STUDIES ON HIGH PERFORMANCE COOPERATIVE COMMUNICATION IN FREE SPACE OPTICAL LINKS WITH APPLICATION TO LEVEL CROSSING WARNING SYSTEM FOR RAILWAYS

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by

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I would like to dedicate this thesis to my loving husband and daughter...

CERTIFICATE

The thesis entitled "**Studies on high performance cooperative communication in free space optical links with application to level crossing warning system for Railways"** is being submitted by **Mrs. Vineeta Dubey (Nee Khare)** to Indian Institute of Technology Delhi for the award of degree of **doctor of philosophy** is a record of original bonafide research work carried out by her. She has worked under our guidance and supervision, and fulfilled the requirement for the submission of this thesis, which has attained the standard required for a Ph.D. degree of this Institute. The results represented in this thesis have not been submitted elsewhere for the award of any degree or diploma.

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ABSTRACT

Free Space Optics (FSO), as an advanced technology of data transmission, offers high bandwidth, high data rate, secured transmission and ease of installation. It faces adverse effects in the performance due to atmospheric effects and the limitations of the equipments used in the system. In this thesis, we have carried out detailed analysis of FSO cooperative communication systems which is one of the mitigation techniques used to compensate the effect of atmospheric effects in an FSO system. Level crossing (LC) warning system for Railways has been discussed as an application of cooperative FSO communication system with radio frequency (RF) backup.

Cooperative systems have been widely used in RF communication system, which offers the advantage of diversity with redundancy and high reliability. Cooperative FSO systems, with different relaying techniques and different combining schemes at receiver end, have been discussed to get the advantage of cooperation and FSO for high data rate applications. A new proposed combining technique named as Multiple Gain Combiner is also the part of the analytical study. Outage probability analysis has been analyzed for Decode and forward (DF) cooperative FSO communication system using power series expansion. Reflect and forward has been introduced as a new relaying technique, in which mirror with good reflectivity has been placed at relay end and hence it makes the system simple and there is no requirement of any passive components in it. We have studied quadrature phase shift keying as advanced modulation format with I and Q channel detection system for multiple relays cooperative FSO system. Availability and Mean Time Between Failure (MTBF) are the parameters, which have also been analyzed in single relay cooperative FSO system using RF backup and multiple relays cooperative FSO system, which shows that both the systems meet the requirement of

communication grade standard. We have tested the feasibility of cooperative FSO system at 500 Mbps with simulated effect of fading using modified optical chopper (MOC). The effect of fading by placing MOC at different locations has also been discussed.

Level crossing warning system for Railways has been suggested as an application of cooperative FSO communication system with RF backup. Cooperative FSO system ensures good availability of communication system during rainy season. When implemented with RF backup, it also ascertains the availability in the condition of fog. Hence the complementary nature of FSO system and RF backup can be utilized to avoid accidents where the railway track and highways intersect each other.

सार

डेटा ट्रांसमिशन की एक उन्नत तकनीक के रूप में फ्री स्पेस ऑप्टिक्स (एफएसओ), उच्च बैंडविड्थ, उच्च डेटा रेट, सुरक्षित ट्रांसमिशन और स्थापना की आसानी प्रदान करता है। एटमोस्फियरिक इफेक्ट्स और सिस्टम में उपयोग किए जाने वाले उपकरणों की सीमाओं के कारण प्रदर्शन में प्रतिकूल प्रभाव पड़ते हैं। इस थीसिस में, हमने एफएसओ कोआपरेटिव कम्युनिकेशन सिस्टम्स का विस्तृत विश्लेषण किया है जो एक एफएसओ सिस्टम में एटमोस्फियरिक इफेक्ट्स के प्रभाव की भरपाई करने के लिए उपयोग की जाने वाली तकनीकों में से एक है। रेलवे के लिए लेवल क्रॉसिंग (एलसी) वार्निंग सिस्टम पर रेडियो फ्रीक्वेंसी (आरएफ) बैकअप के साथ कोआपरेटिव एफएसओ सिस्टम के रूप में चर्चा की गई है।

कोआपरेटिव प्रणाली का व्यापक रूप से आरएफ कम्युनिकेशन सिस्टम्स में उपयोग किया जाता है, जो डाइवर्सिटी का लाभ रिडण्डेंसी और हाई रिलायबिलिटी के साथ प्रदान करता है। कोआपरेटिव एफएसओ सिस्टम, विभिन्न रिलेइंग तकनीकों और रिसीवर अंत में विभिन्न कम्बाइनिंग योजनाओं के साथ, उच्च डेटा रेट और एफएसओ का लाभ प्राप्त करने के लिए चर्चा की गई है। मल्टीपल गेन कम्बाइनर नामक एक नई प्रस्तावित कम्बाइनिंग तकनीक भी विश्लेषणात्मक अध्ययन का हिस्सा है। आउटेज प्रोबेबिलिटी एनालिसिस का विश्लेषण पावर सीरीज एक्सपेंशन का उपयोग करते हुए डिकोड एंड फॉरवर्ड (डी एफ) कोआपरेटिव एफ एस ओ कम्युनिकेशन सिस्टम के लिए किया गया है। रिफ्लेक्ट एंड फॉरवर्ड एक नई रिलेइंग तकनीक के रूप में पेश किया गया है, जिसमें रिले एंड पर गुड रिफ्लेक्टिविटी के साथ मिरर रखा गया है और इसलिए यह सिस्टम को सरल बनाता है और इसमें किसी भी पैसिव कंपोनेंट्स की आवश्यकता नहीं होती है। हमने कई रिले कोआपरेटिव एफएसओ सिस्टम के लिए I और Q चैनल के साथ उन्नत मॉड्यूलेशन प्रारूप के रूप में क्वाडरेचर फेज शिफ्ट कींग का अध्ययन किया है। अवेलेबिलिटी और मीन टाइम बिटवीन फेलियर (एमटीबीएफ) पैरामीटर हैं, जिनका आरएफ बैकअप और एकाधिक रिले कोआपरेटिव एफएसओ सिस्टम का उपयोग करके सिंगल रिले कोआपरेटिव एफएसओ सिस्टम में भी विश्लेषण किया गया है, जो दिखाता है कि दोनों सिस्टम कम्युनिकेशन ग्रेड स्टैण्डर्ड की आवश्यकता को पूरा करते हैं। हमने मॉडिफाइड ऑप्टिकल चॉपर (एम ओ सी) का उपयोग करके सिमुलेटेड इफ़ेक्ट ऑफ़ फेडिंग के साथ 500 एमबीपीएस पर कोआपरेटिव एफएसओ प्रणाली की व्यवहार्यता का परीक्षण किया है। विभिन्न स्थानों पर एमओसी रखकर सिमुलेटेड इफ़ेक्ट ऑफ़ फेडिंग भी चर्चा की गई है।

रेलवे के लिए लेवल क्रॉसिंग वार्निंग सिस्टम को आरएफ बैकअप के साथ कोआपरेटिव एफएसओ सिस्टम के आवेदन के रूप में सुझाव दिया गया है। कोआपरेटिव एफएसओ सिस्टम,बरसात के मौसम के दौरान कम्युनिकेशन सिस्टम्स की अच्छी अवेलेबिलिटी सुनिश्चित करता है। आरएफ बैकअप के साथ लागू होने पर, यह धुंध की स्थिति में अवेलेबिलिटी का भी पता लगाता है। इसलिए एफएसओ सिस्टम और आरएफ बैकअप का उपयोग उन दुर्घटनाओं से बचने के लिए किया जा सकता है, जहां रेलवे ट्रैक और राजमार्ग एक-दूसरे को क्रॉस करते हैं।

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List of Abbreviations

AF: Amplify and Forward

AWGN: Additive White Gaussian Noise

BER: Bit Error Rate

BPSK: Binary Phase Shift Keying

CDF: Cumulative Density Function

CRC: Cyclic Redundancy Check

CSI: Channel State Information

DF: Decode and Forward

DPSK: Differential Phase Shift Keying

DWDM: Dense Wavelength Division Multiplexing

EGC: Equal Gain Combiner

EMI: Electro Magnetic Interference

FFT: Fast Fourier Transform

FSO: Free Space Optics

IM/DD: Intensity Modulation/ Direct Detection

IR: Infrared

LC: Level Crossing

LD: Laser Diode

LDPC: Low Density Parity Check

MGC: Multiple Gain Combiner

MGF: Moment Generating Function

MIMO: Multiple Input Multiple Output

MOC: Modified Optical Chopper

MRC: Maximal Ratio combiner

MTBF: Mean Time Between Failures

NRZ: Non Return to Zero

OFDM: Optical Frequency Division Modulation

OOK: On-Off Keying

PD: Photo Detector

PDF: Probability Density Function

PE: Pointing Error

PLC: Programmable Logic Control

PPM: Pulse Position Modulation

QPSK: Quadrature Phase Shift Keying

RF: Radio Frequency

RTF: Reflect and Forward

RZ: Return to Zero

SC: Selection Combiner

SIM: Subcarrier Intensity Modulation

SISO: Single Input Single Output

SSDAC: Single Section Digital Axle Counter

List of symbols

I_{DF}: Mutual Information for DF transmission

hsr, *hrd* and *hsd:* channel fades between the source to relay, relay to destination and source to destination

I_{AF}: Mutual Information for AF transmission

P_S and P_R : power transmitted at the source and the power transmitted at relay node, respectively

γ_{MRC} and γ_{EGC}: optimum output SNR in case of MRC and EGC, respectively

γ_{sd} and γ_{rd}: SNR for source to destination link and SNR for relay to destination link, respectively

y: Received signal

x : transmitted signal

h: Normalized channel fading coefficient due to the atmosphere

n: AWGN

$\sigma^2{}_n$: Variance of AWGN

h_a: Channel coefficient due to atmospheric turbulence

h_p: Channel coefficient due to pointing errors

α: Effective number of large-scale eddy parameter in gamma-gamma channel

β: Effective number of small-scale eddy parameter in gamma-gamma channel

Γ : gamma function

$K_{\alpha-\beta}(.)$: Modified Bessel function of the second kind of order $(\alpha-\beta)$

λ : wavelengh

D: Diameter of the receiver collecting lens aperture

Cn^2 : Index of the refraction structure parameter

w_{zeq}: equivalent beam diameter

ξ: The ratio of the equivalent beam radius at the receiver and the pointing error displacement standard deviation (jitter) at the receiver

$\mathrm{erf}(\cdot)$: Error function

w_z :Beam waist at distance z

z_1 and z_2 : weighing factors in case of MGC

λ_d : Direct link failure rate due to equipment failure

μ_d : Direct link repair rate in case of equipment failure

λ_{dt} : Direct link failure rate due to turbulence and PE

μ_{dt} : Direct link repair rate with power boost up

λ_f : Direct link failure rate due to fog

μ_p : Direct link repair rate with power boost up for fog

μ_r : Repair rate in case of RF backup

λ_{sys} : Total system failure rate

μ_{sys} : Total system repair rate

λ_i : Indirect link failure rate

μ_i : Indirect link repair rate

λ_b : Both the links failure rate

μ_b : Both the links repair rate

λ_{bt} : Both the links failure rate due to turbulence and PE

μ_{bt} : Both the links repair rate due to turbulence and PE

Q: State transition rate matrix

$P(t)$: Transition probability matrix

M: Non singular matrix formed with the eigen vectors of Q

D: Diagonal matrix with the distinct eigen values of Q