UNIVERSITI PUTRA MALAYSIA

AN ADAPTIVE ERROR CORRECTION SCHEME FOR SYNCHRONOUS DIGITAL HIERARCHY-BASED WAVELENGTH DIVISION MULTIPLEXED OPTICAL NETWORK

CHEAH CHENG LAI

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By

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Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia, in Fulfilment of the Requirements for the Degree of Doctor of Philosophy

November 2007

To Siew Yeng, Zhiyi, Huiyang and Zhiheng

Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfilment of the requirement for the degree of Doctor of Philosophy

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In optical communications there are a variety of noise and distortion sources which can cause errors. These errors become essential and more intense in the high-capacity and long-haul wavelength-division multiplexing (WDM) systems. Therefore, the development of a forward error correction (FEC) technique to mitigate errors in WDM optical networks is very relevant and important.

The existing FEC techniques for optical communications are based on fixed codes, which consume unnecessary overhead bandwidth even when there are no errors. This thesis proposes an adaptive forward error correction (AFEC) scheme for synchronous digital hierarchy (SDH)-based WDM optical networks, referred to as the SDH-AFEC. The scheme supports adaptive codes because it uses a dedicated WDM channel for transmission of different sizes of FEC redundancy for the payloads. Unlike most previous adaptive FEC techniques which change to a stronger code after an error has occurred, the SDH-AFEC is able to do so before an error occurs. This is achieved by using the combination of B2 error and corrected error

count as the input parameters for the algorithm. Then the algorithm is designed in such a way that it adaptively assigns a suitable value of error correction capability, t for error correction, and the number of corrected errors is maintained not exceeding $t/2$.

The SDH-AFEC adopts Bose–Chaudhuri–Hocquenghem (BCH) and Reed–Solomon (RS) codes for correcting random and burst errors respectively. A new technique is also proposed for estimation of the error pattern so that a suitable type of code can be assigned accordingly. This technique is based on the analysis of the corrected error locations, referred to as the error location analysis (ELA).

Simulation results show that the SDH-AFEC is able to use different values of t adaptively for error correction. It assigns stronger t with increasing channel bit error rate (BER) or average burst length (ABL) to maintain the output BER below the target BER of 10^{-9}, until the strongest value of t is assigned. The SDH-AFEC uses the maximum FEC overhead for high BER or long ABL. However, the FEC overhead requirement reduces with decreasing BER or ABL. Hence, in addition to the adaptive BER performance, the SDH-AFEC also provides a way to use the FEC overhead efficiently. Lastly, the results also show that by using ELA, the performance of the SDH-AFEC is further improved that it is able to correct about three times more random errors and three times longer burst length. Meanwhile, the average FEC overhead reduction after ELA is about 38% and 36% for random and burst errors respectively.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk ijazah Doktor Falsafah

SUATU SKIM PEMBETULAN RALAT MENYESUAI UNTUK RANGKAIAN OPTIK PEMULTIPLEKSAN PEMBAHAGIAN PANJANG GELOMBANG BERDASARKAN HIERARKI DIGITAL SEGERAK

Oleh

CHEAH CHENG LAI

November 2007

Pegerusi : Profesor Mohamad Khazani Abdullah, PhD

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Di dalam komunikasi optik terdapat pelbagai sumber hingar dan herotan yang menyebabkan ralat. Ralat ini menjadi lebih jelas dan hebat di dalam sistem pemultipleksan pembahagian panjang gelombang (WDM) yang berkapasiti tinggi dan berheretan panjang. Oleh kerana itu, pembinaan suatu skim pembetulan ralat depan (FEC) untuk meringankan ralat di dalam rangkaian-rangkaian optik WDM adalah sangat sesuai dan memainkan peranan yang amat penting.

Skim-skim FEC untuk komunikasi optik yang sedia ada berdasarkan kod tetap, dimana mereka menggunakan overhed lebar jalur yang tidak diperlukan walaupun tiada ralat. Tesis ini mencadangkan suatu skim penyesuaian FEC (AFEC) untuk rangkaian-rangkaian optik WDM berdasarkan hierarki digital segerak (SDH), dinamakan sebagai SDH-AFEC. Skim ini menyokong kod penyesuaian kerana ia menggunakan satu saluran WDM khusus untuk menghantar lebihan-lebihan FEC yang berlainan saiz untuk beban-bebannya. Berbeza dengan kebanyakan skim-skim penyesuian FEC yang terdahulu, dimana penukaran kepada suatu kod yang lebih

kuat terjadi hanya selepas ralat telah berlaku, SDH-AFEC boleh melakukan perkara seperti ini sebelum ralat berlaku. Ini dapat dicapai dengan menggunakan kombinasi ralat B2 dan bilangan ralat yang dibetulkan sebagai parameter input untuk algroritmanya. Kemudian mencorakkan algroritma ini supaya ia boleh menugaskan suatu nilai keupayaan pembetulan ralat, t yang sesuai secara penyesuaian untuk pembetulan ralat, dan bilangan ralat yang dibetulkan dikekalkan supaya tidak melebihi $t/2$.

SDH-AFEC menggunakan kod Bose–Chaudhuri–Hocquenghem (BCH) dan Reed–Solomon (RS) untuk membetulkan ralat-ralat rawak dan letusan masing-masing. Suatu teknik baru juga dicadangkan untuk penganggaran corak ralat supaya jenis code yang sesuai boleh ditugaskan seperti yang telah dinyatakan. Teknik ini adalah berdasarkan analisa lokasi-lokasi ralat yang telah dibetulkan, dinamakan sebagai analisa lokasi ralat (ELA).

Keputusan-keputusan simulasi menunjukan bahawa SDH-AFEC berupaya untuk menggunakan nilai t yang berlainan secara penyesuaian untuk pembetulan ralat. Ia menugaskan nilai t yang lebih kuat dengan kenaikan kadar ralat bit (BER) saluran atau purata panjang letusan (ABL) untuk mengekalkan BER keluaran dibawah BER sasaran, iaitu 10^{-9}, sehingga nilai t yang terkuat ditugaskan. SDH-AFEC memakai overhed FEC yang maksimum untuk BER yang tinggi atau ABL yang panjang. Akan tetapi, keperluan overhed FEC menurun dengan penurunan BER atau ABL. Justeru itu, tambahan daripada keupayaan pembetulan ralat secara penyesuaian, SDH-AFEC juga memperuntukan suatu cara menggunakan overhed FEC yang cekap. Akhir sekali, keputusan-keputusan juga menunjukkan bahawa dengan menggunakan ELA, keupayaan SDH-AFEC adalah ditingkatkan lagi, iaitu ia boleh memperbaiki tiga kali ganda lebih ralat-ralat rawak dan tiga kali lebih panjang letusan. Semenatra itu, keturunan overhed FEC purata selepas ELA adalah lebih kurang 38% dan 36% untuk ralat-ralat rawak dan letusan masing-masing.

ACKNOWLEDGEMENTS

I would like to take this opportunity to thank everyone who has directly or indirectly contributed to the research of this thesis. The following list, by no means exhaustive, is an attempt to acknowledge at least a few of them.

First and foremost, I wish to express my deepest gratitude and appreciation to Prof. Dr. Mohamad Khazani Abdullah, the chairman of the supervisory committee for his guidance, inspiration and many invaluable comments and suggestions throughout the research period.

I am grateful to the supervisory committee members Prof. Dr. Borhanuddin Mohd Ali and Associate Prof. Dr. Mohd Adzir Mahdi for their continual supervision, encouragement, invaluable comments and suggestions for carrying out the research in a proper manner.

I would like to thank Mr. Hor Huey Wu for his invaluable efforts and help in correcting various grammatical and typo errors throughout the thesis.

Finally, I wish take this opportunity to express my sincere gratitude to all my fellow friends in UPM Photonics Laboratory for their help, friendship and insightful discussions, especially to P'ng Won Tiang, Siti Barirah Ahmad Anas and Makhfudzah Mokhtar.

I certified that an Examination Committee has met on 2nd November 2007 to conduct the final examination of Cheah Cheng Lai on his Doctor of Philosophy thesis entitled "An Adaptive Error Correction Scheme for Synchronous Digital Hierarchy-Based Wavelength Division Multiplexed Optical Network" in accordance with Univesiti Pertanian Malaysia (Higher Degree) Act 1980 and Universiti Pertanian Malaysia (Higher Degree) Regulations 1981. The committee recommends that the student be awarded the degree of Doctor of Philosophy. Member of the Examination Committee were as follows:

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DECLARATION

I declare that the thesis is my original work except for quotations and citations which have been duly acknowledged. I also declare that it has not been previously, and is not concurrently, submitted for any other degree at Universiti Putra Malaysia or at any other institution.

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CHEAH CHENG LAI

Date: 20 February 2008

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LIST OF ABBREVIATIONS / NOTATIONS

List of Abbreviations

2.5G-PLS	2.5 Gb/s Power Limited System.
10G-PLS	10 Gb/s Power Limited System.
ABL	Average Burst Length.
ACK	ACKnowledgement.
AD	Averaging Duration.
AFEC	Adaptive FEC.
AFECCC	Adaptive FEC Code Control.
ANSI	The American National Standard Institute.
ARQ	Automatic Repeat-reQuest.
ASE	Amplified Spontaneous Emission.
ATM	Asynchronous Transfer Mode.
AU-n	Administrative Unit-level n.
B2	A BIP-$N \times 24$ code using even parity.
BBSG	Bernoulli Binary Signal Generator.
BCH	Bose–Chaudhuri–Hocquenghem.
BCHt	BCH (4320+13t, 4320).
BER	Bit Error Rate.
BIP	Bit Interleaved Parity.
BSC	Binary Symmetrical Channel.
BTC	Block Turbo Code.
CD	Chromatic Dispersion.

CEA	Corrected Errors Analysis.
CEC	Corrected Error Count.
CW	Continuous Wave.
DDD	Drop-Down Delay.
DED	Double Error Detecting.
DLC	Data Link Control.
DSF	Dispersion Shifted Fiber.
DS-*n*	Digital Signal-level *n*.
E/O	Electrical-to-Optical Signal Converter.
E2E	End-to-End.
ECC	Error Correcting Coding.
EDFA	Erbium-Doped Fibre Amplifier.
ELA	Error Location Analysis.
ELN	Explicit Loss Notification.
FEC	Forward Error Correction.
FWM	Four Wave Mixing.
GUI	Graphical User Interface.
GVD	Group Velocity Dispersion.
HARQ	Hybric ARQ.
INC	INcreased Acknowledgement.
IP	Internet Protocol.
ITU-T	The International Telecommunication Union-Telecommunication Standardization Sector.
LAN	Local Area Network.
LDPC	Low-Density Parity Check.

MAC	Medium Access Control.
MAN	Metropolitan Area Network.
MA-FEC	Multicast adaptive FEC.
MSOH	Multiplex section overhead.
M-DABL	Mean of Detected ABL.
NAK	Negative AcKnowledgement.
NG-SDH	Next Generation SDH.
NRZ	Non-Return to Zero.
NZ-DSF	Non-Zero Dispersion Shifted Fiber.
O/E	Optical-to-Electrical Signal Converter.
OOB FEC	Out-Of-Band FEC.
QoS	Quality of Service
OTN	Optical Transport Network.
PC	Personal Computer.
PC-WDMC	Product-coded WDM coding.
PER	Packet Error Rate.
PMD	Polarization Mode Dispersion.
PRBS	Pseudo-Random Binary Signal.
PTCM	Pragmatic Trellis Coded Modulation.
RCPC	Rate Compatible Punctured Convolutional.
RS	Reed–Solomon.
RS*t*	RS (180+2*t*, 180).
RSE	RS Erasure.
SDH	Synchronous Digital Hierarchy.

SDH-AFEC	SDH-based Adaptive FEC.
SD-DABL	Standard Deviation of Detected ABL
SEC	Single Error Correcting.
SES	Severely Errored Second.
SNR	Signal-to-Noise Ratio.
SOH	Section overhead.
SONET	Synchronous Optical Network.
SSMF	Standard Single Mode Fiber.
STM-*N*	Synchronous Transport Module-level *N*.
STS-*n*	Synchronous Transport Signal-level *n*.
TCP	Transmission Control Protocol.
TDM	Time Division Multiplexing.
WAN	Wide Area Network.
WDM	Wavelength Division Multiplexing.
WLAN	Wireless local area network.
W-WBRM	Wireless Web-Based Reliable Multicast.

List of Notations

ABL	Average Burst Length.
ABL_{d}	Detected ABL.
ABL_{min}	Minimum ABL.
B	Bad state.
BL	Burst Length.
b	The number of bits.