Graduate School of Global Information and Telecommunication Studies, Waseda University

Abstract of Doctoral Dissertation

Study on Control and Planning of Heterogeneous Optical Networks

ヘテロジニアス光ネットワークの制御及び設計の研究

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A heterogeneous optical network is an efficient and cost-effective architecture to cope with the exponentially growing and highly diverse nature of the Internet traffic. The first type of such network was the mixed line rate (MLR) wavelength division multiplexing (WDM) optical network which is currently the cornerstone of modern telecommunications. It accommodates lightpaths of 10, 40 and 100 Gbps that are achieved through on-off keying (OOK), differential quadrature phase shift keying (DQPSK) and polarization multiplexing quadrature phase shift keying (PM-QPSK) schemes, respectively. However, the biggest obstacle in the planning of such network is cross-phase modulation (XPM) problem that 10 Gbps lightpaths cause to the co-propagating lightpaths of 40 and 100 Gbps. This type of impairment problem becomes more critical in a dynamic case scenario where the traffic across the network constantly changes and a dynamic provisioning of the lightpaths is required.

Furthermore, over the past decade, optical orthogonal frequency division multiplexing (OFDM) has emerged as a candidate technology for future optical networks. With OFDM it is possible to achieve a wider range of transmission rates and a greater efficiency in the fibre's spectrum usage. The transponders that make use of OFDM are called in the literature as bandwidth variable transponders (BVT) whereas a network that is made up of BVTs is called elastic optical network (EON). This new heterogeneous network however is expected to cost significantly more than the conventional WDM one and therefore, a strategic planning is required by the network operators to reduce the total capital expenditure as much as possible. Nevertheless, the complexity of planning such a network is significantly higher and it can no longer be dealt with conventional algorithms or mathematical models that were used until now.

This dissertation is a study on the two afore-mentioned topics in heterogeneous optical networks. It consists of three main chapters preceded by an introduction and terminated by conclusions. All the chapters are described as follows:

Chapter 1 introduces the background, motivation behind this dissertation, and briefly summarizes the research contributions of this study. This chapter also gives an overview and structure of this dissertation.

Chapter 2 covers fundamental knowledge and recent advancements in optical networks that are necessary to the reader in order to comprehend the research works that are presented in Chapters 3 and 4.

Firstly, a short introduction of the physical components in an optical network is provided. The list of the presented components includes optical fibres, optical amplifiers, transponders and 3R regenerators, optical switches and switching node architectures. In addition to the function of the above components, each one's role and the way they interconnect and form an optical network is also shown.

Then, a brief overview is given on the evolution of optical networks and how the need for flexibility led to the advent of heterogeneous optical networks. MLR optical networks are a straightforward evolutionary step over legacy single line rate (SLR) networks. With

coherent technology it became possible to achieve data rates up to 100 Gbps within the standard 50 GHz spectrum grid and a gradual upgrade of the 10 Gbps network infrastructure took place over the last decade. OFDM on the other hand is a new transmission technology that uses multiple low data rate subcarriers. The number as well as the modulation scheme of the subcarriers can be adjusted, and this can generate various data rates for short and long-haul transmission. However, this flexibility also introduces additional complexity in the planning of an EON.

Furthermore, the issues of physical impairment that are encountered in optical transmission are presented. In the end of this chapter, the goals and challenges in optimizing the planning and control of optical networks are explained.

Chapter 3 deals with the problem of optimal lightpath provisioning in a MLR optical network with dynamic traffic and the presence of physical impairment. This part of this study is intended to be utilized by vendors and network operators of an optical network where connections are established dynamically and legacy 10 Gbps OOK transponders co-exist with 40 and 100 Gbps transponders. At the beginning of the chapter, the modulation/demodulation technique for each transmission scheme is shown. Then, mathematical models for the calculation of the physical impairment for each scheme are presented. The impairments that are taken into consideration are amplified spontaneous emission (ASE) noise and XPM. The first one, which is of linear type, is caused by the optical amplifiers that a signal goes through, and it affects all three modulation schemes. XPM on the other hand is non-linear and it affects the 40 and 100 Gbps lightpaths that use phase modulation formats. The level of XPM's criticality depends on the launch power of 10 Gbps lightpaths and their spectral distance from the phase modulated lightpaths.

By making use of these models, a novel method is proposed for the selection of the route with the minimum XPM for the phase modulated lightpaths. Specifically, in each link of the topology, a weight that corresponds to the variance of the induced phase noise is applied and then Dijkstra algorithm is put into practice to find the optimal route. This is combined with a specific wavelength selection strategy that forestalls the spectral placement of 40 and 100 Gbps lightpaths next to 10 Gbps ones. Based on this method, two schemes of lightpath provisioning are proposed where the routing and wavelength assignment for an incoming connection request depends on its data rate (10-40-100 Gbps). Both of them use the novel method to find the optimal route for phase modulated 40 and 100 Gbps lightpaths. The difference however of these two schemes lies on the way that the 10 Gbps lightpaths are served. In the first scheme, the wavelength for the 10 Gbps lightpath is assigned first, while in the second one, the route is found first. In addition, in order to reduce the online calculation time of the algorithms, the pre-computation of the phase noise variances is proposed, and a simple way to derive each link's weight is shown. The novel algorithms are then compared with the straightforward and widely used shortest length path and minimum hop first schemes in various simulation scenarios. In the end, simulation results show that performance gains in terms of blocking probability reduction can be achieved through the

proposed algorithms. For example, in a network where 10 and 100 Gbps are dynamically established, the average blocking probability is approximately 0.05 when the proposed schemes are used, and 0.07 in the case of the conventional ones.

Chapter 4 concerns the optimal planning of future heterogeneous optical networks with the objective of minimizing the total combined cost of employed transponders/3R regenerators and the total amount of power consumption. The related works in this topic focus on optimizing an OFDM-based EON and then compare it with a MLR and a conventional SLR optical network. This study however takes a step further and examines the case of a hybrid optical network. The term "hybrid" defines an optical network in which both BVTs (that are employed in OFDM-based EONs) and conventional single carrier transponders (that are employed in MLR optical networks) coexist in the same optical network. For this reason, a sophisticated integer linear programming (ILP) formulation is proposed that can be used as a reference mathematical model for all three concerned types of optical networks, namely, MLR, OFDM-based EON and hybrid optical networks. Then, for the sake of reduced computational time, a cut-down and simplified version of the reference model is provided, which is employed to yield the near optimal solutions and perform numerical evaluations. The novelty of this model, compared to other related works, is that it does not follow the single path and contiguous spectrum constraints which can lead to spectrum fragmentation and inefficient utilization of a network's capacity. Instead, a restriction in the possible sets of transmitted subcarriers is applied which sufficiently reduces the reference model's complexity.

As a result, the ILP solver can return a solution where a connection request between two network nodes can be served by one or multiple lightpaths. In the case where more than one pair of transponders are required, which means more than one lightpath between those two nodes can be employed simultaneously, the allocated spectrum for different lightpaths does not have to be contiguous, the established lightpaths can use different physical routes and can also be a combination of WDM lightpaths and OFDM-based elastic ones. The numerical evaluations are conducted on the NSFNET and JPN-12 topologies and with traffic patterns that are based on actual population data. Evaluation results show that the hybrid optical network can provide the merits of the other two architectures, namely the cost-effectiveness of a MLR network and the energy and spectrum efficiency of an EON. In a hybrid optical network architecture, by strategically combining the single carrier transponders and the BVTs, it is possible to match the capacity of an EON with a cost that is even lower than that of a WDM MLR optical network. For example, in the NSFNET topology and for traffic loads that exceeded the capacity of the MLR network, the long term combined total combined cost of transponders/3R regenerators and total power consumption was 20% less in the hybrid network than the EON, whereas in the JPN-12 topology it was 15% less.

Finally, Chapter 5 summarizes the achieved results in this dissertation and concludes with a brief view on future work.

List of Academic Achievements

Category	
Journals	○(1) Filippos Balasis, Sugang Xu, and Yoshiaki Tanaka, “Analysis of the Cost and Energy Efficiency of Future Hybrid and Heterogeneous Optical Networks”, IEICE Transactions on Communications, Vol.E101-B, No.5, pp.1222-1232, May 2018. ○(2) Filippos Balasis, Xin Wang, Sugang Xu, and Yoshiaki Tanaka, “Dynamic Physical Impairment-Aware Routing and Wavelength Assignment in 10/40/100 Gbps Mixed Line Rate Optical Networks”, ICACT Transactions on Advanced Communications Technology, Vol.2, No.6, pp.343-351, November 2013.
International Conferences	○(3) Filippos Balasis, Sugang Xu, and Yoshiaki Tanaka, “Examining the Cost Efficiency of Future Heterogeneous Optical Networks”, IEICE Information and Communication Technology Forum (ICTF 2016), Patras, Greece, Session B2.2, July 2016. (4) Filippos Balasis, Xin Wang, Sugang Xu, and Yoshiaki Tanaka, “A Dynamic Physical Impairment-Aware Routing and Wavelength Assignment Scheme for 10/40/100 Gbps Mixed Line Rate Wavelength Switched Optical Networks”, 15th International Conference on Advanced Communications Technology (ICACT2013), Phoenix Park, Korea, Session 01F-02, pp.116-121, January 2013.
Domestic Technical Meetings	(5) Filippos Balasis, Sugang Xu, and Yoshiaki Tanaka, “A Cost Comparison of OFDM-based Elastic and Mixed Line Rate Optical Networks”(Encouragement Talk), IEICE Technical Report on Network Systems, Paper No.NS2014-108, Vol.114, No.252, pp.37-42, October 2014.
Domestic Annual Conferences	(6) Filippos Balasis, Sugang Xu, and Yoshiaki Tanaka, “Minimizing the Cost of SDM Optical Networks with Multi-Core and Single-Core Fibre Cables”, 2018 IEICE General Conference, No.BS-2-38, pp.S-74-S-75, March 2018. (7) Filippos Balasis, Sugang Xu, and Yoshiaki Tanaka, “Planning of Optical Networks with Sliceable Bandwidth Variable Transponders”, 2017 IEICE Communications Society Conference, No.BS-7-23, pp.S-86-S-87, September 2017. (8) Filippos Balasis, Sheng Xu, Sugang Xu, and Yoshiaki Tanaka, “A Simple and Fast ILP Model for Multi-Core SDM Optical Networks”, 2017 IEICE General Conference, No.BS-1-43, pp.S-84-S-85, March 2017. (9) Filippos Balasis, Sheng Xu, Sugang Xu, and Yoshiaki Tanaka, “Examining the Cost and Energy Efficiency of Future Heterogeneous Optical Networks”, 2017 IEICE Communications Society Conference, No.BS-5-1, pp.S-52-S-53, September 2017. (10) Filippos Balasis, Sheng Xu, Sugang Xu, and Yoshiaki Tanaka, “Minimizing Cost in Multi-Core Fibre Optical Networks”, 2016 IEICE General Conference, No.BS-3-2, pp.S-15-S-16, March 2016. (11) Filippos Balasis, Sheng Xu, Sugang Xu, and Yoshiaki Tanaka, “Design of Spectrally and Spatially Flexible Optical Networks”, 2015 IEICE Communications Society Conference, No.BS-6-32, pp.S-76-S-77, September 2015.

List of Academic Achievements

Category	
Domestic Annual Conferences	(12) Filippos Balasis, Sheng Xu, Sugang Xu, and Yoshiaki Tanaka, “Design of Heterogeneous Optical Networks under Physical Layer Constraints”, 2015 IEICE General Conference, No.BS-3-59, pp.S-120-S-121, March 2015. (13) Filippos Balasis, Sheng Xu, Sugang Xu, and Yoshiaki Tanaka, “Design of Optical Networks with Fixed and Flexible Grid”, 2014 IEICE Communications Society Conference, No.BS-6-34, pp.S-102-S-103, September 2014. (14) Filippos Balasis, Di Zhang, Sheng Xu, Sugang Xu, and Yoshiaki Tanaka, “Minimizing the Cost of OFDM-Based Elastic Optical Networks”, 2014 IEICE General Conference, No.BS-1-29, pp.S-56-S-57, March 2014. (15) Filippos Balasis, Xin Wang, Sugang Xu, and Yoshiaki Tanaka, “Traffic Grooming in Wavelength Switched Optical Networks with Mixed Line Rates”, 2013 IEICE Communications Society Conference, September 2013. (16) Filippos Balasis, Xin Wang, Sugang Xu, and Yoshiaki Tanaka, “Offline Impairment-Aware RWA and Regenerator Placement in Optical Networks with Mixed Line Rates”, 2013 IEICE General Conference, No.BS-1-47, pp.S-92-S-93, March 2013. (17) Filippos Balasis, Xin Wang, Sugang Xu, and Yoshiaki Tanaka, “A Physical Impairment-Aware RWA Scheme for Mixed-Line-Rate Wavelength Switched Optical Networks”, 2012 IEICE Communications Society Conference, No.BS-5-46, pp.S-116-S-117, September 2012. (18) Filippos Balasis, Xin Wang, Sugang Xu, and Yoshiaki Tanaka, “Challenges in the Design of Mixed Line Rate Wavelength Switched Optical Networks”, 2012 IEICE General Conference, No.BS-3-32, pp.S-62-S-63, March 2012.

Curriculum Vitae

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Educational Background

September 1996 - July 1999
4th General High School of Galatsi, Greece

September 2000 - March 2010
Bachelor of Engineering, School of Electrical and Computer Engineering (Major in Telecommunication and Computer Network Systems), National Technical University of Athens

October 2011 - September 2013
Master of Science in Global Information and Telecommunications Studies, Graduate School of Global Information and Telecommunication Studies, Waseda University

September 2013 - September 2016
Doctorate Programme, withdrew from the programme in Graduate School of Global Information and Telecommunication Studies, Waseda University

Research Experience

September 2016 - Present
Invited Researcher, Global Information and Telecommunication Institute, Waseda University

April 2011 - September 2011
Research Student (Non-degree), Waseda University

Working Experience

September 2016 - March 2019
Mathematics and IT Instructor, Little Angles International School, Mitaka-shi, Tokyo, Japan

June 2010 - March 2011
Telecommunications Engineer, Hellenic Telecommunications Organization-OTE S.A., Athens, Greece

May 2009 - March 2010
Radar Systems Operator, Military Service in the Artillery of Greek Army, Greece

June 2008 - November 2008
Assistant employee in the Loans Department, National Bank of Greece, Athens, Greece

February 2004 - April 2009
Teaching Assistant in Computer Seminars, Athens, Greece

Awards

ICACT Outstanding Paper Award 2013
IEICE Young Researcher’s Award 2014
IEICE English Session Award of NS Committee 2014