NEW METHOD OF POLAR CHANNEL CODING FOR REDUCING THE BIT ERROR RATE WITH LOW COMPLEXITY IN THE F-OFDM UNDERWATER ACOUSTIC COMMUNICATIONS

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To the memory of my grandfather, my grandmother, who would have been glad to see me at this moment.
To my beloved mother and father for their constant and unconditional love.
To my wife and beloved child, Yasin, for their love and support.
To the great woman, who has loved me more than herself
To my brothers and my sisters for their support and encouragement
To all my family members and friends for their love and supports

To science,

enlightening us.

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ABSTRACT

Underwater Acoustic (UWA) communication system plays a crucial role in various applications and contributes significant performance in comparison to other communication systems. UWA is essential in various applications such as oceanographic, oil exploration, military applications etc. However, it is characterized by a high Bit Error Rate (BER), the main obstacle of the UWA system in real applications because the sound waves are subjected to Underwater Acoustic Noise (UWAN), which is either manmade or natural. Channel coding is one of the effective BER reduction techniques that has been employed for reducing the BER. Nonetheless, high computational complexity is the main drawback of this technique. This thesis studies the UWAN in the shallow waters of tropical seas as a field data which have a significant impulsive behaviour. The analysis of the field data showed that the UWAN does not satisfy the assumption of Gaussian noise, it nonetheless fits well to t-distribution with three degrees of freedom. Also, the derivation of Binary Phase Shift Keying (BPSK) and Quadrature Phase Shift Keying (QPSK) for the UWA was proposed and validated with the channel simulation. In addition, this thesis proposes a new method in UWA for reducing the BER value with low computational complexity. The proposed method has been applied to Orthogonal Frequency Division Multiplexing (OFDM) and Filtered-OFDM (F-OFDM) systems through MATLAB software simulation, where F-OFDM refers to the waveform design candidate in the new technology. The efficiency of the proposed method is verified by comparing the results with the existing channel coding in the literature using MATLAB software simulation. The results obtained using the proposed method and turbo code achieved a superior gain in the signal-noise ratio (SNR) about 11.2 dB and 13.5 dB respectively at BER of 1×10^{-3} compared to the uncoded (without channel coding). In addition, the computational complexity levels have been reduced about 84% and 68% for the information block length (k) of 256 and 1024 respectively. In conclusion, The F-OFDM shows a better as compared to OFDM.

ABSTRAK

Sistem komunikasi *Underwater Acoustic* (UWA) memainkan peranan penting dalam pelbagai aplikasi dan menyumbang prestasi yang signifikan berbanding dengan sistem komunikasi lain. UWA penting dalam pelbagai aplikasi seperti oseanografi, penerokaan minyak, aplikasi ketenteraan dan lain-lain. Namun, UWA dicirikan dengan Kadar Ralat Bit (BER) yang tinggi, yang merupakan halangan utama sistem ini dalam aplikasi sebenar kerana gelombang bunyi tertakluk kepada Kebisingan Akustik Bawah Air (UWAN), sama ada buatan manusia atau semulajadi. Pengekodan saluran adalah salah satu teknik pengurangan BER yang berkesan yang telah digunakan untuk mengurangkan BER. Walau bagaimanapun, kerumitan komputasi yang tinggi adalah kelemahan utama teknik ini. Tesis ini mengkaji UWAN di perairan dangkal di laut tropika sebagai data lapangan yang mempunyai tingkah laku impulsif yang ketara. Analisis data lapangan menunjukkan bahawa UWAN tidak memenuhi andaian kebisingan Gauss, namun sangat sesuai dengan pembahagian t dengan tiga darjah kebebasan. Selain itu, terbitan dari *Binary Phase Shift Keying* (BPSK) dan *Quadrature Phase Shift Keying* (QPSK) untuk UWA dicadangkan dan disahkan dengan simulasi saluran. Sebagai tambahan, tesis ini mencadangkan kaedah baru dalam UWA untuk mengurangkan nilai BER dengan kerumitan komputasi yang rendah. Kaedah yang dicadangkan telah diterapkan pada sistem Multipleksi Bahagian Frekuensi Ortogonal (OFDM) dan sistem Penyaringan-OFDM (F-OFDM) melalui simulasi perisian MATLAB, di mana F-OFDM merujuk kepada calon reka bentuk bentuk gelombang dalam teknologi baru. Kecekapan kaedah yang dicadangkan disahkan dengan membandingkan hasilnya dengan pengekodan saluran yang terdapat dalam literatur menggunakan simulasi perisian MATLAB. Hasil yang diperolehi menggunakan kaedah yang dicadangkan dan kod turbo memperoleh keuntungan yang lebih tinggi dalam nisbah isyarat-bunyi (SNR) masing-masing sekitar 11.2 dB dan 13.5 dB pada BER 1×10^{-3} berbanding dengan tidak dikodkan (tanpa pengekodan saluran). Di samping itu, tahap kerumitan komputasi telah dikurangkan sekitar 84% dan 68% untuk panjang blok maklumat (k)

256 dan 1024, masing-masing. Kesimpulannya, F-OFDM menunjukkan prestasi yang lebih baik berbanding OFDM.

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LIST OF SYMBOLS AND ABBREVIATIONS

ANN	-	Artificial Neural Network
AWGGN	-	Additive White Generalized Gaussian Noise
AWGN	-	Additive White Gaussian Noise
BCH	-	Bose–Chaudhuri–Hocquenghem Codes
BER	-	Bit Error Rate
CP	-	Cyclic Prefix
Data Pick-Rake	-	DP-Rake
dB	-	Decibel
EM	-	Expectation Maximization
$f(n)$	-	Spectrum Shaping Filter
FBMC	-	Filter Bank Multi-Carrier
FFT	-	Fast Fourier Transform
FMT	-	Filtered Multi-Tone
F-OFDM	-	Filtered-Orthogonal Frequency Division Multiplexing
GG	-	Generalized Gaussian
GMM	-	Gaussian Mixture Model
h	-	Depth
H	-	parity check matrix
$h_{LPF}(n)$	-	Sinc Impulse Response
I	-	Number of Iterations
ICI	-	Inter-Carrier Interference
IDFT	-	Inverse Discrete Fourie Transform
IFFT	-	Inverse Fast Fourier Transform
ISI	-	Inter-Symbol Interference
L	-	Filter Length
LDPC	-	low density parity check
LPF	-	Low Pass Filter
M-PSK	-	Phase Shift Keying

N	-	Number of Subcarriers
OFDM	-	Orthogonal Frequency Division Multiplexing
OOBE	-	Out-of-Band Emission
P/S	-	Parallel to Serial Converter
PAPR	-	Peak-to-Average-Power Ratio
PSD	-	Power Spectral Density
R	-	Range in meters
r	-	Roll-Off Factor
RRC	-	Rooted Raised Cosine
RS	-	Reed Solomon
RS-BTC	-	Reed Solomon Block Turbo code
S	-	Salinity
S/P	-	Serial to Parallel Converter
SC	-	Successive Cancellation
SGS	-	Spherical Geometric Spreading
SISO	-	soft-input soft-output
SNR	-	Signal-to-Noise Ratio
SSP	-	Sound Speed Profile
$S\alpha S$	-	symmetrical alpha-stable
T	-	Temperature
TCM	-	Trellis Coded Modulation
UFMC	-	Universal Filtered Multi-Carrier
UTHM	-	Universiti Tun Hussein Onn Malaysia
UWA	-	Underwater Acoustic
UWAN	-	Underwater Acoustic Noise
UWE	-	Underwater Environment
$w(n)$	-	Windowing Mask Impulse Response
$x(n)$	-	OFDM Time-Domain Samples
α	-	Determination Value
$\Gamma(\cdot)$	-	gamma function
A	-	Signal amplitude
$N_{th}(f)$	-	Thermal noise
P	-	Hydrostatic pressure
PL	-	Total path loss

$PL_{absorbtion}$	-	Absorption loss
$PL_{spreading}$	-	Geometric spreading loss
R	-	Transmission range
S_f	-	Spreading factor
T_m	-	Time delay spread
c	-	Sound speed in sea water
s	-	Shipping density parameter
f_T	-	Relaxation frequency
f	-	Frequency
σ_v^2	-	Variance of noise
(R)	-	Natural value total path losses
$\alpha(f)$	-	Absorption coefficient

LIST OF APPENDICES

CHAPTER 1

INTRODUCTION

1.1 Research background

Signal processing has attracted increased research interests especially in the underwater environment (UWE) for various industrial applications such as in the offshore oil industries, security as well as several commercial operations. The UWE possesses high attenuation rate of electromagnetic waves making it practical to explore acoustic waves for communications, navigations, and other associated applications. Three major factors considerably describe acoustic propagations, and these are: time-dependent multipath propagation, low speed of sound at 1500 *m/s* and attenuation which is dependent on the signal frequency [1]. Depending on the network, node placement within the deployment regions of the ocean possess varied depths from tens of meters to a few kilometres. Under water systems, therefore, operate at low frequencies (tens of kHz) since sound attenuation is frequency-dependent [2]. Lower bandwidth, high signal-to-noise- ratio (SNR) and high propagation delays are the main constraints. Given these constraints of the communication channel, data communication links for underwater are designed to generally support low data rates [2] [3]. The sources of underwater acoustic noise (UWAN) could be natural or manmade. The natural sources include wind, rain, marine lives and seismic while the manmade sources include ships, aircraft over the sea, echo locating devices and any other machineries over the water body [4].

The ocean acts as a low-pass filter for ambient noise as the attenuation of Underwater Acoustic (UWA) is frequency dependent and is described as coloured. Therefore, more and less power is exhibited by the results of ambient noise power spectral density (PSD) at the lower and higher frequencies, respectively [5]. The sources of the ambient noise include rain, breaking waves, turbulence, and distant shipping. Although, ambient noise is often approximated as Gaussian, it is coloured in practice and exhibits a decaying PSD with the rate of decay at approximately 18 dB/decade [3]. Underwater environment noises are also characterized as being site-specific for instance, snapping shrimp in warmer waters and ice-cracking in polar regions [3]. Site-specific noise unlike the ambient noise usually contains insignificant Gaussian components.

Usually, noises are assumed additive white Gaussian noise (AWGN) in most signal applications. Thus, vectors of observations are transformed with correlated noise samples to all the uncorrelated ones [6]. In this thesis, improvement in the performance of UWA communication binary signalling is presented. This is investigated by reducing the error symbols with low computational complexity occurring as a result of UWAN characteristics. These probability of the symbol error can be reduced by different channel coding methods. This study gives a better understanding of how the UWE operate by conducting comprehensive investigations with measurements of UWAN at different Malaysian seas.

1.2 Problem statement

UWAN affects the probability of symbol error for uncoded binary signalling where the noise is non-white and non-Gaussian. The sound attenuation in the sea is frequency-dependent, and this causes the sea to behave as a low-pass filter for UWAN. According to the results of power spectral density (PSD) of UWAN obtained by [7], the noise was coloured, which means that it has more power at lower frequencies compared to that at higher frequencies. Therefore, the noise samples are uncorrelated and the assumption of independent and identically distributed (i.i.d) is no longer valid.

The UWAN system is influenced by the characteristic of the physical layer (seawater characteristics). The signal of the system follows non-white and non-Gaussian noise and thus, the bit error rate of the system will be high. Moreover, the UWA system works at sound frequency that operates in the frequency range between 10 and 15 kHz, so the bandwidth of the acoustic system is very low (5 kHz) [8] [9]. Therefore, the data rate of the system is lower compared to other transmission systems [10].

In practice, the signal observed on certain sites has significant non-Gaussian components. For example, ice cracking in the polar region and snapping shrimp in warmer waters [11]. As a result, the detection methods that assume Gaussian pdf do not achieve the optimum performance in UWAN. The effect of non-Gaussian pdf and coloured noise further degrades the performance of the communication system such as underwater data communication and target locating. Further communication system improvement can be achieved by using channel coding techniques and orthogonal frequency division multiplexing (OFDM). In addition, applying OFDM technique in UWA results in BER degradation in the system [12].

1.3 Objectives

This research presents the characterization of underwater acoustic communication (UWAC) and improvement of the performance of BER based on t-distribution channel in selected Malaysia seas. Specifically, the objectives of this research are:

i. To characterize UWAN for shallow water in selected Malaysian seas based on statistical properties such as probability density function (PDF).

ii. To derive an expression of the probability of symbol error for uncoded BPSK and QPSK based on real measurements of the UWAN characteristics.

iii. To improve the BER with low computational complexity and PSD performances in the underwater acoustics system (UWAS) by applying a new technique, polar codes based on F-OFDM system.

1.4 Scope of work

This research focuses on improving the channel coding technique concerning BER reduction and computational complexity. Hence, the research scope is bounded by the assumptions and constraints as follows:

i. The measurements were done in the sea shallow water at Senggarang, Batu Pahat, Johor, Malaysia (1°49'21.8''N 102°50'14.3''E).

ii. Samples of UWAN are collected using a broadband hydrophone (7 Hz ~ 22 kHz) DolphinEAR 200 Series model with a maximum cable length 16 meters.

iii. The Nyquist rate is used to convert the measured signal approximates into continuous time from the discrete time. Since the underwater acoustic signals is about 0 - 2500 Hz in frequency band, the sampling frequency is $f_s = 2f$ which is the minimum requirement for digital sonar system. By making the sampling frequency greater than $2f$, the sampling frequency selected is 8000 Hz.

iv. Different modulation signals generated in MATLAB can be transmitted in underwater using BII-8030 underwater acoustic transmitter for frequency range (20 Hz to 100 kHz).

v. The UWAN can be assumed stationary because the variability of the predominant sources (wind speed and shipping density) and propagation variation (such as temperature and density) changes slower compared to the signal duration of interest.

vi. Comparisons are made between the distributions obtained from the collected data with Gaussian distribution by using distribution fitting tool in MATLAB to obtain the pdf of the UWAN.

vii. The derivation of UWA of the error performance is for the BPSK and QPSK.

viii. Digital communication signals are used in the system.

ix. Several parameters are used in the F-OFDM system such as subcarriers number, filter length, oversampling factor, BPSK and QPSK family as a constellation mapping.

x. For the evaluation purposes, the BER, PSD, and computational complexity simulations are used in the evaluation of the proposed methods.

xi. This work focuses on performance analysis simulations based on the basic OFDM or F-OFDM block regardless of channel estimation and Doppler Shift, thereby the additive t-distribution noise channel is adopted between the transmitter and receiver.

xii. In F-OFDM, low pass filter (LPF) with rooted raised cosine (RRC) window is adopted as the transmit/receive filters.

xiii. The simulation of PSD in this thesis is for comparison.

1.5 Thesis contributions

The contributions of this thesis focus on improving the BER reduction performance with low computational complexity in the channel coding based on the OFDM and F-OFDM UWAS. The major contributions of this thesis are:

i. Analysing the noise characteristics of selected Malaysian sea in a specified area (shallow water).
ii. Presenting a new expression of error performance of Binary PSK (BPSK) and Quadrature PSK (QPSK) constellation based on real measurements of the UWAN characteristics.
iii. Applying the proposed technique to OFDM and F-OFDM UWAS such that the channel coding achieved superior performance for reducing the BER value and the computational complexity for both systems.

1.6 Organisation of the thesis

This thesis consists of five (5) chapters. Each chapter is briefly described as follows: Chapter 1 begins with an introduction that presents research background, the problem statement, objectives, scope and limitations of the research work, and the contributions that have been achieved in this study.

Chapter 2 describes the previous studies related to the characteristics of underwater acoustic, the previously proposed techniques to improve the bit error rate, and it was concluded with a summary of the chapter which gives explanation of the research gap.

The research methodology is elaborated in Chapter 3 which details the approaches taken to introduce the new technique including the flow chart of the research methodology.

Chapter 4 discusses the analysis of the research results based on the works introduced in Chapter 3. In addition, a detailed evaluation of all the proposed technique is presented and verified by comparing with the techniques presented in the literature review.

Chapter 5 provides a conclusion and details on future work while suggesting some further improvements that could be made to the research.

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