

Prof. dr hab. inż. Krzysztof WALKOWIAK
Faculty of Electronics
Wrocław University of Science and Technology

REVIEW

Ph.D. thesis of mgr inż. Mustafa Abdulsahib

„Strict-sense and Wide-sense Non-blocking W-S-W Switching Fabrics for Elastic Optical Networks”

Supervisor: prof. dr hab. inż. Wojciech Kabaciński

1. The purpose and scope of the doctoral dissertation

The dissertation focuses on switching fabrics for Elastic Optical Networks (EONs). The concept of EON is a natural successor to the currently most popular optical technology Wavelength Switched Optical Networks based on the Wavelength Division Multiplexing (WDM). EON is an innovative and promising solution for optical networks proposed for the first time in 2008 as a spectrum-sliced elastic optical path network (SLICE) technology. The key advantages of the EON architecture are enabling provisioning beyond 100 Gb/s connections and support of sub-wavelength, and multiple-rate data traffic accommodation in a spectrum-efficient way. The development of EON has been mainly driven by business requirements. More specifically, the rapid network traffic growth has brought existing Wavelength Switched Optical Network systems to the capacity limit. One potential solution to this capacity problem is simply lighting new fibers to increase the bandwidth of existing network links. However, this approach is not highly scalable and does not provide economies of scale. Therefore, since more cost-effective solutions are needed by telecoms, the EON concept addresses a number of business requirements which are currently gaining in importance. One of the components required for successful deployment of EONs are switching fabrics.

The thesis considers various combinatorial aspects of switching fabrics for EONs. In particular, two Wavelength-Space-Wavelength (WSW) switching fabric architectures for EONs denoted as WSW1 and WSW2 are analyzed. Both architectures are of special design based on the Clos switching fabrics, and in consequence they consist of three stages. Moreover, it is assumed that the first and third stages have wavelength conversion capabilities, while the second stage supports only switching in the space domain. The dissertation includes both theoretical and practical results. In the field of theoretical considerations, Mustafa Abdulsahib provided various analytical results on WSW switching fabric architectures for EONs including: formulation of the strict-sense nonblocking for WSW1 architecture, study on the wide-sense nonblocking conditions for WSW1 and WSW2 architectures, ten control algorithms for WSW1 and WSW2 architectures and optimization of WSW1 and WSW2 architectures in terms of the number of required elements. On the other hand, the practical aspect of the dissertation is connected with carrying out extensive simulation studies showing the main features of analyzed WSW architectures and proposed algorithms.

2. The content of the dissertation

The dissertation consists of 8 chapters. The first chapter contains an introduction to the subject of the dissertation, as well as the goal and thesis of the dissertation. Chapter 2 presents basic information related to switching including definition of switching, short historical background and description of current switching techniques. Chapter 3 describes evolution of optical networks with a special focus on Elastic Optical Networks. Chapter 4 depicts details of the switching architectures considered in this thesis, namely, two versions of Wavelength-Space-Wavelength (W-S-W) switching fabric architectures are considered: WSW1 and WSW2. Moreover, Chapter 4 reports contemporary advances in switching fabrics. Chapter 5 presents the strict-sense nonblocking conditions and the wide-sense nonblocking conditions of control algorithms for the WSW1 architecture. In turn, Chapter 6 reports the strict-sense nonblocking conditions and the wide-sense nonblocking conditions of control algorithms for the WSW2 architecture. Chapter 7 focuses on optimization of proposed architectures in terms of the number of required switching elements. Finally, the last Chapter 8 concludes the research presented in the dissertation and includes proposals for future work. The thesis is well structured, written in a fluent English language. Figures are well understandable and graphs readable.

3. Correctness and originality of the thesis

The thesis of the work is formulated as follows:

The considered switching fabrics can have a nonblocking operation when the number of switches/slots in the middle stage is properly assigned and this number of resources can be reduced when the decomposition algorithms are utilized while the number of switching elements required to implement the switching fabrics can be further reduced when the design parameters are optimized.

In my opinion, the thesis of the work is formulated in a proper way. Mustafa Abdulsahib correctly determined the scope of his work based on a literature review and his own knowledge, focusing on various aspects of WSW switching fabrics for Elastic Optical Networks. The Author solved the formulated research problem using correctly selected research methods including analytical analysis of various properties of the considered WSW1 and WSW2 architectures and performing broad simulation studies showing evaluation of the proposed approaches followed by a thorough discussion. In consequence, the goals of the work have been achieved.

4. Analysis of sources (including world literature and state of the art)

The thesis of Mustafa Abdulsahib focuses on current issues related to switching fabrics for Elastic Optical Networks. The PhD student carried out a thorough bibliographic review, the list of literature in the dissertation contains 126 items. Among them are the most important works related to:

- switching technologies,
- switching fabrics,
- Elastic Optical Networks.

I can unequivocally state that PhD student has sufficient knowledge of contemporary literature in the field of various aspects related to telecommunication networks, with particular emphasis on switching architectures in Elastic Optical Networks.

5. The position of the dissertation in relation to the state of the art represented by world literature

The subject of the dissertation is related to up-to-date research directions in the field of telecommunication networks. The choice of the topic is appropriate, as the optical technology considered, namely Elastic Optical Network, is the most advanced and actual innovation in the field of optical networking. Moreover, the topic of switching technologies is an important research area in the ICT sector, since the continuous increase of network enforces development of new solutions that allow to provision higher volumes of traffic in a cost efficient way. I want to underline that Mustafa Abdulsahib continues the research on switching technologies conducted for many years in the Chair of Communication and Computer Networks at the Poznan University of Technology.

6. The significance of the results obtained for a given scientific discipline

As the most important original achievements of the doctoral dissertation should be mentioned:

- The formulation and proof of the strict-sense nonblocking for the $WSW1(r, n, k)$ architecture. The conditions are used to estimate the number of frequency slots units necessary in the inter-stage links to provide that the switch is nonblocking.
- Formulation of five control algorithms for the $WSW1(r, n, k)$ architecture. The proposed algorithms decompose the frequency slots units in the inter-stage links into subsets of various number of elements (two, three or more). The subsets are used to serve a certain group of m -slot demands.
- Formulation of five control algorithms for the $WSW2(q, p, r, n, k)$ architecture. The proposed algorithms decompose the frequency slots units in the inter-stage links into subsets of various number of elements (two, here or more). The subsets are used to serve a certain group of m -slot demands.
- A detailed analysis of the control algorithms proposed for $WSW1(r, n, k)$ and $WSW2(q, p, r, n, k)$ architectures made by simulations. The analysis reports pros and cons of each algorithm as well as comparisons of the algorithms for different configurations of switching fabrics in terms of main parameters' values.
- The optimization of $WSW1(r, n, k)$ and $WSW2(q, p, r, n, k)$ architectures in terms of the number of required elements. The proposed optimization procedures allow to construct the optimum switching fabric in the sense of the minimum number of switching elements, for the same design parameters.

It should be emphasized that the concepts and results obtained have practical significance. In particular, the Author defined and then solved a real and up-to-date research problem related to analysis and optimization of switching architectures for Elastic Optical Networks.

7. Main disadvantages of the dissertation and critical remarks

General remarks

- Some of the obtained results are not practical in the value of k obtained for the $WSW1(r, n, k)$ architecture to provide nonblocking in the strict-sense for m -slot connections. In more detail, depending on the values of other parameters (i.e., n, m) the obtained values of k are much larger than 350 or 320, while usually the number of FSUs in EONs is assumed

as 350 or 320 (what follows from properties of the fiber and size of the C-band). Therefore, all results showing values of k larger of 350 have only theoretical meaning.

- The Author writes in page 68: “It should be noted, that for EON switches, we have about 350 FSUs available in the C-band” and nest he writes “Limiting the number of FSUs in the links between nodes of EON is not practical.” I do not understand the second sentence, especially when compared with against the first one.

Polemical remarks

- The formulation and proof of the nonblocking conditions for the WSW1(r, n, k) architecture is based on the assumption that one FSU (frequency slot unit) connections can be established in the network. Due to this fact, the analysis is very conservative and the obtained values are very large. In theory, EONs support 1 FSU connections. But usually, it is assumed that in EONs connections with larger number of FSUs are allowed. In more details, it is assumed that each connection (lighpath) is generated by a transceiver that serves a particular number of FSUs. For instance, in paper [C. Rottondi, M. Tornatore, A. Pattavina and G. Gavioli, "Routing, modulation level, and spectrum assignment in optical metro ring networks using elastic transceivers," in *IEEE/OSA Journal of Optical Communications and Networking*, vol. 5, no. 4, pp. 305-315, April 2013] one of analyzed transceivers serves 37.5 GHz , what means 3 FSUs. Since EONs allow using superchannels (i.e., if the capacity of a single transceiver does not support all the groomed traffic between two nodes, the aggregated traffic can still be mapped over a single optical path formed by signals generated by multiple adjacent transceivers, such optical path is referred to as a “superchannel” and is handled by the optical nodes as a single entity). Then the connections established as superchannels using transeivers serving 3 FSUs need $3k+1$ FSUs, where k denotes the number of transceivers and 1 is for the guard-band. Using the assumptions that connections can have $3k+1$ FSUs the strict-sense nonblocking conditions would be formulated in a different way. However, the dissertation does not include such results.

Detailed remarks

- Symbols m_1 and m_2 used in figures presenting algorithms (e.g., Figure 5.4, 5.5, 5.6) do not have ‘1’ or ‘2’ in lower index, while in the text it is written as m_1 and m_2 (‘1’ and ‘2’ are in lower index).
- Some language flaws:
 - Page 20: “Coherent Optical Orthogonal Frequency-Division Multiplexing (CO-OFDM) has been demonstrated as promising candidates (...).”
 - Page 47 “The work in this thesis also use algorithms (...).”
 - Page 114: “This procedure is an effort to find the the optimum switching fabric, that requires the minimum number of switching elements, for the same design parameters.”

8. Conclusions

The reviewed PhD thesis is an original solution of a clearly formulated scientific problem. Mustafa Abdulsahib demonstrated the ability to conduct scientific research independently, as well as to correctly and insightfully interpret the obtained results. The critical remarks mentioned above do not have a significant impact on the overall positive evaluation of the PhD thesis. I believe that the doctoral dissertation of Mustafa Abdulsahib presented to me for review meets the requirements of the Act on Academic Degrees and Academic Title (Ustawa o stopniach naukowych i tytule naukowym z dnia 14 marca 2003 roku, Dz. U. z 2003 r., nr 65, poz. 595 z późniejszymi zmianami) and I recommend for admission to a public defense. Moreover, in my opinion the PhD thesis of Mustafa Abdulsahib deserves recognition.