ON THE EFFECT OF REDUCED LINK MARGIN, THE ROLE OF EQUIPMENTS AND THEIR BUDGETING IN THE DESIGN OF HIGH CAPACITY ELASTIC OPTICAL NETWORKS

ABHIJIT MITRA

DEPARTMENT OF ELECTRICAL ENGINEERING
INDIAN INSTITUTE OF TECHNOLOGY DELHI
JULY 2017

ON THE EFFECT OF REDUCED LINK MARGIN, THE ROLE OF EQUIPMENTS AND THEIR BUDGETING IN THE DESIGN OF HIGH CAPACITY ELASTIC OPTICAL NETWORKS

by

ABHIJIT MITRA

Department of Electrical Engineering

Submitted
in fulfilment of the requirements of the degree of Doctor of Philosophy
to the

Indian Institute of Technology Delhi
JULY 2017

Certificate

This is to certify that the thesis entitled **"On the Effect of Reduced Link Margin, the Role of Equipments and their Budgeting in the Design of High Capacity Elastic Optical Networks"** being submitted by **Abhijit Mitra** 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 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.

Subrat Kar
Department of Electrical Engineering
Bharti School of Telecom and Management
Indian Institute of Technology Delhi
Hauz Khas, New Delhi, 110016
India.

Andrew Lord
Head of Optics Research
Polaris House
British Telecommunication
Ipswich, IP53RE
United Kingdom.

Acknowledgements

I would first like to express my special appreciation and thanks to my PhD supervisors Prof. Subrat Kar from Electrical Engineering Department at IIT Delhi and Andrew Lord who heads the optics research at British Telecom, UK. They both have been tremendous mentors for me. Their profound technical knowledge and passion for authentic novel work that has strong impact to catalyze growth in the telecom sector has always inspired me to grow as a good researcher. Away from home, they have been strong mentors for me and provided me enough moral support both in professional and personal life. I am very grateful to Prof. V.K. Jain, Prof. V. Chandra and Prof. M. R. Shenoy for reviewing my research progress every semester as a part of my Student Research Committee at IIT Delhi. I would also like to extend my gratitude towards Mr. Paul Wright for his development of Optimod simulation tool for flexgrid at BT and providing me with a platform over which I could extend the optical layer to do simulations pertaining to this thesis. I would also like to thank the Optics Network Group at UCL under Dr. Seb Savory for initiating technical discussion pertaining to the nonlinear model for equipment testing and would extend my gratitude to Dr. David Ives at

UCL for providing the nonlinear coefficients for this study. Further, I would also like to thank Dr. Steve Desbruslais who is Director at Xtera Technologies for his guidance that helped me to model the Raman amplification part. I am very grateful to British Telecom and EBTIC headed by Dr. Nader Azarmi for funding my entire research at IIT Delhi. The IIT Delhi - BT collaboration has given me unconditional fiscal and moral support. I am also grateful to all the professors at IIT Delhi from whom I have learned a lot during the courses and the Bharti School of Telecom Technology and Management for providing me space to carry out this research work. I would also like to thank all my friends and members of the communications group. I feel lucky to have so many incredible friends around. I thank each and every one of them for their trust and friendship. Most importantly, my heartfelt gratitude is for my parents Mr. Subir Kumar Mitra and Mrs. Nupur Mitra, who have always supported me in my academic pursuits and encouraged me to do my best. It is due to their unconditional sacrifices, patience and hard work that I have been able to progress in life.

Abhijit Mitra

Abstract

The access network traffic is growing with a rise in high data rate consuming applications like video on demand and cloud based applications. This increases the traffic load on the core network. In order to increase the core network capacity an operator needs higher number of lightpaths operating at or beyond 100 Gbps. Therefore the operators need to utilize flexible spectrum provisioning under Elastic Optical Network (EON) technology while utilizing high order Polarization Multiplexed m-ary modulations.

In this thesis, we focus on the optical part of the communication system. The EON optical transponders enable software control to adapt modulation formats based upon the OSNR condition of a lightpath. Therefore, service providers can operate a lightpath close to the OSNR limit without keeping a high margin for link degradation. This enables lightpaths to operate at higher m-ary modulation thereby giving better day one network capacity. This idea of operating with reduced Link Margin has been proposed in the thesis and has been explored over various networks. The results show that smaller networks like the BT UK have high inherent OSNR to convert the

reduced margin benefits into high network capacity on day one. It has been shown that the flexibility of EON in spectrum allocation and modulation formats are necessary to increase the network capacity while operating with reduced margin for both variable baud rate and fixed baud rate transponders. For fixed baud rate transponders we have introduced the concept of demand multiplexed transponders which can cater multiple 100 Gbps demands over a single ligthpath between same source and destination. Using these transponders we have shown that a frequency granularity of 12.5 GHz is a good choice to generate subcarriers with 37.5 GHz spacing and the modulation sweet spot of the BT UK network is at PM-16QAM. These results were used in world's first 1.4 Tbps Superchannel field trial by BT where each of the 7 subcarriers operated at prescribed PM-16QAM with no margin and subcarrier spacing of 37.5 GHz. We have also evaluated the capacity benefits by reducing margins while operating with lightpaths at 400 Gbps and 1000 Gbps using Nyquist WDM Superchannel technology. The results show that the Superchannels will quickly exhaust the extra available spectrum (while using flexgrid) due to their large spectrum requirement. Therefore operators prefer to increase lightpath capacity in steps of 100 Gbps. Further, we have evaluated the benefits of operating at reduced margin over a life time of 25 years while considering single fiber failure events. It has been shown that it is easier for a smaller network to re-provision the failed 100 Gbps demands while operating with reduced margin.

As OSNR became an important figure of merit, an operator has

to make a cogent decision on whether to procure better amplifiers or ROADMs. To evaluate the capacity benefits for each equipment we have proposed a lightpath OSNR estimation model while considering the fiber nonlinearity being modeled as a Gaussian process. Using this model we have shown that a network having less ASE noise from in-line amplifiers and high node density will benefit more while using superior ROADM nodes. It was shown that small BT UK network can benefit the most in terms of network capacity while using better ROADMs as compared to larger networks. Finally we have also proposed an offline strategy to justify the upfront procurement of the amplifiers which has been considered by BT.

सार

मांग और क्लाउड आधारित अनुप्रयोगों पर वीडियो जैसे उच्च डाटा दर उपभोक्ता अनुप्रयोगों में वृद्धि के कारण पहुंच नेटवर्क यातायात बढ़ रहा है। इससे कोर नेटवर्क पर ट्रैफ़िक लोड बढ़ जाता है। मुख्य नेटवर्क की क्षमता बढ़ाने के लिए ऑपरेटर को 100 जीबीपीएस पर या उसके बाद से चलने वाले प्रकाशपथों की अधिक संख्या की आवश्यकता होती है। इसलिए ऑपरेटरों को लचीला ऑप्टिकल नेटवर्क (ईओएन) प्रौद्योगिकी के तहत लचीला स्पेक्ट्रम प्रावधान का उपयोग करना चाहिए, जबकि उच्च क्रम ध्रुवीकरण मल्टिप्लेक्स एम-एरी मॉड्यूलेशन का उपयोग करना चाहिए।

इस थीसिस में, हम संचार प्रणाली के ऑप्टिकल भाग पर ध्यान देते हैं। ईओएन ऑप्टिकल ट्रांसपोंडर प्रकाशपथ की ओएसएनआर स्थिति के आधार पर मॉड्यूलेशन प्रारूपों को अनुकूलित करने के लिए सॉफ्टवेयर नियंत्रण का उपयोग करता है। इसलिए, सेवा प्रदाताओं ओएनएसएनआर सीमा के करीब लिंक के लिए उच्च मार्जिन को बनाए रखने के बिना एक प्रकाशपथ संचालित कर सकते हैं। यह प्रकाशपथ को उच्चतर एम-एरी मॉड्यूलेशन पर संचालित करने में सक्षम बनाता है जिससे बेहतर दिन एक नेटवर्क क्षमता होती है। कम लिंक मार्जिन के साथ काम करने का यह विचार थीसिस में प्रस्तावित किया गया है और विभिन्न नेटवर्कों पर इसका पता लगाया गया है। परिणाम बताते हैं कि बीटी यूके जैसे छोटे नेटवर्कों में बहुत अधिक निहित ओएसएनआर है, जो कि एक दिन में कम मार्जिन लाभ को उच्च नेटवर्क क्षमता में बदलने में सक्षम है। यह दिखाया गया है कि स्पेक्ट्रम आवंटन और मॉड्यूलेशन प्रारूपों में ईओएन का लचीलेपन नेटवर्क क्षमता को बढ़ाने के लिए आवश्यक है जब चर बॉड दर और निश्चित बॉड दर ट्रांसपोंडर दोनों कम मार्जिन के साथ काम करते हैं। तय बॉड दर ट्रांसपोंडर के लिए हमने मांग मल्टीप्लेक्ड ट्रांसपोंडर की अवधारणा को शुरू किया है जो एक ही स्रोत और गंतव्य के बीच एक एकल प्रकाशपथ पर कई 100 जीबीपीएस मांगों को पूरा कर सकता है। इन ट्रांसपोंडरों का उपयोग करके हमने दिखाया है कि 12.5 गीगाहर्ट्ज की आवृत्ति ग्रान्युलैरिटी और 37.5 गीगाहर्ट्ज स्पेसिंग के साथ सबकैरियर बनाने के लिए एक अच्छा विकल्प है। बीटी यूके नेटवर्क की मॉड्यूलेशन स्पॉट पीएम -16 क्यूएएम पर है। इन परिणामों का उपयोग बीटी पर दुनिया के पहले 1.4 टीबीपीएस सुपरचैनल फील्ड टेस्ट में किया गया था, जहां 7 में से प्रत्येक सबकैरियर निर्धारित पीएम -16 क्यूएएम पर संचालित होता था जिसमें 37.5 गीगाहर्ट्ज का कोई मार्जिन और सबकैरियर रिक्ति नहीं थी। हमने 400 जीबीपीएस और 1000 जीबीपीएस पर प्रकाशपथों के साथ काम करते समय मार्जिन को घटाकर

क्षमता लाभ का मूल्यांकन किया है, जो कि Nyquist WDM सुपरचैनल प्रौद्योगिकी का उपयोग कर रहा है। परिणाम दिखाते हैं कि सुपरचैनल अपने बड़े स्पेक्ट्रम आवश्यकता के कारण अतिरिक्त उपलब्ध स्पेक्ट्रम (फ़्लेक्स-ग्रिड का उपयोग करते हुए) का तुरंत उपयोग कर लेते हैं । इसलिए ऑपरेटर 100 जीबीपीएस के चरणों में प्रकाशपथ क्षमता को बढ़ाने के लिए पसंद करते हैं। इसके अलावा, हमने 25 साल के जीवनकाल में कम मार्जिन पर काम करने के लाभों का मूल्यांकन किया है जबकि एकल फाइबर असफल होता हैं। यह दिखाया गया है कि कम मार्जिन पर काम करते हूए नेटवर्क के लिए असफल 100 जीबीपीएस मांगों को फिर से प्रावधान करना आसान है।

जैसा कि ओएसएनआर योग्यता का एक महत्वपूर्ण अंग बन गया है, एक ऑपरेटर को बेहतर एम्पलीफायरों या रोडमैम्स की खरीद के लिए एक ठोस निर्णय करना होगा। प्रत्येक उपकरण के लिए क्षमता के लाभ का मूल्यांकन करने के लिए हमने एक प्रकाशपथ ओएसएनआर आकलन मॉडल का प्रस्ताव किया है जबकि फाइबर नॉनलाइनैरिटी को गाऊसी प्रक्रिया के रूप में तैयार किया जा रहा है। इस मॉडल का उपयोग करके हमने दिखाया है कि उच्चतर रोडम नोड्स का उपयोग करते समय कम एएसई शोर वाले इन-लाइन एम्पलीफायर और उच्च नोड घनत्व वाले नेटवर्क को अधिक लाभ होगा। यह दिखाया गया था कि बड़े नेटवर्क की तुलना में बीएटी यूके नेटवर्क क्षमता के मामले में सबसे अधिक लाभान्वित कर सकता है। बेहतर रोडमैम का इस्तेमाल बीएटी यूके में किया जा सकता है। अंत में हमने एम्पलीफायरों की अग्रिम खरीद को सही करने के लिए ऑफलाइन रणनीति भी प्रस्तावित की है जिसे बीटी द्वारा विचार किया गया है।

Table of Contents

List of Figures

List of Tables

List of Symbols

α : Fiber attenuation per km (0.25dB/km)

α_p : Pump attenuation

β_2 : Dispersion Coefficient for SMF fiber

η_{NLI}^{i} : Net NLI contribution to the AWGN noise in the i^{th} optical link

η_{NLI}^{Total} : Total NLI in a lightpath for NLI model

γ : Non linear coefficient for SMF fiber

γ_o : Raman Gain factor

$\triangle Pcapf_{net}^{i}$: Change in network Pcap if an amplifier is added to an i^{th} optical link

ASE : ASE noise contribution by the each intermediate amplifier compensating for previous span loss of g in the i^{th} optical link

ASE^{i} :Total ASE noise due to in-line amplifiers in the i^{th} optical link

ASE_R : ASE noise due to post amplification at a ROADM by EDFA compensating for cumulative characteristic ROADM loss

ASE_{Total} : Total ASE noise in a lightpath for NLI model

B_{ref} :Reference Bandwidth of 12.5 GHz

C_R : Raman Gain efficiency

F^i_{fib} : Expected Number of Failures for i^{th} fiber link

F_{net} : Expected Number of Failures in the network in 25 years

$Fitness^i$: Fitness value for adding an amplifier to i^{th} optical link

g : Linear gain; analogous to G (dB) span loss

$G(f)$: Power Spectrum Density for all frequencies entire C band

$g(f)$: Normalized Power Spectrum Density for all frequencies entire C band

G^{int}_{EDFA} : Gain of the EDFA part for the intermediate H-Raman amplifier in an optical link

G^{last}_{EDFA} : Gain of the EDFA part for the last H-Raman amplifier in an optical link

G_{net} : Net optical Gain

$G_{NLI,ss}$: Nonlinear Power Spectrum Density

G_{oo} : Raman on-off gain in H-Raman amplifier setup

h : Planck's Constant

L_{eff} : Effective Length of the link

N : Geometric distributed discrete random variable accounting for number of demands elapsed until a failure occurs

N_s^i : Number of spans in an i^{th} optical link

N_{FAIL}^{Total} : Total Number of failed demands after all 3000 demands have been put to the network

N_L : Link number of the last traversed optical link by a lightpath

n_p^0 : Input photon number

N_R : Noise figure for Raman amplifier

N_R : Number of intermediate ROADM nodes traversed by a lightpath

N_T : Noise figure of Distributive H-Raman amplifier system

n_{16qam}^i : Number of lightpaths operating at 16-QAM over i^{th} fiber link

n_{16qam}^{net} : Number of lightpaths operating at 16-QAM overall in a network at a given network state

n_{32qam}^i : Number of lightpaths operating at 32-QAM over i^{th} fiber link

n_{32qam}^{net} : Number of lightpaths operating at 32-QAM overall in a network at a given network state

n_{8qam}^i : Number of lightpaths operating at 8-QAM over i^{th} fiber link

n_{8qam}^{net} : Number of lightpaths operating at 8-QAM overall in a network at a given network state

N_{ADJ} : Average number of adjusted 100G demands in network per failure event

n^{i}_{bpsk} : Number of lightpaths operating at BPSK over i^{th} fiber link

n^{net}_{bpsk} : Number of lightpaths operating at BPSK overall in a network at a given network state

N_{EDFA} : Noise figure of the EDFA in the H-Raman amplifier setup

N^{int}_{EDFA} : Noise figure for the EDFA in the intermediate H-Raman amplifier in an optical link

N^{last}_{EDFA} : Noise figure for the EDFA in the last H-Raman amplifier in an optical link

N^{H-Ram}_{eff} : Effective Noise figure of an imaginary discrete amplifier equivalent to distributive H-Raman amplifier system

N^{H-Ram}_{eff} : Effective noise figure of H-Raman amplifier setup

N^{Ram}_{eff} : Effective noise figure of only Raman part

n_{eq} : Spontaneous Photon number

N^{H-Ram}_{int} : Effective noise figure for the intermediate H-Raman amplifiers in NLI model

N^{H-Ram}_{last} : Effective noise figure for the last H-Raman amplifier

n^{i}_{qpsk} : Number of lightpaths operating at QPSK over i^{th} fiber link

n^{net}_{qpsk} : Number of lightpaths operating at QPSK overall in a network at a given network state

N_{SPIL} : Average number of failed 100G demands that a network has to reprovision by generation of new lightpaths per failure event

n_{sp} : Spontaneous Emission Factor

NSI : Network Survival Index

O^{i}_{gain} : Link OSNR gain if an amplifier is added to an i^{th} optical link

$OSNR^{i}$: Contribution to OSNR of lightpath due to OSNR Conditions over i^{th} optical link

$OSNR_{R}$: Contribution to OSNR of lightpath due to OSNR conditions at ROADMs

$OSNR_{path}$: OSNR of lightpath in the NLI model

P^{+}_{A} : Spontaneous Noise Power

P_{r} : Fixed Signal Power at the ROADM nodes in NLI model

p^{i}_{fib} : Probability of failure of i^{th} fiber

P^{i}_{opt} : Optimum signal launch power for i^{th} fiber link

P_{P0} : Pump Power remaining in the fiber

$Pcap^{ori}_{n}$: Pcap of network at a given state. At starting stage it is original Pcap factor

$Pcapf^{i}$: Pcapf for i^{th} fiber link

$Pcapf^{net}$: Pcapf for the entire network over all lightpaths

R_b : Bit Rate

R_s : Symbol/Baud Rate

$ROADM_{ASE}$: Total ASE noise contribution in lightpath by intermediate ROADMs

SNR_b : Signal to noise ratio per bit

T_n : Total accumulated noise in mW

v : Central C Band frequency for 1550 nm

$X_m(L)$: Normalized Non-Linear Coefficient

Acronyms

ASE Amplified Spontaneous Emission, 14

AWG Arrayed Wavelength Grating, 19

AWGN Additive White Gaussian Noise, 14

BTC Block Turbo Codes, 15

BVT Bandwidth Variable Transponders, 20

CBP Cumulative Blocking Probability, 53

CC Capacity Constraint, 109

CD Chromatic Dispersion, 9

CDF Cumulative Density Function, 92, 209

Co-OFDM Coherent Orthogonal Frequency Division Multiplexing, 25

DCF Dispersion Compensating Fiber, 9

DOF Degree of Freedom, 8

DP-QPSK Dual Polarization-Quadrature Phase Shift Keying, 2

DPSK Differential Phase Shift Keying, 8

DWDM Dense Wavelength Division Multiplexing, 2

EON Elastic Optical Networks, 3

FEC Forward Error Correction, 5

FG Frequency Granularity, 3

FIT Failure in Time, 89

FMF Few Mode Fiber, 165

FSU Frequency Slot Unit, 39

FWM Four Wave Mixing, 189

GMPLS Generalized Multiprotocol Label Switching, 36

GN Gaussian Noise, 109

HD-FEC Hard Decision FEC, 16

LCOS Liquid Crystal on Silicon, 19

LDPC Low Density Parity Check, 15

LiSP Light Switched Path, 36

LiSPDB LiSP Database, 36

LM Link Margin, 40

LO Local Oscillator, 11

LOOSNR	Link Operational OSNR, 52
MDM	Mode Division Multiplexing, 165
MEMS	Micro-electrical and Mechanical Systems, 19
MIMO	Multiple Input Multiple Output, 165
MSSI	Mid-span Spectral Inversion, 168
MZM	Mach-Zehnder modulators, 10
NFV	Network Function Virtualization, 35
NMS	Network Management System, 35
N-WDM	Nyquist Wavelength Division Multiplexing, 25
NCG	Net Coding Gain, 14
NLI	Nonlinear Impairments, 14
OADM	Optical Add Drop Multiplexer, 2
OCN	Optical Core Networks, 2
OOK	On-Off Keying, 8
OSNR	Optical Signal to Noise, 4
OXC	Optical Cross-Connects, 37
PBS	Polarization Beam Splitter, 10
Pcapf	Potential Capacity Factor, 128

PCE Path Computation Element, 36

PM Polarization Multiplexing, 6

PMD Polarization Mode Dispersion, 9

PSD Power Spectrum Density, 195

QAM Quadrature Amplitude Modulation, 4

RC Routing Controller, 36

RFS Recirculating Frequency Shifter, 32

ROADM Reconfigurable Optical Add Drop Multiplexers, 19

RSA Routing and Spectrum Assignment, 39

RWA Routing Wavelength Assignment, 2

SCI Single Channel Interference, 193

SMF Single Mode Fiber, 202

SP Set Partitioning, 168

S-PCE Stateful-Path Computational Element, 37

S-BVT Sliceable- Bandwidth Variable Transponders, 6, 21

SD-FEC Soft Decision FEC, 16

SDM Space division Multiplexing, 32, 165

SDN Software Defined Network, 35

SSMF	Standard Single Mode Fiber, 119
ST	Subcarrier Transmission, 26
TDM	Time Division Multiplexing, 2
TED	Traffic Engineering Database, 36
UT	Uncompensated Transmission, 189
WDM	Wavelength Division Multiplexing, 2
WSS	Wavelength Selective Switch, 19
XCI	Cross Channel Interference, 193
XPM	Cross Phase Modulation, 189