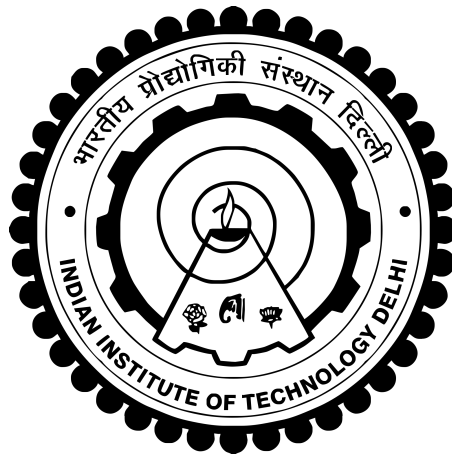


**FULL-DUPLEX OPERATIONS AND RELIABILITY  
ENHANCEMENT IN INDOOR VISIBLE LIGHT  
COMMUNICATION NETWORKS**

**ANJALI GUPTA**



**DEPARTMENT OF ELECTRICAL ENGINEERING  
INDIAN INSTITUTE OF TECHNOLOGY DELHI**

May 2025

© Indian Institute of Technology Delhi (IITD), New Delhi, May 2025

**Full-duplex operations and reliability  
enhancement in indoor visible light  
communication networks**

by

**ANJALI GUPTA**

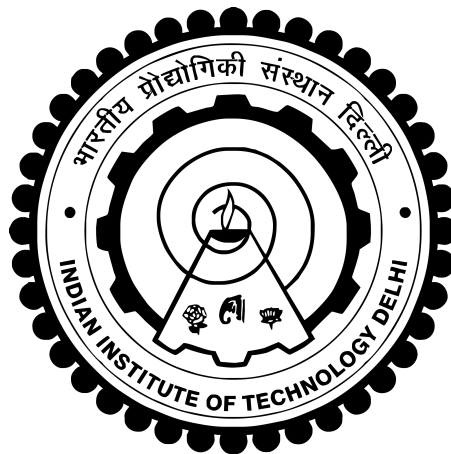
Department of Electrical Engineering

Submitted

*in fulfillment of the requirements of the degree of*

**Doctor of Philosophy**

to the



**Indian Institute of Technology Delhi**

**May 2025**

## CERTIFICATE

This is to certify that the thesis entitled “Full-duplex operations and reliability enhancement in indoor visible light communication networks”, submitted by Anjali Gupta to the Indian Institute of Technology Delhi, for the award of the degree of Doctor of Philosophy in 2025 is a record of the original, bona fide research work carried out by her under my supervision and guidance. The thesis has reached the standards fulfilling the requirements of the regulations related to the award of the degree.

The results in this thesis have not been submitted in part or in full to any other University or Institute for awarding any degree or diploma to the best of my knowledge.



Prof. Abhishek Dixit  
Dept. of Electrical Engineering  
IIT Delhi, 110016

Place: New Delhi

Date: May 2025

## ACKNOWLEDGEMENTS

The PhD journey is a tough one, something that I was not fully aware of when I started. It has been challenging in many ways, but as I reach the end of this thesis, I feel nothing but grateful. The experiences, learnings, and growth that I have undergone during this time will remain with me forever.

The motivation to pursue a Ph.D. came from two remarkable women. The first is my dear friend from my bachelor's days, Ms. Swati Dandekar, who might still be unaware of the inspiration she has been to me. The second is my master's thesis co-supervisor, Prof. Carmen Mas Machuca, whose guidance and example deeply influenced my decision.

At the outset of this acknowledgment, I would like to express my heartfelt gratitude to my supervisor, Prof. Abhishek Dixit, who has been a tremendous support throughout my Ph.D. journey. I have been associated with him for more than eight years, and he has left a lasting impact on my critical thinking and research approach. I am truly thankful for the opportunity(ies) he gave me to work with him during my master's thesis and for enabling me to undertake my master's thesis under the guidance of Prof. Carmen Mas Machuca, an experience that ultimately paved the way for this Ph.D. thesis.

I am deeply grateful to my research committee members, Prof. Vivek Venkataraman, Prof. Swades De, and Prof. R.K. Varshney, for their valuable feedback and suggestions at various stages of my work. I also wish to express my sincere gratitude to Late Prof. Vinod Chandra for his unwavering support in research and for the life lessons he imparted; his influence will remain with me always.

I would like to thank my external examiners, Dr. Aravind Kumar Mishra and Dr. Majid Safari, for their valuable feedback on my thesis. A special note of thanks to Dr. Mishra for being available in person to formally confer the title of "Dr." upon me, an unforgettable moment.

The support of friends has always pushed me forward, and I consider myself fortunate to have known such good people in my life. Special thanks to Dr. Jagdeep Singh for his constant support throughout this journey. I am also thankful to my dear friends Nitin K. Lohar, Abhilasha Verma, Dr. Devika Dass, Shruti Jain, Chandan Kumar, Ruchi Gahlot, Vaibhav Singh, Resu Anwesh, and Vishal Shrivastava for helping me stay grounded and sane through the ups and downs of the Ph.D.

I appreciate the support and warmth provided by my seniors, Dr. Sonali and Dr. Rishu Raj, and my juniors, Vaishali, Sakshi, Tehreem, and Gourab, who contributed to creating an amiable and collaborative work environment. I also thank the lab staff Ms. Neeru Asihja, Mr. Rajesh Kumar, and Mr. Sunil Kumar, for their assistance in procuring equipment, supporting my experimental work, and handling the necessary administrative tasks.

Last but not least, I am deeply thankful to my family for their endless patience and understanding throughout this journey, especially my husband, who made countless sacrifices. I also owe a heartfelt thanks to my parents, who bore the weight of societal pressures so that I could pursue this path. I am truly grateful for their strength and belief in me. Finally, I thank God for granting me the strength, resilience, and opportunity to complete this Ph.D.

*Anjali Gupta*

Anjali Gupta

2018EEZ8164

New Delhi, May 2025

# ABSTRACT

This thesis explores novel methods to enhance indoor visible light communication (VLC) networks by leveraging their inherent full-duplex capabilities. Unlike traditional radio frequency (RF) networks, which primarily utilize half-duplex communication due to hardware constraints and self-interference issues, VLC networks employ directional transceivers that enable simultaneous two-way communication. This research aims to enhance VLC network throughput and tackle several challenges, including limited cell coverage areas and inter-cell interference, which arise from using the same wavelength in neighboring cells. It thoroughly examines indoor VLC media access control (MAC) protocols, typically contention-based and contention-free access methods. Contention-based access is simple to implement, does not require accurate device synchronization, and allows devices to freely join and leave the network. In contrast, contention-free access, suitable for deterministic traffic requiring high quality of service (QoS), is ideal for mission-critical applications.

This thesis first introduces a pioneering approach to enable full-duplex communication in the contention-free access of the MAC of the VLC standard IEEE 802.15.7. It compares the proposed full-duplex optical MAC (FD-OMAC) and IEEE 802.15.7 MAC to display enhanced throughput without compromising latency. Furthermore, it investigates the backward compatibility of the proposed full-duplex MAC to the standards and extends its functionality in multiple access point (AP) networks, tackling inter-cell interference. The proposed full-duplex MAC employs separate frequencies for upstream and downstream communication to enhance user convenience but can also support in-band full-duplex communication when required.

The dissertation then delves into the mathematical analysis of full-duplex contention-based schemes, focusing on the carrier sense multiple access with collision avoidance (CSMA/CA) MAC protocol of IEEE 802.15.7. While the prior works have performed the CSMA/CA

mathematical analysis using the Markov models, they display significant deviation from the simulation results. This thesis removes the analytical deviation from the simulation results by thoroughly reevaluating the Markov model. Furthermore, it performs the mathematical analysis of the network along with the hidden node problem, a significant challenge in VLC networks. This problem is solved in literature by using various full-duplex communication methods, such as bi-directional data transmission and the busy tone signal; the latter is utilized in the proposed FD-OMAC scheme. These techniques increase the coverage area of the nodes by utilizing an AP as a relay node. However, the AP response is delayed by the processing time, causing an unexpected network behavior. The quantitative effect of this delay remains unexplored, which is critical for optimizing the VLC network. The thesis bridges this gap by extending the proposed Markov analysis to model CSMA/CA for the aforementioned full-duplex techniques, particularly with busy tone.

This thesis presents the basic hardware blocks of a full-duplex VLC transceiver and the methodology to develop a primary full-duplex VLC link for video transmission. It further offers methods to enhance the reliability of full-duplex VLC AP transceivers and calculate their reliability parameters. Utilizing both mean time between failure (MTBF) calculations and Markov chain modeling, the study identifies failure-prone modules and assesses system downtime, facilitating fault-tolerant system designs. Additionally, a life cycle cost analysis aids decision-making for diverse application scenarios. This comprehensive analysis provides valuable insights into optimizing VLC networks, paving the way for enhanced performance and reliability in indoor wireless communication systems.

## सार

यह थीसिस उनकी अंतर्निहित पूर्ण-द्वैध क्षमताओं का लाभ उठाकर इनडोर दृश्यमान प्रकाश संचार (वीएलसी) नेटवर्क को बढ़ाने के लिए उपन्यास विधियों की पड़ताल करता है। पारंपरिक रेडियो फ्रीक्वेंसी (आरएफ) नेटवर्क के विपरीत, जो मुख्य रूप से हार्डवेयर बाधाओं और आत्म-हस्तक्षेप के मुद्दों के कारण आधे-द्वैध संचार का उपयोग करते हैं, वीएलसी नेटवर्क दिशात्मक ट्रांसमिशन को नियुक्त करते हैं जो एक साथ दो-तरफ़ा संचार को सक्रिय करते हैं। इस शोध का उद्देश्य वीएलसी नेटवर्क थ्रूपुट को बढ़ाना और सीमित सेल कवरेज क्षेत्रों और अंतर-सेल हस्तक्षेप सहित कई चुनौतियों से निपटना है, जो पड़ोसी कोशिकाओं में एक ही तरंग दैर्घ्य का उपयोग करने से उत्पन्न होते हैं। यह पूरी तरह से इनडोर वीएलसी मीडिया एक्सेस कंट्रोल (एमएसी) प्रोटोकॉल, आमतौर पर विवाद-आधारित और विवाद-मुक्त पहुंच विधियों की जांच करता है। विवाद-आधारित पहुंच को लागू करने के लिए सरल है, सटीक डिवाइस सिंक्रनाइजेशन की आवश्यकता नहीं है, और उपकरणों को स्वतंत्र रूप से नेटवर्क में शामिल होने और छोड़ने की अनुमति देता है। इसके विपरीत, विवाद-मुक्त पहुंच, उच्च गुणवत्ता (क्यूओएस) की आवश्यकता वाले नियतात्मक यातायात के लिए उपयुक्त है, मिशन-क्रिटिकल अनुप्रयोगों के लिए आदर्श है।

यह थीसिस पहले वीएलसी मानक आईईईई 802.15.7 के मैक के विवाद-मुक्त पहुंच में पूर्ण-द्वैध संचार को सक्रिय करने के लिए एक अग्रणी दृष्टिकोण का परिचय देता है। यह प्रस्तावित पूर्ण-डुप्लेक्स ऑप्टिकल मैक (एफडी-ओएमएसी) और आईईईई 802.15.7 मैक की तुलना विलंबता से समझौता किए बिना बढ़ाया थ्रूपुट प्रदर्शित करने के लिए करता है। इसके अलावा, यह प्रस्तावित पूर्ण-द्वैध मैक की पिछड़ी संगतता की जांच मानकों के लिए करता है और इंटर-सेल हस्तक्षेप से निपटने के लिए कई एक्सेस पॉइंट (एपी) नेटवर्क में इसकी कार्यक्षमता का विस्तार करता है। प्रस्तावित पूर्ण-द्वैध मैक उपयोगकर्ता की सुविधा को बढ़ाने के लिए अपस्ट्रीम और डाउनस्ट्रीम संचार के लिए अलग-अलग आवृत्तियों को नियुक्त करता है, लेकिन आवश्यकता पड़ने पर इन-बैंड पूर्ण-द्वैध संचार का भी समर्थन कर सकता है।

शोध प्रबंध तब पूर्ण-द्वैध विवाद-आधारित योजनाओं के गणितीय विश्लेषण में देरी करता है, जो कि टक्कर से बचने के साथ कई बार एक्सेस (सीएसएमए/सीए) मैक प्रोटोकॉल के साथ कई एक्सेस पर ध्यान केंद्रित करता है। जबकि पूर्व कार्यों ने मार्कोव मॉडल का उपयोग करके सीएसएमए/सीए गणितीय विश्लेषण का प्रदर्शन किया है, वे सिमुलेशन परिणामों से महत्वपूर्ण विचलन प्रदर्शित करते हैं। यह थीसिस मार्कोव

मॉडल को अच्छी तरह से पुनर्मूल्यांकन करके सिमुलेशन परिणामों से विश्लेषणात्मक विचलन को हटा देता है। इसके अलावा, यह छिपे हुए नोड समस्या के साथ-साथ नेटवर्क के गणितीय विश्लेषण को वीएलसी नेटवर्क में एक महत्वपूर्ण चुनौती देता है। यह समस्या विभिन्न पूर्ण-द्वैध संचार विधियों, जैसे द्वि-दिशात्मक डेटा ट्रांसमिशन और व्यस्त टोन सिग्नल का उपयोग करके साहित्य में हल की जाती है; उत्तरार्द्ध को प्रस्तावित एफडी-ओएमएसी योजना में उपयोग किया जाता है। ये तकनीक एक रिले नोड के रूप में एपी का उपयोग करके नोड्स के कवरेज क्षेत्र को बढ़ाती हैं। हालांकि, एपी प्रतिक्रिया को प्रसंस्करण समय से देरी होती है, जिससे एक अप्रत्याशित नेटवर्क व्यवहार होता है। इस देरी का मात्रात्मक प्रभाव अस्पष्टीकृत रहता है, जो वीएलसी नेटवर्क के अनुकूलन के लिए महत्वपूर्ण है। थीसिस ने इस अंतराल को पूर्वोक्त पूर्ण-द्वैध तकनीकों के लिए सीएसएमए/सीए को मॉडल करने के लिए प्रस्तावित मार्कोव विश्लेषण का विस्तार करके इस अंतर को पुल किया है, विशेष रूप से व्यस्त टोन के साथ।

यह थीसिस एक पूर्ण-डुप्लेक्स वीएलसी ट्रांसीवर के मूल हार्डवेयर ब्लॉक और वीडियो ट्रांसमिशन के लिए एक प्राथमिक पूर्ण-द्वैध वीएलसी लिंक विकसित करने के लिए कार्यप्रणाली प्रस्तुत करता है। यह आगे पूर्ण-द्वैध वीएलसी एपी ट्रांसीवर्स की विश्वसनीयता को बढ़ाने और उनकी विश्वसनीयता मापदंडों की गणना करने के तरीके प्रदान करता है। विफलता (एमटीबीएफ) गणना और मार्कोव श्रृंखला मॉडलिंग के बीच दोनों माध्यम का उपयोग करते हुए, अध्ययन विफलता-प्रवण मॉड्यूल की पहचान करता है और सिस्टम डाउनटाइम का आकलन करता है, गलती-सहिष्णु सिस्टम डिजाइनों की सुविधा देता है। इसके अतिरिक्त, एक जीवन चक्र लागत विश्लेषण विविध अनुप्रयोग परिदृश्यों के लिए निर्णय लेने में मदद करता है। यह व्यापक विश्लेषण वीएलसी नेटवर्क के अनुकूलन में मूल्यवान अंतर्दृष्टि प्रदान करता है, इनडोर वायरलेस संचार प्रणालियों में बढ़ाया प्रदर्शन और विश्वसनीयता के लिए मार्ग प्रशस्त करता है।

# Contents

<b>ACKNOWLEDGEMENTS</b>	<b>i</b>
<b>ABSTRACT</b>	<b>iii</b>
<b>LIST OF TABLES</b>	<b>xi</b>
<b>LIST OF FIGURES</b>	<b>xv</b>
<b>1 Introduction</b>	<b>1</b>
1.1 Internet traffic and user connectivity trends . . . . .	1
1.1.1 Action towards future-proof networks . . . . .	3
1.1.2 Indoor wireless network solutions . . . . .	3
1.1.3 Motivation for VLC as a next-generation indoor network . . . . .	4
1.1.4 Power Efficiency Analysis of IR and RF Links . . . . .	6
1.2 Visible light communication . . . . .	8
1.2.1 Nomenclature . . . . .	8
1.2.2 Principle . . . . .	8
1.2.3 Advantages . . . . .	9
1.2.4 Applications . . . . .	10
1.3 VLC system model . . . . .	11
1.3.1 PHY layer processing . . . . .	13
1.3.2 MAC layer processing . . . . .	14
1.3.3 Reliability Analysis . . . . .	16
1.4 Standardization efforts . . . . .	17
1.5 Challenges in VLC . . . . .	18
1.5.1 Directionality of light . . . . .	18

1.5.2	Small cell area . . . . .	18
1.5.3	User mobility . . . . .	19
1.6	Motivation and objectives . . . . .	19
1.7	Unique contribution of the thesis . . . . .	21
1.8	Structure of the thesis . . . . .	22
<b>2</b>	<b>A novel full-duplex MAC for VLC networks: FD-OMAC</b>	<b>25</b>
2.1	Background . . . . .	26
2.1.1	Literature review . . . . .	26
2.1.2	Related work . . . . .	27
2.2	IEEE 802.15.7 OWC-MAC overview . . . . .	31
2.2.1	GTS allocation process . . . . .	33
2.3	Proposed FD-OMAC scheme . . . . .	34
2.3.1	FD-OMAC . . . . .	35
2.3.2	Beacon frame changes . . . . .	37
2.4	Performance evaluation . . . . .	38
2.4.1	Network calculus . . . . .	38
2.4.2	Simulation environment . . . . .	41
2.4.3	Analytical calculations . . . . .	42
2.5	Simulation results . . . . .	46
2.5.1	OWC-MAC simulation and analytical results . . . . .	47
2.5.2	OWC-MAC vs FD-OMAC . . . . .	49
2.6	Multiple access point scenario . . . . .	50
2.6.1	Micro-beacon synchronization . . . . .	51
2.6.2	Network superframe structure . . . . .	54
2.7	Multiple access point results . . . . .	56
2.8	Use cases . . . . .	59
2.9	Conclusion and future work . . . . .	59
<b>3</b>	<b>Mathematical analysis of the contention period of FD-OMAC</b>	<b>61</b>
3.1	Background . . . . .	61
3.1.1	Problem statement . . . . .	63

3.1.2	Contribution . . . . .	63
3.1.3	Chapter outline . . . . .	64
3.2	Related Work . . . . .	64
3.3	Medium Access Control Layer Algorithm . . . . .	65
3.4	Mathematical Analysis . . . . .	66
3.4.1	Abstract Node State Probabilities . . . . .	72
3.4.2	Channel State Probabilities . . . . .	73
3.4.3	Calculating probability of collision . . . . .	76
3.4.4	Calculating probability of channel busy . . . . .	77
3.4.5	Analysis with variable packet sizes . . . . .	78
3.5	CSMA/CA with busy tone . . . . .	80
3.5.1	Channel State Probabilities . . . . .	81
3.5.2	Calculating probability of collision . . . . .	84
3.5.3	Calculating probability of channel busy . . . . .	86
3.5.4	Analysis with variable packet sizes . . . . .	87
3.6	Evaluation and results . . . . .	88
3.6.1	Standard CSMA/CA (without busy tone) . . . . .	89
3.6.2	CSMA/CA with busy tone . . . . .	93
3.7	Discussion . . . . .	96
3.8	Conclusion . . . . .	97
<b>4</b>	<b>Reliability analysis of a full-duplex OWC transceiver system</b>	<b>99</b>
4.1	Link setup . . . . .	102
4.1.1	Hardware implementation . . . . .	103
4.1.2	Software implementation . . . . .	106
4.2	Reliability theory . . . . .	108
4.3	Modular reliability analysis . . . . .	110
4.3.1	Module 1: Buck converter . . . . .	111
4.3.2	Module 2: Processor . . . . .	111
4.3.3	Module 3 to 6: Transmitter front-end . . . . .	113
4.3.4	Module 7 to 10: Receiver front-end . . . . .	113
4.4	Fault-tolerant design and MTBF analysis . . . . .	115

4.4.1	Parallel redundancy in the LED module . . . . .	115
4.4.2	Voting redundancy in the processor module . . . . .	116
4.4.3	Diode redundancy in the buck converter module . . . . .	118
4.4.4	A highly reliable fault-tolerant OWC transceiver design . . . . .	119
4.5	Markov model analysis . . . . .	119
4.5.1	Parallel redundancy in the LED module . . . . .	124
4.5.2	Voting redundancy in the processor module . . . . .	126
4.5.3	Diode redundancy in the buck converter module . . . . .	127
4.5.4	A highly reliable fault-tolerant OWC transceiver design . . . . .	128
4.6	Results . . . . .	130
4.7	Life cycle cost analysis . . . . .	133
4.8	Conclusion . . . . .	138
<b>5</b>	<b>Conclusion and future scope</b>	<b>141</b>
5.1	Thesis conclusion . . . . .	141
5.2	Future research directions . . . . .	144
5.2.1	Advanced mobility and handover mechanisms . . . . .	144
5.2.2	Advanced fault diagnosis and system reconfiguration . . . . .	145
5.2.3	Multi-link operation . . . . .	145
5.2.4	Multi-link reliability analysis . . . . .	145
5.2.5	Cumulative acknowledgement . . . . .	146
	<b>BIBLIOGRAPHY</b>	<b>147</b>
	<b>PUBLICATIONS</b>	<b>157</b>
	<b>AUTHOR BIO-DATA</b>	<b>158</b>

# List of Tables

1.1	Comparison of Small Cells (Pico/Femto Cells) vs WiFi and VLC. . . . .	5
1.2	Parameters for IR and RF link. . . . .	7
2.1	Related research work. . . . .	30
2.2	Network Parameters . . . . .	41
2.3	Spectrum efficiency. . . . .	49
2.4	GTS requirement. . . . .	57
3.1	List of constants and variables used in the mathematical model . . . . .	69
3.2	Simulation Parameters . . . . .	89
3.3	Comparison of the various Markov model parameters for 18 nodes . . . . .	93
4.1	Visible light emitter and detector specifications . . . . .	105
4.2	Infrared light emitter and detector specifications . . . . .	106
4.3	FIT, MTBF, and Reliability values for each module. . . . .	112
4.4	LED and LED driver combinations leading to the OWC transceiver failure. . . . .	126
4.5	Comparison of various fault-tolerant systems using Reliability block diagram . . . . .	131
4.6	Availability of various fault-tolerant systems using Markov chain modeling . . . . .	132
4.7	Availability values at various repair rates for the highly Reliable fault-tolerant transceiver . . . . .	134
4.8	Transceiver component costs. . . . .	135
4.9	Cost of all the modules for various transceiver designs. . . . .	136
4.10	Technician cost for five years based on MTTR values. . . . .	137
4.11	Various components of the cost function for 500 transceivers. . . . .	138

## List of Figures

1.1	Mobile and fixed-broadband traffic rates in Exabytes [2]. (1 Exabyte= $10^{12}$ MB) . . . . .	2
1.2	a) Number of Internet users (in billions) connected to the Internet [2]. b) Number of IoT-connected devices worldwide with forecasts from 2024 to 2033 [5]. . . . .	2
1.3	VLC Applications . . . . .	11
1.4	VLC downlink schematic diagram. . . . .	13
1.5	Generic block diagram of transmitter and receiver PHY. . . . .	14
1.6	Issues in VLC networks. . . . .	18
2.1	The OWC-MAC superframe structure [49]. The active period contains 16 superframe slots to bound the beacon frame, the contention access period, and the contention-free period. No data transfer happens during the optional inactive period. . . . .	27
2.2	OWC-MAC GTS allocation process. A user requests for a GTS during the CAP. The coordinator assigns the GTS, if resources are available, and sends the information in the next beacon frame. . . . .	33
2.3	An example of full-duplex communication during the CFP of a superframe. User A has a downstream GTS, while user B has the same superframe slots for upstream GTS. . . . .	36
2.4	An example a) OWC-MAC CFP has a length of 11 superframe slots for 7 users. b) FD-OMAC CFP has a length of 6 superframe slots while having the same set of 7 users. . . . .	36
2.5	OWC-MAC beacon frame. . . . .	37
2.6	Proposed FD-OMAC beacon frame. . . . .	38
2.7	Maximum delay and buffer bounds of arrival curve $\alpha(t)$ and for service curve $\beta(t)$ [81]. . . . .	39
2.8	Arrival curve and service curve for different GTS lengths (1, 2, and 3 superframe slot) [81]. The circle represents the magnified service function for one superframe slot. . . . .	40

2.9	GTS request size $n$ per user for different values of offered load and $SO$ for packet size of 1523 bytes. . . . .	44
2.10	Parameter presentation for delay calculations. . . . .	44
2.11	Division of the users connected in the CFP and the CAP for OWC-MAC at different load values, same for $SO \in [7, 14]$ at packet size of 103 bytes. . . .	47
2.12	a) Normalized throughput in the CFP traffic for different load and $SO$ values. b) Average delay (on a logarithmic scale) per packet in the CFP at different load and $SO$ values. . . . .	48
2.13	Simulation result of the total normalized network throughput considering both the CAP and CFP traffic at different load and $SO$ values. . . . .	49
2.14	For $SO = 9$ , a) Comparison of the number of users not assigned GTS in FD-OMAC and OWC-MAC. b) Comparison of OWC-MAC and FD-OMAC for normalized network throughput considering both the CFP and CAP. c) Comparison of delay for upstream and downstream traffic of OWC-MAC and FD-OMAC, displayed separately. . . . .	50
2.15	An example of infrastructural deployment of APs along with their interference regions. In this example, four APs transmit beacons in the network simultaneously without their neighbors' interference. . . . .	51
2.16	An example, a) User location under the coverage area of four LEDs (A, B, C, and D) where $U_i$ denotes different user locations, b) A superframe structure with allotted GTS for users $U_i$ . . . . .	55
2.17	For $SO = 9$ , Comparison of OWC-MAC, IM-OWC-MAC (with interference mitigation) and FD-OMAC for normalized network throughput in the CFP for example, multi-AP scenario provided in figure 2.16a. . . . .	57
2.18	(a) Example scenario with new user locations. b) Best-case: A single user under the common interference area of four LEDs demands one superframe slot; other nodes fully utilize the CFP for full-duplex communication. (c) Worst case: A single user under four LEDs (A, B, C, and D) demands all 15 superframe slots; the rest of the users are connected in CAP. d) VLC-MAC common superframe for the best-case scenario. e) VLC-MAC common superframe for the worst-case scenario. . . . .	58
3.1	a) full duplex optical media access control (FD-OMAC) [104] suggests changes to the OWC-MAC beacon to make the contention free period (CFP) of OWC-MAC full-duplex. Users 1, 3, 4, and 6 send data in downstream, while users 2, 5, and 7 can send their data in upstream at the same time (hence full-duplex), reducing CFP size by 45%. b) User 1 is unable to sense the transmission of user 2 (hidden from each other) and hence, transmits at the same time, causing packet collision in upstream. . . . .	62
3.2	Flow chart of OWC-MAC [49] slotted carrier sense multiple access with collision avoidance (CSMA/CA) algorithm. . . . .	67

3.3	2D-DTMC for an OWC node under saturated traffic with slotted CSMA/CA [97]. Each $\langle x, y \rangle$ denotes a Markov chain state, with colors representing different CSMA/CA phases of an OWC node. . . . .	70
3.4	Discrete time Markov chain model for the channel states where the nodes using CSMA/CA to transmit their packets are considered in saturation. . .	74
3.5	Updated transmission and collision states for uniformly distributed variable packet sizes during the first transmission attempt in the 2D-DTMC model for an OWC node. . . . .	79
3.6	The timing diagram for CSMA/CA with a busy tone. User 1, user 2, and user 3 are hidden from each other, and their data collide as they start their transmissions in the vulnerable window. . . . .	81
3.7	Discrete time Markov chain model displaying the channel states where the AP sends busy tone after $d$ slots delay whenever network nodes transmit their packets using CSMA/CA. . . . .	82
3.8	Comparison of analytical and simulation results with the semi-analytic results of Nober <i>et al.</i> [92] for the standard CSMA/CA (without busy tone). (a) $\alpha$ vs. the number of network nodes. (b) $p_c$ vs. the number of network nodes. (c) $\phi_0$ vs. the number of network nodes. (d) Normalized throughput vs. the number of network nodes at different values of back-off exponents where $BE = \{minBE, \dots, maxBE\} = [minBE, maxBE]$ . . . . .	90
3.9	Simulation results comparing the, a) Network throughput $S_{sN}$ and node throughput $S_s$ in a network with no hidden node vs. single hidden node as the number of nodes increases, b) Conditional probability $\alpha$ and $p_c$ values as the number of nodes increases in a network having a single hidden node. . . . .	92
3.10	Comparison of analytical and simulation results for the CSMA/CA with busy tone delay of one and two slots, i.e., $d = 1, 2$ . Here, $d = 0$ represents the standard CSMA/CA (without busy tone) with no hidden nodes. The direction of the arrow in each graph displays the increasing $d$ values. (a) $\alpha$ vs. the number of network nodes. (b) $p_c$ vs. the number of network nodes. (c) $\phi_0$ vs. the number of network nodes. (d) Normalized throughput vs. number of network nodes. (e) Delay vs. the number of network nodes. . . . .	94
3.11	Throughput comparison with the Bianchi style analysis for busy tone delay $d = 1, 2$ slots. $d = 0$ represents standard CSMA/CA with no hidden nodes. . . . .	96
4.1	Block diagram of the duplex OWC link setup. . . . .	103
4.2	i) Visible light front-ends a) and b) are the top and bottom views of the visible light transmitter front end. c) and d) are the top view and the bottom view of the visible light receiver front end. ii) IR front-ends, a) and b) are the top and bottom views of the visible light transmitter front end. c) and d) are the top view and the bottom view of the visible light receiver front end. . . . .	104
4.3	Full-duplex OWC hardware link setup. . . . .	107
4.4	Block diagram of the MAC implementation on a duplex link setup. . . . .	107

4.5	Standard OWC transceiver block diagram. . . . .	110
4.6	OWC transceiver block diagram for the access point. . . . .	111
4.7	The internal circuit of module 1, buck converter. . . . .	113
4.8	The internal circuit of module 3 to 6, transmitter front-end. . . . .	114
4.9	The internal circuit of module 7 to 10, receiver front-end. . . . .	114
4.10	Reliability block diagram of the transceiver circuit. . . . .	115
4.11	Reliability block diagram of the transceiver circuit with 12 LED drivers and LEDs. . . . .	116
4.12	Reliability block diagram of the transceiver circuit with three processors and a voting control unit. . . . .	117
4.13	Reliability block diagram of the transceiver circuit with two buck converter modules. Two diodes $D_1$ and $D_2$ provide OR operation to the two parallel buck-converter modules. . . . .	118
4.14	Reliability block diagram of a highly reliable fault-tolerant circuit design for the OWC transceiver circuit. . . . .	119
4.15	State diagram of the OWC transceiver circuit without redundancy. . . . .	123
4.16	State diagram of the OWC transceiver with parallel redundancy in the LED module. . . . .	125
4.17	State diagram of the OWC transceiver circuit with voting redundancy in the processor module. . . . .	127
4.18	State diagram of the OWC transceiver circuit with diode redundancy in the buck-converter module. . . . .	128
4.19	State diagram of the OWC transceiver with all three redundancies. . . . .	129
4.20	Availability of the fault-tolerant transceiver with all three redundancies at different values of fault-detection and repair time for non-replicated ( $1/\mu_{fd2} + 1/\mu_2$ ) and replicated ( $1/\mu_{fd1} + 1/\mu_1$ ) components and a constant repair time of notified component failures ( $1/\mu_3 = 10$ days). . . . .	133

## List of Abbreviations

### A

<b>ACK</b>	ACKnowledgement frame
<b>ADSL</b>	Asymmetric Digital Subscriber Line
<b>AP</b>	Access Point

### B

<b>BI</b>	Beacon Interval
<b>BJT</b>	Bipolar Junction Transistor
<b>BO</b>	Beacon Order

### C

<b>CAP</b>	Contention Access Period
<b>CDMA</b>	Code Division Multiple Access
<b>CFP</b>	Contention Free Period
<b>CSK</b>	Color Shift Keying
<b>CSMA/CA</b>	Carrier Sense Multiple Access with Collision Avoidance
<b>CSMA/CD</b>	Carrier Sense Multiple Access with Collision Detection

### D

<b>DD</b>	Direct Detection
<b>DS</b>	Down-Stream

### F

<b>FCFS</b>	First Come First Serve
<b>FCS</b>	Frame Check Sequence

<b>FD-OMAC</b>	Full Duplex Optical Media Access Control
<b>FDMA</b>	Frequency Division Multiple Access
<b>FIT</b>	Failure In Time
<b>FPGA</b>	Field Programmable Gated Array
<b>FSO</b>	Free Space Optical
<b>FTTX</b>	Fiber-to-the-X
<b>FWA</b>	Fixed Wireless Access
<b>G</b>	
<b>GPS</b>	Global Positioning System
<b>GTS</b>	Guaranteed Time Slot
<b>H</b>	
<b>HFC</b>	Hybrid Fiber-Coaxial
<b>HPF</b>	High Pass Filter
<b>I</b>	
<b>IC</b>	Integrated Circuits
<b>ICT</b>	Information and Communications Technology
<b>IEEE</b>	Institute of Electrical and Electronics Engineers
<b>IM</b>	Intensity Modulation
<b>IoT</b>	Internet of Things
<b>IP</b>	Internet Protocol
<b>IR</b>	Infra-Red
<b>L</b>	
<b>LAN</b>	Local Area Network
<b>LC</b>	Light Communication
<b>LDR</b>	LightDependent Resistor
<b>LED</b>	Light Emitting Diode
<b>Li-Fi</b>	Light Fidelity
<b>LIFS</b>	Long Inter-Frame Space
<b>LoS</b>	Line of Sight

## M

<b>MAC</b>	Media Access Control
<b>MC</b>	Master Controller
<b>MIMO</b>	Multiple Input Multiple Output
<b>MLO</b>	Multi-Link Operation
<b>MOSFET</b>	Metal-Oxide-Semiconductor Field-Effect Transistor
<b>MTBF</b>	Mean Time Between Failures
<b>MTTF</b>	Mean Time To Failures
<b>MTTR</b>	Mean Time To Repair

## N

<b>NIC</b>	Network Interface Card
<b>NOMA</b>	Non-Orthogonal Multiple Access

## O

<b>OFDM</b>	Orthogonal Frequency Division Multiplexing
<b>OOK</b>	On-Off Keying
<b>OWC</b>	Optical Wireless Communication

## P

<b>PAPR</b>	Peak to Average Power Ratio
<b>PD</b>	Photo Detector
<b>PHY</b>	PHYSical layer
<b>PoE</b>	Power over Ethernet

## Q

<b>QoS</b>	Quality of Service
------------	--------------------

## R

<b>RF</b>	Radio Frequency
<b>RM</b>	Relation Matrix
<b>RS</b>	Reed Solomon

**RTS/CTS** Request-To-Send/Clear-To-Send

## **S**

**SD** Superframe Duration

**SDM** Space Division Multiplexing

**SIC** Successive Interference Cancellation

**SO** Superframe Order

**SS** Superframe Slot

## **T**

**TDMA** Time Division Multiple Access

**TIA** Trans Impedance Amplifier

## **U**

**UART** Universal Asynchronous Receiver and Transmitter

**US** Up-Stream

## **V**

**VLC** Visible Light Communication

## **W**

**Wi-Fi** Wireless Fidelity