid intersymbol and intercarrier interferences. The time length of the cyclic prefix is chosen to be larger than the expected delay spread. Suppose the time length of cyclic prefix is T_{cp} and the useful data duration is T_s . In this paper, the number of points in the IFFT is $N = 2048$ and the number of useful subcarriers is $M = 512$. The signal frequency band is 6000 Hz, so $T_s = 512/6000 = 0.0853s$. We set $T_{cp} = (1/4)T_s$, the total time for a DFT-spread OFDM symbol was $T = T_s + T_{cp} = 0.1067s$.

3. Channel Estimation

3.1. Channel Model. The transmitted signal in DFT-spread OFDM is

$$s(t) = \frac{1}{N} \sum_{k=0}^{M-1} \sum_{l=0}^{M-1} x_l e^{j2\pi(n-Ql)k/N} e^{j2\pi f_c t}, \quad (7)$$

where f_c is the carrier frequency.

After being transmitted over a frequency selective fading channel, the received signal is

$$r(t) = \sum_{k=0}^{M-1} \sum_{l=0}^{M-1} \alpha_k x_l e^{j2\pi(n-Ql)k/N} e^{j2\pi f_c t} e^{j\phi_k} + n_0(t), \quad (8)$$

where α_k and ϕ_k are the amplitude fade and phase offset on the k th carrier. $n_0(t)$ is the additive white Gaussian noise (AWGN).

The real underwater acoustic channel in which we tested our system was far too simplistic compared with the real ocean channels. Considering the frequency-domain signal of the OFDM communication system, the transmitted signal is

X , and the receiving signal is Y . The system can be described as

$$Y[m, k] = H[m, k]X[m, k] + W[m, k], \quad (9)$$

where $H[m, k]$ and $W[m, k]$ are the column vectors representing the channel and the noise at the k th subcarrier for the m th OFDM symbol.

3.2. Least Squares Channel Estimation. In order to coherently demodulate DFT-spread OFDM and OFDM signals, channel state information (CSI) must be available at the receiver. Added channel information via the use of pilot sequence, which is predefined, is frequently employed within OFDM systems [21]. We choose block-pilot in our systems, the pattern of the transmit signals is shown in Figure 2. Both of the DFT-spread OFDM and OFDM signals are divided into blocks. Through the paper, adjacent signal blocks are grouped together, without overlapping between adjacent groups. In each group, the first signal block is used to transmit a pilot signal and it is called the pilot block. The remaining four blocks bear information data and thus are called information blocks. The channel state information must be estimated continually, because the underwater acoustic channels are time varying. The time length between two pilot blocks is limited and can be designed according to the channel state. In our scheme, the time length of each group is $5T$.

There are many techniques to estimate the channel state information exploiting pilot blocks, such as leastsquares (LS), minimum mean square error (MMSE), and linear minimum mean square error (LMMSE). A detailed description of channel estimation can be found in [21]. In this paper, we use LS channel estimation, which is the simplest method. Starting from system model of OFDM given in (9) the LS estimation of $H[m, k]$ is

$$\hat{H}_{LS}[m, k] = \frac{Y[m, k]}{X[m, k]} = H[m, k] + \frac{W[m, k]}{X[m, k]}. \quad (10)$$

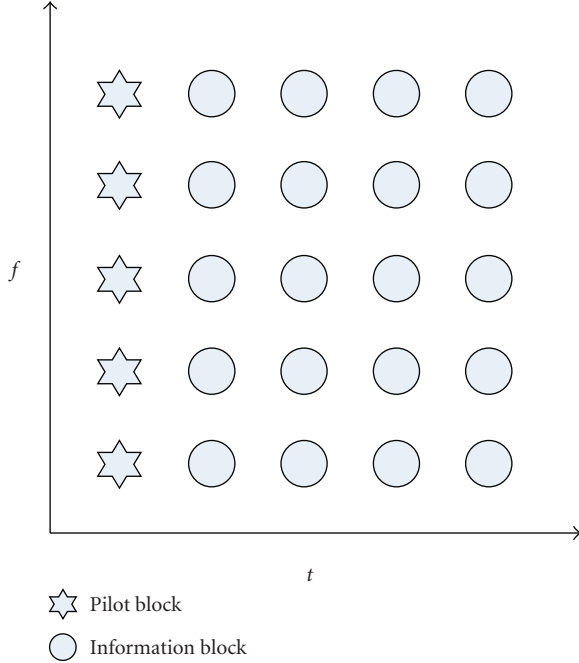


FIGURE 2: The pattern of transmit signals.

In matrix notations,

$$\hat{H}_{LS} = \text{diag}(X)^{-1}Y + \text{diag}(X)^{-1}W. \quad (11)$$

4. Simulation and Experiment Results

4.1. Simulation Result. In order to test the performance of DFT-spread OFDM and OFDM systems, both of them are simulated in a Rayleigh fading channel, supposing that the time synchronization and frequency synchronization are perfect. The simulation of the performance of DFT-spread OFDM and OFDM systems in Rayleigh fading channel using MATLAB is shown in Figure 3. As shown in the simulation result, the performance of the DFT-spread OFDM system is better than that of the OFDM system in a Rayleigh fading channel, just because the former has a diversity gain in the frequency domain.

4.2. Experiment Design. The experiment was carried out at the experimental pool in Xiamen University. Figure 4 depicts the location of transmitter and receiver transducers. Both of them were kept still during the whole experiment. The distance between the transmitter and the receiver is 10 m.

In order to know the frame boundary, LFM signals are appended before the data sequence before being transmitted into the channel. At the receiver, time synchronization is achieved via correlating the received samples with the known LFM sequence. After that, the received data is divided into DFT-spread OFDM or OFDM symbols.

System specification for the experiment is shown in Table 1.

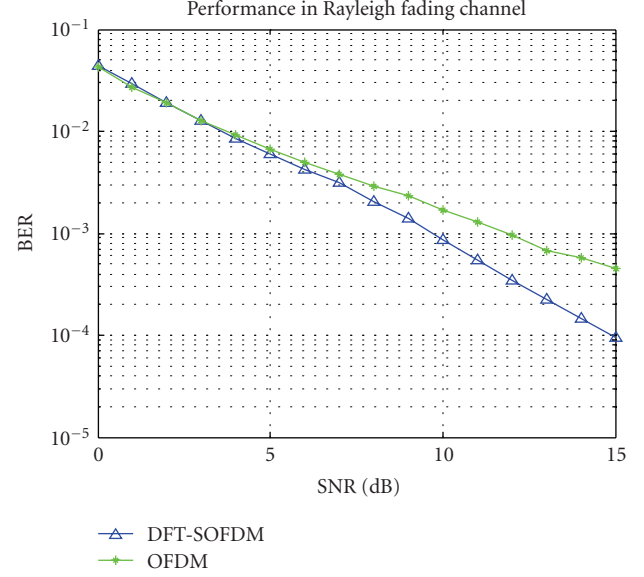


FIGURE 3: The simulation result of the performance in Rayleigh fading channel.

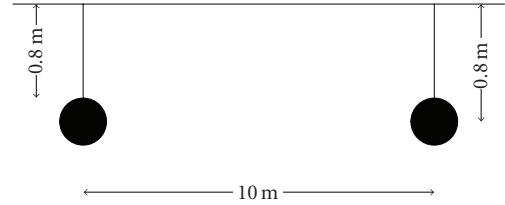


FIGURE 4: Location of Transducer.

TABLE 1: System specification.

Mapping mode	QPSK
Bandwidth	6000 Hz
Carrier frequency	27000 Hz
Transmission frequency band	27000–33000 Hz
Symbol duration	117.3 ms

4.3. Experimental Results and Analysis. Figures 5–8 are the power spectral density of the DFT-spread OFDM system and the OFDM system in both transmitter and receiver. Comparing Figures 5 and 6, Figures 7 and 8, the power spectral density of the receive data is quite different from transmit data, which confirms that the real underwater acoustic channel is a frequency-selective fading channel.

Table 2 is the result of the experiment. From Table 2, we can see that the average bit-error rate of the OFDM system is 0.00666 nearly 10 times of the result of the DFT-spread OFDM system, of which the average bit-error rate is 0.000786. The results of the experiment confirm that, in the underwater acoustic channel, the DFT-spread OFDM system has better performance than the OFDM system primarily as a result of the improved peak-to-average power ratio characteristics.

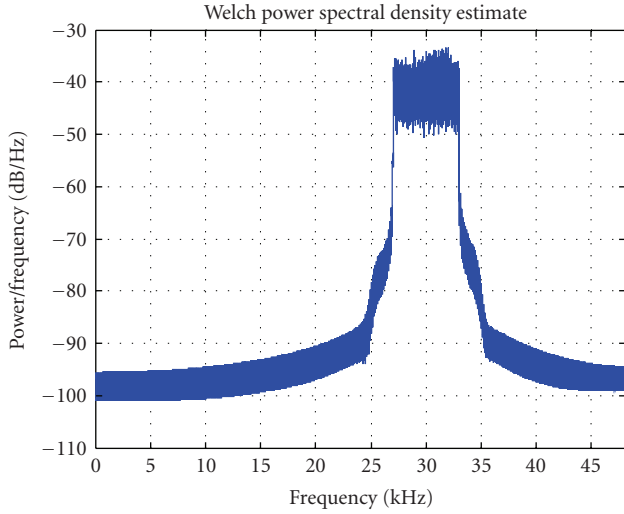


FIGURE 5: The transmit data power spectral density of the DFT-spread OFDM system.

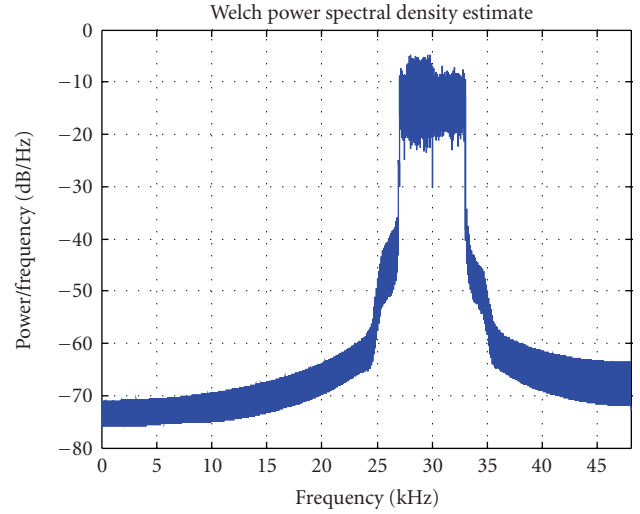


FIGURE 7: The transmit data power spectral density of the OFDM system.

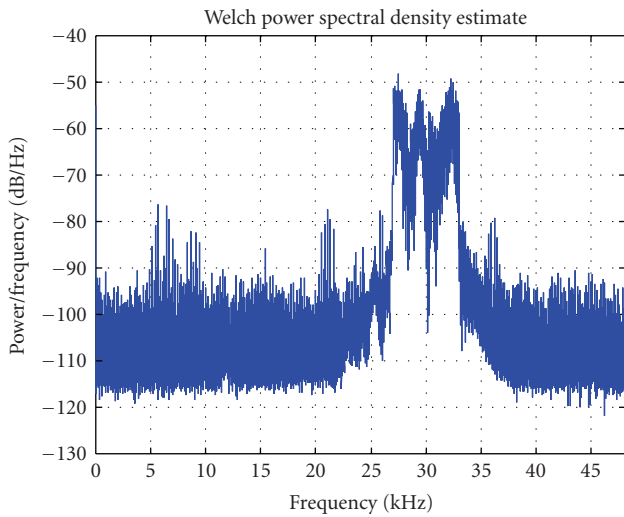


FIGURE 6: The receive data power spectral density of the DFT-spread OFDM system.

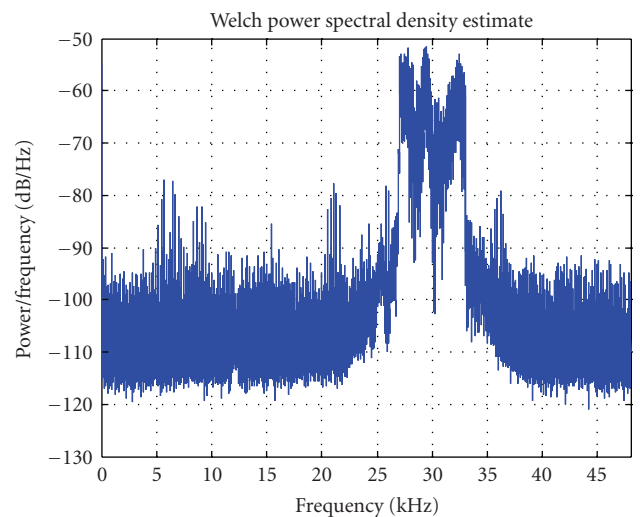


FIGURE 8: The receive data power spectral density of the OFDM system.

TABLE 2: Experiment results.

Number of the test	OFDM	DFT-spread OFDM
1	0.0069	0.00074
2	0.0067	0.00076
3	0.0067	0.00081
4	0.0066	0.00079
5	0.0064	0.00083
Average	0.00666	0.000786

5. Conclusions

In this paper, we have proposed a new design of DFT-spread OFDM system. The simulation results and the experiment

results in a benign underwater channel show that, compared with the typical OFDM system, the proposed DFT-spread OFDM system could achieve excellent performance. The study demonstrated that DFT-spread OFDM system is applicable for underwater acoustic communication.

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