PERFORMANCE EVALUATION OF UNDERWATER OPTICAL WIRELESS COMMUNICATION SYSTEM

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by

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Dedicated to

My Family

Certificate

This is to confirm that the thesis titled **"Performance Evaluation of Underwater Optical Wireless Communication System"**, submitted by **Ms. Gunjan Matta** to the Centre for Applied Research in Electronics, Indian Institute of Technology Delhi, for the award of the degree of **Doctor of Philosophy** represents the original and genuine research work conducted by her under our supervision and guidance. The thesis has reached the standards fulfilling the requirements of the regulations related to the award of the degree.

The contents and findings presented in this thesis have not, to the best of our knowledge, been submitted, either partially or in their entirety, to any other University or Institute for the purpose of obtaining any degree or diploma.

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Abstract

The thesis centres on Underwater Optical Wireless Communications (UOWC), a unique and powerful means of utilising optical signals to transmit information through underwater wireless connections. UOWC complements radio-frequency (RF) and acoustic communication, particularly for establishing ultra-high-speed links in underwater environments covering short to medium distances. Nevertheless, challenges must be addressed to create a secure and dependable connection. Hence, a comprehensive understanding of light propagation in the underwater medium is crucial.
The core mission of this thesis is to delve into the impact of various elements within the underwater channel on the propagation of light. This study focuses on factors such as attenuation due to absorption and scattering losses, salinity and air bubbles, and noises, encompassing input-independent and input-dependent noise. The dissertation takes an information-theoretic approach, deriving channel capacity bounds to achieve this. In this research, the UOWC point-to-point link is modelled as intensity modulation with direct-detection (IM/DD) channels with potential interference arising from various underwater components, paving the way for practical applications in the field.
Following an in-depth exploration of UOWC system capacities across various scenarios, the thesis successfully designs a high-capacity and cost-effective UOWC system by incorporating Spectrum-Sliced Wavelength-Division Multiplexing (SS-WDM) technology. In the concluding section, machine learning algorithms are employed to forecast the system's performance. Additionally, the thesis examines the influence of diverse system parameters on the performance of the UOWC system.

Abstract

सार

थीसिस मुख्य रूप से अंडरवाटर ऑप्टिकल वायरलेस कम्युनिकेशंस (UOWC) पर केंद्रित है, जो पानी के नीचे वायरलेस कनेक्शन के माध्यम से सूचना प्रसारित करने के लिए ऑप्टिकल सिग्नल का उपयोग करने का एक अनूठा और शक्तिशाली साधन है। UOWC रेडियो–फ्रीक्वेंसी (RF) और ध्वनिक संचार का पूरक है, विशेष रूप से कम से मध्यम दूरी को कवर करने वाले पानी के नीचे के वातावरण में अल्ट्रा–हाई–स्पीड लिंक स्थापित करने के लिए। फिर भी, एक सुरक्षित और भरोसेमंद कनेक्शन बनाने के लिए चुनौतियों का समाधान किया जाना चाहिए। इसलिए, पानी के नीचे के माध्यम में प्रकाश प्रसार की व्यापक समझ महत्वपूर्ण है। इस थीसिस का मुख्य मिशन पानी के नीचे के चैनल के भीतर विभिन्न तत्वों के प्रकाश के प्रसार पर पड़ने वाले प्रभाव का पता लगाना है। यह अध्ययन अवशोषण और बिखराव के नुकसान, लवणता और हवा के बुलबुले, और शोर के कारण क्षीणन जैसे कारकों पर केंद्रित है, जिसमें इनपुट–स्वतंत्र और इनपुट–निर्भर शोर शामिल हैं। शोध प्रबंध एक सूचना–सैद्धांतिक दृष्टिकोण अपनाता है, इसे प्राप्त करने के लिए चैनल क्षमता सीमाएँ प्राप्त करता है। इस शोध में, यूओडब्ल्यूसी पॉइंट–टू–पॉइंट लिंक को विभिन्न अंडरवाटर घटकों से संभावित हस्तक्षेप के साथ प्रत्यक्ष पहचान (आईएम/डीडी) चैनलों के साथ तीव्रता मॉड्यूलेशन के रूप में मॉडल किया गया है, जो क्षेत्र में व्यावहारिक अनुप्रयोगों के लिए मार्ग प्रशस्त करता है। विभिन्न परिदृश्यों में यूओडब्ल्यूसी सिस्टम क्षमताओं की गहन खोज के बाद, थीसिस स्पेक्ट्रम–स्लाइस्ड वेवलेंथ–डिवीजन मल्टीप्लेक्सिंग (एसएस–डब्ल्यूडीएम) तकनीक को शामिल करके उच्च क्षमता और लागत प्रभावी यूओडब्ल्यूसी सिस्टम को सफलतापूर्वक डिजाइन करती है। समापन अनुभाग में, सिस्टम के प्रदर्शन का पूर्वानुमान लगाने के लिए मशीन लर्निंग एल्गोरिदम का उपयोग किया जाता है। इसके अतिरिक्त, थीसिस यूओडब्ल्यूसी सिस्टम के प्रदर्शन पर विविध सिस्टम मापदंडों के प्रभाव की जांच करती है।

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Abbreviations

AWG	**A**rrayed **W**aveguide **G**rating
BER	**B**it **E**rror **R**ate
CW	**C**ontinuous **W**ave
FSO	**F**ree **S**pace**O**ptical
GB	**G**radient **B**oosting
HNLF	**H**ighly**N**on **L**inear**F**iber
IM/DD	**I**ntensity **M**odulation with **D**irect **D**etection
KNN	**K** **N**earest **N**eighbour
LED	**L**ight **E**mitting **D**iode
LOS	**L**ine of**S**ight
NLOS	**N**on **L**ine of**S**ight
NRZ	**N**on **R**eturn to **Z**ero
OSA	**O**ptical **S**pectrum **A**nalyzer
OSNR	**O**ptical **S**ignal to **N**oise **R**atio
OFDM	**O**rthogonal **F**requency**D**ivision**M**ultiplexing
OPM	**O**ptical **P**erformance **M**onitoring
P2P	**P**oint to **P**oint
PRBS	**P**seudo **R**andom **B**it **G**enerator
Q-Factor	**Q**uality **F**actor
RF	**R**andom **F**orest
SOA	**S**emiconductor **O**ptical **A**mplifier
SS	**S**pectrum **S**liced
SNR	**S**ignal to **N**oise **R**atio
TDM	**T**ime **D**ivision **M**utiplexingr
UOWC	**U**nderwater **O**ptical **W**ireless **C**ommunication
WDM	**W**avelength **D**ivision **M**ultiplexing

Symbols

H_w	channel gain of UOWC system
H_{sh}	channel gain of saline UOWC system for horizontal link
H_{sv}	channel gain of saline UOWC system for vertical link
H_a	channel gain of UOWC system with air bubbles
X	system input
Y	system output
σ	Gaussian noise variance
ζ^2	input-dependent Gaussian noise variance
z	zero mean additive Gaussian noise with variance σ^2
A	peakpower
ξ	average power
α	optical average to peak power ratio
ϕ	irradiance angle
ψ	incident angle
A_r	photodiode area
m	Lambert's mode number
λ	wavelength
$c(\lambda)$	extinction coefficient
$a(\lambda)$	absorption coefficient
$b(\lambda)$	scattering coefficient
Z_0	input-independent Gaussian noise
Z_1	input-dependent Gaussian noise
C	channel capacity
$I(X;Y)$	mutual information between the input and output terminals
$[D(.)\|\|(.)]$	relative entropy
$R(.)$	a generic pdf on the channel output