Two steps Doppler compensation Algorithm from moving AUV to AUV/Mother Ship for OFDM-based UWA communication system

Mohammad Ariful Hoq†, Shiho Oshiro ††, and Tomohisa Wada†††

†Graduate School of Engineering and Science, University of the Ryukyus, Senbaru 1, Nishihara, Okinawa, Japan
††Graduate School of Engineering and Science, University of the Ryukyus, Senbaru 1, Nishihara, Okinawa, Japan
†††Dept. of Engineering, University of the Ryukyus, Senbaru 1, Nishihara, Okinawa, Japan

Summary

In the field of Underwater Acoustic (UWA) Communication Orthogonal frequency division multiplexing (OFDM) has drawn wide attention for its high transmission rate and high spectrum efficiency. In the challenging UWA communication channels, OFDM system is tremendously affected by severe multi-path and Doppler effect. In order to transfer data from deep sea AUV (Autonomous Underwater Vehicle) to AUV/surface mother ship this paper describes a new Doppler compensation algorithm of underwater acoustic OFDM communication system. 2 steps Beta (Shrink-expansion) Detection factor, Peak shape cross correlation method and Linear phase error estimation by LS (Least Square) method has been explained in this algorithm. 2 times resample and de-rotation processing is occupied to estimate the initial sending FFT window. Mathematically less complex LS techniques estimate the suitable phase error. Cross-correlation method estimates foremost correlation peak of the cross-correlation among received signal and transmitted signal. Simulation results illustrates the maximum receiver velocity is nearly 4 m/s. Our system exploited 8 kHz Bandwidth (16 kHz to 24 kHz) OFDM channel and subcarrier spacing of 50 Hz.

Key words:
Underwater Acoustic Communication, OFDM. Autonomous Underwater vehicle, Doppler compensation

1. Introduction

In order to explore marine natural resources (biological diversity, fish and seafood supplies, oil and gas, renewable energy resources) necessity of underwater wireless communication is increasing alike radio communication. AUV (Autonomous Underwater Vehicle) is required as it's free from wire and send real time moving pictures, movie to AUV or the mother ship in sea surface [1]. Acoustic signal is the most popular communication media in underwater communication as Radio wave suffers from high attenuation in water [2]. The propagation speed of acoustic signal is much slower than that of radio signal. The propagation speed is around 1500m/s is much smaller than radio wave speed. Communication in underwater is much more severe than radio communication because of doppler effect. The transmitted acoustic signal is more vulnerable to the doppler effect compared to other communication systems due to the low speed of acoustic signal propagation. Additional doppler shift happened due to speed of Transmitter and swaying of Receiver. Even a slow motion between the transmitter and receiver or the integral current wave's motion can carry significant doppler effect to the transmitted signal. The authors in [3] described a doppler shift technique in which estimation error is contingent on discipline by enabling a learning and punishment accomplishment to fine tune the projected shift in samples iteratively. A BER gradient descent algorithm proposed to achieve iterative Doppler estimation to reduce the BER search times [4]. Doppler compensation method described based on MBER (Minimum Bit Error Rate) to convert the signal level doppler estimation into a bit level one [5]. Author in paper [4] proposed underwater acoustic OFDM communication system with robust doppler compensation. Additional time domain signal processing anticipated to reduce doppler effect. One stage shrink-expansion factor, peak position detection and interpolation phase introduced in the signal processing system. According to simulation result maximum velocity has been originated roughly 1m/s. In this paper a new algorithm adopts to mitigate the doppler shift inspired by paper [6]. This algorithm implements 2 stage Beta (Shrink-expansion) Detection factor, Peak shape cross correlation method and Linear phase error estimation by LS (Least Square) method. 2 stage Beta(β) detection mostly dominant method of the challenge of doppler compensation than previous algorithm [6]. Bit error Rate (BER) drastically improved (almost 70%) by this 2 stage Beta detection method. The rest of method i.e., Peak shape cross correlation method upgraded BER roughly 20% and Linear phase error estimation by LS method upgraded 10%. Above mentioned 3 methods penetrates the receiver's maximum velocity roughly 4m/s. Section II describes previous algorithm and system model. Proposed algorithm and Receiver structure is designated in Section III. Doppler compensation mechanism and all 3 algorithms

Manuscript received December 5, 2020.
Manuscript revised December 20, 2020.
https://doi.org/10.22937/IJCSNS.2020.20.12.31

are defined in Section IV. Numerical Simulation result and comparison between previous and proposed algorithm is pronounced in Section V.

2. System Model

2.1. OFDM System Model

A schematic diagram of underwater communication system with AUV (Autonomous Underwater Vehicle) and Mother ship depicted in fig. 1. AUV stands still in the water and Receiver exists in the Mother ship which is moving because of ship rolling. Our system is capable of transferring data from AUV to AUV/Mother ship.

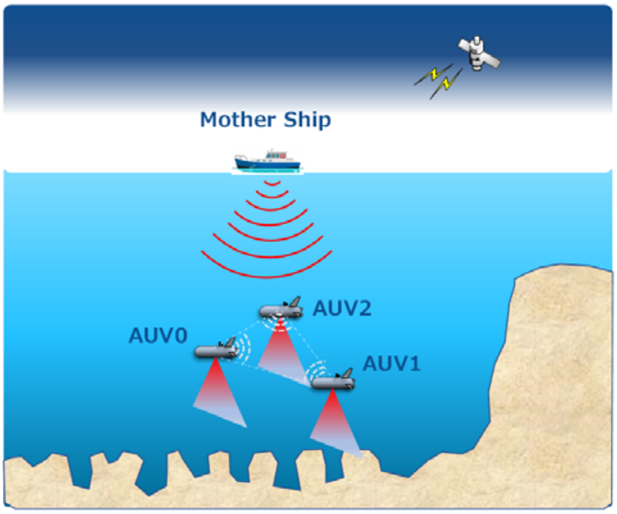

Fig. 1: Swarming AUVs and mother ship for underwater exploration system controlled by UWA communication

Fig. 2 shows the Block diagram of typical UWA OFDM Communication system. The upper side is transmitter (TX) while lower side is the receiver (RX). The TX is Conventional OFDM transmitter but RX has additional Time-Domain doppler compensation potentiality. The binary data is first mapped using digital modulation schemes like quadrature phase shift keying (QPSK) / 16 quadrature amplitude modulation (QAM)/64QAM. Time-varying channel state is measured by Zadoff–Chu sequence Pilot. The modulated data symbols are transformed from serial to parallel form. A Single OFDM symbol formulates one column of data symbols. Each row of data symbols is named as subcarrier. If one OFDM symbol includes of N data symbols, the number of subcarriers is N. Known data is transmitted in the block of pilot insertion. Known pilots contributes in estimating the channel at the receiver. Each OFDM symbol is converted to time domain using an inverse Fast Fourier Transform (IFFT) operation. A Guard Interval (GI) is attached at the beginning of each time domain OFDM symbol to overcome the distortion triggered by Inter Symbol Interference (ISI) in the channel. GI is the copy of last part of any given OFDM symbol. To counteract with the multipath delay distribution GI length is sensibly determined. Then the baseband signal is up converted into the center frequency of 20 kHz. Finally, the OFDM passband signal amplified with the power amplifier is emitted from TX transducer into underwater acoustic channel.

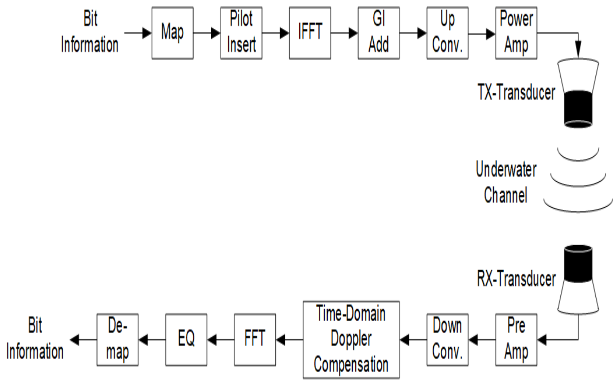

Fig. 2 A Typical UWA OFDM Communication system

In the RX side, generally the reverse operations of TX are performed. Received signal amplified with pre-amplifier and down-converted to baseband signal. Time domain doppler compensation block performs resample and de-rotation function with phase compensation. The resulting OFDM symbols are sent through a Fast Fourier Transform (FFT) block which converts time domain into corresponding frequency domain symbols. Equalizer block uses these symbols to estimate the channel and processes the received data to evaluate transmitted OFDM symbols. Then symbols are de-mapped to obtain the transmitted binary data.

2.2. Receiver Structure

The receiver structure is included an estimation of the GI position (symbol timing), Doppler shift compensation and channel estimation. The receiver block diagram is depicted in Fig. 3. This diagram already mentioned in previous algorithm [6]. 1 stage Shrink-Expansion (Beta) factor, Peak index estimation and interpolation phase shift compensation are the main keys of the Time-Domain doppler compensation block of the previous algorithm. 3rd FFT is accomplished afterward the processing of Time-Domain Doppler compensation. In the time and frequency interpolation block, it is estimated the time and frequency response for all sub-carriers. Finally, Equalizer processes the received data to assess transmitted OFDM symbols. In our proposed algorithm we have implemented

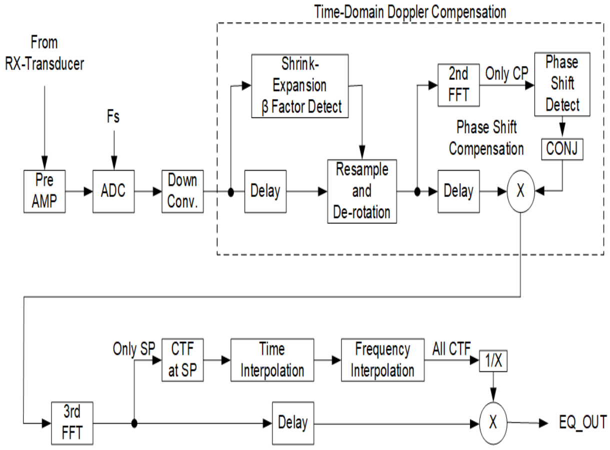

Fig. 3 Receiver Block Diagram

2 stage Beta (Shrink-expansion) Detection factor, Peak shape cross correlation method and Linear phase error estimation by LS method in Time-Domain doppler compensation block which will be discussed in Section III.

2.3. Time-Frequency Representation

The detailed structure of the OFDM packet in a time-frequency grid is shown in Figure 4. The transmission of one OFDM symbol consist of 161 number of subcarriers. Out of which 41 are utilized as Scattered Pilot (SP), 13 as Continuous pilot (CP), while the rest serves as Data. The SP is positioned equally spaced in every 4 subcarriers interval in one OFDM symbol and equally spaced in every 4 OFDM symbols interval noticeable with blue circle. SP allows the accurate interpolation of channel response simultaneously. CP is positioned equally spaced in every 12 sub-carrier intervals visible with yellow circle. The CP is used to estimate phase shift along time axis for phase compensation. For SP and CP values Zadoff-Chu sequence [7] has been applied. One complete OFDM symbol length consists of excluded and included GI length. GI length Tg= 2.8125ms or 288 points. OFDM symbol length denoted with T = 20ms or 2048 (2K). Details OFDM system feature is shown in Table I.

3. System Design

3.1. New Receiver Structure

Previous algorithm presented a new algorithm for doppler compensation is shown in Fig. 5(a). But the algorithm limited with maximum velocity. The BER degraded drastically with increasing velocity. Therefore, this paper proposes a new algorithm of doppler compensation. The doppler compensation diagram depicted in Fig. 5(b). At this point it is shown the modification than the previous doppler compensation block. 2 steps shrink-expansion detection, phase

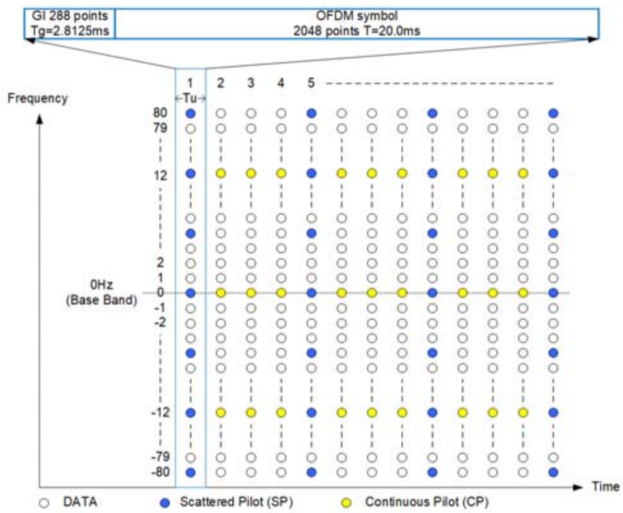

Fig. 4: Time-Frequency structure of OFDM

Parameters	Value
Sampling Frequency Fs	102.4kHz
Band Width	8 kHz
FFT size	2048
OFDM symbol length T	20.0 ms (2048 point)
Guard Interval length Tg	2.8125 ms (288 point)
Sub-carrier spacing	50 Hz
Number of sub-carrier	161
Scattered pilot	41 every 4 OFDM symbol
Continuous pilot	13
Carrier Modulation	QPSK/16QAM/64QAM
Max. Dara Rate w/o FEC	37.1 kbps (64QAM)

Table I: OFDM system parameter

compensation by LS method are the foremost solutions of this doppler compensation algorithm.

3.2. Estimating symbol timing Shrink – Expansion

Time varying shrink-expansion happens due to relative speed of transmitter and receiver. Shrink-expansion factor (β) mentioned in Fig.5 (b) briefly shown in Fig. 6(a) which is defined by

$$\beta = 1 + \frac{de - ds}{4 \times (GI+FFTsize)}$$

whereas, ds is the shrink or expansion point's difference with First FFT window and de is the shrink or expansion point's difference with fifth FFT window.

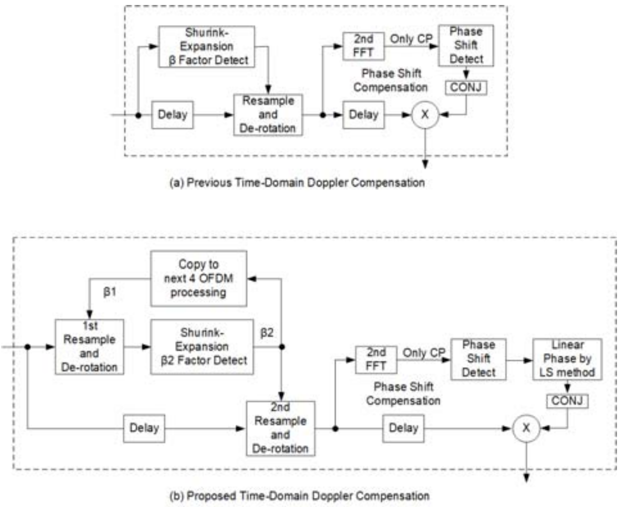

Fig. 5: (a) Previous (b) Proposed Time-Domain Doppler compensation

de and ds points is clearly shown in Fig. 6(b). Difference between de and ds denoted as Delta is shown in fig 6(a). As SP is placed in every 4-subcarriers interval Power Delay Profile can be drawn by detecting the peak position of OFDM symbol. Originating point of the shrink or expanded OFDM symbol specifies the peak position.

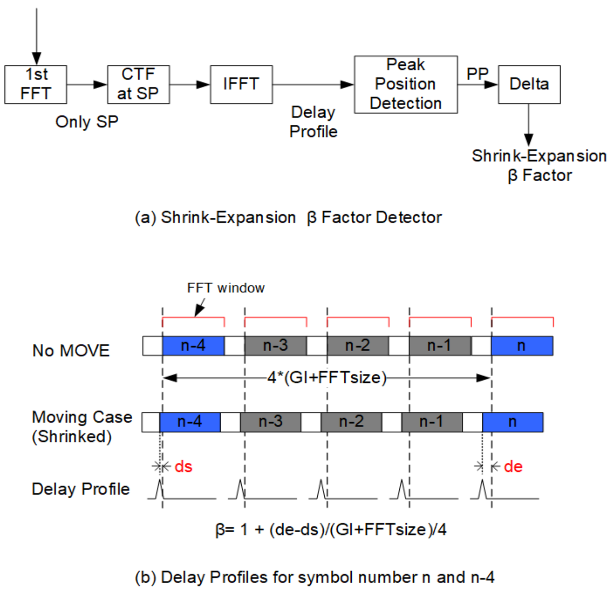

Fig. 6: (a) β Detection (b) Power Delay Profile of symbol n and (n-4)

3.3. *Resample and De-rotation processing*

As Peak Position is detected after in 4 OFDM symbol interval, Sampling Interval T_s ($1/F_s$) shift can be subtracted by comparing the peak position of present OFDM symbol (n) with preceding OFDM symbol (n-4). From the sampling Interval T_s we can predict the after resampled sampling Interval T_s' as

$$T_s' = \beta\, T_s$$

Where T_s is the original sampling Interval is shown is Fig. 7. 13 tap filter is utilized as the resample processing which requires computer interposed points from the initial samples.

For case $\beta = 1$, Resampled points and Initial points are identical. Therefore, De-rotation does not require. In case of $\beta \neq 1$ de-rotation is needed in order to shift the center frequency, f_c to 0 Hz. In the Down conversion unit, the received signal is multiple with $e^{-j2\pi f_c n T_s}$. After 1st resample, down conversion defined as $e^{-j2\pi f_c n T_s T_s'}$.The difference between initial and resampled down converted center frequency is given by

$$\begin{aligned} \text{Difference} &= e^{-j2\pi f_c n (T_s - T_s')} \\ &= e^{-j2\pi f_c n (T_s'/\beta - T_s')} \\ &= e^{-j2\pi f_c n T_s'(1-\beta)/\beta} \end{aligned}$$

Expected De-rotation is the conjugate of the difference, specifically $e^{+j2\pi f_c n T_s'(1-\beta)/\beta}$

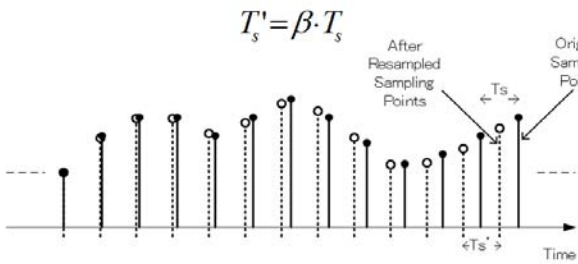

Fig. 7: Resample processing

4. Principle of Proposed Doppler compensation Algorithm

4.1: Two steps Beta (Shrink-expansion) Detection

New doppler compensated receiver structure depicted in Fig. 5(b). In no moving case receiving FFTsize perceives the initial FFT window is shown in Fig.8. Therefore, no shrink-expansion arises. The system process with 4 OFDM symbols (GI+FFTsize) at a time as well as one iteration. In moving case, because of doppler shift there is a mismatch (shrink) between the primary and receiving FFT window. Then compressed OFDM symbols are irregularly resampled and de-rotated by β1. Recurrently, Compressed symbol is resampled and de-rotated by β2. The value of β2 is copied to next 4 OFDM symbols processing for same iteration. β2 represents the same value of β1 in the next 4 OFDM symbols. Subsequently completing whole loop, 2nd Resample and De-rotation is executed and pauses for phase compensation.

4.2: Peak shape cross correlation

Beforehand the cross-correlation computation, up-sample by 10 operation is inserted. Then 1 order accuracy of the de-ds is detected. As mentioned before beta detection is mostly related with difference between de and ds i.e., Delta is depicted in Fig 9(a). Beta detection is achieved in resample and de-rotation processing block by delta progression. Fig 9(b) depicts the how peak is measured for defining Delta. This time it is not only measured the peak but also the peak shape. Cross correlation is executed by interpolation to attain the peak shape.

4.3: Linear phase error estimation by LS

As CP is positioned in every 12-subcarriers interval, consequently symbol by symbol phase shift can be perceived is shown in Fig. 10. CP is utilized to quantify how much rotation took place. The standard rotation in one doppler compensation processing block, from the SP of first OFDM symbol to next CP of adjacent OFDM symbol is shown in Fig. 11. Entirely 13 CP is positioned in one OFDM symbol. Taking average of these 13 CP rotations and acquired integral 4 rotation including the SP position. Time domain linear phase error is estimated by utilizing Least Square method from this rotation.

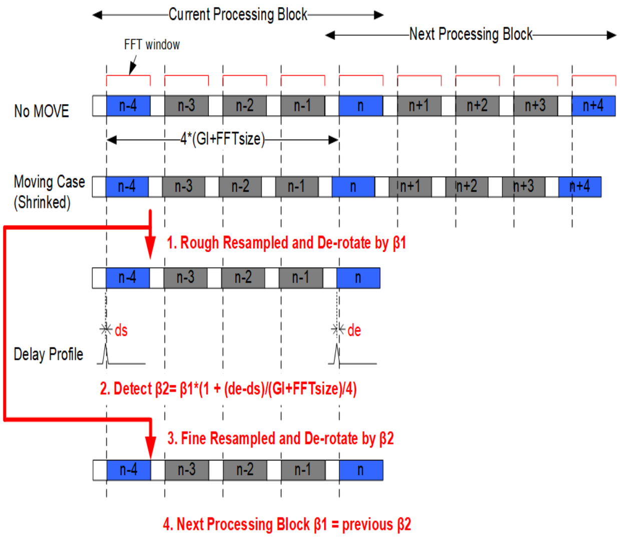

Fig. 8: 2 steps shrink-expansion processing

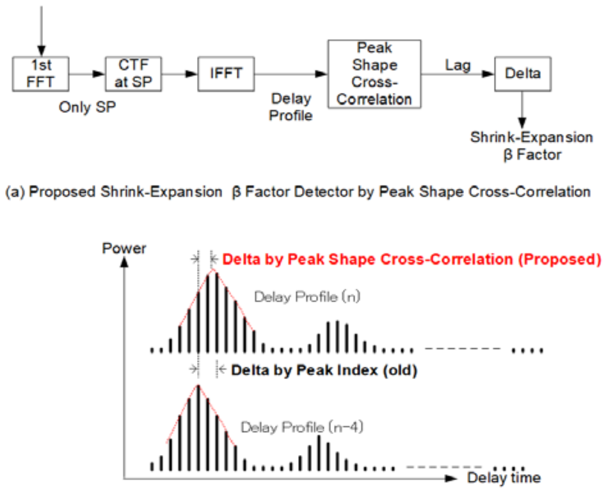

Fig. 9: Peak shape cross correlation

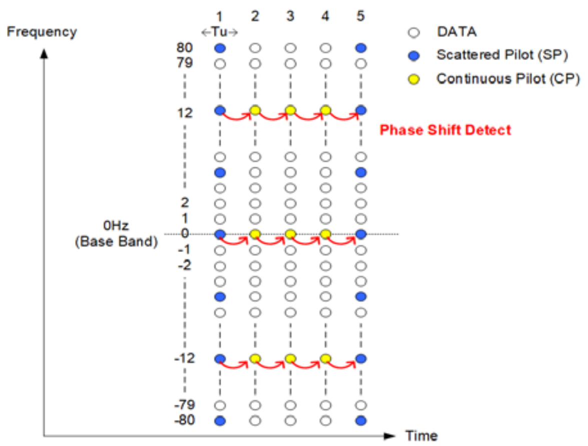

Fig. 10: Frequency-Domain Phase Shift Detection

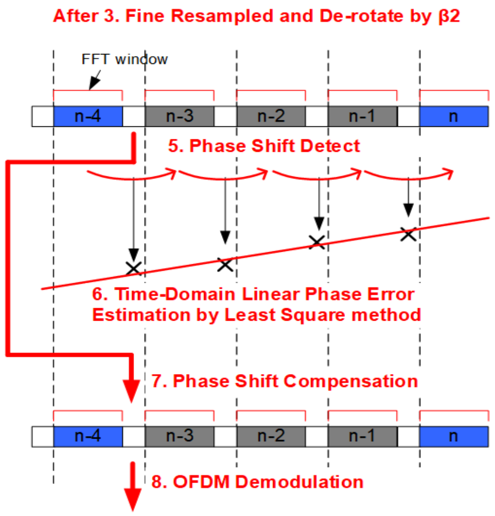

Fig. 11: Phase shift compensation processing

5. Simulation Result

In numerical simulation, the proposed algorithm demonstrates a better performance compared with previous algorithm as well as previous BER (Bit Error Rate) performance approach. Moreover, the convolutional coding is also implemented to further progress the Bit Error Rate (BER). Doppler estimation signal which consists of 4 OFDM symbols is used to calculate BER according to 2 steps shrink-expansion factor, Peak shape cross correlation and Linear phase error estimation by LS method. We have taken into account 2 multipath waves with 0 and 150 points delays with SNR 30dB modulated by 64QAM. Simulation condition of receiver moving velocity is shown in Fig. 12 for 193 OFDM symbols. Maximum velocity, Vmax adopted around 4 m/s according to simulation result. Increasing with receiver moving velocity, BER also increases almost linearly is shown in Fig. 13. At this point, it is shown the comparison with previous BER data with 3 proposed algorithms. Previous data has been implemented with 1 stage shrink-expansion factor, peak position and Interpolation phase method. BER increases linearly with steady velocity, but severely expands after velocity 2 m/s. With only 2 steps shrink expansion algorithm we can observe the BER performance enormously enhanced even after velocity 2 m/s. With new 2 steps shrink-expansion factor and Peak shape cross correlation method obtained linear BER plot almost close with 2 steps shrink-expansion factor algorithm that indicates the effectiveness of doppler compensation algorithm. Finally, with all 3 proposed algorithms attained a preferable BER performance than previous algorithm.

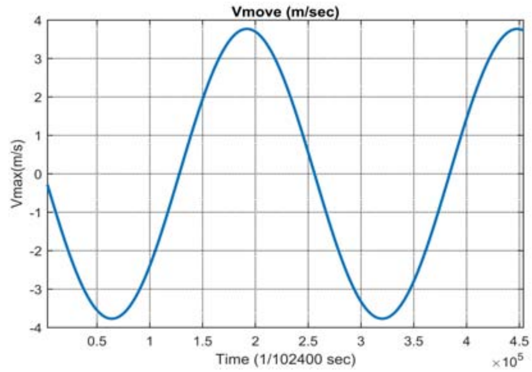

Fig. 12: Simulation condition of moving Receiver

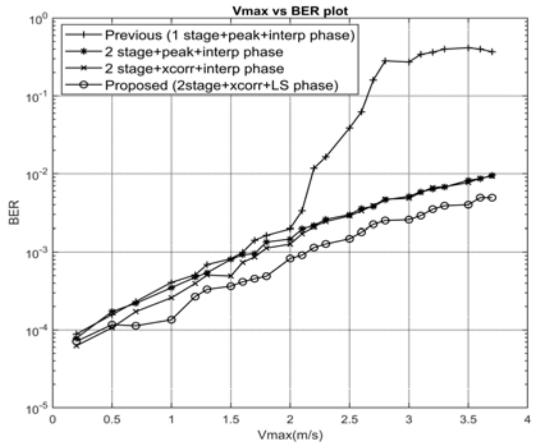

Fig. 13: BER plot of 3 new algorithms with Previous data

At a glance the comparison of BER performance between previous and proposed algorithm is shown in Fig. 14. From Fig. 14 it is evident that proposed algorithm performs much better than previous algorithm.

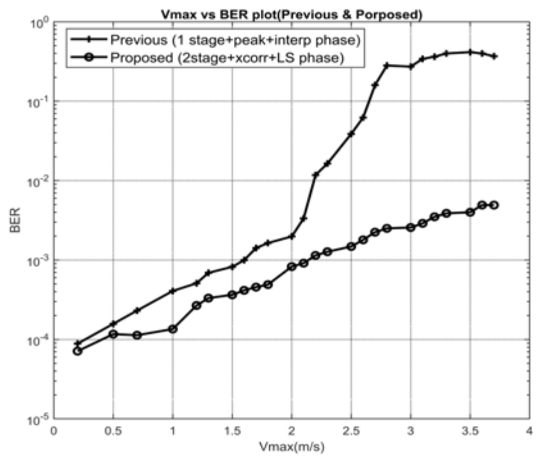

Fig. 14: BER plot of Previous and Proposed algorithm

In an additional comparison between previous and proposed data Fig.15 shows the BER and real part of 64QAM constellation of proposed algorithm and Fig 16 shows previous algorithm at a point of maximum velocity 2.5. From the Figure it can be observed proposed algorithm at a same velocity the real constellation as well as BER is much greater than previous algorithm.

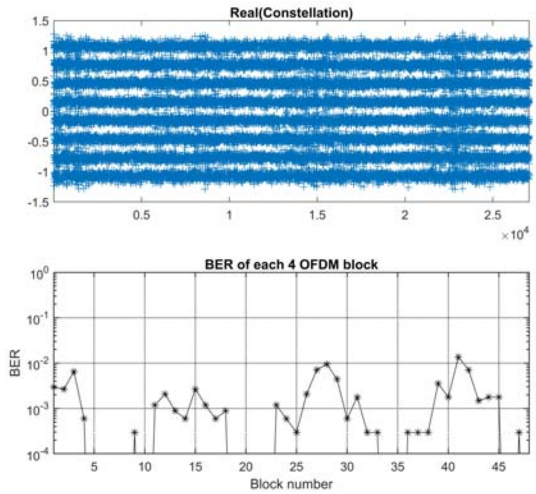

Fig. 15: BER and Real Const. plot of Proposed algorithm

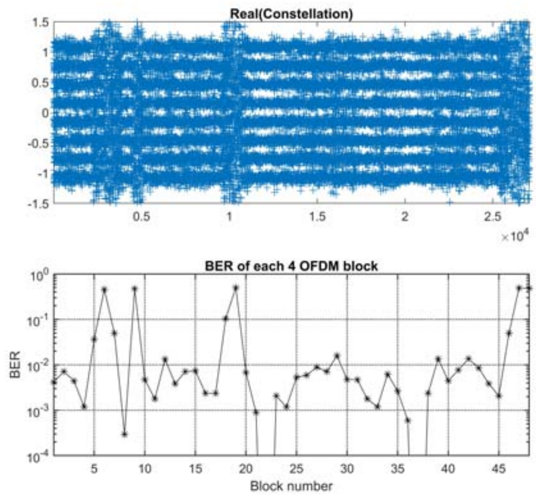

Fig. 16: BER and Real Const. plot of Previous algorithm

Conclusion:

In order to expand the performance of doppler compensation for OFDM-based Underwater acoustic communication system 3 New algorithm proposed by 2 steps Beta (Shrink-expansion) Detection factor, Peak shape cross correlation method and Linear phase error estimation by LS (Least Square) method. Receiver structure and Simulation code updated for getting admirable doppler compensation solution than the previous algorithm. The proposed method is very robust even when the velocity is changing linearly. The obtained maximum velocity is 4 m/s. Though we do not have experimental data, but the simulation result establishes the proposal system, anticipated a stable performance regarding BER when Doppler deviates in time. Finally, numerical simulation validates the proposed algorithm parades pleasing performance compared with previous algorithm in terms of the precision and robustness.

References

[1] Yusuke Onna,Taisaku Suzuki, Hiromasa Yamada, Shigeo Nakagawa, Tomohisa Wada; A 32 kHz Bandwidth, 8 branch Diversity Underwater Acoustic OFDM Communication System, MTS / IEEE OCEANS 2018, Kobe JAPAN, May 2018.

[2] Tran MinhHai, Saotome Rie, Taisaku Suzuki. Tomohisa Wada; An Acoustic OFDM System with Symbol-by-Symbol Doppler Compensation for Underwater Communication, The scientific world journal,Volume 2016, Article ID 7528353.

[3] A.E. Abdelkareema, B.S. Sharif, C.C. Tsimenidis; Adaptive time varying doppler shift compensation algorithm for OFDM-based underwater acoustic communication systems, Ad Hoc Networks 45 (2016) 104–119.

[4] Bin Li, Feng Tong, Siyuan Zheng, Dongsheng Chen; Bit-error rate gradient descent Doppler estimation for underwater acoustic OFDM communication, Applied Acoustics 171 (2021) 107557.

[5] Bin Li, Siyuan Zheng, F. Tong; Bit-error rate based Doppler estimation for shallow water acoustic OFDM communication, Ocean Engineering 182 (2019) 203–210.

[6] Tomohisa Wada, Taisaku Suzuki, Hiromasa Yamada, Shigeo Nakagawa; An Underwater Acoustic 64QAM OFDM Communication System with Robust Doppler Compensation, MTS / IEEE OCEANS 2016, Monterey California USA, September 2016.

[7] Stefania Sesia, Issam Toufik, Matthew baker, LTE The UMTS Long Term Evolution: from theory to practice, WILEY, 2009.