OPTIMUM RECEIVER DESIGN FOR UNDERWATER ACOUSTIC COMMUNICATION

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by

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

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Dedicated to

My Parents, my wife, my son and my family

Certificate

This is to certify that the thesis entitled **"OPTIMUM RECEIVER DESIGN FOR UNDERWATER ACOUSTIC COMMUNICATION "** being submitted by **Mr. Ritesh Kumar** 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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Ritesh Kumar

Abstract

Communicating through the UWA channel is consistently challenging due to its inherent complexity. High attenuation limits the communication range for RF signals, while significant scattering limits the range for light waves. The acoustic wave is the sole means of transmitting the signal over long distances. Acoustic waves exhibit a reduced velocity compared to other types of waves. The Doppler effect has a notable impact, and the UWA delay spread is significant. As the delay spread increases, the coherence bandwidth decreases, and the channel's frequency selectivity within that bandwidth increases. As a result, the UWA channel demonstrates dual selectivity, which includes both temporal selectivity from Doppler spread and frequency selectivity from delay spread. In addition to Doppler and delay spread, the noises in underwater environments do not adhere to the conventional Gaussian distribution. The noise distribution in underwater environments is non-Gaussian, which means that traditional receiver performance is not optimal.

This thesis focuses on the analysis of noise distribution in UWAC. We have conducted an analysis of the noise distribution in the data collected by NOAA, VENUS, and the Indian Ocean. This thesis also examines the characteristics of the prefix signal in order to estimate the channel and initial point of the packet. Prefix signals are evaluated by analysing their correlation and spectral characteristics when affected by Doppler-induced scaling. We have shown that utilising the HFM signal as a probing signal enhances channel estimation in the UWA channel under the linear Doppler effect. Additionally, we have developed a receiver with optimal performance. Once the prefix has been determined, we proceed to estimate the channels that exhibit sparsity. We have employed the OMP technique, which is a widely recognised method, for channel

estimation. The Mean Squared Error (MSE) of the estimated channel relative to the actual channel increases in the presence of noise. In this case, we have employed Singular Value Decomposition (SVD) for the purpose of noise reduction, in conjunction with Orthogonal Matching Pursuit (OMP) to minimise the MSE. The estimated channel is utilised to minimise the delay spread through the use of TRM. This thesis presents an innovative two-stage equaliser designed to mitigate intersymbol interference (ISI) at the receiver. Initially, we employ a Time Reversal Mirror (TRM) to counteract the impact of the channel, and subsequently, we utilise an Artificial Intelligence (AI) based equaliser. We implemented an AI-based equaliser to alleviate the significant performance degradation resulting from high Doppler OFDM. Additionally, the suboptimal performance of the DFE equaliser due to non-Gaussian noise was addressed. In this study, we have conducted a comparative analysis of DFE, DNN, and RNN with GRU and LSTM. RNN-based equalisers outperform other types of equalisers. We have also examined OCDM and compared it with OFDM in the presence of Doppler, as the Doppler effect is significant in UWA. In this study, we also utilise the Time Reversal Mirror (TRM) technique to enhance the channel. A study indicated that the utilisation of TRM (Transmit-Receive Module) results in the realisation of a flat fading channel with real and positive characteristics, and a linear phase shift. To improve channel estimation in underwater communication channels based on OCDM, we implemented linear phase shifts on the channel using a prefix. A study indicates that implementing this approach not only simplifies the process but also leads to a performance improvement of approximately 2 dB in typical underwater communication conditions.

सार

पानी के नीचे ध्वनिक चैनल के माध्यम से संचार करना अपनी अंतर्निहित जटिलता के कारण लगातार चुनौतीपूर्ण है। उच्च क्षीणन आरएफ संकेतों के लिए संचार सीमा को सीमित करता है, जबकि महत्वपूर्ण प्रकीर्णन प्रकाश तरंगों के लिए सीमा को सीमित करता है। ध्वनिक तरंग लंबी दूरी तक सिग्नल संचारित करने का एकमात्र साधन है। ध्वनिक तरंगें अन्य प्रकार की तरंगों की तुलना में कम वेग प्रदर्शित करती हैं। डॉपलर प्रभाव का उल्लेखनीय प्रभाव है, और पानी के नीचे ध्वनिक विलंब प्रसार महत्वपूर्ण है। जैसे-जैसे विलंब प्रसार बढ़ता है, सुसंगतता बैंडविड्थ कम हो जाती है, और उस बैंडविड्थ के भीतर चैनल की आवृत्ति चयनात्मकता बढ़ जाती है। परिणामस्वरूप, पानी के नीचे ध्वनिक चैनल दोहरी चयनात्मकता प्रदर्शित करता है, जिसमें डॉपलर प्रसार से अस्थायी चयनात्मकता और विलंब प्रसार से आवृत्ति चयनात्मकता दोनों शामिल हैं। डॉपलर और विलंब प्रसार के अलावा, पानी के नीचे के वातावरण में शोर पारंपरिक गाऊसी वितरण का पालन नहीं करता है। पानी के नीचे के वातावरण में शोर वितरण गैर-गाऊसी है, जिसका अर्थ है कि पारंपरिक रिसीवर का प्रदर्शन इष्टतम नहीं है।

यह थीसिस पानी के भीतर ध्वनिक संचार में शोर वितरण के विश्लेषण पर केंद्रित है। हमने एनओएए, वीनस और हिंद महासागर द्वारा एकत्र किए गए डेटा में शोर वितरण का विश्लेषण किया है। यह थीसिस पैकेट के चैनल और प्रारंभिक बिंदु का अनुमान लगाने के लिए उपसर्ग सिग्नल की विशेषताओं की भी जांच करती है। डॉपलर-प्रेरित स्केलिंग से प्रभावित होने पर उपसर्ग संकेतों का मूल्यांकन उनके सहसंबंध और वर्णक्रमीय विशेषताओं का विश्लेषण करके किया जाता है। हमने दिखाया है कि जांच सिग्नल के रूप में एचएफएम सिग्नल का उपयोग रैखिक डॉपलर प्रभाव के तहत पानी के नीचे ध्वनिक चैनल में चैनल अनुमान को बढ़ाता है। इसके अतिरिक्त, हमने इष्टतम प्रदर्शन वाला एक रिसीवर विकसित किया है। एक बार उपसर्ग निर्धारित हो जाने के बाद, हम उन चैनलों का अनुमान लगाने के लिए आगे बढ़ते हैं जो विरलता प्रदर्शित करते हैं। हमने चैनल आकलन के लिए ओएमपी तकनीक को नियोजित किया है, जो एक व्यापक रूप से मान्यता प्राप्त विधि है। शोर की उपस्थिति में वास्तविक चैनल के सापेक्ष अनुमानित चैनल की माध्य्य चुकता त्रुटि (एमएसई) बढ़ जाती है। इस मामले में, हमने एमएसई को कम करने के लिए ऑर्थोगोनल मैचिंग परस्यूट (ओएमपी) के साथ मिलकर, शोर में कमी के उद्देश्य से सिंगुलर वैल्यू डीकंपोजिशन (एसवीडी) को नियोजित किया है। अनुमानित चैनल का उपयोग टीआरएम के उपयोग के माध्यम से होने वाली देरी को कम करने के लिए किया जाता है। यह थीसिस रिसीवर पर इंटरसिंबल इंटरफेरेंस (आईएसआई) को कम करने के लिए डिज़ाइन किया गया एक अभिनव दो-चरण

इक्वलाइज़र प्रस्तुत करता है। प्रारंभ में, हम चैनल के प्रभाव का प्रतिकार करने के लिए एक टाइम रिवर्सल मिरर (टीआरएम) का उपयोग करते हैं, और बाद में, हम एक आर्टिफिशियल इंटेलिजेंस (एआई) आधारित इक्वलाइज़र का उपयोग करते हैं। हमने उच्च डॉपलर ओएफडीएम के परिणामस्वरूप होने वाली महत्वपूर्ण प्रदर्शन गिरावट को कम करने के लिए एआई-आधारित इक्वलाइज़र लागू किया। इसके अतिरिक्त, गैर-गाऊसी शोर के कारण डीएफई इक्वलाइज़र के उप-इष्टतम प्रदर्शन को संबोधित किया गया था। इस अध्ययन में, हमने □□□ और एल.एस.टी.एम के साथ डी.एफ.ई, डी.एन.एन और आर.एन.एन का तुलनात्मक विश्लेषण किया है। आरएनएन-आधारित इक्वलाइज़र अन्य प्रकार के इक्वलाइज़र से बेहतर प्रदर्शन करते हैं। हमने ओसीडीएम की भी जांच की है और डॉपलर की उपस्थिति में इसकी तुलना ओएफडीएम से की है, क्योंकि पानी के नीचे ध्वनिक में डॉपलर प्रभाव महत्वपूर्ण है। इस अध्ययन में, हम चैनल को बढ़ाने के लिए टाइम रिवर्सल मिरर (टीआरएम) तकनीक का भी उपयोग करते हैं। एक अध्ययन से संकेत मिलता है कि टीआरएम (ट्रांसमिट-रिसीव मॉड्यूल) के उपयोग से वास्तविक और सकारात्मक विशेषताओं के साथ एक फ्लैट फ़ेडिंग चैनल और एक रैखिक चरण बदलाव का एहसास होता है। ओसीडीएम के आधार पर पानी के भीतर संचार चैनलों में चैनल अनुमान में सुधार करने के लिए, हमने एक उपसर्ग का उपयोग करके चैनल पर रैखिक चरण बदलाव लागू किया। एक अध्ययन से संकेत मिलता है कि इस दृष्टिकोण को लागू करने से न केवल प्रक्रिया सरल हो जाती है बल्कि विशिष्ट पानी के नीचे संचार स्थितियों में लगभग 2 डीबी का प्रदर्शन सुधार भी होता है।

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Abbreviations

Abbreviations

BER	Bit error rate
UWC	Underwater communication
UWAC	Underwater acoustic communication
SVD	Singular value decomposition
RNN	Recurrent neural network
GRU	Gated recurrent Unit
LSTM	Long short term memory
DNN	Deep neural network
DFE	Decision feedback equalizer
AWGN	Additive white Gaussian noise
MMSE	Minimum mean square error
MSE	Mean square error
OFDM	Orthogonal frequency division multiplexing
OCDM	Orthogonal chirp division multiplexing
FnT	Fresnel transform
DFnT	Discrete Fresnel transform
IDFnT	Inverse Discrete Fresnel transform
CLT	Central limit theorem
i.i.d	independent and identical distributed
UWA	Underwater acoustic
LFM	Linear frequency modulation
HFM	Hyperbolic frequency modulation
rms	Root mean square
B	Bandwidth
TRM	Time reversal mirror
ISI	Inter symbol interference
PSD	Power spectral density
PDF	Probability density function
RF	Radio frequency
SNR	Signal-to-noise ratio
NOAA	National Oceanographic and Atmo
ML	Maximum likelihood
CSI	Channel state information