

DESIGN AND PERFORMANCE INVESTIGATION OF OWC SYSTEMS IN INDOOR AND OUTDOOR SCENARIOS

PRANAV SHARDA



DEPARTMENT OF ELECTRICAL ENGINEERING
INDIAN INSTITUTE OF TECHNOLOGY DELHI
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by

PRANAV SHARDA

DEPARTMENT OF ELECTRICAL ENGINEERING

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Certificate

This is to certify that the thesis entitled "**Design and Performance Investigation of OWC Systems in Indoor and Outdoor Scenarios**" being submitted by **Mr. Pranav Sharda** 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.

Date:

New Delhi

(Prof. Manav Bhatnagar)

Professor

Department of Electrical Engineering

Indian Institute of Technology Delhi

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Abstract

Over the recent few years, optical wireless communication (OWC) has attracted significant attention in both academia and the research community. Contrary to radio frequency (RF) systems, the spatial confinement of the optical beams makes the OWC system a potential system offering higher data rates and secured communication. OWC systems find applications in several areas, such as terrestrial outdoor (free-space optical (FSO) communication), indoor and outdoor visible light communication (VLC), etc. For the terrestrial outdoor FSO systems, spatial diversity techniques are employed over FSO links to enhance the diversity and overall performance. To this end, the spatial diversity techniques corresponding to the state-of-the-art are repetition coding (RC), transmit laser selection (TLS), and orthogonal space-time block codes. Note that, TLS is the optimal transmission scheme in the FSO systems. In this dissertation, we name the conventional TLS scheme as a single TLS (STLS) scheme. However, the performance of the conventional STLS scheme is highly dependent on the feedback errors. On the other side, the outdoor VLC finds applications in vehicle-to-vehicle (V2V) communications, infrastructure-to-vehicle (I2V) communications, etc. Emphasizing the state-of-the-art corresponding to the outdoor V2V-VLC systems, there is a lack of comprehensive modeling and performance investigation under the adverse challenges of the outdoor VLC environment. Moreover, to address the challenges of the next-generation-based outdoor intelligent transportation systems (ITSs), an indoor testbed design for an outdoor I2V-VLC system is still missing.

In order to enhance the diversity and overall performance of the terrestrial outdoor FSO systems, the study begins by proposing two novel TLS schemes. We call the proposed schemes as two TLS (TTLS) and modified error-tolerant weighting scheme

(METWS). Note that, the conventional STLS scheme gives optimal performance under a perfect feedback scenario. However, its performance degrades significantly under an imperfect feedback scenario. To this end, the two proposed schemes overcome the practical limitations of the conventional STLS scheme. Moreover, we analyze the performance of the two proposed schemes for both perfect and imperfect channel state information (CSI)-based communication scenarios. Further, different performance metrics, such as bit error rate (BER), diversity gain, etc., are thoroughly analyzed. Furthermore, to gain more insights, the performance of the two proposed schemes is also compared with the conventional STLS and RC schemes.

We then investigate the diversity-multiplexing tradeoff (DMT) for the OWC systems. To this end, we mainly focus on the indoor VLC and outdoor FSO systems. For the DMT investigation of the indoor VLC system, we consider the random radial movement of the end-user in the proposed system model. The optimal DMT for both the single-input single-output (SISO) and multiple-input multiple-output (MIMO) VLC systems are analyzed. Novel analytical expressions for the probability distribution function (PDF), outage probability, and outage diversity order for the SISO-VLC and MIMO-VLC systems are derived. Moreover, we extend our study to the outdoor FSO system. For the first time in literature, a limited feedback-based DMT is investigated for the FSO system under different transmission scenarios. To this end, we consider a MIMO-FSO setup and investigate the DMT for single-rate and adaptive-rate transmission scenarios.

Further, we venture into the area of vehicular VLC and comprehensively explore the area of vehicular VLC. To this end, contrary to the state-of-the-art, we emphasize comprehensive modeling of the V2V-VLC system under the practical challenges of an outdoor VLC environment. For the first time, we model the vehicle's mobility as random with a specific PDF. Therefore, we emphasize a more realistic approach to model the vehicle's mobility. Moreover, a novel channel model that incorporates the joint impact of the outdoor V2V-VLC random path loss and atmospheric turbulence (AT) is emphasized. Further, different performance metrics are analytically examined, such as path loss, outage probability, average BER (ABER), diversity order, discrete-

input continuous-output memoryless channel (DCMC) capacity, etc., under different weather conditions.

We also extend our work on vehicular VLC by proposing a shadowing/blocking-based V2V-VLC model. In a line-of-sight (LOS) VLC system, the communication link is exposed to temporary shadowing due to physical obstructions by vehicles in the same lane or nearby parked vehicles. Since VLC is highly dependent on the LOS, proposing and analyzing a V2V-VLC model under a shadowing-based transmission scenario is of extreme importance. The performance of the proposed V2V-VLC model is analyzed with the DMT metric. Moreover, to minimize the path loss at the receiver (Rx), a novel hemispherical optical concentrator-based Rx structure (offering an omnidirectional gain) is also proposed. Some striking insights are envisioned for the proposed work.

Finally, as a part of the next-generation-based ITSs, we also develop an indoor testbed for an outdoor I2V-VLC system. For the first time in literature, we experimentally demonstrate the communication between the traffic light acting as the transmitter (Tx) and the camera (i.e., the Rx) under different realistic I2V-VLC scenarios in a controlled indoor environment. Moreover, all the experimental findings are demonstrated for different exposure times of the camera for the first time, which is a very critical parameter when using a camera-based Rx. Further, different performance metrics are experimentally examined, such as BER, peak signal-to-noise ratio (PSNR), and capacity. Furthermore, LOS blockage-based communication scenarios are also experimentally analyzed.

सार

हाल के कुछ वर्षों में, ऑप्टिकल वायरलेस संचार (ओडब्ल्यूसी) ने शिक्षा जगत और अनुसंधान समुदाय दोनों में महत्वपूर्ण ध्यान आकर्षित किया है। रेडियो फ्रीक्वेंसी (आरएफ) प्रणालियों के विपरीत, ऑप्टिकल बीम का स्थानिक कारावास ओडब्ल्यूसी प्रणाली को उच्च डेटा दरों और सुरक्षित संचार की पेशकश करने वाली एक संभावित प्रणाली बनाता है। ओडब्ल्यूसी सिस्टम का अनुप्रयोग कई क्षेत्रों में होता है, जैसे स्थलीय आउटडोर (फ्री-स्पेस ऑप्टिकल (एफएसओ) संचार), इनडोर और आउटडोर दृश्य प्रकाश संचार (वीएलसी), आदि। स्थलीय आउटडोर एफएसओ प्रणालियों के लिए, विविधता और समग्र प्रदर्शन को बढ़ाने के लिए एफएसओ लिंक पर स्थानिक विविधता तकनीकों को नियोजित किया जाता है। इस प्रयोजन के लिए, अत्याधुनिक के अनुरूप स्थानिक विविधता तकनीकें पुनरावृत्ति कोडिंग (आरसी) हैं, ट्रांसमिट लेजर सिलेक्शन (टीएलएस), और ऑर्थोगोनल स्पेस-टाइम ब्लॉक कोड। ध्यान दें कि, टीएलएस एफएसओ सिस्टम में इष्टतम ट्रांसमिशन योजना है। इस शोध प्रबंध में, हम पारंपरिक टीएलएस योजना को एकल टीएलएस (एसटीएलएस) योजना का नाम देते हैं। हालाँकि, पारंपरिक एसटीएलएस योजना का प्रदर्शन फीडबैक त्रुटियों पर अत्यधिक निर्भर है। दूसरी ओर, आउटडोर वीएलसी वाहन-से-वाहन (वी2वी) संचार, बुनियादी ढांचे-से-वाहन (आई2वी) संचार आदि में अनुप्रयोगों को शामिल करता है। आउटडोर वी2वी-वीएलसी के अनुरूप अत्याधुनिक पर जोर दिया जाता है। सिस्टम, प्रतिकूल के तहत व्यापक मॉडलिंग और प्रदर्शन जांच की कमी है बाहरी वीएलसी वातावरण की चुनौतियाँ। इसके अलावा, अगली पीढ़ी-आधारित आउटडोर इटेलिजेंट ट्रांसपोर्टेशन सिस्टम (आईटीएस) की चुनौतियों का समाधान करने के लिए, आउटडोर आई2वी - वीएलसी सिस्टम के लिए एक इनडोर टेस्टबेड डिज़ाइन अभी भी गायब है।

स्थलीय आउटडोर एफएसओ प्रणालियों की विविधता और समग्र प्रदर्शन को बढ़ाने के लिए, अध्ययन दो नई टीएलएस योजनाओं का प्रस्ताव करके शुरू होता है। हम प्रस्तावित योजनाओं को दो टीएलएस (टीटीएलएस) और संशोधित त्रुटि-सहिष्णु भार योजना (एमईटीडब्ल्यूएस) कहते हैं। ध्यान दें कि, पारंपरिक एसटीएलएस योजना एक आदर्श फीडबैक परिदृश्य के तहत इष्टतम प्रदर्शन देती है। हालाँकि, अपूर्ण प्रतिक्रिया परिदृश्य के तहत इसका प्रदर्शन काफी कम हो जाता है। इस प्रयोजन के लिए, दो प्रस्तावित योजनाएं पारंपरिक एसटीएलएस योजना की व्यावहारिक सीमाओं को पार करती हैं। इसके अलावा, हम सही और अपूर्ण चैनल राज्य सूचना (सीएसआई)-आधारित संचार परिदृश्यों के लिए दो प्रस्तावित योजनाओं के प्रदर्शन का विश्लेषण करते हैं। इसके अलावा, विभिन्न प्रदर्शन मेट्रिक्स, जैसे बिट त्रुटि दर (बीईआर), विविधता लाभ, आदि का गहन विश्लेषण किया जाता है। इसके अलावा, अधिक जानकारी प्राप्त करने के लिए, दो प्रस्तावित योजनाओं के प्रदर्शन की तुलना पारंपरिक एसटीएलएस और आरसी योजनाओं से भी की जाती है।

फिर हम ओडब्ल्यूसी सिस्टम के लिए विविधता-मल्टीप्लेक्सिंग ट्रेडऑफ़ (डीएमटी) की जांच करते हैं। इस उद्देश्य से, हम मुख्य रूप से इनडोर वीएलसी और आउटडोर एफएसओ सिस्टम पर ध्यान केंद्रित करते हैं। इनडोर वीएलसी प्रणाली की डीएमटी जांच के लिए, हम प्रस्तावित सिस्टम मॉडल में अंतिम उपयोगकर्ता के यादृच्छिक रेडियल आंदोलन पर विचार करते हैं। सिंगल-इनपुट सिंगल-आउटपुट (SISO) और मल्टीपल-इनपुट मल्टीपल-आउटपुट (MIMO) वीएलसी सिस्टम दोनों के लिए इष्टतम डीएमटी का विश्लेषण किया जाता है। संभाव्यता वितरण के लिए नवीन विश्लेषणात्मक अभिव्यक्तियाँ एसआईएसओ-वीएलसी और एमआईएमओ-वीएलसी सिस्टम के लिए फ़ंक्शन (पीडीएफ), आउटज संभावना और आउटज विविधता क्रम प्राप्त किया गया है। इसके अलावा, हम अपने अध्ययन को आउटडोर एफएसओ प्रणाली तक विस्तारित करते हैं। साहित्य में पहली बार, विभिन्न ट्रांसमिशन परिदृश्यों के तहत एफएसओ प्रणाली के लिए सीमित फीडबैक-आधारित डीएमटी की जांच की जाती है। इस प्रयोजन के लिए, हम MIMO- एफएसओ सेटअप पर विचार करते हैं और एकल-दर और अनुकूल-दर ट्रांसमिशन परिदृश्यों के लिए डीएमटी की जांच करते हैं।

इसके अलावा, हम वाहन वीएलसी के क्षेत्र में उद्यम करते हैं और वाहन वीएलसी के क्षेत्र का व्यापक रूप से पता लगाते हैं। इस प्रयोजन के लिए, अत्याधुनिक के विपरीत, हम बाहरी वीएलसी वातावरण की व्यावहारिक चुनौतियों के तहत वी2वी-वीएलसी प्रणाली के व्यापक मॉडलिंग पर जोर देते हैं। पहली बार, हम एक विशिष्ट पीडीएफ के साथ वाहन की गतिशीलता को यादृच्छिक रूप में मॉडल करते हैं। इसलिए, हम वाहन की

गतिशीलता को मॉडल करने के लिए अधिक यथार्थवादी दृष्टिकोण पर जोर देते हैं। इसके अलावा, एक नए चैनल मॉडल पर जोर दिया गया है जो बाहरी वी2वी-वीएलसी यादृच्छिक पथ हानि और वायुमंडलीय अशांति (एटी) के संयुक्त प्रभाव को शामिल करता है। इसके अलावा, विभिन्न प्रदर्शन मेट्रिक्स की विश्लेषणात्मक जांच की जाती है, जैसे पथ हानि, आउटज संभावना, औसत बीईआर (एबीईआर), विविधता क्रम, अलग-अलग मौसम स्थितियों के तहत असतत-इनपुट निरंतर-आउटपुट मेमोरीलेस चैनल (डीसीएमसी) क्षमता इत्यादि।

हम शैडोइंग/ब्लॉकिंग-आधारित वी2वी - वीएलसी मॉडल का प्रस्ताव करके वाहन वीएलसी पर भी अपना काम बढ़ाते हैं। लाइन-ऑफ-विजन (एलओएस) वीएलसी प्रणाली में, संचार लिंक एक ही लेन में या पास में पार्क किए गए वाहनों द्वारा भौतिक बाधाओं के कारण अस्थायी छाया के संपर्क में आता है। चूंकि वीएलसी एलओएस पर अत्यधिक निर्भर है, इसलिए प्रस्ताव दिया गया है और छायांकन-आधारित ट्रांसमिशन परिदृश्य के तहत वी2वी - वीएलसी मॉडल का विश्लेषण करना अत्यधिक महत्वपूर्ण है। प्रस्तावित वी2वी - वीएलसी मॉडल के प्रदर्शन का विश्लेषण डीएमटी मीट्रिक के साथ किया जाता है। इसके अलावा, रिसीवर (आरएक्स) पर पथ हानि को कम करने के लिए, एक नवीन गोलार्ध ऑप्टिकल सांद्रक-आधारित आरएक्स संरचना (एक सर्वदिशात्मक लाभ की पेशकश) भी प्रस्तावित है। प्रस्तावित कार्य के लिए कुछ आश्चर्यजनक अंतर्दृष्टियों की कल्पना की गई है।

अंत में, अगली पीढ़ी-आधारित आईटीएस के एक भाग के रूप में, हम एक आउटडोर आई2वी - वीएलसी सिस्टम के लिए एक इनडोर टेस्टबेड भी विकसित करते हैं। साहित्य में पहली बार, हम नियंत्रित इनडोर वातावरण में विभिन्न यथार्थवादी आई2वी - वीएलसी परिदृश्यों के तहत ट्रांसमीटर (Tx) और कैमरे (यानी, Rx) के रूप में कार्य करने वाली ट्रेफिक लाइट के बीच संचार को प्रयोगात्मक रूप से प्रदर्शित करते हैं। इसके अलावा, सभी प्रायोगिक निष्कर्षों को पहली बार कैमरे के विभिन्न एक्सपोजर समय के लिए प्रदर्शित किया गया है, जो कैमरा-आधारित आरएक्स का उपयोग करते समय एक बहुत ही महत्वपूर्ण पैरामीटर है। इसके अलावा, विभिन्न प्रदर्शन मेट्रिक्स की प्रयोगात्मक रूप से जांच की जाती है, जैसे बीईआर, पीक सिग्नल-टू-शोर अनुपात (पीएसएनआर), और क्षमता। इसके अलावा, एलओएस रुकावट-आधारित संचार परिदृश्यों का भी प्रयोगात्मक रूप से विश्लेषण किया जाता है।

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Abbreviations

ABER	Average Bit Error Rate
AWGN	Additive White Gaussian Noise
AT	Atmospheric Turbulence
BER	Bit Error Rate
CSI	Channel State Information
CSIT	Channel State Information at the Transmitter
DB	Dashboard
DMT	Diversity-Multiplexing Tradeoff
DCMC	Discrete-Input Continuous-Output Memoryless Channel
FSO	Free Space Optical
FOV	Field-of-View
I2V	Infrastructure-to-Vehicle
ITSs	Intelligent Transportation Systems
i.i.d.	independent and identically distributed
IM/DD	Intensity-Modulation/Direct-Detection
LOS	Line-of-Sight
LED	Light Emitting Diode
MISO	Multiple-Input Single-Output
MIMO	Multiple-Input Multiple-Output
NLOS	Non-Line-of-Sight
OWC	Optical Wireless Communication
OSTBCs	Orthogonal Space Time Block Codes
OOK	On/Off Keying

PD	Photodetector
PDF	Probability Distribution Function
RF	Radio Frequency
RV	Random Variable
RC	Repetition Coding
Rx	Receiver
SNR	Signal-to-Noise Ratio
STLS	Single Transmit Laser Selection
SISO	Single-Input Single-Output
Tx	Transmitter
TLS	Transmit Laser Selection
VLC	Visible Light Communication
V2V	Vehicle-to-Vehicle
V2I	Vehicle-to-Infrastructure

Notation

$\approx$	Approximately equal to
$<$	Less than
$\leq$	Less than equal
$>$	Greater than
$\geq$	Greater than equal
$\sqrt{\cdot}$	Square root
$\doteq$	Exponential equality
$\exp(\cdot)$	Exponential function (i.e., $e^{(\cdot)}$)
$\mathbf{w}_i$	i^{th} column of the identity matrix
$\mathbf{w}$	Vector
$\mathbf{W}$	Matrix
$[\cdot]_{M \times N}$	A matrix with M rows and N columns
$\text{Tr}(\cdot)$	Trace of matrix
$\mathbf{I}_{L_t}$	Identity matrix of order $L_t \times L_t$
$\mathbb{E}[\cdot]$	Expectation operator
$[\cdot]^T$	Transpose operator
$ \cdot $	Absolute value
$f(\cdot)$	PDF
$f(\cdot \cdot)$	Conditional PDF
$\text{Pr}[\cdot]$	Probability of event
P_e	Probability of error
P_c	Probability of correct detection
$Q(\cdot)$	Gaussian q-function

$\Gamma(\cdot, \cdot)$	Upper incomplete gamma function
$\Gamma(\cdot)$	Complete gamma function
$\log_x(y)$	The log, base x, of y
$G_{p,q}^{m,n} \left(\cdot \middle \cdot \right)$	Meijer-G function
$\inf(\cdot)$	Infimum of a function