INTL JOURNAL OF ELECTRONICS AND TELECOMMUNICATIONS, 2018, VOL. 64, NO. 4, PP. 433-438
Manuscript received December 6, 2017; revised October, 2018. DOI: 10.24425/123542

Damped Zero-Pseudorandom Noise OFDM Systems

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***Abstract*—This paper proposed a new OFDM scheme called damped zero-pseudorandom noise orthogonal frequency division multiplexing (DZPN-OFDM) scheme. In the proposed scheme, ZPN-OFDM non-zero part is damped to reduce its energy, thus the mutual interference power in-between the data and training blocks with conservative the pseudo-noise conventional properties required for channel estimation or synchronization. The motivation of this paper is the OFDM long guard interval working in wide dispersion channels, whereas a significant energy is wasted when the conventional ZPN-OFDM is used as well as the BER performance is also degraded. Moreover, the proposed scheme doesn't duplicate the guard interval to solve the ZPN-OFDM spectrum efficiency loss problem. Both detailed performance analysis and simulation results show that the proposed DZPN-OFDM scheme can, indeed, offer significant bit error rate, spectrum efficiency and energy efficiency improvement.**

***Keywords*—Time reversal (TR), channel estimation (CE), compressed sensing (CS), orthogonal frequency division multiplexing (OFDM)**

I. INTRODUCTION

SPECTRUM and energy efficiency are very important for current and future wireless communication system. OFDM has been extensively adopted and it is widely recognized for future wireless communication system as a modulation technique. Generally, there are three major types of techniques mitigate OFDM inter-block interference: cyclic prefix OFDM (CP-OFDM), zero padding OFDM (ZP-OFDM), and known symbol padding OFDM (KSP-OFDM) [1, 2]. In CP-OFDM the CP is used as a guard interval to avoid inter-block interferences (IBIs) in multipath fading channels. Such CP is replaced in ZP-OFDM by zeros to solve the channel transmission zero problem and guarantee symbol recovery in any case of the channel zero locations [3, 4]. Also, ZP-OFDM reduce the consumption of the guard interval power [5-8]. For these reasons, it is usually preferred for long tap delay channels such as underground and underwater communication channel. However, in such channels, a long guard interval is required to avoid IBIs OFDM whereas waste spectral efficiency [5-11]. For spectral efficiency improvement, recently time reversal OFDM has proved a promising spectral efficient scheme for a single-input multi-output communications (SIMO) system over time-dispersive fading channels. It can convert sparse and multi-path channels into an "impulse-like" channel [5, 12]. In conventional ZP-OFDM and CP-OFDM schemes, the guard interval contents are not relevant, and not fully utilized for channel estimation and sometimes insufficient for synchronization purposes [1, 13]. For full guard interval utilization, a pseudorandom noise (PN) sequence known for both transmitter (TX) and receiver (RX) can be used for channel estimation and synchronization in KSP-OFDM[1, 14]. In this paper, a new OFDM scheme attempt to improve the performance by avoid ZPN-OFDM [9] waste of spectral and energy.

For the major types of KSP-OFDM multicarrier systems, such as time domain synchronization OFDM (TDS-OFDM) [15], dual pseudorandom noise OFDM (DPN-OFDM) [16] and zero-pseudorandom noise OFDM (ZPN-OFDM) [9] includes a PN sequence as a guard interval for synchronization and channel estimation. However, there are delicate differences among them, resulting in differences in performance. For TDS-OFDM, the received PN sequence is subject to mutual interference between the PN training sequence and OFDM data block. To address this issue, DPN-OFDM proposed to include two periodical PN sequences and the second PN sequence is free form the mutual interference [16]. To improve energy efficiency, the first PN sequence in DPN-OFDM replaced by a zeros in ZPN-OFDM. However, the DPN-OFDM and ZPN-OFDM waste spectrum efficiency due to guard interval duplication. Along with this line, by combing the advantages of both KSP-OFDM and ZP-OFDM schemes, this paper modified ZPN-OFDM sequences by damped the PN sequence without duplicate the guard interval to improve the energy efficiency and bit error rate (BER) without affecting PN autocorrelation feature.

The rest of this paper is organized as follows. First, proposed DZPN-OFDM scheme is introduced and discussed in Section II. Then, the performance of the proposed scheme is analyzed and evaluated by simulations and emulated experimental results in Section III. Finally, Section IV concludes the paper.

II. PROPOSED OFDM SCHEME

Energy is one of the most important problems of the battery based communication systems and in underwater communication the problem will be more complicated, where in addition to suffering from the limited power source the recharging capability will be hard. Since, researchers try to increase the battery life by utilizing a finite energy efficiently as much as possible. In this way of research, the ZPN-OFDM has been proposed to improve the energy efficiency of the

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multi-carrier OFDM system used in underwater communication [9]. However, ZPN-OFDM use dual guard interval so it has low spectrum efficiency and it still has degradation in the BER performance. The BER performance problem has been solved in [17] by using the TDS-OFDM based on time reversal technique. This paper proposed DZPN-OFDM system based on time reversal technique to avoid such harsh problems (BER performance, energy and spectrum efficiency) in underwater OFDM multicarrier techniques.

Among the three KSP-OFDM sub-types, i-th TDS-OFDM transmitted signal frame denoted by, $s_i = \left[s_{i,0}, s_{i,1}, \ldots, s_{i,P-1}\right]^T$, consist two independent parts, first part is the known PN sequence, $c_i = \left[\alpha \cdot c_{i,0}, \alpha \cdot c_{i,1}, \ldots, \alpha \cdot c_{i,M-1}\right]^T$ with M length and the second one is data blocks, $x_i = \left[x_{i,0}, x_{i,1}, \ldots, x_{i,N-1}\right]^T$ with length N.

$$S_i = \begin{bmatrix} C_i \\ X_i \end{bmatrix}_{P\times 1}, \tag{1}$$

where α is a constant amplitude factor imposed on the time-domain guard interval and the length of TDS-OFDM signal frame is $\boldsymbol{P = M + N}$. While i-th DPN-OFDM transmitted signal frame is:

$$S_i = \begin{bmatrix} C_i \\ C_i \\ X_i \end{bmatrix}_{Q\times 1}, \tag{2}$$

and in the ZPN-OFDM case, i-th transmitted signal frame will be:

$$S_i = \begin{bmatrix} \mathbf{0}_{M\times 1} \\ C_i \\ X_i \end{bmatrix}_{Q\times 1}, \tag{3}$$

thus, the DPN-OFDM and ZPN-OFDM frame length is $Q = 2M + N$.

In the proposed DZPN-OFDM scheme, the transmitted signal frame will be:

$$S_i = \begin{bmatrix} \mathbf{0}_{\frac{M}{2}\times 1} \\ \mathbb{C}_{\frac{M}{2}\times 1} \\ X_i \end{bmatrix}_{A\times 1}, \tag{4}$$

where the zeros sequence and the damped PN sequence length will be $\frac{M}{2}$, and the total frame length will be $A = M + N$. The damped PN training sequence, $\mathbb{C}_i = \left[a_{i,0} \cdot c_{i,0}, a_{i,1} \cdot c_{i,1}, \cdots, a_{i,\frac{M}{2}} \cdot c_{i,\frac{M}{2}}\right]^T$ is a PN sequence multiplied by damped factor, a_i, imposed on the time-domain guard interval.

In multipath channels, IBIs between the OFDM data blocks and PN sequence in different KSP-OFDM multicarrier shemes can be illustrated as shown in Fig. 1. The basic principle of KSP-OFDM is that, with perfect channel estimation, mutual interference can be completely removed from the KSP-OFDM data block [18]. Unfortunately, as shown in Fig. 1. (a), the received PN sequence is corrupted by the mutual interference, hence the perfect channel estimation will not be applicable. In DPN-OFDM [16] and zero-pseudorandom noise training OFDM (ZPN-OFDM) [9] the TDS-OFDM IBI problems can be solved, where a perfect channel can be applied using noise-free PN sequence.

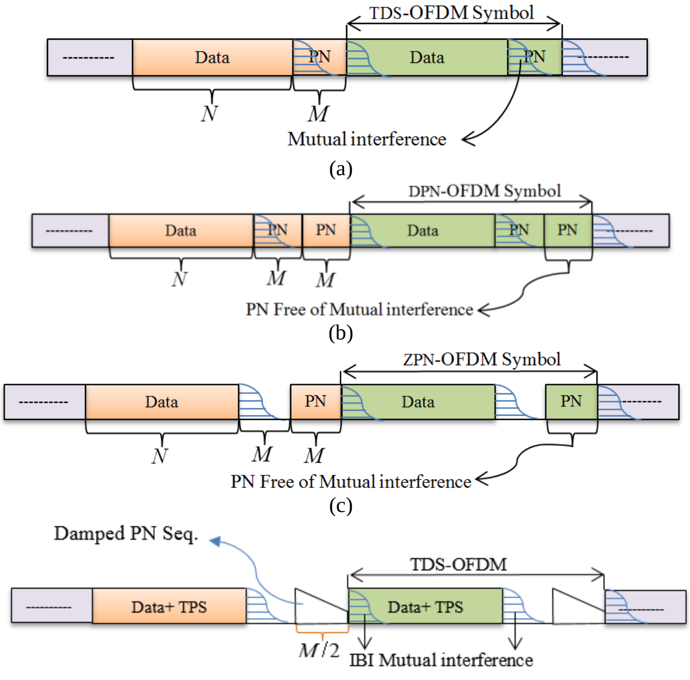


Fig. 1. KSP-OFDM received frames in time dispersive fading channels; (a) TDS-OFDM scheme; (b) DPN-OFDM; (c) ZPN-OFDM scheme; (d) Proposed DZPN-OFDM;

DZPN-OFDM Channel Estimation

Channel estimation in the proposed DZPN-OFDM based on damped PN sequence shown in Fig. 1. (c), can be estimated based on structured compressive sensing (SCS) as discussed in [14, 19, 20]. Where an efficient, acquired and reconstructed signal can be obtained by using the SCS through finding solutions to underdetermined linear systems [20]. In DZPN-OFDM, the received PN sequence, $d_i = \left[d_{i,0}, d_{i,1}, \ldots, d_{i,M-1}\right]^T$ can be written as:

$$d_i = \boldsymbol{\psi}_i h_i + w_i, \tag{5}$$

where w_i represent the noise terms, and sensing matrix is:

$$\boldsymbol{\psi}_i = \begin{bmatrix} a_{i,0}\cdot c_{i,0} & x_{i-1,N+\frac{M}{2}-1} & x_{i-1,N+\frac{M}{2}-2} & \cdots & x_{i-1,N+\frac{M}{2}-L+1} \\ a_{i,1}\cdot c_{i,1} & a_{i,0}\cdot c_{i,0} & x_{i-1,N+\frac{M}{2}-1} & \cdots & x_{i-1,N+\frac{M}{2}-L+2} \\ a_{i,2}\cdot c_{i,2} & a_{i,1}\cdot c_{i,1} & a_{i,0}\cdot c_{i,0} & \cdots & x_{i-1,N+\frac{M}{2}-L+3} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ a_{i,L-1}\cdot c_{i,L-1} & a_{i,L-2}\cdot c_{i,L-2} & a_{i,L-3}\cdot c_{i,L-3} & \cdots & a_{i,0}\cdot c_{i,0} \\ a_{i,L}\cdot c_{i,L} & a_{i,L-1}\cdot c_{i,L-1} & a_{i,L-2}\cdot c_{i,L-2} & \cdots & a_{i,1}\cdot c_{i,1} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ a_{i,\frac{M}{2}-1}\cdot c_{i,\frac{M}{2}-1} & a_{i,\frac{M}{2}-2}\cdot c_{i,\frac{M}{2}-2} & a_{i,\frac{M}{2}-3}\cdot c_{i,\frac{M}{2}-3} & \cdots & a_{i,\frac{M}{2}-L}\cdot c_{i,\frac{M}{2}-L} \end{bmatrix}. \tag{6}$$

The received training sequence d_i in multipath channel is contaminated by the portion $\left[x_{i-1,N+\frac{M}{2}-L+1}, x_{i-1,N+\frac{M}{2}-L+2}, \ldots, x_{i-1,N+\frac{M}{2}-1}\right]^T$ of the previous OFDM data block x_{i-1} in case of insufficient guard interval length (guard interval length is less than the maximum tap delay of channel). Fortunately, based on proposed DZPN-OFDM, this contamination has low effect due to the zero sequence in-between the data and PN sequence. To this end, the existing compressed sensing (CS) theory can be applied to ensure that, the high-dimensional original signal can be reconstructed from the low-dimensional observations if the signal is (approximately) sparse, i.e., [14, 19].

Spectral and Energy Efficiency

The OFDM energy efficiency can be calculated as:

$$\eta_0 = \frac{E(D)}{E(D)+E(GI)} \times 100\%, \qquad (7)$$

where $E(D)$ is the energy loss due to data transmission and $E(GI)$ is the energy loss due to guard interval (GI) transmission.

The normalized throughput, γ_0, of OFDM schemes can be written as:

$$\gamma_0 = \frac{N}{N+GIL} \times \log(1+SIR), \qquad (8)$$

where GIL is the guard interval length.

TR-SIMO-DZPN-OFDM

Thanks to its capability for multipath focusing and multipath reduction, TR-SIMO-OFDM is widely used in long tap delay channels such as underground and underwater communications [5, 12]. In time reversal technique, the channel information is collected at the beginning based on a probe signal transmitted and recorded at the receiver side [12]. Proposed DZPN-OFDM can be implemented based on TR-SIMO-OFDM to reduce the mutual interference between DZPN-OFDM parts (data blocks and training) in multipath fading channel from received frame at high signal–to–noise ratios (SNRs). The major part of noise originates TR-SIMO-DZPN-OFDM performance can be evaluated by using the signal–to–interference ratio (SIR) ρ_{SIR} of receiver data blocks. ρ_{SIR} value is clearly dependent on the guard interval length and receiver number used on the receiver side. As the number of the antenna in receiver side increases, the multipath power will be reduced and convert the multipath channel into an impulsive channel centered at the zero-tab delay. Hence, the TR-SIMO-DZPN-OFDM SIR can be calculated as:

$$\rho_{SIR-DZPN} = \frac{\sum_{n=0}^{M} \left|q[i;n]\right|^2}{\sum_{n\leq 1} \left|\alpha[i;n] \cdot q[i;n]\right|^2}. \qquad (9)$$

III. SIMULATION RESULTS

In this section, the performance of the proposed scheme will be evaluated for underwater communication channel using randomly generated information bits. The proposed scheme will be evaluated for encoded and un-encoded BER performance. In un-encoded case random information bits are generated and modulated to generate the data symbols, but in the encoded case it will be encoded first by using conventional coder. The system BER performance is evaluated for an underwater acoustic channel model adopted from experimental data collected in the ASCOT01 experiment conducted off the coast of New England in June 2001, as reported in [9, 21]. With a maximum of 128 channel tap delay as in [9]. Channel is estimated frame by frame by using simultaneous orthogonal matching pursuit (SOMP) algorithm [14, 22]. The OFDM data is recovered by using multi-tap equalizer. The OFDM data subcarrier number is $N = 512$ and QPSK is used as a modulation technique.

Signal–to–Interference

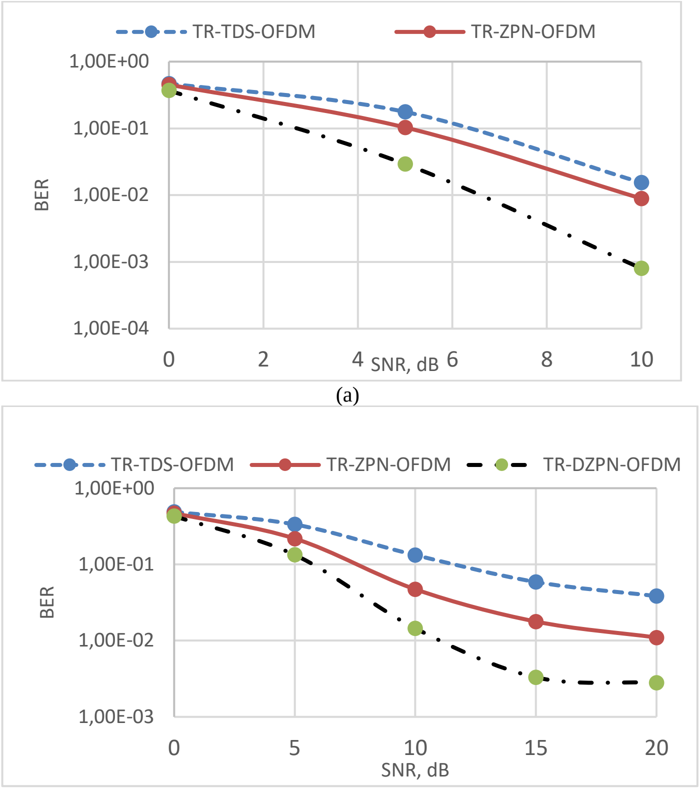
In this experiment, the SIR is evaluated for the proposed TR-SIMO-DZPN-OFDM and conventional TR-SIMO-ZPN-OFDM schemes. SIR is evaluated for single antenna receiver and four antenna receiver. Table I shows the SIRs of different schemes. Based on simulation results proposed scheme provides a significant improvement.

TABLE I
THE SIR OF TR-SIMO-DZPN-OFDM COMPARED TO OTHERS

		TR-SIMO-DZPN-OFDM	TR-SIMO-ZPN-OFDM	TR-SIMO-TDS-OFDM
Single antenna	$GIL = 128$	0.9441	0.9184	0.904
	$GIL = 16$	0.8878	0.8289	0.837
Four antenna receivers	$GIL = 128$	0.9746	0.9662	0.9223
	$GIL = 16$	0.9581	0.9359	0.9053

BER Performance

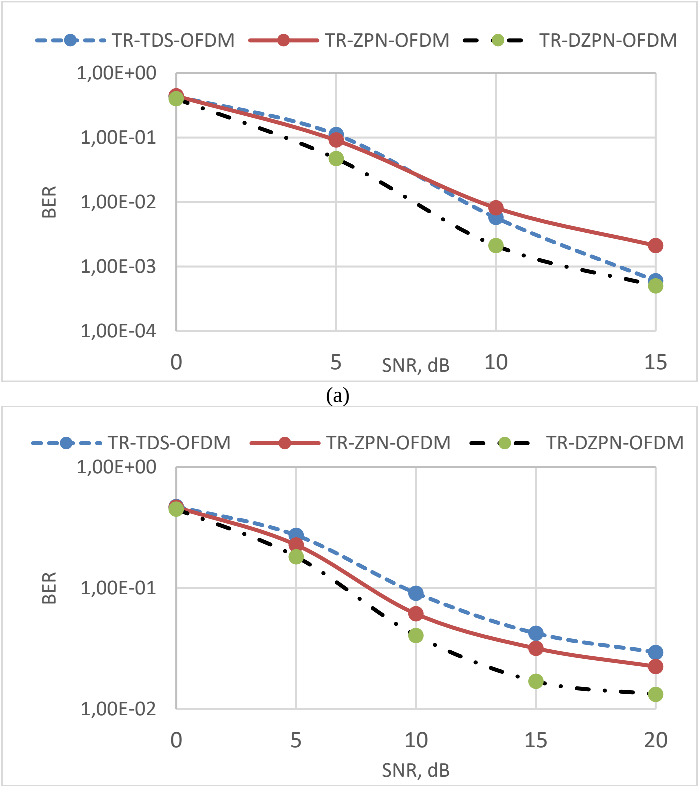
This paper propose the DZPN-OFDM to improve the ZPN-OFDM energy efficiency, spectral efficiency and BER. This experiment to evaluate the BER performance. The systems performances are considered in two different cases in respect of the guard interval length; 1) when the guard interval length is equal to the maximum channel tap delay ($GIL = 128$); 2) when the guard interval length is shorter than the maximum channel tap delay ($GIL = 16$) (please note that: ZPN-OFDM duplicate guard interval length). Also, in terms of perfect and estimated channel at different receiver numbers. Based on simulation results in Figs 2~8, the proposed TR-SIMO-DZPN-OFDM improve the BER performance of encoded and un-encoded system compared to the conventional TR-SIMO-ZPN-OFDM in the different cases considered. This improvement is due to the mutual interference reduction between training sequence and OFDM data blocks by using the damped PN sequence.



(a)

(b)

Fig. 2. BER performance of coded TR-SIMO-DZPN-OFDM compared to conventional TR-SIMO-ZPN-OFDM and TR-SIMO-TDS-OFDM; one antenna receiver and $GIL = 128$. (a) Using perfect channel (b) Using estimated SCS channel



(a)

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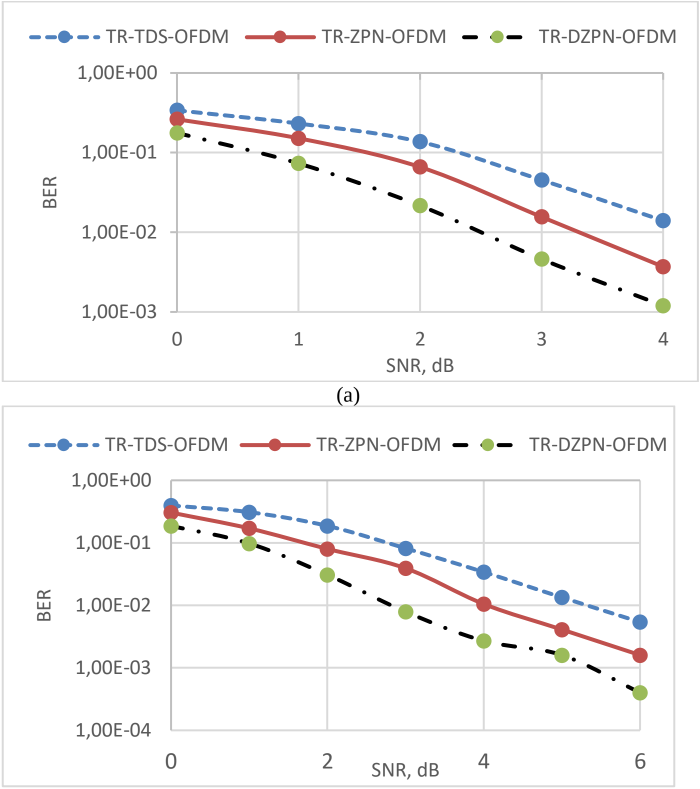
Fig. 3. BER performance of coded TR-SIMO-DZPN-OFDM compared to conventional TR-SIMO-ZPN-OFDM and TR-SIMO-TDS-OFDM; one antenna receiver and $GIL = 16$. (a) Using perfect channel (b) Using estimated SCS channel



(a)

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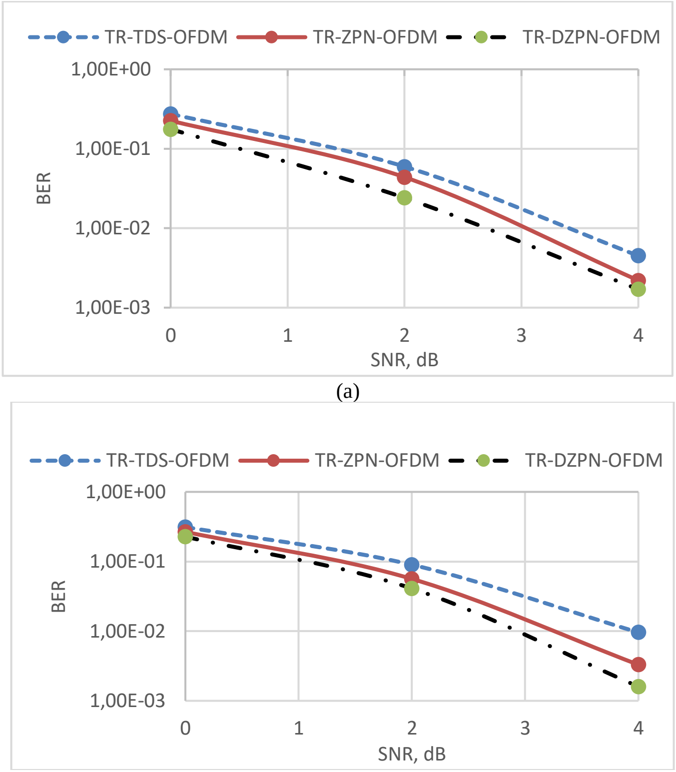
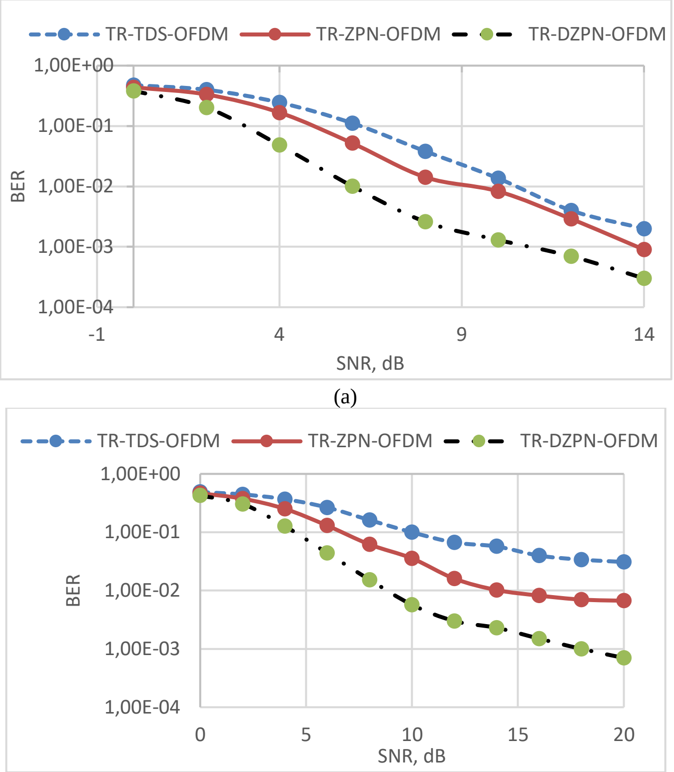
Fig. 4. BER performance of coded TR-SIMO-DZPN-OFDM compared to conventional TR-SIMO-ZPN-OFDM and TR-SIMO-TDS-OFDM; Four antenna receiver and $GIL = 128$. (a) Using perfect channel (b) Using estimated channel



(a)

(b)

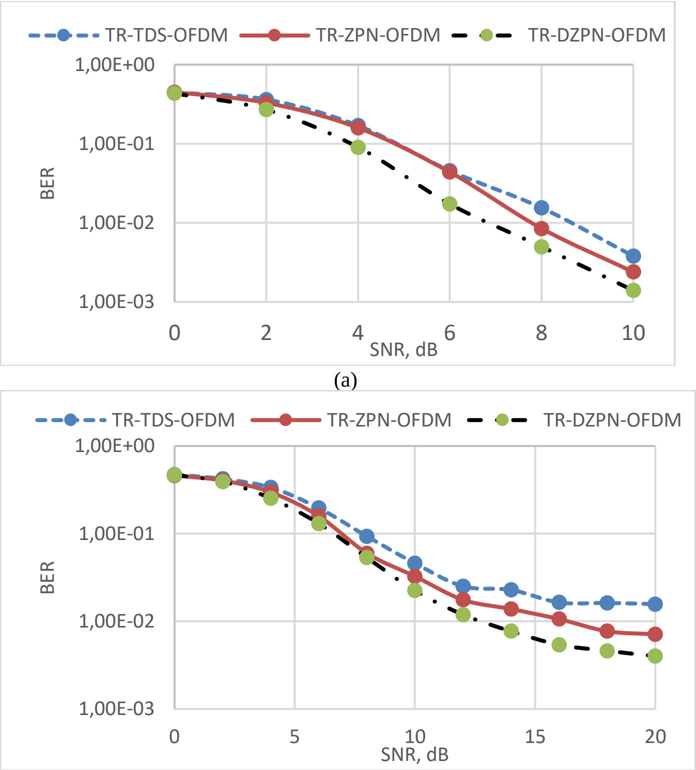
Fig. 5. BER performance of coded TR-SIMO-DZPN-OFDM compared to conventional TR-SIMO-ZPN-OFDM and TR-SIMO-TDS-OFDM; Four antenna receiver and $GIL = 16$. (a) Using perfect channel (b) Using estimated channel



(a)

(b)

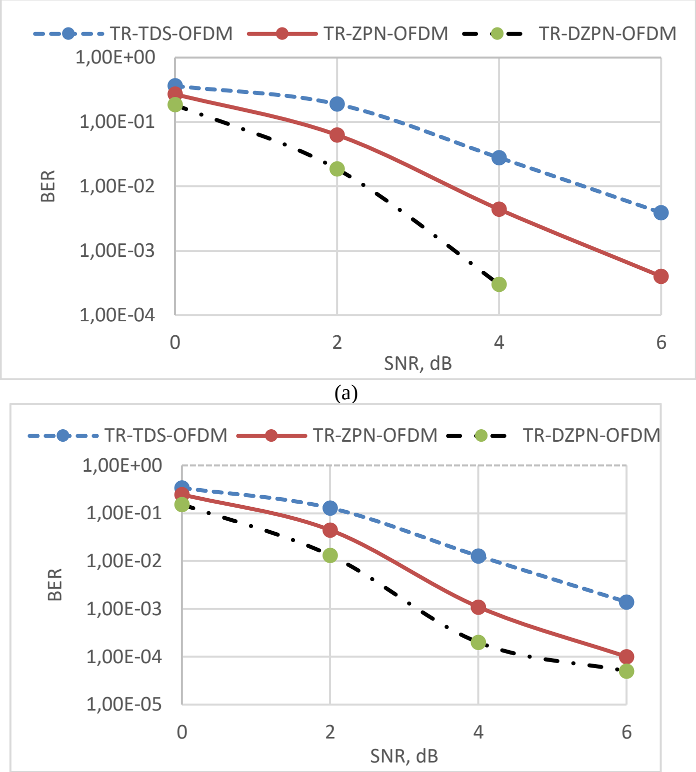
Fig. 6. BER performance of un-coded TR-SIMO-DZPN-OFDM compared to conventional TR-SIMO-ZPN-OFDM and TR-SIMO-TDS-OFDM; one antenna receiver and $GIL = 128$. (a) Using perfect channel (b) Using estimated channel



(a)

(b)

Fig. 7. BER performance of un-coded TR-SIMO-DZPN-OFDM compared to conventional TR-SIMO-ZPN-OFDM and TR-SIMO-TDS-OFDM; one antenna receiver and $GIL = 16$. (a) Using perfect channel (b) Using estimated channel



(a)

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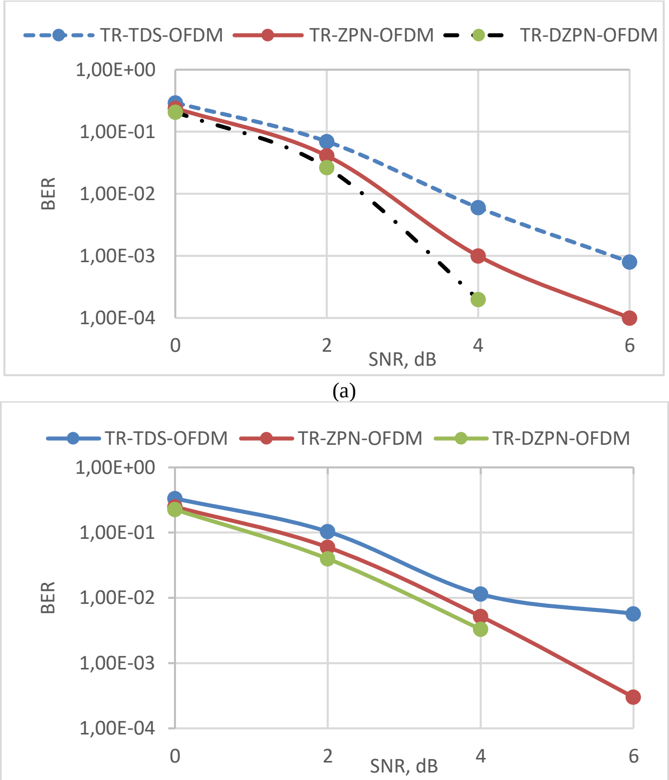
Fig. 8. BER performance of un-coded TR-SIMO-DZPN-OFDM compared to conventional TR-SIMO-ZPN-OFDM and TR-SIMO-TDS-OFDM; four antenna receivers and $GIL = 128$. (a) Using perfect channel (b) Using estimated channel



(a)

(b)

Fig. 9. BER performance of un-coded TR-SIMO-DZPN-OFDM compared to conventional TR-SIMO-ZPN-OFDM and TR-SIMO-TDS-OFDM; four antenna receivers and $GIL = 16$. (a) Using perfect channel (b) Using estimated channel

Spectrum and Energy Efficiency Comparisons

In this experiment, the spectrum and energy efficiency improvement using the new proposed OFDM scheme are evaluated. In Fig. 10. the normalized throughput is compared based on eq. (8) among TR-SIMO-TDS-OFDM and TR-SIMO-ZPN-OFDM schemes. The normalized throughput using proposed scheme is highly improved due to the SIR improvement as well as reducing the GIL.

DZPN-OFDM is significantly improve the normalized energy efficiency as shown in table II due to GIL reduction.

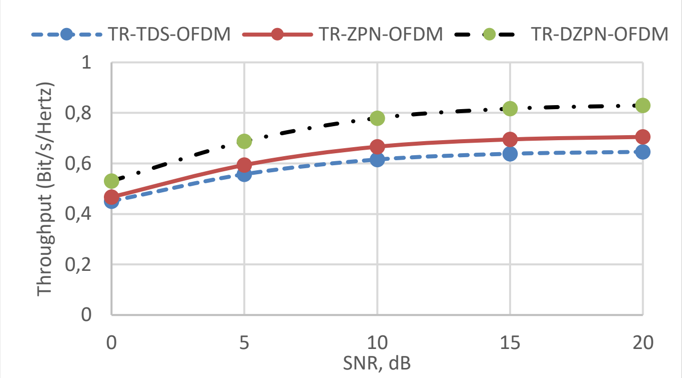


Fig. 10. System throughput of proposed TR-SIMO-DZPN-OFDM compared to conventional TR-SIMO-ZPN-OFDM and TR-SIMO-TDS-OFDM schemes

Table II
The Energy Efficiency of TR-SIMO-DZPN-OFDM Compared to Other Schemes

	TR-SIMO-TDS-OFDM	TR-SIMO-ZPN-OFDM	TR-SIMO-DZPN-OFDM
$GIL = 128$	0.6667	0.9412	0.9591
$GIL = 16$	0.9412	0.9922	0.9938

IV. Conclusion

In underwater communication, energy supply is one of the most important challenges, due to limited power resources and recharging difficulties. Multicarrier systems with a high energy efficiency are very important. Unfortunately, the underwater channel has a long channel tap delay which requires a long guard interval to avoid inter-block interference, since, loss high consumed. In this paper, a damped zero-pseudorandom noise technique is proposed to improve the ZPN-OFDM for better, throughput, BER and energy efficiency. BER improvement can be achieved, where the mutual interference in OFDM data block reduced by using a damped PN sequence. The proposed technique has been illustrated in time reversal SIMO communication system by using simulation experiments based on a real underwater acoustic channel measured from one sea experiment.

References

[1] D. Van Welden, H. Steendam, and M. Moeneclaey, "Iterative Decision-Directed Joint Frequency Offset and Channel Estimation for KSP-OFDM," *IEEE Transactions on Communications,* vol. 60, pp. 3103-3110, 2012.

[2] D. Van Welden and H. Steendam, "Near Optimal Iterative Channel Estimation for KSP-OFDM," *IEEE Transactions on Signal Processing,* vol. 58, pp. 4948-4954, 2010.

[3] T. van Waterschoot, V. Le Nir, J. Duplicy, and M. Moonen, "Analytical Expressions for the Power Spectral Density of CP-OFDM and ZP-OFDM Signals," *IEEE Signal Processing Letters,* vol. 17, pp. 371-374, 2010.

[4] B. Muquet, W. Zhengdao, G. B. Giannakis, M. de Courville, and P. Duhamel, "Cyclic prefixing or zero padding for wireless multicarrier transmissions," *IEEE Transactions on Communications,* vol. 50, pp. 2136-2148, 2002.

[5] Z. Liu and T. C. Yang, "On Overhead Reduction in Time-Reversed OFDM Underwater Acoustic Communications," *IEEE Journal of Oceanic Engineering,* vol. PP, pp. 1-13, 2013.

[6] M. Stojanovic, "Low complexity OFDM detector for underwater acoustic channels," in *OCEANS*, 2006, pp. 1-6.

[7] B. Li, S. Zhou, M. Stojanovic, and L. Freitag, "Pilot-tone based ZP-OFDM demodulation for an underwater acoustic channel," in *OCEANS*, 2006, pp. 1-5.

[8] L. Baosheng, Z. Shengli, M. Stojanovic, L. Freitag, and P. Willett, "Multicarrier Communication Over Underwater Acoustic Channels With Nonuniform Doppler Shifts," *IEEE Journal of Oceanic Engineering,* vol. 33, pp. 198-209, 2008.

[9] H. Esmaiel and D. Jiang, "Zero-pseudorandom noise training OFDM," *Electronics Letters,* vol. 50, pp. 650-652, 2014.

[10] H. Esmaiel and D. Jiang, "Review Article: Multicarrier Communication for Underwater Acoustic Channel," *International Journal of Communications, Network and System Sciences,* vol. 6, pp. 361-376, 2013.

[11] H. A. H. Esmaiel, "Advanced multi-band modulation technology for underwater communication systems," University of Tasmania, 2015.

[12] L. Zhiqiang and T. C. Yang, "On the Design of Cyclic Prefix Length for Time-Reversed OFDM," *IEEE Transactions on Wireless Communications,* vol. 11, pp. 3723-3733, 2012.

[13] L. Deneire, B. Gyselinckx, and M. Engels, "Training sequence versus cyclic prefix-a new look on single carrier communication," *IEEE Communications Letters,* vol. 5, pp. 292-294, 2001.

[14] L. Dai, J. Wang, Z. Wang, P. Tsiaflakis, and M. Moonen, "Spectrum- and Energy-Efficient OFDM Based on Simultaneous Multi-Channel Reconstruction," *IEEE Transactions on Signal Processing,* vol. PP, pp. 1-13, 2013.

[15] W. Jun, Y. Zhi-Xing, P. Chang-Yong, S. Jian, and Y. Lin, "Iterative padding subtraction of the PN sequence for the TDS-OFDM over broadcast channels," *IEEE Transactions on Consumer Electronics,* vol. 51, pp. 1148-1152, 2005.

[16] F. Jian, W. Jun, S. Jian, P. Chang-Yong, and Y. Zhi-Xing, "A Simplified Equalization Method for Dual PN-Sequence Padding TDS-OFDM Systems," *IEEE Transactions on Broadcasting,* vol. 54, pp. 825-830, 2008.

[17] H. Esmaiel and D. Jiang, "Time reversal time-domain synchronisation orthogonal frequency division multiplexing over multipath fading channels with significant tap delays," *The Journal of Engineering,* vol. 1, 2014.

[18] D. Linglong, W. Jintao, W. Zhaocheng, P. Tsiaflakis, and M. Moonen, "Spectrum- and Energy-Efficient OFDM Based on Simultaneous Multi-Channel Reconstruction," *IEEE Transactions on Signal Processing,* vol. 61, pp. 6047-6059, 2013.

[19] D. L. Donoho, "Compressed sensing," *IEEE Transactions on Information Theory,* vol. 52, pp. 1289-1306, 2006.

[20] M. F. Duarte and Y. C. Eldar, "Structured Compressed Sensing: From Theory to Applications," *IEEE Transactions on Signal Processing,* vol. 59, pp. 4053-4085, 2011.

[21] T. C. Yang, "Temporal resolutions of time-reversal and passive-phase conjugation for underwater acoustic communications," *IEEE Journal of Oceanic Engineering,* vol. 28, pp. 229-245, 2003.

[22] J. A. Tropp, A. C. Gilbert, and M. J. Strauss, "Algorithms for simultaneous sparse approximation. Part I: Greedy pursuit," *Signal Processing,* vol. 86, pp. 572-588, 2006.