

**NOVEL METHODS TO COMBAT TIME
VARYING NON-STATIONARY UNDERWATER
ACOUSTIC CHANNEL**

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**BHARTI SCHOOL OF TELECOMMUNICATION
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INDIAN INSTITUTE OF TECHNOLOGY DELHI
NOVEMBER 2021**

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non-stationary underwater acoustic channel**

by

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**BHARTI SCHOOL OF TELECOMMUNICATION
TECHNOLOGY AND MANAGEMENT**

Submitted

in fulfillment of the requirements of the degree of Doctor of Philosophy

to the



INDIAN INSTITUTE OF TECHNOLOGY DELHI

November 2021

Dedicated to

My Parents, my wife, my son and my family

Certificate

This is to certify that the thesis entitled “**Novel methods to combat time varying non-stationary underwater acoustic channel** ” being submitted by **Mr. Vijay Singh Bhadouria** to the Bharti School of Telecommunication Technology and Management, Indian Institute of Technology Delhi, for the award of the degree of **Doctor of Philosophy** is the record of the bona-fide research work carried out by him under our supervision. In my opinion, the thesis has reached the standards fulfilling the requirements of the regulations relating to the degree.

The results contained in this thesis have not been submitted either in part or in full to any other university or institute for the award of any degree or diploma.

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Acknowledgements

I would like to express my heartfelt gratitude to Professor Monika Agarwal, CARE-IIT Delhi, for providing me with the opportunity to investigate the technologies and services that had been of assistance to me throughout my doctoral dissertation work. Throughout the thesis, I am compelled to put my faith in her and rely on her for the trust, confidence, and steadfast support she has given me to extend my vision, ability, and potential.

A special thanks to my senior and colleagues at SAC ISRO for the support provided. I would like to express my gratitude to Ritesh Kumar and Arun Goel, CARE, IIT Delhi, for providing stimulating recommendations and encouragement, which assisted me in coordinating my work, particularly in producing this report.

I would like to take this opportunity to express my gratitude to the Ministry of Electronics & Information Technology (MeitY), Government of India, for supporting my fellowship for the first two years of my research under the Visvesvaraya Ph.D. Scheme for Electronics & Information Technology.

Most importantly, I would like to express my gratitude to my mother, father, wife Archana, son Aarush, and other family members for never losing faith in me. It is due to their unending love and support that I am where I am today.

Vijay Singh Bhadouria

Abstract

Due to the inherent complexity of the underwater acoustic (UWA) channel, the transmission of information is always a difficult task. The primary disadvantage of the UWA channel is that the sound travels at a slower speed. When information is transmitted via radio waves that travel at the speed of light, velocities of a few kilometers per hour do not produce a significant Doppler effect. As a result, Doppler spread contributes a negligible fraction to the center frequency in the radio frequency (RF) case. However, in the case of an acoustic signal transmitted over the UWA channel, movement of a few kilometers per hour may significantly deteriorate the channel condition due to the lower frequency range. The extended delay spread is another effect of the slower sound speed. The delay spread of a channel is related to the channel's frequency selectivity. The larger the delay spread, the smaller the coherence bandwidth and the greater the channel's frequency selectivity within that bandwidth. As a result, the UWA channel is doubly selective, meaning that it is both time selective (due to Doppler spread) and frequency selective (due to delay spread). This thesis focuses on the study and analysis of the UWA channel's communication system. It is demonstrated that when the time reversal mirror (TRM) is used, the channel's delay spread becomes significantly smaller. The more receivers there are, the more improvement in terms of delay spread there will be. This thesis also analyses the properties of the prefix signals to be used in the channel estimation. A detailed comparative analysis of various prefix signals is provided in this work. Prefix signals are compared based on their correlation and spectral properties under the influence of Doppler-induced scaling. We have demonstrated that using hyperbolic frequency modulation (HFM) signal as a probing signal improves channel estimation under the linear Doppler effect in the UWA channel. The

hyperbolic time-frequency coupling in the HFM signal also aids in the joint estimation of the Doppler scale and the channel. As a result, we propose a novel algorithm for simultaneously estimating the Doppler scale factor and channel using look-up table (LUT) formation. The underwater channel typically has considerable variation in the received signal Doppler scale value. It is primarily due to the wide range of the angle of arrival of received multipath signals. Traditionally, the communication receiver is designed to compensate for the Doppler effect by considering a single Doppler scale value. However, such a type of receiver produces a sub-optimum result for the channels with significant Doppler scale distribution. Additionally, designing the receiver to compensate all the Doppler scale values observed in the communication interval would dramatically enhance the receiver's complexity. This thesis proposes a novel scale lag rake receiver based on unsupervised clustering of the estimated Doppler scale factor. It is shown that the proposed receiver provides performance close to the optimum receiver with reduced complexity. Its architecture also incorporates both the TRM and phase-locked loop (PLL). TRM is used to minimize the delay spread of the channel, thereby minimizing the number of equalizer coefficients required. Under time-varying channel conditions, PLL is used to reduce the update rate of the equalizer coefficients. This thesis also examines multi-carrier communication techniques such as orthogonal frequency division multiplexing (OFDM). We demonstrate that using TRM enhances the performance of the OFDM receiver for underwater channel configurations. It has also been shown that the TRM operation makes the effective channel real; hence, the complexity of the receiver can be reduced without compromising the performance.

सार

पानी के भीतर ध्वनिक (यूडब्ल्यूए) चैनल की अंतर्निहित जटिलता के कारण, सूचना का प्रसारण हमेशा एक कठिन काम होता है। पानी के भीतर ध्वनिक चैनल का प्राथमिक नुकसान यह है कि ध्वनि धीमी गति से यात्रा करती है। जब प्रकाश की गति से यात्रा करने वाली रेडियो तरंगों के माध्यम से सूचना प्रसारित की जाती है, तो कुछ किलोमीटर प्रति घंटे के वेग से महत्वपूर्ण डॉप्लर प्रभाव उत्पन्न नहीं होता है। नतीजतन, डॉप्लर स्प्रेड रेडियो फ्रीक्वेंसी (आरएफ) मामले में केंद्र आवृत्ति के लिए एक नगण्य अंश का योगदान देता है। हालांकि, पानी के भीतर ध्वनिक चैनल पर प्रसारित एक ध्वनिक संकेत के मामले में, कुछ किलोमीटर प्रति घंटे की गति कम आवृत्ति रेंज के कारण चैनल की स्थिति को काफी खराब कर सकती है। विस्तारित विलंब प्रसार धीमी ध्वनि गति का एक और प्रभाव है। चैनल का विलंब प्रसार चैनल की आवृत्ति चयनात्मकता से संबंधित है। जितना बड़ा विलंब फैलता है, उतनी ही छोटी सुसंगतता बैंडविड्थ और उस बैंडविड्थ के भीतर चैनल की आवृत्ति चयनात्मकता जितनी अधिक होती है। नतीजतन, पानी के नीचे ध्वनिक चैनल दोगुना चयनात्मक है, जिसका अर्थ है कि यह समय चयनात्मक (डॉप्लर प्रसार के कारण) और आवृत्ति चयनात्मक (विलंब प्रसार के कारण) दोनों है। यह थीसिस पानी के नीचे ध्वनिक चैनल की संचार प्रणाली के अध्ययन और विश्लेषण पर केंद्रित है। यह प्रदर्शित किया जाता है कि जब टाइम रिवर्सल मिरर का उपयोग किया जाता है, तो चैनल का विलंब प्रसार काफी छोटा हो जाता है। जितने अधिक रिसीवर होंगे, विलंब प्रसार के संदर्भ में उतना ही अधिक सुधार होगा। यह थीसिस चैनल अनुमान में उपयोग किए जाने वाले उपसर्ग संकेतों के गुणों का भी विश्लेषण करती है। इस कार्य में विभिन्न उपसर्ग संकेतों का विस्तृत तुलनात्मक विश्लेषण प्रदान किया गया है। उपसर्ग संकेतों की तुलना डॉप्लर-प्रेरित स्केलिंग के प्रभाव में उनके सहसंबंध और वर्णक्रमीय गुणों के आधार पर की जाती है। हमने दिखाया है कि एक जांच संकेत के रूप में हाइपरबोलिक आवृत्ति मॉड्यूलेशन सिग्नल का उपयोग पानी के नीचे ध्वनिक चैनल में रैखिक डॉप्लर प्रभाव के तहत चैनल अनुमान में सुधार करता है। हाइपरबोलिक फ्रीक्वेंसी मॉड्युलेटेड सिग्नल में हाइपरबोलिक टाइम-फ्रीक्वेंसी कपलिंग भी डॉप्लर स्केल और चैनल के संयुक्त अनुमान में सहायता करता है। नतीजतन, हम लुक-अप टेबल फॉर्मेशन का उपयोग करके डॉप्लर स्केल फैक्टर और चैनल का एक साथ आकलन करने के लिए एक उपन्यास एल्गोरिथ्म का प्रस्ताव करते हैं। पानी के नीचे के चैनल में आमतौर पर प्राप्त सिग्नल डॉप्लर स्केल वैल्यू में काफी भिन्नता होती है। यह मुख्य रूप से प्राप्त मल्टीपाथ सिग्नल के आगमन के कोण की विस्तृत श्रृंखला के कारण है। परंपरागत रूप से, संचार रिसीवर को एकल डॉप्लर स्केल मान पर विचार करके

डॉपलर प्रभाव की क्षतिपूर्ति करने के लिए डिज़ाइन किया गया है। हालांकि, इस प्रकार का रिसीवर महत्वपूर्ण डॉपलर स्केल वितरण वाले चैनलों के लिए एक उप-इष्टतम परिणाम उत्पन्न करता है। इसके अतिरिक्त, संचार अंतराल में देखे गए सभी डॉपलर स्केल मानों की क्षतिपूर्ति करने के लिए रिसीवर को डिज़ाइन करने से रिसीवर की जटिलता में नाटकीय रूप से वृद्धि होगी। यह थीसिस अनुमानित डॉपलर स्केल फैक्टर के असुरक्षित क्लस्टरिंग के आधार पर एक उपन्यास स्केल लैग रेक रिसीवर का प्रस्ताव करता है। यह दिखाया गया है कि प्रस्तावित रिसीवर कम जटिलता के साथ इष्टतम रिसीवर के करीब प्रदर्शन प्रदान करता है। इसके आर्किटेक्चर में टाइम रिवर्सल मिरर और फेज-लॉक लूप दोनों शामिल हैं। टाइम रिवर्सल मिरर का उपयोग चैनल के विलंब प्रसार को कम करने के लिए किया जाता है, जिससे आवश्यक तुल्यकारक गुणांकों की संख्या कम से कम हो जाती है। समय-भिन्न चैनल स्थितियों के तहत, तुल्यकारक गुणांक की अद्यतन दर को कम करने के लिए चरण लॉक लूप का उपयोग किया जाता है। यह थीसिस ऑर्थोगोनल फ्रीक्वेंसी डिवीजन मल्टीप्लेक्सिंग जैसी बहु-वाहक संचार तकनीकों की भी जाँच करती है। हम प्रदर्शित करते हैं कि टाइम रिवर्सल मिरर का उपयोग अंडरवाटर चैनल कॉन्फिगरेशन के लिए ऑर्थोगोनल फ्रीक्वेंसी डिवीजन मल्टीप्लेक्सिंग रिसीवर के प्रदर्शन को बढ़ाता है। यह भी दिखाया गया है कि टाइम रिवर्सल मिरर ऑपरेशन प्रभावी चैनल को वास्तविक बनाता है; इसलिए, प्रदर्शन से समझौता किए बिना रिसीवर की जटिलता को कम किया जा सकता है।

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Abbreviations

AWGN	Additive white Gaussian Noise
BER	Bit error rate
BPSK	Binary phase-shift keying
CSI	Channel state information
CEB	Channel estimate based
CIR	Channel impulse response
DA	Data aided
DDSF	Doppler delay spread function
DSD	Doppler spread density
DNN	Deep neural network
DFE	Decision Feedback Equalizer
DLL	Delay Locked Loop
FSE	Fractionally spaced equalizer
FIR	Finite impulse response
FCF	Frequency correlation function
FLL	Frequency Locked Loop
HFM	Hyperbolic frequency modulation
ISI	Inter symbol interference
ICI	Inter carrier interference
IDSF	Input delay spread function
IDFT	Inverse discrete Fourier transform
i.i.d.	Independent and identically distributed
LUT	Look up table
LFM	Linear frequency modulation

LTI	Linear time invariant
LSTM	Long short term memory
MC	Monte Carlo
MSML	Multi scale multi lag
MISO	Multi input single output
MMSE	Minimum mean square error
MIMO	Multi input multi output
OFDM	Orthogonal frequency division multiplexing
PLL	Phase locked loop
PRBS	Pseudo random bit sequence
PS	Probe signal
PDP	Power delay profile
PSD	Power spectral density
PDF	Probability density function
RF	Radio frequency
RLS	Recursive least square
RMS	Root mean square
ROC	Receiver operating characteristics
ReLU	Rectified linear unit
RNN	Recurrent neural network
SNR	Signal-to-noise ratio
SIMO	Single input multiple output
SISO	Single input single output
SLL	Side lobe level
SIR	Signal-to-interference ratio
TRM	Time reversal mirror
TVTF	Time varying transfer function
TCF	Time correlation function
UWA	Underwater acoustic
WSSUS	Wide sense stationary and uncorrelated scattering

Symbol List

T	Symbol duration
f_c	Centre frequency
τ	Propagation delay
$\psi(z, f)$	Mode depth function at depth z and frequency f
α_m	Mode attenuation function
B	Bandwidth
μ	Doppler frequency shift
B_{coh}	Coherence bandwidth
t_{coh}	Coherence time
d_t	Depth of the transmitter
d_r	Depth of the receiver
d_w	Water column depth
d_{tr}	Separation between the transmitter and the receiver
N_r	Number of receivers