

DESIGN AND DEVELOPMENT OF HIGH DATA RATE INDOOR VISIBLE LIGHT COMMUNICATION LINKS

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INDIAN INSTITUTE OF TECHNOLOGY DELHI
JANUARY 2022**

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Design and Development of High Data Rate Indoor Visible Light Communication Links

by

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submitted in fulfillment of the requirements of the degree of

Doctor of Philosophy

to the



Indian Institute of Technology Delhi

January 2022

CERTIFICATE

This is to certify that the thesis entitled “Design and development of high data rate indoor visible light communication links” being submitted by Mr. Rishu Raj to the Department of Electrical Engineering, Indian Institute of Technology Delhi, for the award of the degree of Doctor of Philosophy is the record of the bonafide research work carried out by him under my 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

It gives me immense pleasure to be able to present this thesis on my research work which has been a crucial learning experience for me. What began as a slight inclination towards the field of optics has opened up an entirely new world of exploration and research for me. This, however, would not have been possible without some people whom I shall always remain indebted to, for the support and assistance that they lent out unconditionally, and I wish to offer my sincere thanks to all of them for making this endeavor successful.

I would start by thanking my supervisor, Prof. Abhishek Dixit, who gave me the opportunity to work with him. I feel very fortunate to have been advised by Prof. Dixit. His dedicated approach towards any task is very inspiring. I truly enjoyed the many conversations with him that forced me to think critically. His support throughout this work is highly appreciable. He truly has an eye for detail. Without him, this thesis would have been nothing but a distant dream.

I would also like to express my thanks to the members of my research committee, Prof. Vivek Venkataraman, Prof. Subrat Kar, and Prof. R. K. Varshney, for their valuable comments, feedback, and suggestions. I also take this opportunity to express my cordial gratitude to Prof. Vinod Chandra. His enthusiasm for research is infectious, and it was always refreshing to talk with him. I was particularly motivated by his regular inquiries about the progress of my work whenever I used to meet him.

I am especially thankful to my friends and colleagues, Sonali, Kshitiza, and Sukriti, for their constant encouragement and cooperation. I also thank Karan, Sonu, Gaurav, and Kumud, for their invaluable contributions to my work. I would like to express my deep and sincere gratitude to the laboratory staff, Ms. Neeru Asija and Mr. G. S. Negi, for providing and helping me with all the required equipment to achieve the optimal results reported in this thesis.

I also want to thank my family – my parents and my brother – for their unconditional love, support, sacrifices, constant prayers, and patience. I cherish my family members deeply as they have been with me through good times and bad. In the end, I thank the Almighty for His blessings.

Rishu Raj
2016EEZ8069
New Delhi, Jan. 2022.

ABSTRACT

Visible light communication (VLC) is being envisioned as an enabling technology to provide the much-needed spectral relief for the ever-increasing demand for Internet connectivity and data consumption. In this thesis, we tackle the challenges in the development of high data rate indoor VLC systems to cater to the ambitious targets of the fifth generation and beyond of communication networks.

The visible light signals, which carry information from transmitter panels, can reach the receiver through numerous paths because of the reflections from walls. Due to these multipath reflections and spatial distribution of light-emitting diode (LED) transmitters, there is an inherent delay spread in the VLC channels. So, there is a need to include the effect of multiple reflections (occurring in the practical indoor environment) in the performance evaluation of indoor VLC links. We present the detailed derivation of the multipath VLC channel model and obtain various channel parameters (RMS delay and coherence bandwidth) to characterize the multipath channel. We incorporate the effect of inter-symbol interference (ISI) in the bit error rate (BER) performance of the multipath VLC system and analyze the average BER of the system under different practical scenarios. We also provide some key recommendations for the design of practical VLC systems by outlining the data rates that can be served under various system configurations.

Since VLC uses illumination sources for lighting as well as communication, it is required to provide dimming control for proper lighting and enhanced error performance for reliable data communication. We address both these issues holistically. We formulate and study the power spectral densities of dimming-based modulation schemes, namely variable on-off keying (VOOK) and variable pulse position modulation (VPPM), and hence, derive their bandwidth requirements and spectral efficiencies. Moreover, the capacity of VLC systems is severely limited by the ISI occurring as a result of the multipath propagation of light signals in VLC. We propose to ameliorate the error performance of VLC systems by using channel equalization for ISI mitigation, thereby enhancing the system capacity. We develop the analytical model of a dimmable VLC system employing channel equalization and use this model to study the effect of dimming and data rate on the error performance of VOOK and VPPM schemes. We present simulation and analytical results to show that the performance of dimming-based modulation schemes is significantly improved using channel equalization.

Besides ISI, another major hindrance to the achievable data rate in VLC systems is the low modulation bandwidth of the light sources. This limitation can be significantly overcome by using non-orthogonal multiple access (NOMA) to multiplex users in the power domain. We propose to enhance the fairness among users in terms of their error performance and the achievable data rate in a NOMA-VLC system. Based on numerical and simulation results, we show that the fair power allocation (FPA) scheme not only provides significantly higher fairness but it also entails better error performance, improved energy efficiency, and enhanced system throughput as compared to the existing power allocation schemes. We also demonstrate that the FPA scheme exhibits superior performance even when the system parameters, like the number of users, transmitter semi-angle, and detector field-of-view, are changed. However, due to high inter-user interference at the receivers, NOMA suffers from a poor outage performance, especially if the number of users is large.

We propose to boost the outage performance of a NOMA-based VLC system by incorporating multi-user cooperative diversity over radio frequency (RF) links, thereby transforming it into a hybrid VLC-RF system with cooperative NOMA (CoNOMA). We formulate the expressions for the outage probability of the proposed system and analyze the outage performance for various power allocation schemes used in NOMA. We study the effects of increasing the number of users and the target data rate on the system's overall outage performance. We also model the reliability of the multi-user CoNOMA system using Markov chains and evaluate the various reliability parameters for each user.

We also explore the application of VLC to indoor localization. Indoor positioning systems (IPSs) based on VLC shall be at the forefront of indoor localization technology in the near future. However, the existing VLC-based IPSs employ active devices that consume power and are costly. We develop a novel VLC-based IPS that circumvents the requirement of active devices by using the proposed optical identification algorithm, thereby enabling the IPS to be highly scalable, robust, energy-efficient, inexpensive, and flexible. To implement this algorithm, we propose the designs of a wavelength-sensitive receiver and a passive optical identifier which consists of a unique combination of optical reflectors. We present an analysis of several practical aspects related to the physical realization of the proposed IPS, like system scalability, target mobility, system reliability, algorithmic complexity, and implementation cost. To analyze the system performance, we determine its spatial resolution and the positioning error for different grid sizes.

सार

दृश्यमान प्रकाश संचार (वीएलसी) को इंटरनेट संयोजगता और डेटा खपत की लगातार बढ़ती मांग के लिए आवश्यक वर्णक्रमीय राहत प्रदान करने हेतु एक सक्षम तकनीक के रूप में देखा जा रहा है। इस शोध निबंध में, हम पांचवीं पीढ़ी (5जी) और उसके आगे के संचार नेटवर्क के महत्वाकांक्षी लक्ष्यों को पूरा करने के लिए उच्च डेटा प्रवाह दर प्रदान करने वाले आभ्यंतरिक वीएलसी तंत्र के विकास में चुनौतियों का सामना करते हैं।

दृश्यमान प्रकाश संकेत, जो ट्रांसमीटर पैनल से सूचना ले जाते हैं, दीवारों से परावर्तन के कारण कई रास्तों से प्राप्तकर्ता तक पहुंच सकते हैं। इन बहुपथ परावर्तन और प्रकाश उत्सर्जक डायोड (एलईडी) ट्रांसमीटरों के स्थानिक वितरण के कारण, वीएलसी प्रणालियों में एक अंतर्निहित देरी-विस्तार होती है। इसलिए, आभ्यंतरिक वीएलसी लिंक के प्रदर्शन मूल्यांकन में (व्यावहारिक आभ्यंतरिक वातावरण में होने वाले) बहुविध प्रतिबिंबों के प्रभाव को शामिल करने की आवश्यकता है। हम बहुपथ वीएलसी प्रणाली के मॉडल की विस्तृत व्युत्पत्ति प्रस्तुत करते हैं और बहुपथ वीएलसी प्रणालियों के विवरण हेतु विभिन्न मापदंड (आरएमएस विलंब और सुसंगतता बैंडविड्थ) प्राप्त करते हैं। हम बहुपथ वीएलसी प्रणाली के बिट त्रुटि दर (बीईआर) प्रदर्शन में अंतर-प्रतीक हस्तक्षेप (आईएसआई) के प्रभाव को शामिल करते हैं और, विभिन्न व्यावहारिक परिदृश्यों के तहत, तंत्र के औसत बीईआर का विश्लेषण करते हैं। वीएलसी तंत्र के विभिन्न प्रारूपों के तहत उपयुक्त डेटा प्रवाह दरों को रेखांकित करते हुए, हम व्यावहारिक वीएलसी तंत्रों की योजना के लिए कुछ प्रमुख सुझाव भी प्रदान करते हैं।

चूंकि वीएलसी में रोशनी स्रोतों का उपयोग प्रकाश के साथ-साथ संचार के लिए भी होता है, इसलिए विश्वसनीय डेटा संचार के लिए उन्नत त्रुटि प्रदर्शन और उचित प्रकाश व्यवस्था के लिए प्रकाश-मंदी नियंत्रण प्रदान करना आवश्यक है। हम इन दोनों मुद्दों को समग्र रूप से संबोधित करते हैं। हम प्रकाश-मंदी पर आधारित मॉड्यूलेशन योजनाओं की शक्ति वर्णक्रमीय घनत्वों का निर्माण और अध्ययन करते हैं, और फलतः उनकी बैंडविड्थ आवश्यकताओं और वर्णक्रमीय क्षमता को प्राप्त करते हैं। यह अध्ययन दो मॉड्यूलेशन योजनाओं, नामतः, वेरिबल ऑन-ऑफ कीइंग (वीओओके) और वेरिबल पल्स पोजीशन मॉड्यूलेशन (विपीपीएम), पर केंद्रित है। इसके अलावा, वीएलसी में प्रकाश संकेतों के बहुपथ प्रसार के परिणामस्वरूप होने वाले आईएसआई के कारण वीएलसी तंत्र की क्षमता गंभीर रूप से सीमित है। हम आईएसआई शमन के लिए प्रणाली समकरण का उपयोग करके वीएलसी तंत्र के त्रुटि प्रदर्शन को सुधारने

का प्रस्ताव करते हैं, जिससे तंत्र क्षमता में वृद्धि होती है। हम प्रणाली समकरण को नियोजित करने वाले प्रकाश-मंदी नियंत्रित वीएलसी तंत्र का एक विश्लेषणात्मक प्रतिरूप विकसित करते हैं। हम इस प्रतिरूप का उपयोग वीओओके और वीपीपीएम योजनाओं के त्रुटि प्रदर्शन पर प्रकाश-मंदी और डेटा प्रवाह दर के प्रभाव का अध्ययन करने के लिए करते हैं। विश्लेषणात्मक और (संगणक में किये गए) अनुकरण के परिणाम प्रस्तुत करके हम यह दर्शाते हैं कि प्रणाली समकरण का उपयोग करके, प्रकाश-मंदी पर आधारित मॉड्यूलेशन योजनाओं के प्रदर्शन में यथेष्ट सुधार हुआ है।

आईएसआई के अलावा, प्रकाश स्रोतों की कम मॉड्यूलेशन बैंडविड्थ वीएलसी तंत्र में प्राप्त करने योग्य डेटा प्रवाह दर के लिए एक और बड़ी बाधा है। उपयोगकर्ताओं को शक्ति अनुक्षेत्र में बहुभागित करने के लिए गैर-ऑर्थोगोनल मल्टीपल एक्सेस (एनओएमए या नोमा) का उपयोग करके इस सीमा को काफी हद तक दूर किया जा सकता है। हम नोमा-वीएलसी तंत्र में उपयोगकर्ताओं के बीच उनके त्रुटि प्रदर्शन और प्राप्त करने योग्य डेटा प्रवाह दर के संदर्भ में निष्पक्षता बढ़ाने का प्रस्ताव करते हैं। संख्यात्मक और अनुकरण परिणामों के आधार पर, हम दिखाते हैं कि प्रस्तावित निष्पक्ष शक्ति आवंटन (एफपीए) योजना न केवल उच्च निष्पक्षता प्रदान करती है बल्कि मौजूदा शक्ति आवंटन योजनाओं की तुलना में बेहतर त्रुटि प्रदर्शन, बेहतर ऊर्जा दक्षता और उन्नत डेटा प्रवाह क्षमता भी प्रदान करती है। हम यह भी प्रदर्शित करते हैं कि एफपीए योजना बेहतर प्रदर्शन तब भी प्रदर्शित करती है, जब तंत्र मापदंड, जैसे उपयोगकर्ताओं की संख्या, ट्रांसमीटर सेमी-एंगल, और डिटेक्टर फ़ील्ड-ऑफ़-व्यू, बदल जाते हैं। हालांकि, प्राप्तिकर्ताओं में उच्च अंतर-उपयोगकर्ता हस्तक्षेप के कारण, नोमा असंतोषजनक आउटेज प्रदर्शन से ग्रस्त है, विशेषतः यदि उपयोगकर्ताओं की संख्या अधिक है।

हम रेडियो फ्रीक्वेंसी (आरएफ) लिंक पर बहु-उपयोगकर्ता सहकारी विविधता को शामिल करके नोमा-आधारित वीएलसी तंत्र के आउटेज प्रदर्शन को बढ़ावा देने का प्रस्ताव करते हैं। फलतः हमें सहकारी नोमा (सीओएनओएमए या कोनोमा) पर आधारित एक संकर वीएलसी-आरएफ तंत्र प्राप्त होता है। हम इस प्रस्तावित कोनोमा तंत्र की आउटेज संभावना के लिए अभिव्यक्ति तैयार करते हैं और नोमा में उपयोग की जाने वाली विभिन्न शक्ति आवंटन योजनाओं के लिए आउटेज प्रदर्शन का विश्लेषण करते हैं। हम तंत्र के समग्र आउटेज प्रदर्शन पर उपयोगकर्ताओं की संख्या और लक्ष्य डेटा प्रवाह दर में वृद्धि के प्रभावों का अध्ययन करते हैं। हम मार्कोव श्रृंखलाओं का उपयोग करते हुए बहु-उपयोगकर्ता कोनोमा प्रणाली की विश्वसनीयता को भी प्रतिरूपित करते हैं और प्रत्येक उपयोगकर्ता के लिए विभिन्न विश्वसनीयता मापदंडों का मूल्यांकन करते हैं।

हम आभ्यंतरिक स्थानीयकरण के लिए वीएलसी के अनुप्रयोग का भी अन्वेषण करते हैं। वीएलसी पर आधारित आभ्यंतरिक स्थानीयकरण तंत्र (आईपीएस) निकट भविष्य में आभ्यंतरिक स्थानीयकरण प्रौद्योगिकी के मामले में सबसे आगे होंगे। मौजूदा वीएलसी-आधारित आईपीएस सक्रिय उपकरणों को नियोजित करते हैं जो ऊर्जा की खपत करते हैं और महंगे हैं। हम एक नया वीएलसी-आधारित आईपीएस विकसित करते हैं जो प्रस्तावित प्रकाशीय पहचान एल्गोरिदम का उपयोग करके सक्रिय उपकरणों की आवश्यकता को दूर करता है, जिससे आईपीएस को अत्यधिक मापक्रमणीय, मजबूत, ऊर्जा-कुशल, सस्ती और लचीला होने में सक्षम बनाता है। इस एल्गोरिथम को लागू करने के लिए, हम एक तरंग दैर्ध्य-संवेदनशील प्राप्तिकर्ता और एक निष्क्रिय प्रकाशीय पहचानकर्ता के डिजाइन का प्रस्ताव करते हैं जिसमें प्रकाशीय परावर्तकों का एक अनूठा संयोजन होता है। हम प्रस्तावित आईपीएस की भौतिक कार्यान्वयन से संबंधित कई व्यावहारिक पहलुओं का विश्लेषण प्रस्तुत करते हैं, जैसे तंत्र मापक्रमणीयता, लक्ष्य गतिशीलता, तंत्र विश्वसनीयता, एल्गोरिथम जटिलता और कार्यान्वयन लागत। प्रस्तावित तंत्र के प्रदर्शन का विश्लेषण करने के लिए, हम इसके स्थानिक पृथक्करण और विभिन्न ग्रिड आकारों के लिए स्थानीयकरण त्रुटि निर्धारित करते हैं।

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LIST OF ACRONYMS

μ C	Micro-Controller
μ -LED	Micro Light Emitting Diode
1G	First Generation
2G	Second Generation
3G	Third Generation
4G	Fourth Generation
5G	Fifth Generation
6G	Sixth Generation

A

ABER	Average Bit Error Rate
AC	Alternating Current
ACF	Auto Correlation Function
AM	Amplitude Modulated
AOA	Angle of Arrival
AP	Access Point
APD	Avalanche Photodiode
ASIC	Application Specified Integrated Circuit
AWGN	Additive White Gaussian Noise

B

BDMA	Beam Division Multiple Access
BER	Bit Error Rate
BLP	Blue LED with Phosphor
BW	Bandwidth

C

CBSC	Cross-Band Selection Combining
CDMA	Code Division Multiple Access
CIR	Channel Impulse Response
CoNOMA	Cooperative Non-Orthogonal Multiple Access
CTMC	Continuous-Time Markov Chain

D

DC	Direct Current
DD	Direct Detection
DEF	Digital Equalizer Filter

E

EDGE Enhanced Data Rate for GSM Evolution

F

FDMA Frequency Division Multiple Access
FET Field effect transistor
FIT Failure in Time
FoV Field of View
FPA Fair Power Allocation
FPGA Field Programmable Gate Array

G

GPS Global Positioning System
GRPA Gain Ratio Power Allocation
GSM Global System for Mobile Communication

H

HCI Human-Computer Interaction

I

I2V Infrastructure to Vehicle
IEEE Institute of Electrical and Electronics Engineers
IM Intensity Modulation
IoE Internet of Everything
IoT Internet of Things
IPS Indoor Positioning System
IR Infra-Red
IRC Infra-Red Communication
IrDA Infrared Data Association
ISI Inter-Symbol Interference
ITU International Telecommunication Union

J

JEITA Japan Electronics and Information Technology Industries Association

L

LED Light Emitting Diode
Li-Fi Light Fidelity
LoS Line of Sight

LPF	Low Pass Filter
LTE	Long-Term Evolution

M

MBER	Maximum Bit Error Rate
MDT	Mean Down Time
MIMO	Multiple-Input-Multiple-Output
MMSE	Minimum Mean Square Error Equalizer
MPPM	Multiple Pulse Position Modulation
MTBF	Mean Time Between Failures
MTTR	Mean Time to Restore
MUT	Mean Up Time

N

NGDPA	Normalized Gain Difference Power Allocation
NLoS	Non-Line of Sight
NOMA	Non-Orthogonal Multiple Access
NRZ	Non-Return to Zero

O

OFDM	Orthogonal Frequency Division Multiplexing
OID	Optical Identifier
OLED	Organic Light Emitting Diode
OMEGA	hOME Gigabit Access
OOK	On-Off Keying
OPPM	Overlapping Pulse Position Modulation

P

PD	Photodiode
PIN	Positive-Intrinsic-Negative
PPA	Proportional Power Allocation
PPM	Pulse Position Modulation
PS	Power Splitter
PSD	Power Spectral Density
PWM	Pulse Width Modulated

R

RF	Radio Frequency
RFC	Radio Frequency Communication
RFID	Radio Frequency Identifier
RGB	Red, Green and Blue
RLL	Run Length Limited

RMS	Root Mean Square
RONJA	Reasonable Optical Joint Access
RSS	Received Signal Strength

S

SDN	Software Defined Networking
SIC	Successive Interference Cancellation
SINR	Signal to Interference and Noise Ratio
SMS	Short Message Service
SNR	Signal to Noise Ratio
SPA	Static Power Allocation

T

TDMA	Time Division Multiple Access
TDOA	Time Difference of Arrival
TL	Tunable Laser
TOA	Time of Arrival

U

UMTS	Universal Mobile Telecommunications System
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V

V2I	Vehicle to Infrastructure
V2V	Vehicle to Vehicle
VLC	Visible Light Communication
VLCA	Visible Light Communications Association
VLCC	Visible Light Communication Consortium
VOOK	Variable On-Off Keying
VPPM	Variable Pulse Position Modulation

W

WCDMA	Wideband Code Division Multiple Access
Wi-Fi	Wireless Fidelity
WiMAX	Worldwide Interoperability for Microwave Access

Z

ZFE	Zero-Forcing Equalizer
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