



UNIVERSITI PUTRA MALAYSIA

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

CHEAH CHENG LAI

FK 2007 79



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

By

CHEAH CHENG LAI

**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

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

By

CHEAH CHENG LAI

November 2007

Chairman : Professor Mohamad Khazani Abdullah, PhD

Faculty : Engineering

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

Fakulti : Kejuruteraan

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 overhead 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 lebih-lebih FEC yang berlainan saiz untuk beban-bebannya. Berbeza dengan kebanyakan skim-skim penyesuaian 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 algoritmanya. Kemudian mencorakkan algoritma 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 menunjukkan 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 overhead FEC yang maksimum untuk BER yang tinggi atau ABL yang panjang. Akan tetapi, keperluan overhead FEC menurun dengan penurunan BER atau ABL. Justeru itu, tambahan daripada keupayaan pembetulan ralat secara penyesuaian, SDH-AFEC juga memperuntukan suatu cara menggunakan overhead 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 overhead 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:

Abdul Rahman Ramli, PhD

Associate Professor,
Faculty of Engineering,
Universiti Putra Malaysia.
(Chairman)

Mohamed Othman, PhD

Associate Professor
Faculty of Computer Science and Information Technology
Universiti Putra Malaysia
(Internal Examiner)

Sabira Khatun, PhD

Associate Professor
Faculty of Engineering
Universiti Putra Malaysia
(Internal Examiner)

Abu Bakar Mohamad, PhD

Professor
Faculty of Electrical Engineering
Universiti Teknologi Malaysia
(External Examiner)

HASANAH MOHD. GHAZALI, PhD

Professor and Deputy Dean
School of Graduate Studies
Universiti Putra Malaysia

Date: 21 February 2008



This thesis was submitted to the Senate of Universiti Putra Malaysia and has been accepted as fulfilment of the requirement for the degree of Doctor of Philosophy. The members of the Supervisory Committee were as follows:

Mohamad Khazani Abdullah, PhD

Professor
Faculty of Engineering
Universiti Putra Malaysia
(Chairman)

Borhanuddin Mohd Ali, PhD

Professor
Faculty of Engineering
Universiti Putra Malaysia
(Member)

Mohd Adzir Mahdi, PhD

Associate Professor
Faculty of Engineering
Universiti Putra Malaysia
(Member)

AINI IDERIS, PhD

Professor and Dean
School of Graduate Studies
Universiti Putra Malaysia

Date: 21 February 2008



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.

CHEAH CHENG LAI

Date: 20 February 2008

TABLE OF CONTENTS

	Page
DEDICATION	2
ABSTRACT	3
ABSTRAK	5
ACKNOWLEDGEMENTS	8
APPROVAL	9
DECLARATION	11
LIST OF TABLES	15
LIST OF FIGURES	16
LIST OF ABBREVIATIONS / NOTATIONS	21
CHAPTER	
1 INTRODUCTION	27
1.1 Background	27
1.2 Signal Impairments in Optical Communications	29
1.3 Error Control Coding	30
1.4 Problem Statements and Motivation	33
1.4.1 Problem Statements	33
1.4.2 Motivation of Study	34
1.5 Objectives	35
1.7 Organization	36
2 LITERATURE REVIEW	37
2.1 Introduction	37
2.2 The Traditional FEC Techniques for Optical Communications	38
2.2.1 Hamming Codes	38
2.2.2 BCH Code	39
2.2.3 RS Codes	40
2.3 The Enhanced FEC Techniques for Optical Communications	43
2.3.1 Concatenated Codes	43
2.3.2 Product Codes	45
2.3.3 Block Turbo Codes (BTC)	47
2.3.4 Low-Density Parity-Check (LDPC) Codes	47
2.4 The FEC Techniques for WDM Systems	48
2.5 Adaptive FEC	52
2.6 Analysis and Discussion	59
3 METHODOLOGY	64
3.1 Introduction	64
3.2 System Model	64



3.2.1	The BCH-Based Scheme	71
3.2.2	The RS-Based Scheme	72
3.2.3	The Encoder and the Decoder Designs	74
3.2.4	The Features of the Schemes	75
3.3	The Half-t Algorithm	76
3.4	Theoretical Analysis	84
3.4.1	The BCH-Based Scheme	84
3.4.2	The RS-Based Scheme	87
3.5	Error Location Analysis (ELA)	91
3.6	Study Model	94
3.6.1	Design Parameters	96
3.6.2	Performance Parameters	99
3.7	Summary and Discussion	103
4	DELAY ANALYSIS	105
4.1	Introduction	105
4.2	The Main Contribution Components to End-to-End Delay	105
4.3	The Encoding and the Decoding Times	114
4.3.1	Simulation Approach	114
4.3.2	The Encoding and the Decoding Times of the BCH _t Code	116
4.3.3	The Encoding and the Decoding Times of the RS _t Code	119
4.4	End-to-End Delay	121
4.5	Summary and Discussion	124
5	THE END TO END PERFORMANCE OF THE SDH-AFEC	126
5.1	Introduction	126
5.2	The End-to-End (E2E) Simulation System	126
5.3	The Characteristics of the SDH-AFEC	134
5.3.1	Random Errors	135
5.3.2	Burst Errors	137
5.3.3	Discussion	138
5.4	The SDH-AFEC for Different Values of Drop-Down Delay (DDD)	140
5.4.1	The BCH-Based Scheme for Random Errors	140
5.4.2	The RS-Based Scheme for Random Errors	143
5.4.3	The BCH-Based Scheme for Burst Errors	146
5.4.4	The RS-Based Scheme for Burst Errors	149
5.5	Performance Comparison	152
5.6	Summary and Discussion	161
6	THE PERFORMANCE OF THE SDH-AFEC IN AN OPTICAL SYSTEM	164
6.1	Introduction	164
6.2	The Simulated Optical System	164
6.3	Performance of the SDH-AFEC in Power Limited Systems	167



6.4	Performance of the SDH-AFEC in a Fiber Length Limited System	171
6.5	The Coding Gain	173
6.6	Summary and Discussion	176
7	THE ERROR LOCATION ANALYSIS (ELA)	177
7.1	Introduction	177
7.2	The Characteristics of ELA in Time Domain	177
7.3	The Detected BER over Different Values of Averaging Duration (AD)	182
7.4	The Capability of ELA in Identifying the Error Pattern	187
7.5	Code Matching	189
7.6	The SDH-AFEC Performance Improvement by ELA in Time Domain	192
7.7	The SDH-AFEC Performance Improvement by ELA	194
7.8	Summary and Discussion	200
8	CONCLUSION AND FUTURE WORK	202
8.1	Conclusion and Main Contributions of the Thesis	202
8.2	Future Work	205
	REFERENCE	206
	APPENDIX	214
	BIODATA OF STUDENT	217
	LIST OF PUBLICATIONS	218



LIST OF TABLES

Table		Page
1.1	The SDH hierarchy.	28
2.1	The comparison on the coding gains and the FEC overhead requirement of various FEC techniques for optical communications.	61
3.1	The properties of the BCH t code.	71
3.2	The properties of the RS t code.	73
3.3	The design parameters.	99
3.4	The performance parameters.	103
4.1	The component comparison for the SDH-AFEC, the in-band FEC and the system without FEC at (a) the transmitting node and (b) the receiving node.	106
5.1	The performance comparison between the BCH- and the RS-based schemes, and the existing FEC techniques for SDH. These FEC techniques are the in-band FEC, the OOB FEC, the Hamming (2370, 2358) and the Hamming (18880, 18865).	160
6.1	The spectrum of the WDM channels.	166
7.1	The code matching for (a) burst errors, and (b) random errors.	192
7.2	The BER performance improvement by ELA.	199



LIST OF FIGURES

Figure		Page
1.1	The STM- N frame format.	28
2.1	Concatenated coding scheme.	43
2.2	The two-dimensional product code.	46
2.3	(a) FEC frame without wavelength interleaving, and (b) FEC frame with wavelength interleaving. Symbols transmitted on wavelength λ_1 (λ_2) are denoted by 1 (2).	51
3.1	The system architecture of the SDH-AFEC which consists of only two payloads. This architecture is applicable for both BCH- and the RS-based schemes. The number of FEC interleaving $m = N/2$ and $3N/2$, for the BCH- and the RS-based schemes respectively. The interleaving mechanism for the BCH-based scheme is a bit-interleaving whereas it is a byte-interleaving for the RS-based scheme.	66
3.2	The proposed signal format of the redundancy channel.	70
3.3	A row of STM- N re-arranged into two-dimensional format to illustrate the FEC interleaving of the BCH-based scheme. The transmission order is as normal, i.e. it starts from bit #1 and followed by bit #2 and so on, until bit # $2160 \times N$.	72
3.4	A row of STM- N re-arranged into two-dimensional format to illustrate the FEC interleaving of the RS-based scheme. The transmission order is as normal, i.e. it starts from byte #1 and followed by byte #2 and so on, until byte # $270 \times N$.	73
3.5	The flowchart of the half- t algorithm for (a) State 0, (b) State 1, (c) State 2 and (d) State 3.	80
3.6	The state transition diagram of the half- t algorithm. The solid lines indicate the changes of state based on the indicated conditions. The dotted lines indicate the changes back to State 0 after the algorithm has observed the change of t .	83
3.7	The lower bound of input BER that the minimum value of t is needed for different values of DDD for the BCH-based scheme.	86



3.8	The lower bound of input BER that the minimum value of t is needed for different line rates for the BCH-based scheme.	87
3.9	The lower bound of input BER that the minimum value of t is needed for different values of DDD for the RS-based scheme.	89
3.10	The lower bound of input BER that the minimum value of t is needed for different line rates for the RS-based scheme.	90
3.11	An example of ELA with $EFI_{min}=10$ bits.	93
3.12	The study model of the thesis.	95
4.1	The design of the interleaver, the deinterleaver and the FEC encoders for a payload channel at the transmitting node of (a) the BCH-based scheme and (b) the RS-based scheme.	109
4.2	The design of the interleaver, the deinterleaver and the FEC decoder for a payload channel at the receiving node of (a) the BCH-based scheme and (b) the RS-based scheme.	111
4.3	The architecture of the coding time simulation system for evaluating the encoding and the decoding times of both the BCH t and the RS t codes.	115
4.4	The encoding time comparison between the BCH t code and the in-band FEC.	117
4.5	The decoding time comparison between the BCH t code and the in-band FEC against the number of bit errors per codeword.	118
4.6	The encoding time comparison between the RS t code and the in-band FEC.	119
4.7	The decoding time comparison between the RS t code and the in-band FEC against the number of byte errors per codeword.	121
4.8	The end-to-end delay comparison between the BCH-based scheme and the in-band FEC against the number of bit errors per codeword.	122
4.9	The end-to-end delay comparison between the RS-based scheme and the in-band FEC against the number of byte errors per codeword for.	123
5.1	The architecture of the E2E simulation system.	127
5.2	The binary symmetrical channel (BSC).	132

5.3	(a) The burst errors model and (b) the transition diagram during State B.	133
5.4	The input and the output BER per frame, and t versus time for the BCH-based scheme for random errors when DDD is set to 1 frame.	135
5.5	The input and the output BER per frame and t versus time for the BCH-based scheme for random errors when DDD is increased to 40 frames.	136
5.6	The input and the output BER per frame, and t versus time for the RS-based scheme for burst errors when DDD is set to 10 frames.	137
5.7	The input and the output BER per frame and t versus time for the RS-based scheme for burst errors when DDD is increased to 1200 frames.	138
5.8	The BER performance of the BCH-based scheme for different values of DDD for random errors.	141
5.9	The average FEC overhead of the BCH-based scheme for different values of DDD for random errors.	143
5.10	The BER performance of the RS-based scheme for different values of DDD for random errors.	144
5.11	The average FEC overhead of the RS-based scheme for different values of DDD for random errors.	145
5.12	The BER performance of the BCH-based scheme for different values of DDD for burst errors.	147
5.13	The average FEC overhead of the BCH-based scheme for different value of DDD for burst errors.	149
5.14	The BER performance of the RS-based scheme for different values of DDD for burst errors.	150
5.15	The average FEC overhead of the BCH-based scheme for different values of DDD for burst errors.	151
5.16	The BER performance comparison between the BCH- and the RS-based schemes, and several existing FEC techniques for SDH for random errors.	153



5.17	The FEC overhead comparison between the BCH- and the RS-based schemes, and the existing FEC techniques for SDH for random errors.	155
5.18	The BER performance comparison between the BCH- and the RS-based schemes, and the existing FEC techniques for SDH for burst errors.	157
5.19	The FEC overhead comparison between the BCH- and the RS-based schemes, and the existing FEC techniques for SDH for burst errors.	158
6.1	The architecture of the simulated optical system.	165
6.2	The performance of the BCH- and the RS-based schemes under the 2.5G-PLS.	169
6.3	The performance of the BCH- and the RS-based schemes under the 10G-PLS.	170
6.4	The performance of the BCH- and the RS-based schemes under the fiber length limited system.	172
6.5	The coding gain of the SDH-AFEC under a fiber length limited system.	174
6.6	The coding gain comparison between the BCH- and the RS-based schemes and the existing FEC techniques for SDH.	175
7.1	The detected ABL of the BCH-based scheme versus time for $AD=1$ frame for burst errors.	179
7.2	The detected ABL of the BCH-based scheme versus time for $AD=100$ and 1000 frames for burst errors.	180
7.3	The detected ABL of the BCH-based scheme versus time for $AD=100$ and 1000 frames for random errors.	181
7.4	The SD-DABL of the BCH-based scheme for different values of AD for burst errors.	183
7.5	The SD-DABL of the RS-based scheme for different values of AD for burst errors.	184
7.6	The SD-DABL of the BCH-based schemes for different values of AD for random errors.	185



7.7	The SD-DABL of the RS-based schemes for different values of AD for random errors.	186
7.8	The detected ABL of both the BCH- and the RS-based schemes for burst errors.	188
7.9	The detected ABL of both the BCH- and the RS-based schemes for random errors.	189
7.10	The code matching between the BCH_t and the RS_t codes for random errors.	190
7.11	The code matching between the BCH_t and the RS_t codes for burst errors.	191
7.12	An example of the SDH-AFEC performance improvement by ELA in time domain when the error pattern is bursty with $ABL=300$ bits.	193
7.13	An example of SDH-AFEC performance improvement by ELA in time domain when the error pattern is random with the input BER of 10^{-5} .	194
7.14	The BER performance improvement by ELA for random errors. The ELA has detected the random error pattern and the BCH-based scheme is assigned to replace the RS-based scheme.	195
7.15	The average FEC overhead reduction by ELA when the BCH-based scheme is assigned to replace the RS-based scheme for random errors.	196
7.16	The BER performance improvement by ELA for burst errors. The ELA has detected the burst error pattern and the RS-based scheme is assigned to replace the BCH-based scheme.	197
7.17	The average FEC overhead reduction by ELA when the RS-based scheme is assigned to replace the BCH-based scheme for burst errors.	198
A.1	The pseudo code of the half- t algorithm for the BCH-based scheme.	215
A.2	The pseudo code of the half- t algorithm for the RS-based scheme.	216



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.
BCH t	BCH (4320+13 t , 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- <i>n</i>	Digital Signal-level <i>n</i> .
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 AcKnowledgegement.
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 <i>t</i> , 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.