

**DESIGN OF NOVEL OCDMA CODESETS AND THEIR
PERFORMANCE ANALYSIS FOR WIRELESS OPTICAL
NETWORKS**

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by

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Bharti School of Telecommunication Technology and Management

Submitted

in fulfillment of the requirements of the degree of Doctor of Philosophy

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Certificate

This is to certify that the thesis titled “**Design of Novel OCDMA Codesets and their Performance Analysis for Wireless Optical Networks**” being submitted by **Mr. Ajay Yadav** to the Bharti School of Telecommunication Technology and Management, 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 him under our supervision. In our 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

A new 2-D one-coincidence frequency hopping code/congruence codes (OCFHC/ CCs) family of codes is proposed where OCFHC is used for wavelength hopping and CCs are used for time spreading. In the code family, the optical code with cross-correlation value of two i.e., OCFHC/quadratic congruence code (OCFHC/QCC) is superior to the other codes. So, OCFHC/QCC is used for performance evaluation and comparison with the existing 2-D optical codes. Initially, the performance is evaluated considering multiple access interference (MAI) as the only performance degradation factor in the 2-D OCDMA system. In presence of MAI, the effect of variation in code weight, code length, number of available wavelengths on the error probability of 2-D OCDMA system is studied. When code weight, code length, and number of available wavelengths are same, performance of OCFHC/QCC is superior to the existing optical codes. Also, simple design and large cardinality of OCFHC/QCC favors its use over the existing optical codes for multicode keying and multi-rate multimedia applications. Improvement in error probability of the order of 10^{-1} is possible with OCFHC/QCC as compared to synchronous prime code/optical orthogonal code, when the number of simultaneous users are less than twenty. Thus, OCFHC/QCC based OCDMA system can be used for wireless optical access networks. Further, the performance is also evaluated and compared with the existing optical codes considering the effect of MAI and noise using photon-count approach in the fiber-optic medium.

OCFHC/QCC performance is analyzed without a hard limiter in presence of MAI, noise, turbulence, and different weather conditions. The atmospheric turbulence is divided into weak, moderate, and strong turbulence and the weather conditions which have been considered are clear air, haze, light mist, and light fog with a link length 1000 m and data rate 1 Gbps. With weak turbulence, haze and clear air as the weather conditions, the error probability of less than 10^{-3} is achievable when transmitted power is 0.4 dBm for two user 2-D OCDMA system. The error probability is greater than 10^{-3} in presence of moderate and strong turbulence with various weather conditions. Further, we have compared the

performance of four user 1-D OOC- and 2-D OCFHC/OOC-OCDMA systems in presence of turbulence and various weather conditions. The error probability of 1-D OCDMA system is above 10^{-3} irrespective of turbulence regime and weather condition. However, the 2-D OCFHC/OOC-OCDMA system performs better than the 1-D OOC-OCDMA system and its error probability is below 10^{-3} in the weak turbulence regime and weather conditions-clear air and haze. So, the four user 2-D and 1-D OCDMA systems may not work satisfactorily in presence of turbulence and/or various weather conditions. The performance of the OCDMA system can be improved by using performance enhancement techniques.

The performance of 2-D atmospheric OCDMA system is enhanced by using double hard limiter, aperture averaging (AA), spatial diversity, and error correcting code. Two hard limiters, one before the decoder and another post decoder, are used to improve the performance of OCFHC/QCC based OCDMA system in presence of turbulence and different weather conditions. The double hard-limited performance is much superior to the performance with the single hard limiter. Further, an increase in the receiver aperture diameter from 2 to 10 cm also shows performance improvement due to AA. With receiver aperture diameter of 8 cm, the performance is further improved using spatial diversity. The double hard-limited eight user 2-D atmospheric OCDMA system has error probability of 10^{-6} in clear air, haze and light mist with spatial diversity in all turbulence regimes. Further, an error probability below 10^{-6} is achievable in presence of weak turbulence and light fog but not in presence moderate and strong turbulence.

The performance of 2-D atmospheric OCDMA system with hard limiter, spatial diversity, and error correcting code is compared to the performance without hard limiter in presence of turbulence. The performance of the system with spatial diversity and error correcting code is better than the performance without hard limiter above a fixed transmitted power. The improvement in the error probability is highest with the error correcting code when the transmitted power is beyond a fixed value in the weak turbulence regime. The performance enhancement is lowest with the spatial diversity as compared to the other performance enhancing techniques. Overall, the performance with double hard limiter is superior to the performance without hard limiter irrespective of transmitted power and turbulence regimes.

सार

एक नया 2-डी एक-संयोग आवृत्ति होपिंग कोड / संयोग कोड (ओसीएफएचसी/सीसी) के परिवार का प्रस्ताव है जहां ओसीएफएचसी का उपयोग तरंग दैर्घ्य होपिंग और सीसी का समय फैलाने के लिए किया जाता है। कोड परिवार में, क्रॉस-सहसंबंध मूल्य के साथ ऑप्टिकल कोड दो यानी, ओसीएफएचसी/वर्गबद्ध संयोग कोड (ओसीएफएचसी / क्यूसीसी) अन्य कोड से बेहतर है। इसलिए, ओसीएफएचसी/क्यूसीसी का प्रदर्शन प्रदर्शन मूल्यांकन और मौजूदा 2-डी ऑप्टिकल कोड के साथ तुलना के लिए किया जाता है। प्रारंभ में, 2-डी ओसीडीएमए प्रणाली में एकमात्र प्रदर्शन गिरावट कारक के रूप में एकाधिक एक्सेस हस्तक्षेप (एमएआई) पर विचार करने पर प्रदर्शन का मूल्यांकन किया जाता है। एमएआई की उपस्थिति में, कोड वजन, कोड की लंबाई में भिन्नता का प्रभाव, 2-डी ओसीडीएमए प्रणाली की त्रुटि संभावना पर उपलब्ध तरंग दैर्घ्य की संख्या का अध्ययन किया जाता है। जब कोड वजन, कोड की लंबाई, और उपलब्ध तरंग दैर्घ्य की संख्या समान होती है, तो ओसीएफएचसी/क्यूसीसी का प्रदर्शन मौजूदा ऑप्टिकल कोड से बेहतर होता है। इसके अलावा, ओसीएफएचसी/क्यूसीसी की सरल डिजाइन और बड़ी कार्डिनिटी मल्टीकोड कुंजीयन और बहु-दर मल्टीमीडिया अनुप्रयोगों के लिए मौजूदा ऑप्टिकल कोड पर इसका उपयोग अधिक करती है। 10^{-1} के क्रम की त्रुटि संभावना में सुधार ओसीएफएचसी/क्यूसीसी के साथ सिंक्रोनस प्राइम कोड/ऑप्टिकल ऑर्थोगोनल कोड की तुलना में संभव है, जब एक साथ उपयोगकर्ता की संख्या बीस से कम हो। इस प्रकार, ओसीएफएचसी/क्यूसीसी आधारित ओसीडीएमए सिस्टम वायरलेस ऑप्टिकल एक्सेस नेटवर्क के लिए इस्तेमाल किया जा सकता है। इसके अलावा, निष्पादन का मूल्यांकन और फाइबर ऑप्टिक माध्यम में फोटॉन-गिनती दृष्टिकोण का उपयोग करते हुए एमएआई और शोर के प्रभाव पर विचार करने वाले मौजूदा ऑप्टिकल कोडों की तुलना में किया जाता है।

ओसीएफएचसी / क्यूसीसी प्रदर्शन का विश्लेषण एमएआई, शोर, अशांति, और विभिन्न मौसम स्थितियों की उपस्थिति में हार्ड लिमिटर के बिना किया जाता है। वायुमंडलीय अशांति को कमजोर, मध्यम, और मजबूत अशांति में विभाजित किया गया है और मौसम की स्थितियों- स्पष्ट हवा, धुंध, हल्की धुंध, और हल्का कोहरा के साथ एक लिंक लंबाई 1000 मीटर और डेटा दर 1 जीबीपीएस है। मौसम की स्थिति के रूप में कमजोर अशांति, धुंध और स्पष्ट हवा के साथ, 10^{-3} से कम की त्रुटि संभावना तब प्राप्त हो सकती है जब संक्रमित शक्ति दो उपयोगकर्ता 2-डी ओसीडीएमए प्रणाली के लिए 0.4 डीबीएम है। विभिन्न मौसम स्थितियों के साथ मध्यम और मजबूत अशांति की उपस्थिति में त्रुटि संभावना 10^{-3} से अधिक है। इसके अलावा, हमने अशांति और विभिन्न मौसम स्थितियों की उपस्थिति में चार उपयोगकर्ता 1-डी ओओसी- और 2-डी ओसीएफएचसी/ओओसी-ओसीडीएमए सिस्टम के प्रदर्शन की तुलना की है। अशांति शासन और मौसम की स्थिति के बावजूद 1-डी ओसीडीएमए प्रणाली की त्रुटि संभावना 10^{-3} से ऊपर है। हालांकि, 2-डी ओसीएफएचसी/ओओसी-ओसीडीएमए प्रणाली 1-डी ओओसी-ओसीडीएमए प्रणाली से बेहतर प्रदर्शन करती है और कमजोर अशांति शासन और मौसम की स्थिति-साफ हवा और धुंध में इसकी त्रुटि संभावना 10^{-3} से कम है। इसलिए, चार उपयोगकर्ता 2-डी और 1-डी ओसीडीएमए

सिस्टम अशांति और/या विभिन्न मौसम स्थितियों की उपस्थिति में संतोषजनक ढंग से काम नहीं कर सकते हैं। प्रदर्शन वृद्धि तकनीकों का उपयोग करके ओसीडीएमए प्रणाली का प्रदर्शन सुधार किया जा सकता है। 2-डी वायुमंडलीय ओसीडीएमए प्रणाली का प्रदर्शन डबल हार्ड लिमिटर, एपर्चर औसत (एए), स्थानिक विविधता, और कोड को सही करने में त्रुटि का उपयोग करके बढ़ाया जाता है। डिकोडर से पहले और एक अन्य डिकोडर बाद दो हार्ड लिमिटर, अशांति और विभिन्न मौसम स्थितियों की उपस्थिति में ओसीएफएचसी/क्यूसीसी आधारित ओसीडीएमए प्रणाली के प्रदर्शन में सुधार के लिए उपयोग की जाती हैं। डबल हार्ड-सीमित प्रदर्शन एकल हार्ड लिमिटर के प्रदर्शन के मुकाबले बहुत बेहतर है। इसके अलावा, रिसीवर एपर्चर में वृद्धि 2 से 10 सेमी व्यास भी एए के कारण प्रदर्शन सुधार दिखाता है। 8 सेमी की रिसीवर एपर्चर व्यास के साथ, स्थानिक विविधता का उपयोग करके प्रदर्शन को और बेहतर किया जाता है। डबल हार्ड-सीमित आठ उपयोगकर्ता 2-डी वायुमंडलीय ओसीडीएमए प्रणाली में सभी अशांति शासनों में स्थानिक विविधता के साथ स्पष्ट हवा, धुंध और हल्की धुंध में 10^{-6} की त्रुटि संभावना है। इसके अलावा, 10^{-6} से नीचे एक त्रुटि संभावना कमजोर अशांति और प्रकाश कोहरे की उपस्थिति में प्राप्त करने योग्य है लेकिन उपस्थिति में मध्यम और मजबूत अशांति नहीं है।

हार्ड लिमिटर, स्थानिक विविधता, और कोड को सुधारने में त्रुटि के साथ 2-डी वायुमंडलीय ओसीडीएमए प्रणाली का प्रदर्शन अशांति की उपस्थिति में हार्ड लिमिटर के बिना प्रदर्शन की तुलना में किया जाता है। स्थानिक विविधता के साथ प्रणाली का प्रदर्शन और कोड को सही करने में त्रुटि एक निश्चित प्रेषित शक्ति के ऊपर हार्ड लिमिटर के बिना प्रदर्शन से बेहतर है। त्रुटि संभावना में सुधार कोड को सही करने में त्रुटि के साथ उच्चतम है जब प्रेषित शक्ति कमजोर अशांति शासन में एक निश्चित मूल्य से परे है। अन्य प्रदर्शन बढ़ाने तकनीकों की तुलना में प्रदर्शन विविधता स्थानिक विविधता के साथ सबसे कम है। कुल मिलाकर, डबल हार्ड लिमिटर के साथ प्रदर्शन संचारित शक्ति और अशांति शासन के बावजूद हार्ड लिमिटर के बिना प्रदर्शन से बेहतर है।

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List of Abbreviations

EDFA	Erbium-doped fiber amplifier
WDM	Wavelength division multiplexing
OCDMA	Optical code-division multiple access
TDM	Time division multiplexing
PON	Passive optical network
TDMA	Time division multiple access
ONU	Optical network unit
OLT	Optical line terminal
WDMA	Wavelength division multiple access
AWG	Array waveguide grating
FTTH	Fiber to the home
ISP	Internet service provider
DSL	Digital subscriber line
WiFi	Wireless fidelity
WiMAX	Worldwide interoperability for microwave access
FTTx	Fiber-to-the-x
CO	Central office
FTTN	Fiber-to-the-node
PSTN	Public switched telephone network
EPON	Ethernet PON
APON	ATM PON
IP	Internet protocol
CWDM	Course WDM
DWDM	Dense WDM
NGPON	Next generation PON

GE-PON	Gigabit ethernet PON
XG-PON	10-Gigabit-capable PON
OFDMA	Orthogonal fiber division multiple access
FSO	Free space optical
LAN	Local area network
LED	Light emitting diode
MZI	Mach-Zehnder interferometet
OOK	On-off keying
BLL	Beer lambert's law
pdf	probability density function
WOC	Wireless optical communication
MAN	Metropolitan area network
PC	Prime code
MAI	Multiple-access interference
1-D	One-dimensional
2-D	Two-dimensional
3-D	Three-dimensional
PPM	Pulse position modulation
OOC	Optical orthogonal code
LCC	Linear congruence code
QCC	Quadratic congruence code
HCC	Hyperbolic congruence code
CCC	Cubic congruence code
WH/TS	Wavelength-hopping / time-spreading
MWOOC	Multiple wavelength optical orthogonal code
PC/EQCC	PC/extended quadratic congruence code
OCFHC/OOC	One-coincidence frequency hopping code/ OOC
B/U	Bipolar/unipolar
B/B	Bipolar/bipolar
FSOCDMA	Free space optical code division multiple access
HL	Hard limiter
OHL	Optical hard limiter
PFS-ER	Proportional fair scheduling with exponential rate

SISO	Single input single output
SIMO	Single input multiple output
MISO	Multiple input single output
MIMO	Multiple input multiple output
ASE	Amplified spontaneous emission
MRC	Maximal ratio combining
EQC	Equal gain combining
SDRT	Spatial diversity reception technology
LDPC	Low density parity check
MUI	Multiple user interference
CHPC	Carrier hopping prime code
OCFHC/CC	One coincidence frequency hopping code/cubic congruence
OCFHC/NCCC	One coincidence frequency hopping code/new cubic congruence code
OCFHC/QCC	One coincidence frequency hopping code/Quadratic congruence code
syn PC/QCC	Synchronous prime code/quadratic congruence code
PC/OOC	Prime code/optical orthogonal code
APD	Avalanche photodiode
AA	Aperture averaging
FFH	Fast frequency hopping
MAN	Metropolitan area network