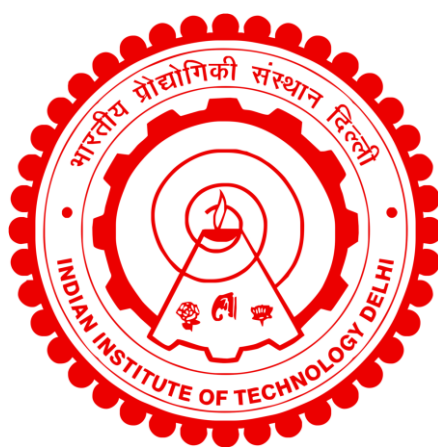


PERFORMANCE EVALUATION OF UNDERWATER OPTICAL WIRELESS COMMUNICATION SYSTEM

GUNJAN MATTA



**CENTRE FOR APPLIED RESEARCH IN ELECTRONICS
INDIAN INSTITUTE OF TECHNOLOGY DELHI
JULY 2024**

© Indian Institute of Technology Delhi (IITD), New Delhi, 2024

PERFORMANCE EVALUATION OF UNDERWATER OPTICAL WIRELESS COMMUNICATION SYSTEM

by

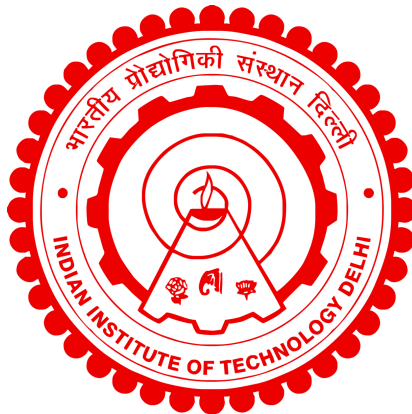
GUNJAN MATTA

CENTRE FOR APPLIED RESEARCH IN ELECTRONICS

Submitted

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

to the



**INDIAN INSTITUTE OF TECHNOLOGY
DELHI**

July 2024

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.

Prof. Monika Agrawal

Centre for Applied Research in
Electronics,
Indian Institute of Technology Delhi.

Prof. Rajendar Bahl

Centre for Applied Research in
Electronics,
Indian Institute of Technology Delhi.

Acknowledgements

“

I sincerely thank God for providing me with the strength to embark on and successfully complete my PhD journey. I am immensely thankful to numerous individuals who provided invaluable help and encouragement.

First and foremost, I express my profound appreciation to my supervisors, Prof. Monika Agarwal and Prof. Rajendar Bahl. Their guidance, dedication, and counsel were instrumental in guiding me through the research process, and their motivation spurred me to tackle challenging research problems.

I also extend my gratitude to the members of my committee. Prof. Ananjan Basu, Prof. Arun Kumar, and Prof. S.D. Joshi. Their indispensable insights and constructive ideas were consistently valuable throughout this journey. How time has flown by. The past few years have been incredibly enjoyable, and I owe a debt of gratitude to the tremendous support from my friends at IIT Delhi.

I express my deepest gratitude to my parents, Mr Hans Raj Manik and Mrs Nirmal Manik, and my siblings, Ms Lucky and Mr Deepanshu, for their unwavering love and support. Your constant prayers have been the bedrock of my strength throughout this journey.

I am profoundly grateful to my husband, Cdr Prince Matta, whose unwavering support and motivation have been a guiding light during my PhD. His encouragement through moments of self-doubt and uncertainty has been invaluable. To my son, Shaurya, although I couldn't spend as much time with you as I would have liked, your consistent cheerfulness and encouragement have meant the world to me. And to my daughter, Shreya, your giggles and joy have been a continuous source of happiness and strength. I am incredibly fortunate to have each of you in my life. Thank you from the bottom of my heart.

Gunjan Matta

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-स्लाइड 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।

Contents

Certificate	i
Acknowledgements	ii
Abstract	iii
Contents	iv
List of Figures	viii
List of Tables	x
Abbreviations	xi
Symbols	xii
1 Introduction	1
1.1 Underwater Optical Wireless Communication	1
1.2 Challenges in Underwater Optical Channel	5
1.3 Motivation	11
1.4 Contribution of the Thesis	12
1.5 Organization of the Thesis	13
2 Capacity analysis of UOWC system over lossy channel in the presence of noises	15
2.1 System Model	17
2.2 Channel Capacity Bounds	20
2.2.1 Upper Bound on Capacity for Input- Independent Gaussian Noise Channel	22

2.2.2	Upper Bound on Capacity for Input-Dependent Gaussian Noise Channel	23
2.2.3	Lower Bound on Capacity for Input- Independent Gaussian Noise Channel	25
2.2.4	Lower Bound on Capacity for input- Dependent Gaussian Noise Channel	27
2.3	Simulation Results	30
2.4	Conclusion	35
3	Capacity analysis of UOWC system in the presence of salinity, air bubbles, and noises	36
3.1	Introduction	36
3.1.1	Fading due to salinity	37
3.1.2	Fading due to air bubbles	39
3.1.3	System Model	40
3.2	Channel Capacity Bounds	43
3.2.1	Lower Bound on Capacity over Input- Independent Gaussian Noise Channel	43
3.2.1.1	lower bound for the horizontal link in saline water	44
3.2.1.2	lower bound for the vertical link in saline water	44
3.2.1.3	lower bound for water with air bubbles	45
3.2.2	Lower Bound on Capacity for Input- Dependent Gaussian Noise Channel	45
3.2.2.1	lower bound for the horizontal link in saline water	45
3.2.2.2	lower bound for the vertical link in saline water	46
3.2.2.3	lower bound for water with air bubbles	47
3.2.3	Upper Bound on Capacity over Input- Independent Gaussian Noise Channel	47
3.2.3.1	Upper bound for the horizontal link in saline water	47
3.2.3.2	Upper bound for the vertical link in saline water	48
3.2.3.3	Upper bound for water with air bubbles	48
3.2.4	Upper Bound on Capacity for Input-Dependent Gaussian Noise Channel	48
3.2.4.1	Upper bound for the horizontal link in saline water	49
3.2.4.2	Upper bound for the vertical link in saline water	49
3.2.4.3	Upper bound for the water with air bubbles	50
3.2.5	Simulation Results	50
3.3	Conclusion	53
4	Spectrum Slicing Wavelength Division Multiplexing	55
4.1	Introduction	55
4.2	System Architecture	58

4.3	Results and Discussion	63
4.4	Conclusion	71
5	Machine Learning Algorithms to Forecast the Performance of UOWC Systems	72
5.1	Introduction	72
5.2	Methodology and Design Procedure	74
5.3	Machine Learning Prediction Models	78
5.4	Results	84
5.5	Conclusion	93
6	Conclusion and Future Work	94
6.1	Conclusion	94
6.2	Future Work	95
A	Appendix A - Derivation of the upper bounds for Input- Independent Gaussian Noise channel	97
B	Appendix B - Derivation of the upper bounds for Input- Dependent Gaussian Noise channel	101
	Bibliography	109
	List of Publications	123
	Technical Biography of Author	125

List of Figures

1.1	Water absorption spectrum [10]	8
2.1	Geometry of LOS channel configuration for UOWC system [68]	18
2.2	The tightness analysis of the capacity bounds for clear water under different cases with $\alpha = 0.2, d = 1$ (signal-dependent Gaussian noise model)	30
2.3	Comparison of upper bound for signal-independent and signal-dependent Gaussian noise model for different values of ζ^2 (case 1 with $\alpha = 0.2, d=3m$, turbid water)	31
2.4	capacity bounds vs OSNR of case 2 with $d=1m$ and $\alpha = 0.6$ (additive Gaussian noise model)	32
2.5	channel capacity vs OSNR of case 1 for $\alpha = 0.4, d = 2, \sigma^2 = 1$ (additive Gaussian noise model)	33
2.6	lower bound vs OSNR for case 3 with $\zeta^2 = 5$ and $d = 1m, d = 2m, d = 3m$ (signal-dependent Gaussian noise model)	34
3.1	Lower bound of capacity for tap water and saline water(input-independent Gaussian noise model,vertical link)	51
3.2	Lower bound capacity for tap water and saline water(input-dependent Gaussian noise model,vertical link)	52
3.3	Comparison of lower bound for different salt concentrations(input-independent Gaussian noise model,horizontal link)	52
3.4	capacity comparison of inputindependent and input-dependent UOWC noise model with air bubbles and without air bubbles	53
4.1	Illustration of the presented system employing various spectrum slicing techniques [66]	59
4.2	Block diagram of AWG [66]	60
4.3	Wide Spectrum of LED source	62
4.4	Spectrum of Narrowband Laser at 450 n	63
4.5	broad spectrum of a narrowband laser with frequency combs appearing after the AWG	64
4.6	Multiplexed spectrum slices of four channels for LED	65
4.7	Multiplexed spectrum slices of four channels for AWG	66

4.8	link lengths versus Q-factor under gamma-gamma turbulence for two spectrum slicing techniques	66
4.9	link lengths versus LoG BER under gamma-gamma turbulence for two spectrum slicing techniques	67
4.10	An eye diagram illustrating the signal characteristics for LED shows noise and distortions	68
4.11	An eye diagram illustrating the signal characteristics for AWG with a better eye opening	69
4.12	Comparison of different line coding techniques for SS-UOWC system in terms of Q-factor	70
4.13	Comparison of different line coding techniques for SS-UOWC system in terms of log BER	70
4.14	Plotting Q-factor for various link lengths for SS-UOWC system for different data rates	71
5.1	Block diagram of UOWC system [86]	76
5.2	Flowchart of K Nearest Neighbour Regression Algorithm [87]	79
5.3	Schematic of Decision Tree Regression Algorithm [88]	80
5.4	Flowchart of Random Forest Regression Algorithm [89]	82
5.5	Flowchart of Gradient Boosting Regression Algorithm [90]	82
5.6	Q Factor Vs receiver's aperture area for distinct variations in link distance.	85
5.7	Q Factor Vs Data rate for diverse water types	85
5.8	plotting Q-factor against link distance for varying transmitter power levels	86
5.9	Graphing BER against link distance, considering different water types under various turbulent conditions	87
5.10	Comparing Q-factor with varying beam divergence angles at varying link distances	88
5.11	Analyzing the Q-factor in relation to wavelength for different types of water	89
5.12	Examining the Q-factor in correlation with link distance for both tap water and saline water	90
5.13	Comparing the Q-factor with wavelength variations for different types of water	91

List of Tables

1.1	Differentiating values of the coefficients of absorption and scattering [14]	9
3.1	Determining constants, denoted as c_1 and c_2 , for various salt concentrations in the context of a horizontal link [39]	41
3.2	values of constants c_3 and c_4 in both the presence and absence of turbidity caused by air bubbles [53]	43
4.1	Parameters utilized in simulating the spectrum slicing technique . . .	61
5.1	System Parameters	75
5.2	Evaluating and contrasting various performance parameters across different turbidity conditions in the UOWC systems	91
5.3	Assessing the effectiveness of various Machine Learning algorithms . .	92

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 ultiplexingr
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
$[D(\cdot) (\cdot)]$	relative entropy
$R(\cdot)$	a generic pdf on the channel output