

JAMMING IN FREE SPACE OPTICAL SYSTEMS

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DEPARTMENT OF ELECTRICAL ENGINEERING

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JAMMING IN FREE SPACE OPTICAL SYSTEMS

by

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DEPARTMENT OF ELECTRICAL ENGINEERING

Submitted

in fulfilment of the requirements of the degree of Doctor of Philosophy

to the



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Dedicated
to
My Parents

Certificate

This is to certify that the thesis entitled "**Jamming in free space optical systems**" being submitted by **Ms. Pratiti Paul** 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.

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Abstract

Free space optical (FSO) communication systems continue to take up a pivotal position in the continuing evolution of cutting-edge global telecommunications and networking systems. The prime advantages of this growing technology is its licence free spectrum and higher spectral efficiency—virtually unlimited bandwidth. FSO communications have excellent features like utilization of unregulated spectrum, lower cost implementation, lesser power consumption, faster deployment capability, etc., due to which it has drawn significant attention in both research and industrial domains. For the past few decades, FSO communication has grown its appeal to a broader extent in the scientific research communities. This contemporary technology provides numerous benefits over typical radio frequency networks. Having acknowledged its popularity for its manifold technical benefits, the broadcast nature of FSO communication can expose the system to various privacy and information security related risks. Thereby, the intervention of illegitimate sources such as jammers in the FSO network has become a raising concern in the present day—which needs closer attention.

The work presented in this dissertation unfolds the detailed investigation of jamming effect over different FSO set-ups and how this denial-of-service (DoS) attack can be a serious threat for this promising high-speed wireless network. The analysis starts with a single-input single-output (SISO) FSO system in the presence of jammer, and closed-form expressions of different performance metrics such as average bit error rate (ABER), outage probability (OP), diversity order, and coding loss are obtained for the Gamma-Gamma and negative exponential fading channels. To get more insights on the error performances, the effects of pointing errors for both the jamming and legitimate sources are also studied. Further, the performance of a multiple-input single-output

(MISO) FSO system is analysed and significant improvement in the error and outage performances is obtained in the presence of jammer. The BER and OP of the MISO FSO system are mathematically derived and are compared with the SISO FSO system performances in the presence of jamming effects.

After a detailed study of SISO and MISO FSO systems in the presence of FSO jammer, a double relay-assisted FSO system is studied under the jamming attack. A novel mathematical framework is developed to obtain the mathematical expression of BER of decode-and-forward (DF) protocol-based cooperative FSO system in presence of random relay jamming effects. Subsequently, the analysis is performed for a general relay-assisted FSO system with an arbitrary number of relays in the presence of multiple random jammers.

In order to study the effect of jamming over an aperture averaged FSO receiver, an exponentiated Weibull (EW) distributed FSO fading channel is considered due to its excellent fit for all aperture sizes over the ranges of atmospheric turbulence conditions. A framework to obtain the mathematical expressions of BER and OP of the considered FSO system under aperture averaging scheme is provided. Additionally, the asynchronous jamming effect over the error performances is described.

This dissertation also explores how the efficacy of FSO communication channel can be affected in the presence of random jamming attacks. In the presence of jammer, the theoretical expression of discrete-input continuous-output memoryless channel (DCMC) capacity of a SISO FSO communication system is derived analytically. The study reveals that the FSO channel capacity is very sensitive to the degree of jamming and the ergodic channel capacity alters crucially even for small change in jamming activity. The presence of a rational jammer is addressed by modelling the interaction between the FSO transmitter and the jammer as a non-cooperative game. Closed-form expressions of the equilibrium of the proposed game are derived.

In short, this dissertation presents the fundamental analytical framework to investigate the jamming effects and its mitigation approaches in different FSO set-ups.

सार

फ्री स्पेस ऑप्टिकल (FSO) संचार प्रणालियाँ एक महत्वपूर्ण स्थान बनाए हुए हैं अत्याधुनिक वैश्विक दूरसंचार और नेटवर्किंग के निरंतर विकास में सिस्टम. इस बढ़ती तकनीक का मुख्य लाभ इसका लाइसेंस मुक्त स्पेक्ट्रम है और उच्च वर्णक्रमीय दक्षता-वस्तुतः असीमित बैंडविड्थ। एफएसओ संचार इसमें अनियमित स्पेक्ट्रम का उपयोग, कम लागत का कार्यान्वयन, कम बिजली की खपत, तेज तैनाती क्षमता आदि जैसी उत्कृष्ट विशेषताएं हैं, जिसके कारण इसमें अनुसंधान और औद्योगिक दोनों क्षेत्रों में महत्वपूर्ण ध्यान आकर्षित किया। पिछले कुछ समय से दशकों से, एफएसओ संचार ने वैज्ञानिक क्षेत्र में अपनी अपील को व्यापक स्तर तक बढ़ाया है अनुसंधान समुदाय. यह समसामयिक तकनीक अनेक लाभ प्रदान करती है विशिष्ट रेडियो फ्रीक्वेंसी नेटवर्क। इसकी लोकप्रियता को इसकी विविधता के लिए स्वीकार किया गया है तकनीकी लाभ, एफएसओ संचार की प्रसारण प्रकृति प्रणाली को उजागर कर सकती है विभिन्न गोपनीयता और सूचना सुरक्षा संबंधी जोखिमों के लिए। जिससे, का हस्तक्षेप एफएसओ नेटवर्क में जैमर जैसे अवैध स्रोत एक बढ़ती चिंता का विषय बन गए हैं वर्तमान समय में-जिस पर अधिक ध्यान देने की आवश्यकता है।

इस शोध प्रबंध में प्रस्तुत कार्य विभिन्न एफएसओ सेट-अप पर जैमिंग प्रभाव की विस्तृत जांच को उजागर करता है और यह कैसे सेवा से इनकार (डीओएस) हमला कर सकता है इस आशाजनक हाई-स्पीड वायरलेस नेटवर्क के लिए एक गंभीर खतरा बनें। विश्लेषण शुरू होता है जैमर की उपस्थिति में एकल-इनपुट एकल-आउटपुट (SISO) FSO प्रणाली के साथ, और औसत बिट त्रुटि दर जैसे विभिन्न प्रदर्शन मेट्रिक्स की बंद-रूप अभिव्यक्तियाँ (ABER), आउटपुट प्रायिकता (OP), विविधता क्रम और कोडिंग हानि प्राप्त की जाती है गामा-गामा और नकारात्मक घातीय लुप्त होती चैनल। पर अधिक जानकारी प्राप्त करने के लिए त्रुटि प्रदर्शन, जामिंग और वैध दोनों के लिए त्रुटियों को इंगित करने के प्रभाव स्रोतों का भी अध्ययन किया जाता है। इसके अलावा, मल्टीपल-इनपुट सिंगल-आउटपुट (MISO) FSO सिस्टम के प्रदर्शन का विश्लेषण किया गया है और त्रुटि और आउटपुट में महत्वपूर्ण सुधार किया गया है। जैमर की उपस्थिति में प्रदर्शन प्राप्त किया जाता है। MISO का ABER और OP एफएसओ प्रणाली गणितीय रूप से व्युत्पन्न होती है और इसकी तुलना एसआईएसओ एफएसओ प्रणाली से की जाती है जैमिंग प्रभाव की उपस्थिति में प्रदर्शन।

एफएसओ की उपस्थिति में एसआईएसओ और एमआईएसओ एफएसओ प्रणालियों के विस्तृत अध्ययन के बाद जैमर, एक डबल रिले-असिस्टेड एफएसओ प्रणाली का जैमिंग हमले के तहत अध्ययन किया जाता है। ए की गणितीय अभिव्यक्ति प्राप्त करने के लिए नवीन गणितीय ढाँचा विकसित किया गया है डीकोड-एंड-फॉरवर्ड (DF) प्रोटोकॉल-आधारित सहकारी एफएसओ प्रणाली की बीईआर उपस्थिति में यादृच्छिक रिले जैमिंग प्रभाव। इसके बाद, विश्लेषण सामान्य के लिए किया जाता है एकाधिक की उपस्थिति में रिले की मनमानी संख्या के साथ रिले-सहायता प्राप्त एफएसओ प्रणाली यादृच्छिक जैमर।

एपर्चर औसत एफएसओ रिसीवर पर जाम होने के प्रभाव का अध्ययन करने के लिए, एक घातीय वेइबुल (EW) वितरित एफएसओ फ्रेडिंग चैनल को देय माना जाता है वायुमंडलीय अशांति की सीमाओं पर सभी एपर्चर आकारों के लिए यह उत्कृष्ट रूप से फिट है स्थितियाँ। बीईआर और ओपी की गणितीय अभिव्यक्ति प्राप्त करने के लिए एक रूपरेखा एपर्चर औसत योजना के तहत सुविचारित एफएसओ प्रणाली प्रदान की गई है। इसके अतिरिक्त, त्रुटि प्रदर्शन पर अतुल्यकालिक जैमिंग प्रभाव का वर्णन किया गया है।

यह शोध प्रबंध यह भी पता लगाता है कि एफएसओ संचार चैनल की प्रभावकारिता कैसी है यादृच्छिक जैमिंग हमलों की उपस्थिति में प्रभावित हो सकता है। जैमर की उपस्थिति में, असतत-इनपुट निरंतर-आउटपुट मेमोरीलेस चैनल

की सैद्धांतिक अभिव्यक्ति एसआईएसओ एफएसओ संचार प्रणाली की (DCMC) क्षमता विश्लेषणात्मक रूप से प्राप्त की जाती है। अध्ययन से पता चलता है कि एफएसओ चैनल क्षमता जाम होने की डिग्री के प्रति बहुत संवेदनशील है और जैमिंग में छोटे बदलाव के लिए भी एर्गोडिक चैनल क्षमता महत्वपूर्ण रूप से बदल जाती है गतिविधि। एक तर्कसंगत जैमर की उपस्थिति को इंटरैक्शन मॉडलिंग द्वारा संबोधित किया जाता है एफएसओ ट्रांसमीटर और जैमर के बीच एक असहयोगी खेल के रूप में। पूर्ण-सूत्र प्रस्तावित खेल के संतुलन की अभिव्यक्तियाँ प्राप्त की जाती हैं।

संक्षेप में, यह शोध प्रबंध विभिन्न एफएसओ सेट-अप में जैमिंग प्रभावों और इसके शमन दृष्टिकोण की जांच करने के लिए मौलिक विश्लेषणात्मक ढांचा प्रस्तुत करता है।

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Abbreviations

ΓΓ	Gamma-Gamma
ABER	Average Bit Error Rate
AEN	Additive Exponential Noise
APD	Avalanche Photo-Detector
AWGN	Additive White Gaussian Noise
AT	Atmospheric Turbulence
BER	Bit Error Rate
DCMC	Discrete-input Continuous-output Memoryless Channel
DF	Decode-and-Forward
DoS	Denial-of-Service
EW	Exponentiated-Weibull
FoV	Field-of-View
FSO	Free Space Optical
I/O	Input-Output
IR	Infrared
LoS	Line-of-Sight
MGF	Moment Generating Function
MIMO	Multiple-Input Multiple-Output
MISO	Multiple-Input Single-Output
ML	Maximum-Likelihood
NCG	No-Cooperative Game
NE	Nash Equilibrium
OOK	On-Off Keying

OP	Outage Probability
OWC	Optical Wireless Communication
PD	Photo-Detector
PDF	Probability Density Function
PE	Pointing Error
RF	Radio-Frequency
RNE	Robust Nash Equilibrium
RV	Random Variable
SISO	Single-Input Single-Output
SJNR	Signal-to-Jamming-plus-Noise Ratio
SJR	Signal-to-Jamming Ratio
SNR	Signal-to-Noise Ratio