Tạp chí Khoa học và Công nghệ 50 (1) (2012) 1-12

A STUDY ON WAVEBAND ROUTING OPTICAL NETWORKS EMPLOYING WAVEBAND SELECTIVE SWITCH-BASED CROSS-CONNECTS

Nguyen Tien Ban[1], **Le Hai Chau**[2]

[1]*Posts and Telecommunications Institute of Technology, Hanoi, Vietnam*

[2]*Nagoya University, Nagoya, Japan*

Corresponding author: *bannt@ptit.edu.vn*

Received April 15, 2011; Accepted for publication: 28 March 2012

ABSTRACT

A waveband cross-connect architecture is proposed, utilizing small-scale waveband selective switches to make the best use of present optical switch technologies and exploit optical waveband switching for creating cost-effective large capacity optical path networks. An appropriate network design algorithm is then developed for the waveband routing optical networks employing the waveband cross-connect architecture. Numerical experiments prove that applying the small-scale waveband selective switch-based node architecture offers a significant switch scale reduction. The effect of the waveband capacity selection on the overall switch scale reduction was also investigated.

Keywords. WDM, optical circuit switching/path networks, waveband switching, routing and wavelength assignment, optical cross-connects.

1. INTRODUCTION

Recent advances in WDM technologies and related optical switching technologies have significantly increased backbone and metro network capacities. Wavelength path routing (optical circuit/path switching) using reconfigurable optical add/drop multiplexers (ROADMs) or optical cross-connects (OXCs) has been developed and a large-scale deployment of single-layer optical path networks utilizing ROADMs/OXCs is being conducted in Japan and North America [1].

The expected future Internet traffic growth dominated by the penetration of new video-centric broadband services including ultra-High Definition-/3D-TV and e-Science will trigger an explosive increase in the necessary switch scale of OXCs/ROADMs [1 - 2]. The requirement for bandwidth-abundant cost-effective and low-power-consumption transport networks that can support the ever-increasing traffic is becoming more and more critical. One of the attractive approaches to cost-effectively enhancing optical switch capacity is the introduction of waveband switching networks, also called multi-granular optical path networks, along with hierarchical optical cross-connects (HOXCs), which are capable of handling optical signals at different granularities: wavelength paths and waveband paths (bundles of multiple wavelengths) [1 - 10].

Typical hierarchical optical cross-connect architectures include two independently functional switching parts: a waveband cross-connect (WBXC) for switching coarse granular optical paths, waveband paths, and a wavelength cross-connect (WXC) to provide finer granular routing of wavelength paths [3 - 5]. Optical path routing capability of HOXCs depends on the node architecture applied [4]. The efficiency of multi-granular optical path networks, indicated by the obtained cost (or port count) reduction, has been verified [5-10]. It has been shown that the introduction of waveband routing can help reducing greatly the required optical port count and thus, can decrease the entire switch scale needed, especially for the large traffic demand area [6-9]. On the other hand, the key operation to increase fiber utilization and to enhance the effectiveness of the waveband routing is the introduction of intermediate grooming; which includes unbundling waveband paths and merging at intermediate nodes [6, 9]. However, limiting the grooming capability is crucial in cutting down total switch scale of a hierarchical optical cross-connect [8]. Fortunately, the work given in [9] demonstrates that end-to-end waveband scheme (waveband switching only) offers almost the same network cost reduction as that efficiently combines waveband switching and wavelength grooming at intermediate nodes when the given traffic demands become greater. In other words, impact of grooming wavelength paths is negligible for large traffic area. Based on that, this paper focuses on the end-to-end waveband switching to realize very large capacity and cost-effective optical networks.

On the other hand, in hardware point of view, different architectural implementations of optical node systems provide different levels of flexibility and cost efficiency. Various switch technologies can be adopted to realize hierarchical optical cross-connects including planar lightwave circuit (PLC) switch [1, 11], 2-D and 3-D micro-electro mechanical systems (MEMS) [12 - 14] and liquid crystal (LC)/liquid crystal on silicon (LCoS) switches [15]. Among them, 3-D MEMS/LCoS-based selective switch technology is the most popular and widely utilized in present ROADM systems [14]. Wavelength selective switches have become the key of recent DWDM reconfigurable agile optical networks. Along with WSSs, waveband selective switches (WBSSs), an extension of WSSs, which can handle optical paths at the waveband granularity are essential to realize multi-granular optical path routing capable cross-connects. WSS/WBSS-based cross-connect architectures offer a considerable advantage that is the modular growth capability; expanding the node scale requires only the addition of necessary WSSs/WBSSs and hence, incremental cost-effective expansion is possible. Unfortunately, the degree of selective switches is still limited and thus, higher-order WSSs/WBSSs required for large-scale HOXCs that are necessary to accommodate the future ever increasing traffic can be realized by concatenated multiple selective switches. Based on that, we will develop an efficient architecture that utilizes selective switches whose degrees are much less than the number of connected fibers.

In this paper, for creating bandwidth-abundant and cost-effective optical path routing networks, we consider a waveband selective switch-based optical cross-connect architecture that exploits the waveband switching and makes the best use of present optical switch technologies. The architecture is based on multi-stage switch modules of concatenated small-scale 1x*M* optical waveband selective switch components. We also develop an appropriate design algorithm for the waveband routing optical network that utilizes the proposed 1x*M* waveband selective switch based cross-connect architecture. Performance of the waveband routing optical network is verified by numerical experiments. It proved that, depending on waveband capacity, a significant switch scale reduction can be achieved.

2. PROPOSED LARGE CAPACITY CROSS-CONNECT ACHITECTURE BASED ON 1X*M* WAVEBAND SELECTIVE SWITCHES

2.1. Proposed waveband cross-connect architecture

To exploit waveband switching while taking advantage of present selective switch technologies, we propose a waveband cross-connect architecture as shown in Figure 1. The proposed WBXC architecture employs multi-stage WBSS modules based on fixed-size 1x*M* WBSSs. Large size multi-stage WBSS modules are constructed by concatenating 1x*M* WBSS components. Because of the fixed size of WBSSs, the number of stages in the multi-stage WBSS modules is determined by the number of input/output fibers (denoted as *F*) at node. For example, one-stage module can be applied to support only no more than *M* output fibers, 2-stage modules are required as $M < F \leq M^2$ and 3-stage ones are necessary if $M^2 < F \leq M^3$, etc. Hence, switch scale of the WBXC architecture depends on not only the number of input/output fibers required but also the size of the WBSS components adopted. Optical signals from each input fiber are broadcasted to all output fibers by simply using optical couplers (as described in Fig. 1) or by implementing the corresponding multi-stage WBSS modules. Each output fiber is equipped with a multi-stage WBSS module. The add/drop functions with colorless/directionless/contentionless capabilities which are common to conventional WSS-based cross-connects are another important issue to be developed. This issue is not discussed herein.

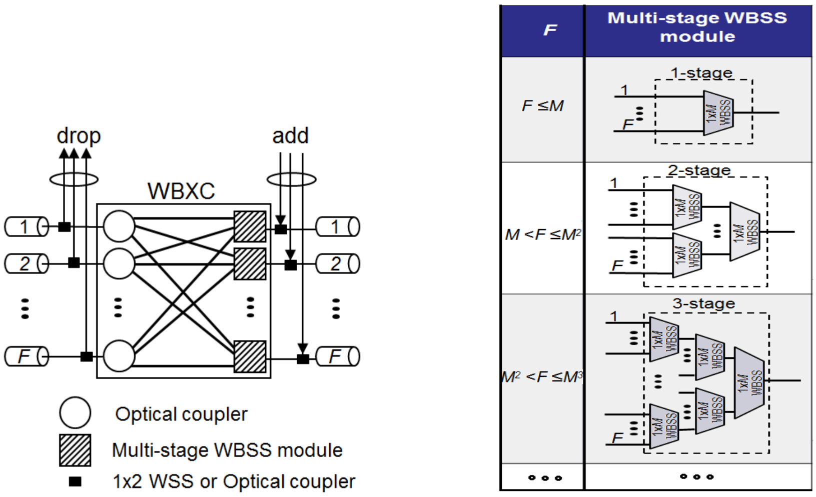

Figure 1. Proposed 1xM WBSS-based waveband cross-connect architecture

2.2. Switch scale evaluation

As explained above, the switch scale of the proposed 1xM WBSS based WBXC strongly depends on the selected WBSS size (M). Figure 2 shows the total number of necessary 1xM WBSSs in the waveband cross-connect architecture regarding the input/output fiber number, F, with different WBSS sizes (M = 4, 6 and 8). The graphs show that the total number of 1xM WBSSs required increases rapidly when the number of input/output fibers becomes greater. Implementing larger WBSS components (i.e. greater M) can reduce the total number of WBSSs required. However, note that, presently, the switch size of WBSS components is still limited and larger WBSSs may be very expensive.

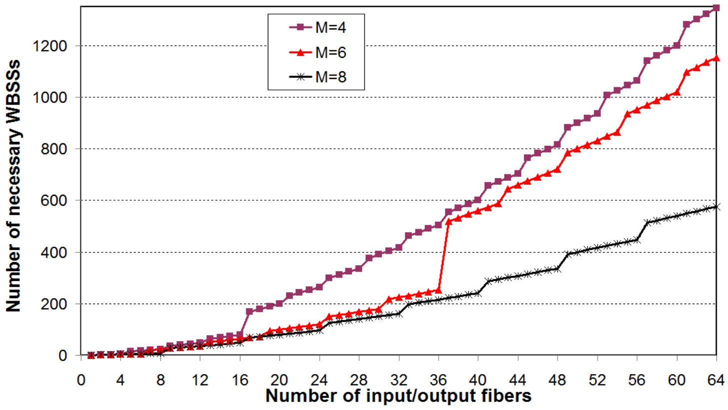

Figure 2. Number of required WBSSs

Furthermore, among optical switch technologies that have been applied to create WSS and WBSS systems, the systems that are based on MEMS technology are the most popular and widely adopted in present ROADM systems [1, 12]. For simplicity, hereafter, we consider MEMS-based WSSs/WBSSs only to evaluate the efficiency of the 1xM waveband selective switch-based WBXC node architecture. The switch scale of MEMS-based cross-connects is measured by the overall number of elemental MEMS mirrors required in their WSS/WBSS components. Because the failure probability and cost of the WSS/WBSS-based node systems heavily depend on the number of switch elements (i.e. mirrors of MEMS systems) required [5], minimizing the necessary switch scale is a crucial requirement for WSS/WBSS-based node architectures.

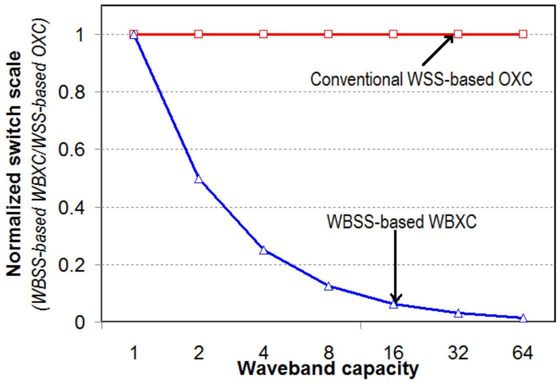

Figure 3. Switch scale comparison

Denote L as the number of wavelength paths per fiber, B as that of wavebands per fiber, and W as the waveband capacity, which is the maximum number of wavelength paths that can be accommodated in a waveband (i.e. $L = B \times W$). MEMS-based wavelength selective switches assign a mirror to each wavelength and each WSS consequently needs L mirrors. However, WBSS can be achieved in the same manner by replacing a group of mirrors, for wavelengths that form a waveband, by a large mirror (if the focal length of the lens is the same) [5]. WBSS switches the wavebands; all wavelengths in a waveband are switched simultaneously by the same mirror, and hence, only B mirrors are required for each WBSS, less than that of a WSS ($B \leq L$). Therefore, the switch scale ratio of the proposed 1xM WBSS-based waveband cross-connect to the corresponding WSS-based OXC is given by, $R = 1/W$. The switch scale ratio does not rely on the size of WSSs/WBSSs applied. The switch scale comparison between our proposed WBXC and conventional OXCs is described in Figure 3 with L of 64 with respects to different values of selected waveband capacity (W = 1, 2, 4, 8, 16, 32 and 64). The proposed 1xM WBSS-based WBXC requires less number of switching elements (MEMS mirrors) than the conventional WSS-based OXC. The switch scale ratio depends on the waveband capacity. It decreases when the waveband capacity is increased.

3. WAVEBAND ROUTING OPTICAL PATH NETWORK DESIGN

3.1. Proposed network design algorithm

In this section, we develop a network design algorithm for waveband routing optical path networks employing the proposed 1xM WBSS-based waveband cross-connect. Our proposed algorithm includes 3 main steps. Firstly, to fully utilize the advantages of the 1xM waveband selective switch-based waveband cross-connect architecture, direct establishment of end-to-end waveband paths is encouraged to accommodate wavelength paths requested between the same source and destination node pairs. Each end-to-end waveband path is, then, routed by applying a shortest path algorithm on an auxiliary multi-layer graph of the network. Finally, waveband path rerouting is iteratively applied to cut down fibers whose number of occupied waveband paths is less than a given threshold. The developed design algorithm is briefly summarized as follows:

<Network design algorithm with waveband rerouting re-optimization>

Step1: Grouping wavelength paths

All wavelength paths requested between the same source and destination node pairs are aggregated into end-to-end waveband paths.

Step2: Routing and waveband assignment

In descending order of hop count between the source and destination nodes, for each end-to-end waveband path, find the shortest waveband path (including the route and the waveband index) on an auxiliary multi-layer waveband graph of the network where each layer is defined for a waveband index and its arcs are weighted to encourage sharing of unoccupied wavebands in established fibers. Then, establish the corresponding end-to-end waveband path to carry the traffic demand.

Step 3: Rerouting waveband paths

Search for the unmarked fiber whose occupied waveband number is the smallest and less than a given threshold (i.e. $L/4$). Block the fiber and try to reroute all belonging waveband paths. If successful, delete the fiber; otherwise unblock and mark the fiber. Repeat until Step 3 until no such fiber is found.

3.2. Performance evaluation

We apply the proposed WBXC architecture and network design algorithm for the pan-European optical network, COST266, that consists of 26 nodes and 51 links. The capacity of a fiber is set at 64 wavelengths with B wavebands and each waveband consists of W wavelengths ($L = B \times W = 64$). Multi-stage waveband selective switch modules utilize only 1x9 WBSSs ($M = 9$). The traffic demand is randomly assigned and is represented as the average number of wavelength paths requested between node pairs. For each traffic demand, we test with 20 different random traffic samples and plot their ensemble averages. The obtained total switch scale of the waveband routing optical networks is normalized by that given by the corresponding traditional single-layer optical path networks based on WSS-based OXCs.

3.2.1. Switch scale reduction

The cost efficiency of multi-granular optical path networks is enhanced by selecting larger waveband capacity as well as increasing the average hop count of established waveband paths or improving the waveband utilization ratio [9, 10]. However, larger waveband capacity and longer waveband paths, that can help reducing the node scale, may cause an insufficient utilization of waveband paths and as a result, more link resources (i.e. necessary fibers) are required. There is a tradeoff between node cost and link cost in waveband switching optical networks. Figure 4 and 5 describe the normalized total switch scale and necessary fiber number of the pan-European COST266 network with the waveband capacity of 8 ($B = W = 8$). The overall node scale and fiber number achieved by our proposed network design algorithm (denoted as Proposed) are also compared to those offered by the end-to-end algorithm (called Conventional), which simply accommodates wavelength paths with the same source and destination nodes into waveband paths (please refer to [6] or [9] for details). The simulation results prove that our proposed algorithm outperforms the conventional one, especially as the traffic demand is less than 9. When the traffic demand is greater than 8, even the obtained switch scales are almost the same, the proposed algorithm offers slightly smaller number of necessary fibers.

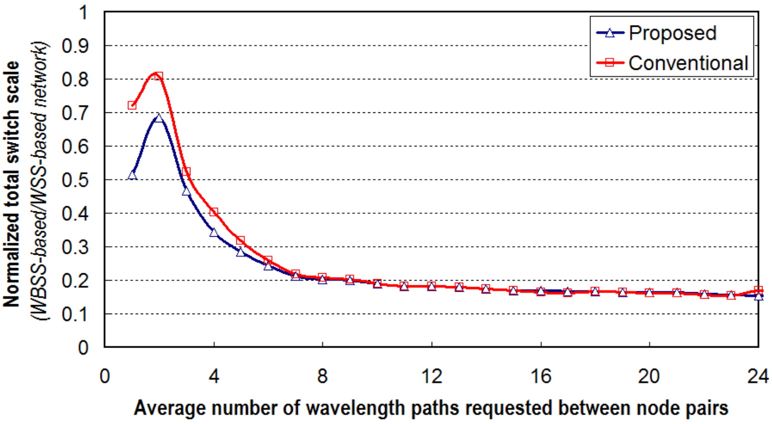

Figure 4. Total switch scale evaluation

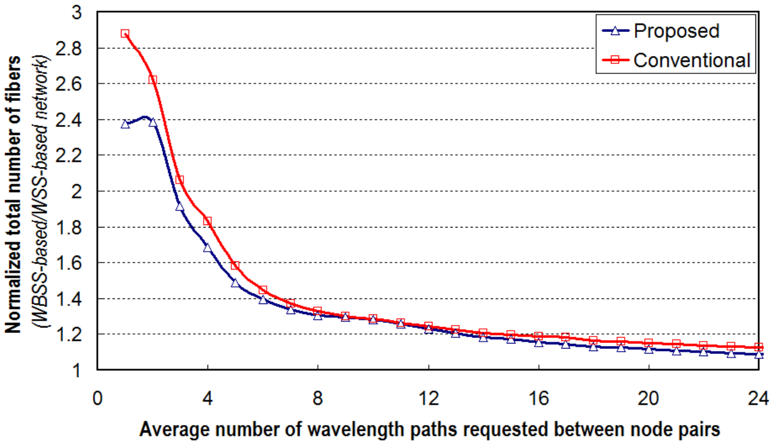

Figure 5. Total number of required fibers

Figure 4 shows that the waveband routing optical networks require much smaller number of switching elements (MEMS mirrors) than the corresponding traditional single layer optical path networks (normalized costs are less than 1). The total node scale reduction becomes greater with larger traffic demands. More than 80% less total switch scale is offered as the average traffic demand is greater than 8. However, as presented in Figure 5, the waveband routing optical networks need more link resources (i.e. number of required fibers) than the corresponding single-layer optical path network utilizing WSS-based OXCs.

3.2.2. Impact of waveband capacity selection

The waveband capacity, *W*, has a strong impact on the efficiency of multi-granular optical path networks [9] and the necessary node scale. As explained in Section 2, if the fiber capacity is fixed, with the same number of input/output fibers, the switch scale of the proposed 1x*M* WBSS-based WBXC becomes more and more smaller than that of a traditional WSS-based OXC, as the waveband capacity is increased (*B* is decreased). To evaluate the impact of waveband capacity selection on the overall switch scale of the network, we set the waveband capacity as 2, 4, 8, 16, and 32 successively while still keep the fiber capacity fixed ($L = B \times W = 64$).

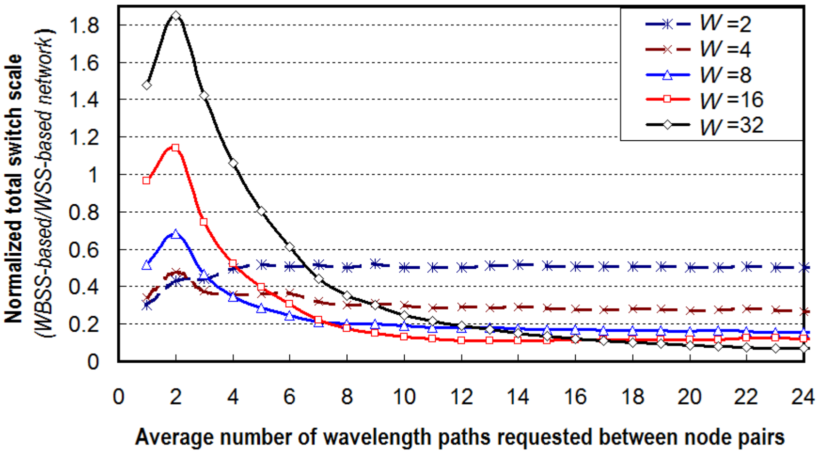

Figure 6. Impact of the waveband capacity in COST266 network

The normalized total switch scales of the COST266 waveband routing optical network with respect to varied traffic demands and different waveband capacities are illustrated in Figure 6. The results demonstrate that the smallest waveband capacity $W = 2$ offers the best cost reduction with very small traffic demands (less than 3). The effective traffic demand area of $W = 4$ is only between 3 and 4. The reason is that, because of the fixed fiber capacity, selecting a smaller waveband capacity can help improve the waveband utilization efficiency but may increase the number of waveband paths (necessary fibers) needed to carry the same given traffic demand, and as a result, more necessary WBSSs are required and the overall switch scale required is increased. On the other hand, the largest waveband capacity ($W = 32$) provides the greatest scale reduction in large traffic area (greater than 16), but it reduces the total switch scale less significantly in smaller traffic volumes due to a fall in waveband utilization efficiency of such huge waveband paths. For intermediate waveband capacities, while W = 8 attains the best scale reduction with traffic demands less than 8, the most effective traffic demand area for W = 16 runs from 8 to 16. These results verify that the optimal waveband path granularity, in terms of maximizing the overall node scale reduction, depends on the range of traffic demand given in the network.

4. CONCLUSION

We have proposed a large capacity single-layer optical cross-connect architecture, that is capable of switching waveband paths and can be built by using small-scale 1x*M* waveband selective switches. We then evaluated the switch scale of the 1x*M* WBSS-based WBXC architecture in comparison with that of traditional WSS-based optical cross-connects. Moreover, we have also developed an appropriate design algorithm for the corresponding optical path network utilizing the proposed 1x*M* WBSS-based WBXC architecture. Numerical results verify that implementing the 1x*M* waveband selective switch based WBXC architecture offers a significant reduction of overall switch scale (i.e. numbers of MEMS mirrors), the key factor that determines the complexity, reliability and cost of the network. Impact of waveband capacity selection on the total switch scale of the network is also verified.

REFERENCES

1. Sato K. and Hasegawa H. - Optical networking technologies that will create future bandwidth abundant networks, OSA/IEEE Journal of Optical Communications and Networking **1** (2) (2009) A81-A93.
2. Izmailov R., Ganguly S., Wang T., Suemura Y., Maeno Y., and Araki S. - Hybrid Hierarchical Optical Networks, IEEE Communications Magazine **21** (2002) 88-94.
3. Harada K., Shimizu K., Kudou T., and Ozeki T. - Hierarchical Optical Path Cross-Connect Systems for Large Scale WDM Networks, In: Proceedings of OFC, February 1999, pp. 356-358.
4. Cao X., Anand V., and Qiao C. - Framework for waveband switching in multigranular optical networks: part I- multigranular cross-connect architectures, Journal of Optical Networking **5** (12) (2006) 1043–1055.

5. Mitsui S., Hasegawa H., and Sato K. - Low Loss and Cost-effective Hierarchical Optical Path Cross-connect Switch Architecture based on WSS/WBSS, In: Proceedings of Photonics in Switching, Pisa, 2009.
6. Li M., Yao W., and Ramamurthy B. - Same-Destination-Intermediate Grouping vs. End-to-End Grouping for Waveband Switching in WDM mesh Networks, In: Proceedings of IEEE International Conference on Communications, Vol. 3, May 2005, pp. 1807-1812.
7. Lee M., Yu J., Kim Y., Kang C., and Park J. - Design of hierarchical cross-connect WDM networks employing a two-stage multiplexing scheme of waveband and wavelength, IEEE Journal on Selected Areas in Communications **20** (1) (2002) 166-171.
8. Yamada Y., Hasegawa H., and Sato K. - Coarse Granular Routing in Optical Path Networks and Impact of Supplemental Intermediate Grooming, In: Proceedings of ECOC2010, September 2010.
9. Yagyu, H. Hasegawa, and K. Sato - An efficient hierarchical optical path network design algorithm based on a traffic demand expression in a Cartesian product space, IEEE Journal on Selected Areas in Communications **26** (6) (2008) 22-31.
10. Torab P., Hutcheon V., Walters D., and Battou A. - Waveband switching efficiency in WDM networks: analysis and case study, In: Proceedings of OFC, paper OtuG3, March 2006.
11. Ishii K., Hasegawa H., Sato K., Okuno M., and Takahashi H. - Ultracompact Waveband Cross-Connect Module Using Waveband Selective Switches: Development and Performance Verification, IEEE Photonics Technology Letters **22** (23) (2010) 1741-1743.
12. Wu M., Solgaard O., and Ford J. - Optical MEMS for Lightwave Communication, Journal of Lightwave Technology **24** (12) (2006) 4433-4454.
13. Wall P., Colbourne P., Reimer C., and McLaughlin S. - WSS Switching Engine Technologies, In: Proceedings of OFC/NFOEC, paper OWC1, March 2008.
14. JDSU White paper - A Performance Comparison of WSS Switch Engine Technologies, May 2009.

   Available online at: http://www.jdsu.com/ProductLiterature/wsscomp_wp_cms_ae.pdf
15. Frisken S., Baxter G., Abakoumov A., Zhou H., Clarke I., and Poole S. - Flexible and Grid-less Wavelength Selective Switch using LCOS Technology, In: Proceedings of OFC/NFOEC, paper OTuM3, March 2011.

TÓM TẮT

MỘT NGHIÊN CỨU VỀ MẠNG QUANG ĐỊNH TUYẾN DẢI SÓNG SỬ DỤNG HỆ THỐNG NỐI CHÉO QUANG DỰA TRÊN CÁC CHUYỂN MẠCH LỰA CHỌN DẢI SÓNG

Bài báo đề xuất một kiến trúc chuyển mạch dải sóng quang sử dụng các phần tử chuyển mạch lựa chọn dải sóng cỡ nhỏ. Kiến trúc đề xuất cho phép khai thác những ưu điểm của công nghệ chuyển mạch dải sóng quang, đồng thời vẫn tận dụng được tối đa khả năng của công nghệ quang hiện tại nhằm xây dựng một mạng định tuyến bước sóng quang có dung lượng lớn và hiệu quả về giá thành. Một giải thuật thiết kế mạng tương ứng cũng được phát triển cho các mạng định tuyến dải sóng quang sử dụng kiến trúc chuyển mạch dải sóng đề xuất. Các kết quả tính toán cho thấy việc sử dụng kiến trúc chuyển mạch dải sóng đề xuất cho phép giảm đáng kể kích thước của các hệ thống chuyển mạch quang trong mạng. Ngoài ra, ảnh hưởng của việc lựa chọn dung lượng dải sóng và hiệu quả giảm kích thước tổng thể của các hệ thống chuyển mạch trong mạng quang cũng được nghiên cứu và đánh giá.

Từ khóa. WDM, mạng chuyển mạch kênh/đường quang, chuyển mạch dải sóng, định tuyến và ấn định bước sóng, nối chéo quang.