

**ANALYTICAL AND EXPERIMENTAL
EVALUATION OF FREE-SPACE OPTICAL
SYSTEMS WITH
CHANNEL CORRELATION**

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

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DEPARTMENT OF ELECTRICAL ENGINEERING

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Certificate

This is to certify that the thesis entitled "**Analytical and experimental evaluation of free-space optical systems with channel correlation**" being submitted by **Mrs. Richa Priyadarshani** 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 bona-fide research work carried out by her 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.

(Prof. Manav Bhatnagar)

Professor

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Abstract

With the tremendous demand and the ever-increasing popularity of data-based internet usage owing to the various technological innovations such as 5G, the internet of things, virtual reality, over the top streaming, etc., wireless communication (WC) has undoubtedly become an integral part of our life. Because of this, the radio frequency (RF) spectrum has become highly congested, and it has become evident that the RF spectrum will not be sufficient to meet the future demands of WC. For future-proofing of the WC, optical WC (OWC) has emerged as a viable complementary technology to the existing RF and fiber-based technologies. OWC is a health-friendly technology that transmits data over free-space using the optical spectrum, which has an abundance of unregulated bandwidth. Free-space optical (FSO) communication is a long-range terrestrial OWC, that uses the infrared spectrum for data transmission. Similar to the RF systems, improved performance can be achieved in FSO systems also by using spatial diversity techniques with multiple transmit and/or receiving apertures. However, due to the limited available space at most of the practical FSO transceivers, the realization of multiple apertures-based FSO systems in practice makes the spatial correlation inevitable.

The work presented in this thesis unfolds the impact of channel correlation on the performance of spatial diversity-based FSO systems employing the widely used modulation and coding schemes. The investigation is carried out both analytically and experimentally. The analytical study is based on various performance metrics such as bit error rate (BER), outage probability, and capacity. Repetition coding (RC) is used as a spatial diversity technique to achieve an improved system performance in presence of atmospheric turbulence (AT). The first part of this work assumes that

the transmit apertures are equidistant and arranged in a manner that results in an FSO channel with constant correlation. The Gamma-Gamma ($\Gamma\Gamma$) distribution with a constant correlation is used for the statistical characterization of the FSO channel. A thorough analysis of the system performance is carried out for on-off keying modulation by deriving a few important parameters such as BER, diversity order, and coding gain as a function of correlation and signal-to-noise ratio. It is observed by simulation and analysis that the correlation does not affect the diversity order of the considered FSO - multiple-input single-output system with RC, however, it significantly abases the coding gain of the system.

In order to consider a generalized FSO system, this thesis presents the derivation of a novel joint probability density function of generic Málaga ($\mathcal{M}$) distribution with arbitrary correlation. The derived distribution is valid for an arbitrary correlation model, applicable to all the AT regimes, and can also be mapped to most of the existing distributions. The derived result is used for the outage performance analysis of a single-input multiple-output FSO system with selection combining.

Further, this thesis explores optical spatial shift keying (OSSK) as a modulation technique with improved spectral efficiency and reduced decoding complexity for a correlated FSO multiple-input multiple-output (MIMO) system. The effect of correlation on the performance analysis of an FSO-MIMO system with OSSK is studied in terms of BER, capacity, diversity order, and coding gain. All the analytical results are validated using MATLAB simulations. Experimental setup of FSO system with two correlated links is also designed to study the throughput and latency of the system at different turbulence levels.

Finally, for a more practical study, this thesis investigates the BER performance of an FSO-MIMO system employing RC for a correlated channel in presence of amplified spontaneous emission noise. The analytical findings are substantiated by developing an experimental set-up of a 2×1 correlated FSO system with RC in the presence of a pre-amplifier at the receiver for the BER study.

सार

5G, इंटरनेट ऑफ थिंग्स, वर्चुअल रियलिटी, ओवर द टॉप स्ट्रीमिंग आदि जैसे विभिन्न तकनीकी नवाचारों के कारण डेटा-आधारित इंटरनेट उपयोग की जबरदस्त मांग और लगातार बढ़ती लोकप्रियता के साथ, वायरलेस संचार (डब्ल्यूसी) निस्संदेह हमारे जीवन का एक अभिन्न अंग बन गया है। इस वजह से, रेडियो फ्रीक्वेंसी (आरएफ) स्पेक्ट्रम अत्यधिक भीड़भाड़ वाला हो गया है, और यह स्पष्ट हो गया है कि डब्ल्यूसी की भविष्य की मांगों को पूरा करने के लिए आरएफ स्पेक्ट्रम पर्याप्त नहीं होगा। डब्ल्यूसी के भविष्य के प्रूफिंग के लिए, ऑप्टिकल डब्ल्यूसी (ओडब्ल्यूसी) मौजूदा आरएफ और फाइबर-आधारित प्रौद्योगिकियों के लिए एक व्यवहार्य पूरक प्रौद्योगिकी के रूप में उभरा है। ओडब्ल्यूसी एक स्वास्थ्य-अनुकूल तकनीक है जो ऑप्टिकल स्पेक्ट्रम का उपयोग करके डेटा को मुक्त-स्थान पर प्रसारित करती है, जिसमें अविनियमित बैंडविड्थ की प्रचुरता होती है। फ्री-स्पेस ऑप्टिकल (एफएसओ) संचार एक लंबी दूरी की स्थलीय ओडब्ल्यूसी है, जो डेटा ट्रांसमिशन के लिए इन्फ्रारेड स्पेक्ट्रम का उपयोग करता है। आरएफ सिस्टम के समान, एफएसओ सिस्टम में भी स्थानिक विविधता तकनीकों की मदद से बेहतर प्रदर्शन प्राप्त किया जा सकता है, जिसमें कई ट्रांसमीटर और/या रिसीवर एंटीना का उपयोग किया जाता है। हालांकि, अधिकांश व्यावहारिक एफएसओ ट्रांसीवर्स में सीमित उपलब्ध स्थान के कारण, व्यवहार में कई एपर्चर-आधारित एफएसओ सिस्टम की प्राप्ति स्थानिक सहसंबंध को अपरिहार्य बनाती है।

इस थीसिस में प्रस्तुत कार्य व्यापक रूप से उपयोग किए जाने वाले मॉड्यूलेशन और कोडिंग योजनाओं को नियोजित करने वाले स्थानिक विविधता-आधारित एफएसओ सिस्टम के प्रदर्शन पर चैनल सहसंबंध के प्रभाव को प्रकट करता है। जांच विश्लेषणात्मक और प्रयोगात्मक दोनों तरह से की जाती है। विश्लेषणात्मक अध्ययन विभिन्न प्रदर्शन मेट्रिक्स जैसे बिट त्रुटि दर (बीईआर), आउटेज संभावना और क्षमता पर आधारित है। वायुमंडलीय अशांति (एटी) की उपस्थिति में बेहतर सिस्टम प्रदर्शन प्राप्त करने के लिए पुनरावृत्ति कोडिंग (आरसी) का उपयोग स्थानिक विविधता तकनीक के रूप में किया जाता है। इस कार्य का पहला भाग मानता है कि संचारण द्वार समान दूरी पर हैं और इस तरह व्यवस्थित हैं कि एफएसओ चैनल में निरंतर सहसंबंध होता है। निरंतर सहसंबंध के साथ गामा-गामा ($\Gamma\Gamma$) वितरण का उपयोग एफएसओ चैनल के सांख्यिकीय लक्षण वर्णन के लिए किया जाता है। ऑन-ऑफ कुंजीयन मॉड्यूलेशन के साथ सिस्टम के प्रदर्शन का गहन विश्लेषण कुछ महत्वपूर्ण मापदंडों जैसे बीईआर, विविधता क्रम, और कोडिंग लाभ की

व्युत्पत्ति सहसंबंध और सिग्नल-टू-शोर अनुपात के संदर्भ में किया गया है। यह अनुकरण और विश्लेषण द्वारा देखा गया है कि सहसंबंध आरसी के साथ एफएसओ - बहु-इनपुट सिंगल-आउटपुट सिस्टम के विविधता क्रम को प्रभावित नहीं करता है, हालांकि, यह सिस्टम के कोडिंग लाभ को महत्वपूर्ण रूप से कम करता है।

एक सामान्यीकृत एफएसओ प्रणाली पर विचार करने के लिए, यह थीसिस जेनेरिक मलागा (एम) वितरण के मनमाने सहसंबंध के साथ एक नवीन संयुक्त संभाव्यता घनत्व फंक्शन की व्युत्पत्ति प्रस्तुत करती है। व्युत्पन्न वितरण एक मनमाना सहसंबंध मॉडल के लिए मान्य है, जो सभी एटी व्यवस्थाओं पर लागू होता है, और इसे अधिकांश मौजूदा वितरणों के लिए भी मैप किया जा सकता है। व्युत्पन्न परिणाम चयन संयोजन के साथ एकल-इनपुट बहु-आउटपुट एफएसओ सिस्टम के आउटेज प्रदर्शन विश्लेषण के लिए उपयोग किया जाता है।

इसके अलावा, यह थीसिस एक सहसंबद्ध एफएसओ बहु-इनपुट बहु-आउटपुट (मिमो) प्रणाली के लिए बेहतर वर्णक्रमीय दक्षता और कम डिफोर्मिंग जटिलता के साथ एक मॉड्यूलेशन तकनीक के रूप में ऑप्टिकल स्थानिक शिफ्ट कुंजीयन (ओएसएसके) की खोज करती है। ओएसएसके के साथ एफएसओ-मिमो प्रणाली के प्रदर्शन विश्लेषण पर सहसंबंध के प्रभाव का अध्ययन बीईआर, क्षमता, विविधता क्रम और कोडिंग लाभ के संदर्भ में किया जाता है। सभी विश्लेषणात्मक परिणाम मैटलैब सिमुलेशन द्वारा सत्यापित हैं। दो सहसंबद्ध कड़ियों के साथ एफएसओ प्रणाली का प्रायोगिक सेटअप भी विभिन्न अशांति स्तरों पर प्रणाली के थ्रूपुट और विलंबता का अध्ययन करने के लिए डिज़ाइन किया गया है।

अंत में, अधिक व्यावहारिक अध्ययन के लिए, यह थीसिस प्रवर्धित सहज उत्सर्जन शोर की उपस्थिति में एक सहसंबद्ध चैनल के लिए RC को नियोजित करने वाले एफएसओ-मिमो प्रणाली के बीईआर प्रदर्शन की जांच करती है। बीईआर अध्ययन के लिए रिसीवर पर एक प्री-एम्पलीफायर की उपस्थिति में आरसी के साथ 2×1 सहसंबद्ध एफएसओ प्रणाली का एक प्रयोगात्मक सेट-अप विकसित करके विश्लेषणात्मक निष्कर्षों की पुष्टि की जाती है।

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Abbreviations

ABER	Average Bit Error Rate
AOA	Angle of Arrival
APEP	Average Pair-wise Error Probability
ASE	Amplified Spontaneous Emission
AT	Atmospheric Turbulence
AWGN	Additive White Gaussian Noise
BER	Bit Error Rate
BERT	BER Tester
BS	Base Station
BW	Bandwidth
CDF	Cummulative Distribution Function
DCMC	Discrete-Input Continuous-Output Memoryless Channel
EDFA	Erbium-Doped Fiber Amplifier
FSO	Free-Space Optical
ΓΓ	Gamma-Gamma
GRIN	Gradient Index
ICI	Inter-channel Interference
IM/DD	Intensity-Modulation/Direct-Detection
I/O	Input/Output
LAN	Local Area Network
LOS	Line of Sight
$\mathcal{M}$	Malaga
MGF	Moment Generating Function

MIMO	Multiple-Input Multiple-Output
MISO	Multiple-Input Single-Output
NRZ	Non Return to Zero
OOK	On-Off Keying
OSA	Optical Spectrum Analyzer
OSM	Optical Spatial Modulation
OSSK	Optical Space Shift Keying
OSTBC	Orthogonal Space-Time Block Code
OWC	Optical Wireless Communication
PAM	Pulse Amplitude Modulation
PDF	Probability Density Function
PE	Pointing Error
PPM	Pulse Position Modulation
QAM	Quadrature Amplitude Modulation
RC	Repetition Coding
RF	Radio-Frequency
RV	Random Variable
Rx	Receiver
RZ	Return to Zero
SC	Selection Combining
SE	Spectral Efficiency
SIMO	Single-Input Multiple-Output
SLSE	Small-and Large-Scale Eddies
SM	Spatial Modulation
SMF	Single Mode Fibers
SNR	Signal-to-Noise Ratio
Tx	Transmitter