UNIVERSITI PUTRA MALAYSIA

IMPACTS OF NONLINEAR STIMULATED RAMAN SCATTERING ON THE PERFORMANCE OF OPTICAL CODEDIVISION MULTIPLE-ACCESS TRANSMISSION SYSTEMS

ZAINEB A. TAQI AL-QAZWINI

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By

ZAINEB A. TAQI AL-QAZWINI

Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia, in Fulfilment of the Requirement for the Degree of Master of Science

May 2008

Dedicated to

My Dear Sick Father
and
My Dear Patient Mother

Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfilment of the requirement for the degree of Master of Science

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Chairman: Professor Mohamad Khazani Abdullah, PhD

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Code-division multiple access (CDMA) is a well-known scheme for multiplexing communication channels that is based on the method of direct-sequence spread spectrum. This concept was introduced into fiber optic communication systems in the middle of 1980's as optical CDMA (OCDMA), where encoding and decoding operations are all performed in optical domain using optical devices and large number of users with asynchronous access capability. In addition to the good performance at high number of users and asynchronous access to the network, OCDMA systems provide the users with high security by coding the data before transmission and at the same time using this code to recover the data at the receiver.

However, there are various nonlinear effects that limit the performance of OCDMA systems. In particular, nonlinear stimulated Raman scattering (SRS) causes the optical power from one mode to be transferred in the forward direction to the same, or other modes, at a different frequency. The process of SRS can severely limit the performance of multi-channel communication systems through the transfer of energy between the signals at different wavelengths.

The main motivation behind this research is the need to understand signal distortion due to SRS in OCDMA transmission systems. Specially, there is no real attention paid to investigate this issue in OCDMA systems while most of researches that study nonlinear effects are based on wavelength-division multiplexing (WDM) systems. Therefore, this work is attempting to understand SRS effects on the performance of OCDMA systems as a function of system design parameters (i.e. power per chip, transmission distance, and number of users), and hence, to determine the fundamental transmission limits in OCDMA systems in the presence of SRS nonlinear effects. The system performance is evaluated by measuring the bit-error-rate (BER) and tilt ratio which indicates the power transfer between the chips at different wavelength.

It is demonstrated through numerical simulations that the performance of OCDMA systems, at high input powers, large number of users and/or long transmission distances, is significantly degraded due to SRS effects. Furthermore, the transmission limits to keep the performance of the system under study within acceptable levels in the presence of SRS effects is estimated according to the BER threshold of 10^{-9} and 10^{-12}.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia
sebagai memenuhi keperluan untuk ijazah Master Sains

MENGKAJI KESAN RANGSANGAN TAK LINEAR SERAKAN RAMAN KE ATAS PRESTASI SISTEM PENGHANTARAN PEMBAHAGIAN KOD OPTIK PELBAGAI CAPAIAN (OCDMA)

Oleh

ZAINEB A. TAQI AL-QAZWINI

Mei 2008

Pengerusi: Professor Mohamad Khazani Abdullah, Ph.D

Fakulti: Kejuruteraan

Sistem pembahagian kod pelbagai capaian (CDMA) adalah kaedah yang terkenal di dalam saluran pemultipleksan komunikasi berasaskan kaedah spektrum rebak jujukan langsung. Konsep ini mula diperkenalkan dalam sistem gentian optik pada pertengahan 1980- an dan dikenali sebagai pembahagian kod optik pelbagai capaian (OCDMA). Dalam sistem ini proses pengekodan dan penyahkodan dilakukan dalam domain optik dengan menggunakan peranti optik dan pengguna yang ramai dengan keupayaan capaian tak segerak. Selain kelebihan menyokong pengguna yang ramai dalam capaian tak segerak, sistem OCDMA turut menyediakan kawalan sekuriti yang tinggi dengan mengekod data sebelum dihantar dan menyahkod data tersebut pada terminal penerima.

Walau bagaimanapun, terdapat beberapa kesan tak linear yang menghadkan prestasi sistem OCDMA. Rangsangan tak linear serakan Raman (SRS)

menyebabkan kuasa optik dari satu mod berpindah ke arah depan mod yang sama atau mod berlainan pada frekuensi berbeza. Proses SRS ini menyebabkan kehilangan kuasa yang besar di dalam gentian terutamanya dengan masukan kuasa yang tinggi. Selain itu, ia juga boleh membataskan prestasi sistem telekomunikasi berbilang saluran melalui pemindahan tenaga antara cip-cip pada pelbagai panjang gelombang .

Dorongan utama dalam penyelidikan ini adalah untuk memahami dan mengurangkan herotan isyarat yang disebabkan oleh SRS di dalam sistem OCDMA. Tambahan pula, kurang isu penyelidikan ini dalam sistem OCDMA kerana kebanyakan penyelidikan mengkaji kesan-kesan tak sekata berdasarkan gelombang bahagian multipleksan (WDM). Projek ini adalah untuk memahami kesan SRS ke atas prestasi sistem OCDMA sebagai fungsi parameter rekabentuk (seperti kuasa per cip, jarak, dan bilangan pengguna) maka untuk menentukan asas had penghantaran di dalam sistem OCDMA dengan kehadiran kesan tak linear SRS. Prestasi sistem dinilai dengan cara pengukur kadar ralat bit (BER) dan nisbah herotan pindahan kuasa antara cip-cip berbanding panjang gelombang berbeza.

Ini telah ditunjukan melalui kaedah simulasi ke atas prestasi sistem OCDMA, iaitu pada masukan kuasa yang tinggi, bilangan pengguna yang besar dan/atau jarak yang jauh, ternyata prestasi sistem merosot disebabkan kesan SRS. Tambahan pula, had penghantaran bagi prestasi bawah kajian dengan sistem pelbagai tahap dalam tempoh terima dengan kehadiran kesan tak linear SRS boleh dianggarkan menurut ambang BER 10^{-9}dan10^{-12}.

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I certify that Examination Committee met on 21st May 2008 to conduct the final examination of Zaineb A. Taqi Al-Qazwini on her Master of Science thesis entitled "The Impacts of Nonlinear Stimulated Raman Scattering on the Performance of Optical Code-Division Multiple Access Transmission Systems" in accordance with Universiti Pertanian Malaysia (Higher Degree) Act 1980 and Universiti Pertanian Malaysia (Higher Degree) Regulations 1981. The Committee recommends that the candidate be awarded the relevant degree. Members of the Examination Committee are as follows:

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DECLARATION

I hereby declare that the thesis is based on my original work except for quotations and citations which have been duly acknowledged. I also declare that it has not been previously or concurrently submitted for any other degree at UPM or other institutions.

ZAINEB A. TAQI AL-QAZWINI

Date: 19 June 2008

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LIST OF ABBREVIATIONS

AWG	Arrayed-Waveguide Grating
BER	Bit-Error Rate
CDM	Code-Division Multiplexing
CDMA	Code-Division Multiple Access
DCM/Diff.D	Double Carrier Modulation with Differential Detection
DW	Double-Weight
EDFA	Erbium-Doped Fiber Amplifier
FBG	Fiber Bragg Grating
FDM	Frequency-Division Multiplexing
FDMA	Frequency-Division Multiple Access
FFT	Fast Fourier Transform
FODL	Fiber-Optic Delay Line
FWM	Four-Wave Mixing
GVD	Group-Velocity Dispersion
IM/DD	Intensity Modulation with Direct Detection
KS	Khazani-Syed
LAN	Local Area Network
LED	Light-Emitting Diode
MAI	Multiple-Access Interference
MAN	Metropolitan Area Network
MDW	Modified Double-Weight
MEMS	Micro-Electromechanical System
MFH	Modified Frequency Hopping
MKS	Meter-Kilogram-Second
MQC	Modified Quadratic Congruence

NDSF	Non-Dispersion Shifted Fiber
NLS	Nonlinear Schrödinger
NOLM	Nonlinear Optical Loop Mirror
NRZ	Non-Return-to-Zero
OCDMA	Optical Code-Division Multiple Access
OOC	Optical Orthogonal Code
OTDM	Optical Time-Division Multiplexing
OTDMA	Optical Time-Division Multiple Access
PIIN	Phase Induced Intensity noise
PLC	Planar Lightwave Circuit
PMD	Polarization Mode Dispersion
PSK	Phase-Shift Keying
RK2	Runge-Kutta 2^{nd} Order
RK4	Runge-Kutta 4^{th} Order
SAC	Spectral-Amplitude-Coding
SAN	Storage Area Network
SBS	Stimulated Brillouin Scattering
SC	Spatial-Coding
SCM	Sub-Carrier Multiplexing
SIR	Signal-to-Interference Noise Ratio
SLD	Super-Luminescence Diode
SLM	Spatial Light Modulator
SNR	Signal-to-Noise Ratio
SPC-OCDMA	Spectral-Phase-Coded OCDMA
SPM	Self-Phase Modulation
SRS	Stimulated Raman Scattering
SSFBG	Super-Structured Fiber Bragg Grating

TDM	Time-Division Multiplexing
TDMA	Time-Division Multiple Access
TOD	Third-Order Dispersion
TPC-OCDMA	Temporal-Phase-Coded OCDMA
TS	Time-Spreading or Temporal-Spreading
WDM	Wavelength-Division Multiplexing
WDMA	Wavelength-Division Multiple Access
WHTS	Wavelength-Hopping Time-Spreading OCDMA
XPM	Cross-Phase Modulation

CHAPTER 1

INTRODUCTION

1.1 Background

Optical fiber networking is one way of meeting the growing demand for the provision of a range of telecommunication services. At the core of the development is the huge inherent bandwidth of the single mode optical fiber that can support up to several terabits transmission capacity. Since the speed at which electrical signals can modulate optical carriers is limited, optical multiplexing techniques have to be employed to exploit the full transmission capacity (Huang and Andonovic, 1998).

Code-division multiple access (CDMA) is a well-known scheme for multiplexing communication channels that is based on the method of direct-sequence spread spectrum. In CDMA, every channel is identified by a unique pseudo-noise key, whose bandwidth is much larger than that of the input data. Ideally, the key should mimic the correlation properties of white noise and should be as long as possible in order to minimize the interference noise introduced by other channels (Pe'er *et al*., 2004). This concept was introduced into fiber optic communication systems in the middle of 80's as optical CDMA (OCDMA), where encoding and decoding operations are all performed in optical domain using optical devices and large number of users with asynchronous access capability (Fsaifes *et al*., 2006) (Wang *et al*., 2004). In addition to the good performance at high number of users and asynchronous access to the network, OCDMA systems provide the users with high security by coding the data before transmission and then using this code to recover the data at the receiver (Hamarsheh *et al*., 2005).

However, there are various nonlinear effects that limit the performance of OCDMA systems. Optical nonlinearities in fibers fall mainly into two categories; stimulated scattering processes and Kerr effect. Stimulated scattering such as stimulated Raman scattering (SRS) and Brillouin scattering (SBS) leads to intensity-dependent gain or loss. In contrast, the Kerr effect gives rise to an intensity-dependent phase shift of the optical fields (Kaminow and Li, 2002b) (Iannone *et al*., 1998).

In particular, SRS causes the optical power from one mode to be transferred in the forward direction to the same, or other modes, at a different frequency. It depends critically upon the optical power density within the fiber and hence only becomes significant above some threshold power levels (Senior, 1992). The process of SRS leads to a significant loss of signal energy in the fiber, especially at high input powers (Eckert, 2001). Furthermore, SRS can severely limit the performance of multi-channel communication systems through the transfer of energy between the channels separated by the frequency offsets within the Raman gain spectrum, leading to wavelength-dependent loss, with short wavelengths losing power to the longer wavelengths (Kaminow and Li, 2002a) (Wang *et al*., 1998).

1.2 Problem Statement and Motivation

Optical waveguides do not always behave as completely linear channels whose increase in output optical power is directly proportional to the input optical power (Senior, 1992). Systems where there are strong economic incentives to increase inter-amplifier span lengths and distances between electronic regenerators must have correspondingly high channel powers and, thus, optical intensities to achieve sufficiently high signal-to-noise ratios (SNR) (Kaminow and Li, 2002b). All of these system requirements give rise to SRS effects which can severely limit the performance of multi-channel communication systems through the transfer of energy between the channels at different wavelengths (Headley and Agrawal, 2005).

Particularly, Spectral-Amplitude-Coding OCDMA (SAC-OCDMA) systems are expected to be significantly limited due to SRS effects. In any SAC-OCDMA system, multiple chips propagate simultaneously at different wavelengths into the fiber. During that, SRS process affects those chips by inducing power depletion from shorter- to longer-wavelength chips resulting in a spectral tilt in the transmitted chips. SRS-induced tilt becomes more significant as number of users increases mainly due to total power growth. Furthermore, SRS-induced effects evolve as fiber length increases. Therefore, number of users and transmission distance that can be supported by an SAC-OCDMA system are significantly limited by SRS effects.

The main motivation behind this research is the need to understand signal distortion due to SRS in OCDMA transmission systems. Specially, most of researches that study nonlinear effects are based on wavelength-division multiplexing (WDM) systems and there is no real attention paid to investigate this issue in OCDMA systems. Therefore, this work is attempting to understand SRS effects on the performance of OCDMA systems as a function of system parameters, and hence, to determine the fundamental transmission limits in these systems in the presence of SRS effects.

1.3 Scope of Work

This study is focused on SRS nonlinear effects in OCDMA transmission systems. The design parameters involved in this study are power per chip, transmission distance, and number of users. On the other hand, the performance parameters used are tilt ratio and bit-error-rate (BER). SAC-OCDMA system based on direct-decoding scheme is used with Khazani-Syed code (KS-code) throughout this study.

Extensive investigations are performed through computer simulations to study the performance of these OCDMA systems and the fundamental transmission limits in the presence of SRS effects. Figure 1.1 shows the study structure of this research. The shaded color pattern expresses the scope of work.

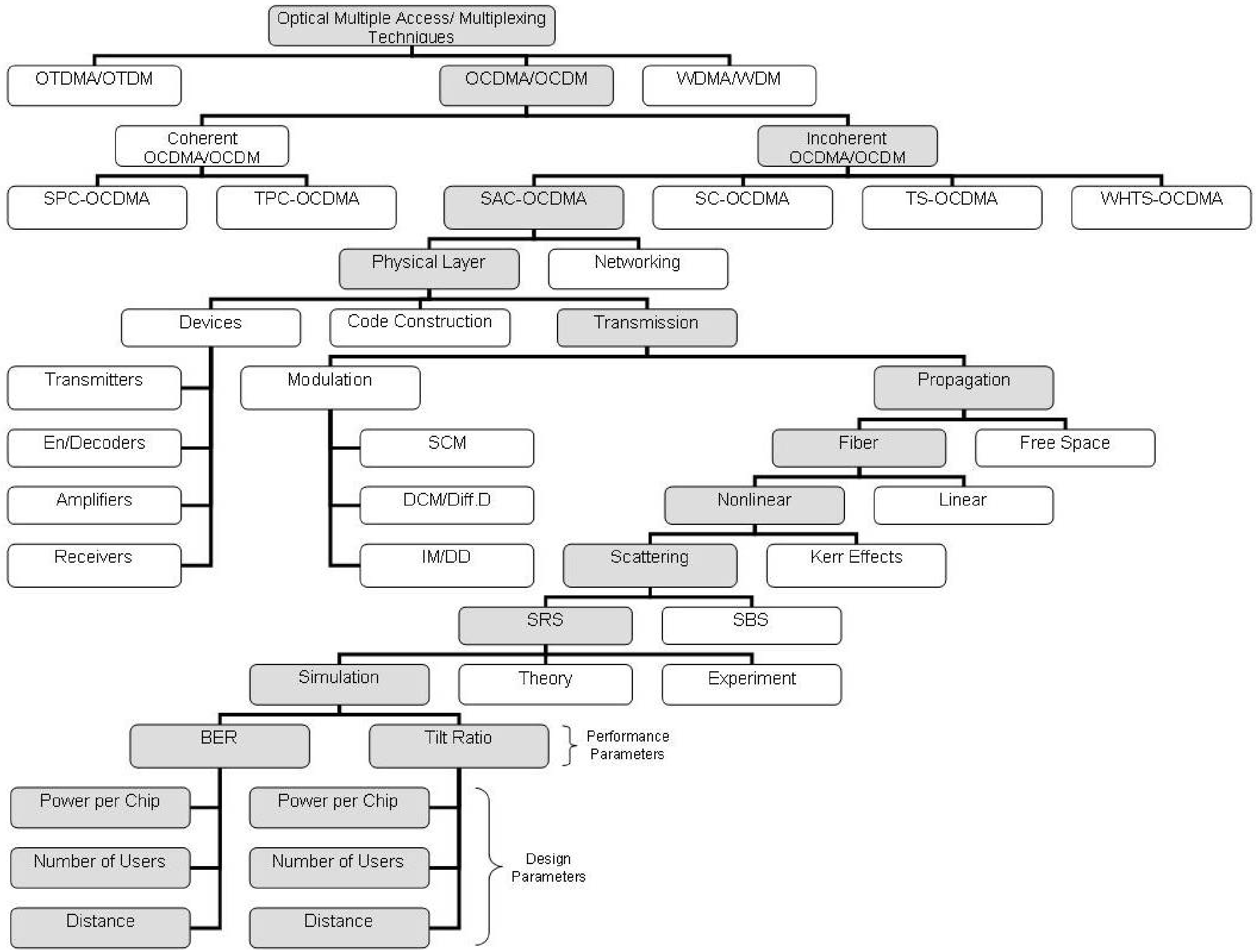

Figure 1.1: A General Study Model for the Research Work