

Design and Study of LDPC Codes For Free-Space Optical Communication System

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by

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CERTIFICATE

This is to certify that the dissertation entitled “**Design and Study of LDPC Codes for Free-Space Optical Communication System**” being submitted by Ms. Sonali (2016EEZ8075) 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 our supervision.

In our opinion, the dissertation 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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Sonali

ABSTRACT

Free-space optical (FSO) communication is the next facet for designing future-generation telecommunication networks. The reasons are manifold - it is an easily deployable and highly secure communication system, which offers large bandwidth at meager transmission powers. However, atmospheric turbulence-induced slow-fading constricts the reliable transmission in an outdoor FSO communication system. Since FSO communication is of paramount importance for the design of next-generation 5G+ wireless networks, we tackle the challenges of the atmospheric effects to cater to the aspiring objectives of the fifth generation and beyond communication networks.

Error control codes (ECCs) are commonly used to enhance reliability. In this dissertation, we first benchmark the performance of two different kinds of ECCs in the gamma-gamma (GG) distributed FSO channel. We use Bose–Chaudhuri–Hocquenghem (BCH) and low-density parity-check (LDPC) codes, which represent a class of algebraic codes and codes on graphs, respectively. We choose two different ECCs because these codes have complexity vs. performance trade-off. While the BCH codes belong to the class of algebraic codes, LDPC codes belong to the modern class of probabilistic decoding. Using both analytical and simulation models, we investigate the performance of a coded communication system under various channel conditions, viz., slow-fading and fast-fading GG channels for different turbulence regimes, and obtain the coding gain. We also derive the expressions of outage capacity for a slow-fading channel and ergodic channel capacity for a fast-fading channel. Ergodic capacity corresponds to the maximum long-term achievable rate when the fading transitions through all possible fading states. As in a slow-fading channel, the channel gain is constant for many symbols, an ergodic capacity is not a very useful metric. Instead, we use outage probability, which lets us know for what probability the channel gain is below the threshold to meet the minimum signal-to-noise ratio (SNR) requirements. On the other hand, in a fast-fading channel, one bit sees many channels instantiation, and outage probability will not be a helpful metric. Instead, we use ergodic capacity.

We conclude that ECCs deteriorate the bit error rate (BER) performance in a slow-fading channel. However, for this kind of channel, the combination of ECCs with an interleaver reduces the burst errors and improves the performance, leading to positive coding gain. The coding gain is not much in a fast-fading channel and remains almost the same in different turbulence conditions. Out of the two codes we used, it is observed from the computed results that the LDPC codes have shown better performance in all scenarios as compared to the BCH codes. Thus, a natural trail is to optimize the LDPC codes further for the FSO channel.

The BER performance of an asymptotically long-length LDPC code is analyzed with the density evolution analysis of the belief propagation (BP) algorithm. The term threshold emerges when we estimate the BER performance of LDPC codes, which follows an inverted-step response as a function of SNR. The threshold is the SNR, after which the BER falls arbitrarily and becomes close to zero. Determining the FSO channel threshold is tedious as the density of the log-likelihood ratio cannot be assumed as Gaussian. It, thus, requires testing different values of SNR as a possible threshold systematically. Therefore, we propose the divide and conquer algorithm. The threshold depends on the degree distributions, channel state information (CSI), and the turbulence level. When CSI is known, we obtain the threshold at an SNR of 8.10 dB in strong turbulence for a regular (3,6) LDPC code. This threshold steps up to 12.48 dB when the CSI is unknown at the receiver.

To achieve the threshold close to the FSO channel's capacity, we require an optimum degree distribution for the LDPC codes. We derive the degree distributions of irregular LDPC codes by optimizing either SNR or code rate. In the SNR-optimized channel, we derive degree distributions for achieving a threshold of 0.5 dB and 5 dB at the highest possible code rate. In contrast, for the rate-optimized channel, we target a code rate of 0.75 and 0.8 at the lowest possible threshold. We obtain the maximum achievable code rate of 0.56 and 0.40 in weak and strong turbulence regimes at a 5 dB threshold. In the rate-optimized case, we obtain the required code rate of 0.8 at the threshold of 11.30 dB and 19.97 dB in weak and strong turbulence regimes, respectively. This work emphasizes the concept of adaptive coding over the FSO channel. We have shown that ECCs give good performance in a fast fading channel. When we use spatial diversity, an effect similar to a fast fading channel can be obtained. We derive the capacity and BER performance of the LDPC codes in receiver diversity and multiple-input multiple-output systems.

In the dissertation, we emphasize that the choice of channel highly influences the performance of ECCs, and a combination of code with an interleaver is a popular choice among researchers for the FSO channel. The slow-fading channel with an interleaver increases latency beyond permissible communication limits and is not a practical solution. Hence, we propose a novel and effective scheme, called the channel assisted coding (CAC), wherein we combine the degree of bits with the channel coefficient. With the CAC-LDPC coding system, we alleviate any interleaving induced latency. The MATLAB simulations show that CAC-LDPC achieves a coding gain of around 13.7 dB with 32 spatial links, compared to the LDPC interleaved systems in strong turbulence. We propose three analytical models to characterize the performance of CAC-LDPC. The analytical results are supported with the simulation study.

सार

फ्री-स्पेस ऑप्टिकल (एफएसओ) संचार भविष्य की पीढ़ी के दूरसंचार नेटवर्क को डिजाइन करने का अगला पहलू है। इसके कई कारण हैं - यह एक आसानी से परिनियोजित करने योग्य और अत्यधिक सुरक्षित संचार प्रणाली है, जो कम पारेषण शक्तियों पर बड़ी बैंडविड्थ प्रदान करती है। हालांकि, वायुमंडलीय टर्बुलेन्स से प्रेरित स्लो फेडिंग बाहरी एफएसओ संचार प्रणाली में विश्वसनीय संचरण को रोकता है। चूंकि अगली पीढ़ी के 5G+ वायरलेस नेटवर्क के डिजाइन के लिए एफएसओ संचार सर्वोपरि है, इसलिए हम पांचवीं संचार नेटवर्क पीढ़ी और परे के महत्वाकांक्षी उद्देश्यों को पूरा करने के लिए वायुमंडलीय प्रभावों की चुनौतियों से निपटते हैं।

त्रुटि नियंत्रण कोड (ईसीसी) आमतौर पर विश्वसनीयता बढ़ाने के लिए उपयोग किए जाते हैं। इस शोध प्रबंध में, हम पहले गामा-गामा (जीजी) वितरित एफएसओ चैनल में दो अलग-अलग प्रकार के ईसीसी के प्रदर्शन को बेंचमार्क करते हैं। हम बोस-चौधुरी-होक्केन्धम (बीसीएच) और लो-डेंसिटी पैरिटी-चैक (एलडीपीसी) कोड का उपयोग करते हैं, जो क्रमशः बीजगणितीय और कोड्स ऑन ग्राफ के एक वर्ग का प्रतिनिधित्व करते हैं। हम दो अलग-अलग ईसीसी चुनते हैं क्योंकि इन कोडों में जटिलता बनाम प्रदर्शन ट्रेड-ऑफ है। जबकि बीसीएच कोड बीजगणितीय कोड के वर्ग से संबंधित हैं, एलडीपीसी कोड संभाव्य डिकोडिंग के आधुनिक वर्ग से संबंधित हैं। विश्लेषणात्मक और सिमुलेशन मॉडल दोनों का उपयोग करते हुए, हम विभिन्न चैनल स्थितियों के तहत एक कोडित संचार प्रणाली के प्रदर्शन की जांच करते हैं, और कोडिंग लाभ प्राप्त करते हैं। हम स्लो फेडिंग चैनल के लिए आउटेज क्षमता और फास्ट फेडिंग चैनल के लिए एर्गोडिक चैनल क्षमता के एक्सप्रेसंस भी प्राप्त करते हैं। एर्गोडिक क्षमता उस अधिकतम दीर्घकालिक प्राप्य दर से मेल खाती है जब फेडिंग सभी संभावित फेडिंग अवस्थाओं के माध्यम से निकलती है। एक स्लो फेडिंग चैनल के रूप में, कई प्रतीकों के लिए चैनल लाभ स्थिर है, एक एर्गोडिक क्षमता बहुत उपयोगी मीट्रिक नहीं है। इसके बजाय, हम आउटेज प्रायिकता का उपयोग करते हैं, जिससे हमें पता चलता है कि न्यूनतम सिग्नल-टू-नॉइज़ अनुपात (एसएनआर) आवश्यकताओं को पूरा करने के लिए चैनल का लाभ किस सीमा से नीचे है। दूसरी ओर, एक फास्ट फेडिंग चैनल में, एक बिट कई चैनलों को तत्काल देखता है, और आउटेज संभावना एक सहायक मीट्रिक नहीं होगी। इसके बजाय, हम एर्गोडिक क्षमता का उपयोग करते हैं।

हम निष्कर्ष निकालते हैं कि ईसीसी स्लो फेडिंग चैनल में बिट त्रुटि दर (बीईआर) के प्रदर्शन को खराब करता है। हालांकि, इस तरह के चैनल के लिए, इंटरलीवर के साथ ईसीसी का संयोजन बर्स्ट त्रुटियों को कम करता है और प्रदर्शन में सुधार करता है, जिससे सकारात्मक कोडिंग लाभ होता है। फास्ट फेडिंग

चैनल में कोडिंग लाभ ज्यादा नहीं है और विभिन्न टर्बुलेन्स की स्थिति में लगभग समान रहता है। हमारे द्वारा उपयोग किए गए दो कोडों में से, गणना किए गए परिणामों से यह देखा गया है कि एलडीपीसी कोड ने बीसीएच कोड की तुलना में सभी परिदृश्यों में बेहतर प्रदर्शन दिखाया है। इस प्रकार, एफएसओ चैनल के लिए एलडीपीसी कोड को और अधिक ऑप्टिमाइज़ करना एक स्वाभाविक मार्ग है।

एक अस्वाभाविक रूप से लंबी-लंबाई वाले एलडीपीसी कोड के बीईआर प्रदर्शन का विश्लेषण बिलीफ प्रोपगेशन (बीपी) एल्गोरिथम के घनत्व विकास विश्लेषण के साथ किया जाता है। जब हम एलडीपीसी कोड के बीईआर प्रदर्शन का अनुमान लगाते हैं, तो थ्रेशोल्ड शब्द उभरता है, जो एसएनआर के कार्य के रूप में एक स्टेप इनवर्स प्रतिक्रिया का अनुसरण करता है। थ्रेशोल्ड एसएनआर है, जिसके बाद बीईआर अप्रत्याशित ढंग से गिरता है और शून्य के करीब हो जाता है। एफएसओ चैनल थ्रेशोल्ड का निर्धारण कठिन है क्योंकि लॉग-संभावना अनुपात के घनत्व को गॉसियन के रूप में नहीं माना जा सकता है। इस प्रकार, इसे व्यवस्थित रूप से संभावित सीमा के रूप में एसएनआर के विभिन्न मूल्यों के परीक्षण की आवश्यकता होती है। इसलिए, हम डिवाइड एंड कॉन्कर एल्गोरिथम का प्रस्ताव करते हैं। थ्रेशोल्ड, डिग्री वितरण, चैनल सूचना स्थिति (सीएसआई), और टर्बुलेन्स स्तर पर निर्भर करता है। जब सीएसआई ज्ञात होता है, तो हम नियमित (३, ६) एलडीपीसी कोड के लिए शक्तिशाली टर्बुलेन्स में ८. १० डीबी के एसएनआर पर थ्रेशोल्ड प्राप्त करते हैं। यह सीमा १२. ४८ डीबी तक बढ़ जाती है जब सीएसआई रिसीवर पर अज्ञात होता है।

एफएसओ चैनल की क्षमता के करीब सीमा को प्राप्त करने के लिए, हमें एलडीपीसी कोड के लिए एक इष्टतम डिग्री वितरण की आवश्यकता है। हम एसएनआर या कोड दर को अनुकूलित करके अनियमित एलडीपीसी कोड के डिग्री वितरण प्राप्त करते हैं। एसएनआर-अनुकूलित चैनल में, हम उच्चतम संभव कोड दर पर ०.५ डीबी और ५ डीबी की थ्रेशोल्ड प्राप्त करने के लिए डिग्री वितरण प्राप्त करते हैं। इसके विपरीत, दर-अनुकूलित चैनल के लिए, हम न्यूनतम संभव थ्रेशोल्ड पर ०. ७५ और ०.८ की कोड दर लक्षित करते हैं। हम ५ डीबी थ्रेशोल्ड पर कमजोर और शक्तिशाली टर्बुलेन्स स्थिति में ०.५६ और ०. ४० की अधिकतम प्राप्य कोड दर प्राप्त करते हैं। दर-अनुकूलित मामले में, हम क्रमशः कमजोर और शक्तिशाली टर्बुलेन्स व्यवस्था में ११. ३० डीबी और १९. ९७ डीबी थ्रेशोल्ड पर ०. ८ की आवश्यक कोड दर प्राप्त करते हैं। यह काम एफएसओ चैनल पर अनुकूली कोडिंग की अवधारणा पर जोर देता है। हमने दिखाया है कि ईसीसी फास्ट फेडिंग चैनल में अच्छा प्रदर्शन करते हैं। जब हम स्थानिक विविधता का उपयोग करते हैं, तो फास्ट फेडिंग चैनल के समान प्रभाव प्राप्त किया जा सकता है। हम रिसीवर विविधता और बहु-इनपुट बहु-आउटपुट सिस्टम में एलडीपीसी कोड की क्षमता और बीईआर प्रदर्शित करते हैं।

शोध प्रबंध में, हम इस बात पर जोर देते हैं कि चैनल का चुनाव ईसीसी के प्रदर्शन को अत्यधिक प्रभावित करता है, और एक इंटरलीवर के साथ कोड का संयोजन एफएसओ चैनल के लिए शोधकर्ताओं के बीच एक लोकप्रिय विकल्प है। एक इंटरलीवर के साथ स्लो फेडिंग चैनल अनुमेय संचार सीमा से परे विलंबता को बढ़ाता है और यह एक व्यावहारिक समाधान नहीं है। इसलिए, हम एक नई और प्रभावी योजना प्रस्तावित करते हैं, जिसे चैनल असिस्टेड कोडिंग (सीएसी) कहा जाता है, जिसमें हम चैनल गुणांक के साथ बिट्स की डिग्री को जोड़ते हैं। सीएसी-एलडीपीसी कोडिंग सिस्टम के साथ, हम किसी भी इंटरलीविंग प्रेरित विलंबता को कम करते हैं। मैटलैब सिमुलेशन से पता चलता है कि शक्तिशाली टर्बुलेन्स में एलडीपीसी इंटरलीव्ड सिस्टम की तुलना में सीएसी-एलडीपीसी ३२ स्थानिक लिंक के साथ लगभग १३.७ डीबी का कोडिंग लाभ प्राप्त करता है। सीएसी-एलडीपीसी के प्रदर्शन को दर्शाने के लिए हम तीन विश्लेषणात्मक मॉडल प्रस्तावित करते हैं। विश्लेषणात्मक परिणाम सिमुलेशन अध्ययन का समर्थन करते हैं।

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LIST OF ACRONYMS

A

APD	Avalanche Photodiode
APP	Aposteriori Probability
AWGN	Additive White Gaussian Noise

B

BER	Bit Error Rate
BCH	Bose–Chaudhuri–Hocquenghem
BP	Belief Propagation
BLBC	Binary Linear Block Code
BNs	Bit Nodes
BCJR	Bahl, Cocke, Jelinek and Raviv

C

CSI	Channel State Information
CAC	Channel-Assisted Coding
CNs	Check Nodes

D

DD	Direct Detection
----	------------------

E

EB	Exabyte
E/O	Electrical to Optical
ECCs	Error-Correcting Codes
EXIT	Extrinsic Information Transfer
EGC	Equal Gain Combiner

F

FSO	Free-Space Optical
FEC	Forward Error Correction

G

GB	Gigabyte
GG	Gamma-Gamma

I

ITU	International Telecommunication Union
IR	Infra-Red
IM	Intensity Modulation
IID	Independent Identically Distributed

L

LED	Light Emitting Diode
LLR	Log Likelihood Ratio
LDPC	Low-Density Parity-Check
LP	Linear Programming

M

MIMO	Multiple-Input Multiple-Output
------	--------------------------------

O

OWC	Optical Wireless Communication
OOK	On-Off Keying
O/E	Optical to Electrical

OAM	Orbital Angular Momentum
OFDM	Orthogonal Frequency Division Multiplexing

P

PIN	Positive-Intrinsic-Negative
PDF	Probability Density Function
PAM	Pulse Amplitude Modulation
PPM	Pulse Position Modulation
PCM	Parity-Check Matrix

Q

QAM	Quadrature Amplitude Modulation
-----	---------------------------------

R

RF	Radio Frequency
RCs	Repetition Codes
RS	Reed Solomon

S

SNR	Signal-to-Noise Ratio
SPCCs	Single Parity-Check Codes
SP	Sum-Product
SPC	Single Parity-Check
SISO	Single Input Single Output
SIMO	Single Input Multiple Output
SFBI	Slow-Fading Binary-Input

W

WDM	Wavelength Division Multiplexing
-----	----------------------------------