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Design of all Optical Packet Switching Networks

Hussein T. Mouftah

Department of Electrical and Computer Engineering, Queen's University Kingston, ON, K7L 3N6, Canada, Email: mouftah@ece.queensu.ca.

تعميم الشبكات ذات حزم المفاتيح البصرية التامة

حسين ت. مفتاح

خلاصة : المفاتيح البصرية ومحولات الطول الموجي تصنفان على انهما اهم مكونين للأنظمة DWDM في الشبكات البصرية التامة مستقبلا.
المفاتيح البصرية تمثل الجزء الأساسي في عمل الموجهات المتغيرة, دوائر OXC القابلة للتنظيم, دوائر حماية الشبكات والإصلاح في الشبكات البصرية.
محولات الطول الموجي تستخدم في التحويل من طول موجي داخل الى طول موجي آخر خارج عند الحاجة. يساعد استخدام هذه المحولات مع المفاتيح البصرية على الحصول على موجهات مستقرة, إدارة وتنظيم المفاتيح والشبكات في الطبقة البصرية بشكل ضروري لظهور الشبكات البصرية التامة.
ولكن يجب الآخذ بنظر الاعتبار الكلفة العالية لمحولات الطول الموجي أثناء التصميم. ويتضمن هذا البحث دراسة كفاءة محولات الطول الموجي عن طريق نمذجة الشبكات البصرية بدرجات مختلفة من الحمل. كما يقدم البحث طريقة كفوءة الكلفة لتصميم مثالي لمحولات الطول الموجي وفي نفس الوقت يراعى ان تكون خوارزمية الموجهات وافتراض الطول الموجي خوارزمية عامة تصلح لكلا الشبكات ذات الحمل الكبير والحمل الصغير. عند اقتران العمل بهذه الخوارزمية العامة مع مفاتيح ومحولات الطول الموجي يمكن الوصول الى الشبكات البصرية التامة.

ABSTRACT: Optical switches and wavelength converters are recognized as two of the most important DWDM system components in future all-optical networks. Optical switches perform the key functions of flexible routing, reconfigurable optical cross-connect (OXC), network protection and restoration, etc. in optical networks. Wavelength Converters are used to shift one incoming wavelength to another outgoing wavelength when this needs to be done. Always residing in optical switches, they can effectively alleviate the blocking probability and help solve contention happening at the output port of switches. The deployment of wavelength converters within optical switches provides robust routing, switching and network management in optical layer, which is critical to the emerging all-optical Internet. However, the high cost of wavelength converters at current stage of manufacturing technology has to be taken into consideration when we design node architectures for an optical network. Our research explores the efficiency of wavelength converters in a long-haul optical network at different degrees of traffic load by running a simulation. Then, we propose a new cost-effective way to optimally design wavelength-convertible switch so as to achieve higher network performance while still keeping the total network cost down. Meanwhile, the routing and wavelength assignment (RWA) algorithm used in the research is designed to be a generic one for both large-scale and small-scale traffic. Removing the constraint on the traffic load makes the RWA more adaptive and robust. When this new RWA works in conjunction with a newly introduced concept of wavelength-convertible switches, we shall explore the impact of large-scale traffic on the role of wavelength converter so as to determine the method towards optimal use of wavelength convertible switches for all-optical networks.

KEYWORDS: All Optical Networks, Packet Switching, Wavelength Division Multiplexing, Wavelength Converters, Routing and Wavelength Assignment.

1. Introduction

It has been widely believed that Dense Wavelength Division Multiplexing (DWDM) is a promising technology for next generation Internet. WDM networks have proved themselves to be capable of offering a transmission capability of Terabit (10^{12} bit per second) or even petabit (10^{15} bit per second) by multiplexing traffic on to a set of wavelength channels within a single fiber as shown in Figure 1. Meanwhile, they do network routing, protection, restoration and management in the optical domain, which greatly improves the whole network performance.

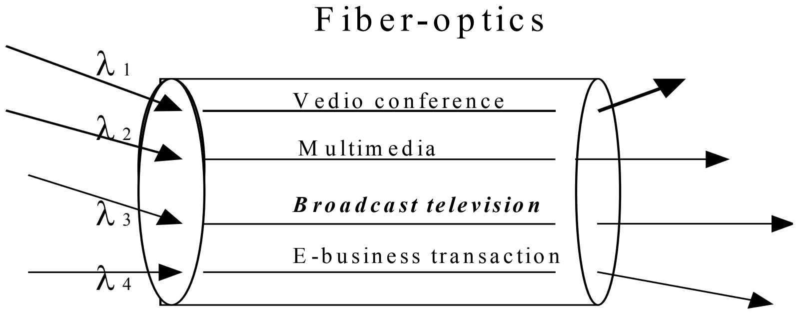

Figure 1. Integrated traffic in fiber optics.

In a WDM network, the traffic between each pair of source and destination (s-d) nodes can be routed based on its wavelength. A WDM network with such a feature is called wavelength-routing network (Mukherjee, 1997). Wavelength routing provides a flexible and efficient mechanism of setting up lightpaths for traffic demands and can do reconfiguration in case of a change in the state of a network.

An important optical component that performs the routing function at each intermediate node along the lightpaths is the optical switch. It switches an entire wavelength from an input port to an output port at each intermediate node according to a certain routing scheme. By utilizing optical switches this way, the optical domain connectivity among nodes and access stations can be dynamically rearranged. This rearrangeability will allow the dynamic allocation of wavelength and capacity throughout the network to meet changing traffic, service, and performance requirement so as to provide a robust, fault-tolerant network. Moreover, as the network functions of operation, administration, maintenance and provisioning move from the traditional electrical layer to the optical layer, optical switches will play a critical role.

An optical switch equipped with wavelength converters is called wavelength-convertible switch. Wavelength converters are used to solve the wavelength-continuity constraint existing in simple wavelength-routing networks. Wavelength-continuity constraint imposes a strict condition that a lightpath must be established on a single wavelength. This leads to very inefficient utilization of wavelength resources and results in higher network blocking probability. By using wavelength converters within a switch node, one incoming traffic flow on a certain wavelength can be directed to an output port on another different available wavelength when needed. This way has the benefit of alleviating output port contention as well as increasing wavelength reuse.

2. Wavelength-Convertible Switches

Despite the preferable advantage of eliminating wavelength continuity constraint so as to decrease network blocking probability, wavelength converters are costly at the current state of technology. Therefore, many studies have attempted to determine the potential benefits of wavelength conversion and the efficient ways to deploy them in optical switches.

In (Lee and Li, 1993), several wavelength-convertible cross-connect architectures were proposed as shown in Figure 2. Depending on the design, wavelength converters can be used in different architectures as dedicated, share-per-link and share-per-node. Connections can choose to bypass the wavelength converter bank and stay on the same wavelengths or be directed to the converter bank to undergo shifting to another wavelength.

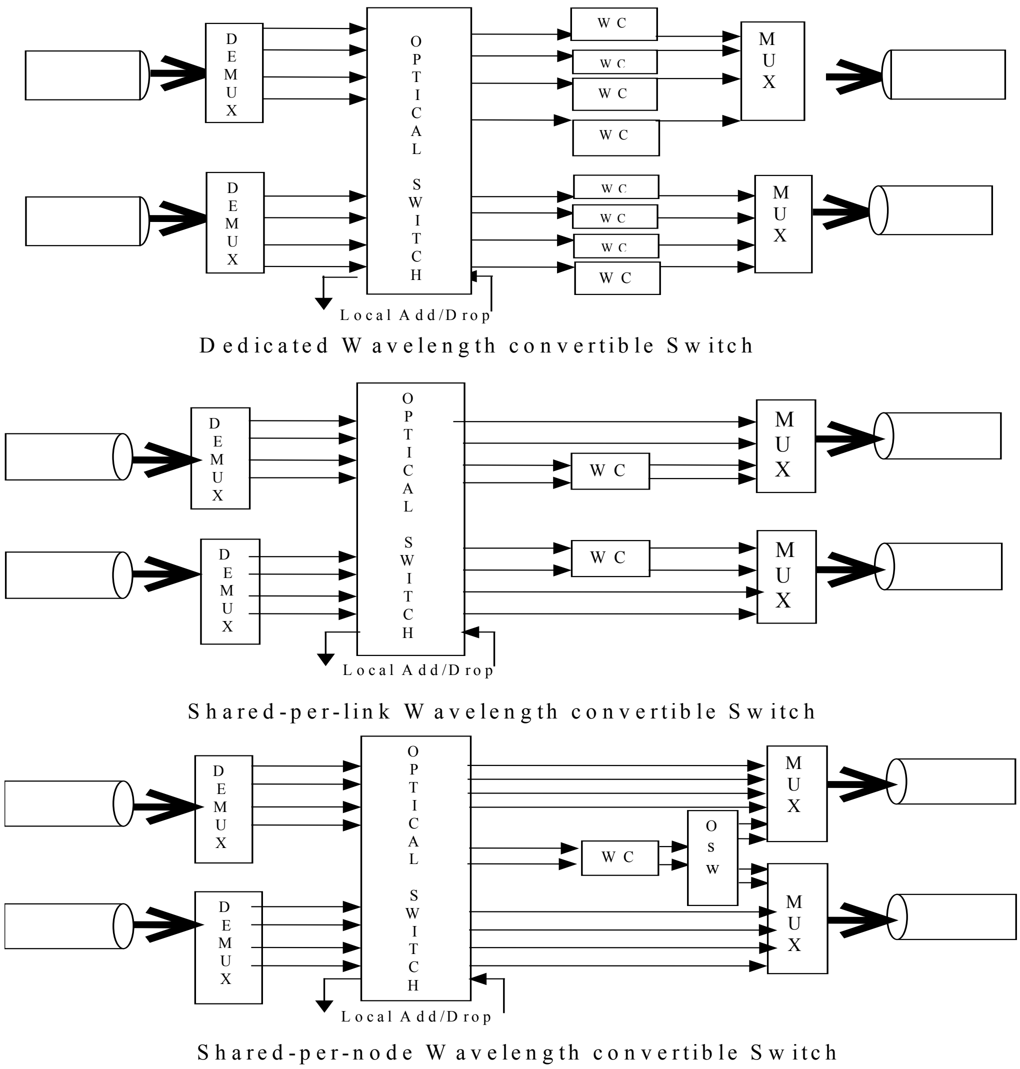

Figure 2. Wavelength-convertible switch architecture alternatives.

The dedicated wavelength convertible switch architecture provides a full conversion capability to any wavelength. However, the high expense and inefficient use of converters make it a poor candidate for industry application. Both share-per-link and share-per-node architectures use a fewer number of converters while still achieving most of the benefits of a full conversion way. In (Yates and Rumsewicz, 1999), the authors show that the performance offered by wavelength converters depends on a number of factors, including the number of available wavelengths, the routing and wavelength assignment algorithms, network topology and network size.

In (Iness and Mukherjee, 1998; and Torrington-Smith, 2000), the authors investigated the issues of optimal use of wavelength converters in lightwave networks. The work in (Iness and Mukherjee, (1998) considers different versions of sparse wavelength conversion - namely, sparse nodal conversion, sparse switch-output conversion and sparse range conversion to determine if the sparse use of wavelength converters can achieve the most benefits provided by full conversion. Based on the observation that most of the studies show that wavelength converters are critical but not needed all the time, a half-clear wavelength-convertible switch architecture was proposed by (Torrington-Smith, 2000). The conclusion from (Torrington-Smith, 2000) was that a half-clear wavelength-convertible switch can have similar performance characteristics as other architectures shown in Figure 2, however, with much less cost.

A common observation from all the above studies is that the network performance improvement due to the use of wavelength converters depends heavily on several factors such as network topology and network size, traffic load, RWA schemes, and the number of wavelengths used on each fiber link. Hence, besides the design of a new optical switch architecture, one must carefully select a Routing and Wavelength Assignment algorithm so as to match most efficiently the characteristics of the network.

3. WACOSOD (WAvelength-Convertible Optical Switch Optimization Design)

Considering the high cost of wavelength converters and their performance dependency on the above factors, our research objectives were to:

- propose a novel optical switch architecture with X% of wavelength conversion capability such that the number X% is tunable so as to achieve the most cost-effective design for the whole network;
- develop new routing and wavelength assignment schemes to deal with both large-scale and ordinary traffic (Generic RWA problem) in light of the fact that all previous research efforts have been focussed on small-scale traffic, which is no more than the capacity of a single wavelength between any pair of source and destination nodes;
- study the impact of large-scale traffic on the efficiency of the new wavelength-convertible switch (bifurcated traffic problem).

3.1 Design of the X% Wavelength-Convertible Switch

Each of the above reports holds its unique contributions to the study of wavelength converters in optical networks. However, none has yet really investigated the optimal percentage of wavelength conversion capability needed in an optical switch node, given a certain type of network topology, traffic load and network constraints. Such an exploration would be very meaningful to network planners, optical switch designers and service providers, because the direct impact of such an optimization process is the cost of the whole network.

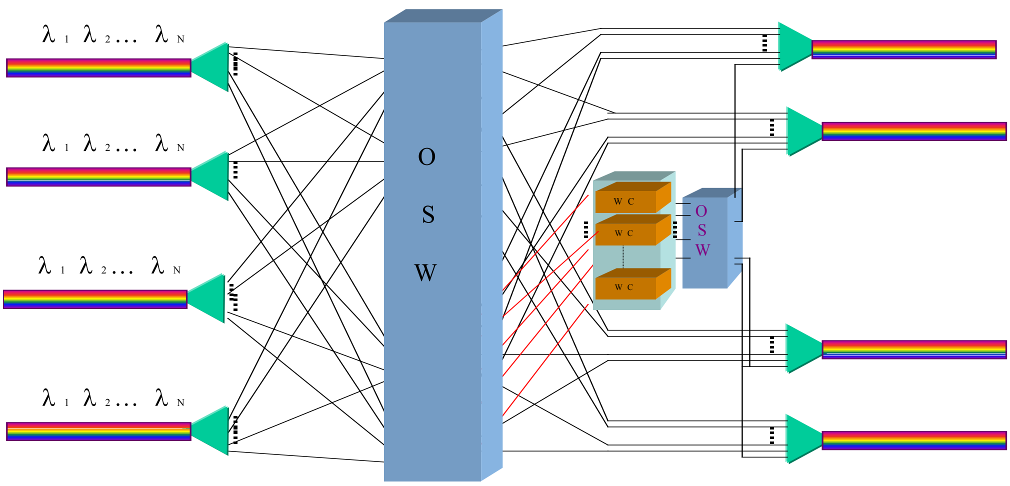

Figure 3. X% Wavelength-convertible switch architecture.

Bearing the above goals in mind, we propose a new, flexible and cost-effective wavelength-convertible switch architecture whose prototype is shown in Figure 3. In such a switch, only a certain percentage of outgoing links after the first stage optical switch can have access to the wavelength converter bank if conversion is needed.

Given a traffic load, a network topology and a traffic matrix, we can use a specially designed routing and wavelength assignment (RWA) algorithm to establish lightpaths for traffic flows in the optical domain with efficient use of wavelength converters. If a contention takes place at a switch output port, that wavelength will be directed to the wavelength converter bank as long as there is one wavelength converter available. With this type of architecture and given network parameters, we shall determine at what percentage of wavelength conversion capacity the network can be most cost-effective in terms of the metrics such as the number of wavelengths, network cost, network blocking probability and average traffic delay.

3.2 The Routing and Wavelength Assignment (RWA) Problem

Since the focus here is on core networks, the mean traffic flowing through the network is fairly steady in time domain. So we can take it as a static traffic for the simplicity and feasibility of the research. Thus, the algorithm used to deal with lightpath establishment is called static RWA. Solving the RWA problem for a given network topology, traffic matrix and network constraints is far from being trivial. Numerical analysis has proved that RWA is an N-P hard problem (Zhang and Acampora, 1995; Naas, 1999; Mukherjee *et al,* 1996) since this is an example of a mixed integer linear mathematical problem (MILP), for which no efficient algorithms are known to be existing for the solution of arbitrary MILPs. Thus, the majority of the research in this area has been focussed on heuristic approaches to solve the RWA problem.

For the routing problem, taking into account all possible source and destination pairs is impractical because the number of state space is exponentially increased with the network size. Hence, the routing function is usually performed by well-known heuristic techniques such as the shortest path algorithm and its variations. Our research has developed the shortest path algorithm to a Weighted Shortest Path (WSP) which not only does a searching for shortest path but also adds a searching order scheme so that the largest traffic will first be selected for path search. The goal is to route the heaviest traffic in one hop for lower congestion.

Once the routing problem is solved, wavelength assignment is performed with the goal of maximizing the wavelength utilization and network throughput. This problem can be presented as a graph-coloring problem that is a NP-complete problem. Therefore, heuristic methods must be used for a practical solution (Mukherjee *et al,* 1996; Garnot *et al,* 1997; Ramaswami and Sivarajan, 1995; Ravikumar *et al,* 1997). Some of the proposed wavelength assignment algorithms are: (1) Random wavelength assignment that allocates a new connection to a wavelength which is randomly chosen from the set of available wavelengths, (2) First-fit wavelength assignment which establishes a connection on the first available wavelength (Mitchem, 1995; Chlamtac *et al,* 1990). This is what we use in our approach. (3) Most-used wavelength assignment which allocates to a new connection the wavelength that is used on the greatest number of fibers in the network (Mokhtar and Azizoglu, 1998).

So far, almost all the work done before simply assumed small-scale s-d traffic which never surpasses the capacity of a single wavelength capacity. However, a more realistic situation in the backbone networks is that a pair of s-d nodes representing two major metropolitan areas may need to transmit very large-scale traffic that is well above the capacity of one wavelength from end to end. Then, how to solve this traffic demand is a nontrivial problem. Thus, we proposed a Generic RWA (G-RWA) for both large and small-scale traffic.

In response to such a challenge, we proposed a traffic splitting and waveband routing algorithm as shown in Figure 4. The example in this figure shows how the large-scale traffic

32Gbps is routed from its source node 1 to destination node 4. Here, the traffic is split into two sub-groups consisting of three 10Gbps and one 2Gbps traffic flows. Then, those three 10Gbps traffic flows are grouped into a waveband and routed to node 4. The remaining 2Gbps traffic is dealt with in wavelength routing module. The reason behind such an algorithm design is the simplicity for network control and lower network cost. Obviously, this introduces computation complexity in RWA, since the pre-processing on waveband will cause the changes in available wavelength resources and network status.

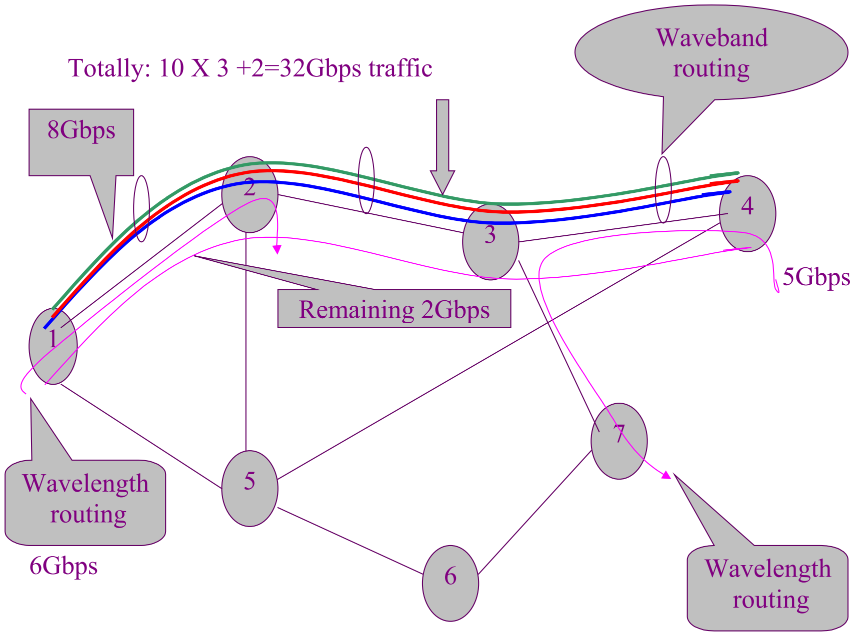

Figure 4. Hybrid waveband and wavelength routing.

Another key issue is the lightpath establishment, which requires efficient reuse of wavelengths. In (Torrington-Smith, 2000; and Naas, 1999), lightpaths were set up in the priority order of unclear lightpath, continuous clear lightpath and non-continuous clear lightpath for the sake of saving cost, because the unclear lightpath takes advantage of the local Add/Drop switches to do O-E-O conversion. This method costs less than the all-optical conversion does. Such an idea is very suggestive and innovative. However, besides the drawback of large O-E-O conversion delay, as the traffic load on the backbone network increases tremendously, the burden on the local conversion switches would become very heavy. In order to deal with such a situation, the local switch has to be much more powerful and hence becomes very expensive. As a result, the cost of a robust local switch surpasses the additional cost by adding more wavelengths or converters. More importantly, our research is forward-looking into the All-optical network, and we expect that no O/E conversion should get involved in the backbone networks. Therefore, our research will initiate a comparison between the RWA algorithms with or without unclear lightpath (UCL) under heavy traffic load to determine which one is more cost-effective.

3.3 WACOSOD Design

With all the above innovative ideas, the simulation software is being developed as expected. The flow chart for the whole WACOSOD is illustrated in Figure 5. Given the network parameters such as network topologies, traffic matrix, traffic load request and system constraints, we first deal with traffic sorting and splitting as described in the above 32Gbps traffic example. Then, the large traffic is combined together into a waveband which in turn is routed to the destination node. This step is repeated until all the large scale traffic is satisfied.

Then, the network resource and status information are updated. Afterwards, wavelength routing takes place to accommodate the small-scale traffic. Simulation results and data are collected at the end for further analysis.

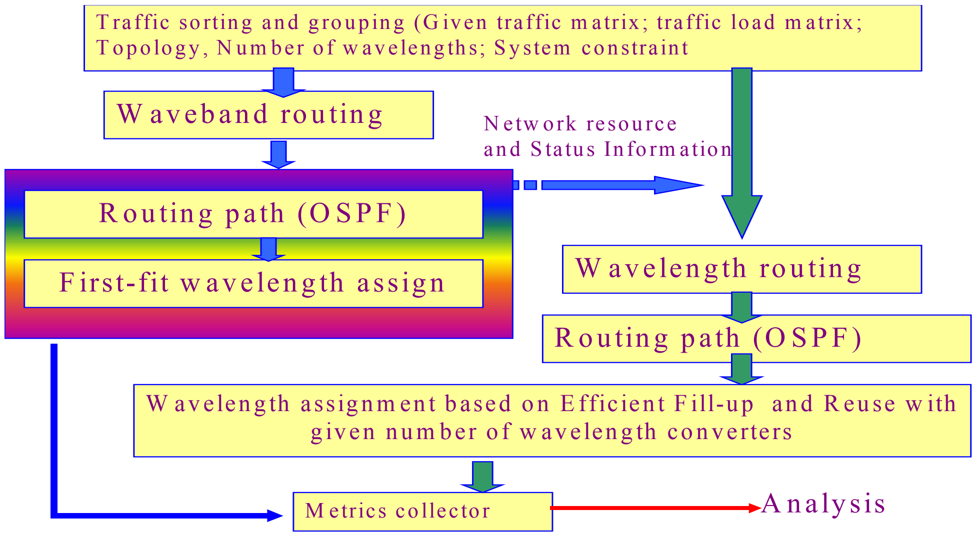

Figure 5. WACOSOD flow chart.

4. Results and Discussion

WACOSOD was run for a NSF network with 14 nodes across North America. The simulation starts with wavelength conversion capability of 0, i.e. no wavelength converters was in optical switches. The values for the network metrics were generated at the end of a simulation. We then increased the conversion capability and repeated the simulations. In this way, network metrics corresponding to different percentages of wavelength conversion capabilities were recorded for quantitative analysis.

In Figure 6, it is clear that the more wavelengths that are used, the better the network throughput that is obtained, because more traffic can fit into the network. The upper group of curves represents the incremental network throughput associated with the changing percentages of wavelength converters. Unclear lightpath (UCL) was allowed in RWA. The plot shows that the network with higher percentage of conversion usually achieves higher network throughput with the same number of wavelengths. This well proves the role of wavelength converters in improving network throughput.

The lower two curves are for the All-optical networks (no UCL) with 50% and 25 % wavelength conversion capacities respectively. As we expected, we also see that removing UCL from network makes a poorer reuse of wavelengths so that a higher number of wavelengths is needed to retain the same level of network throughput. In this case, 18 wavelengths are needed for a 100% throughput for an All-optical network while only 16 are needed for the network with UCL. Such a difference in the number of wavelengths can be ignored as the transport system can support a much higher number of wavelengths (160 per fiber so far) with much less cost on each individual wavelength.

Meanwhile, the O/E conversion involved in UCL will introduce a lot of processing latency as we can see in Figure 7. The plot clearly tells us that on average, traffic in the all-optical networks experiences much less delay (about 20% less) because no O/E conversion gets involved. As more and more real time services, such as online teleconferences or telemedicine, are emerging, all-optical networks will take the responsibility for such QoS requirements. Moreover, eliminating O-E-O conversion from the backbone network will guarantee the optical layer's transparency to data rate, protocols and traffics, which in turn simplifies the network control and management.

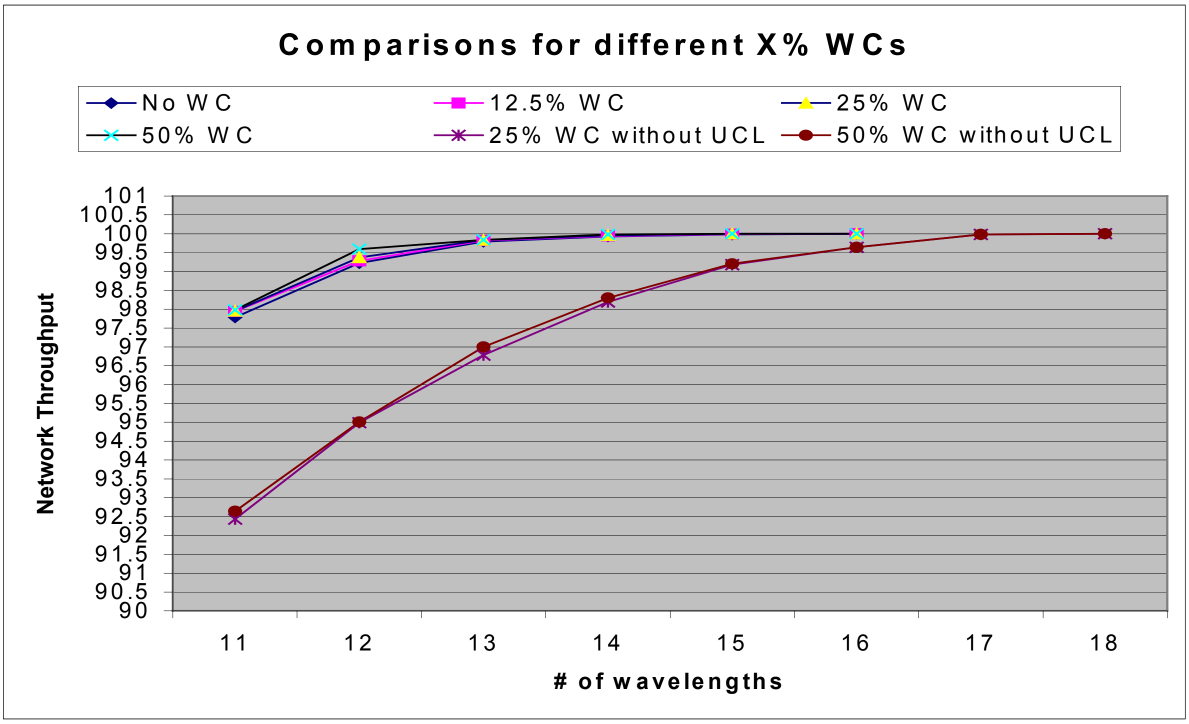

Figure 6. Network throughput vs. number of wavelength.

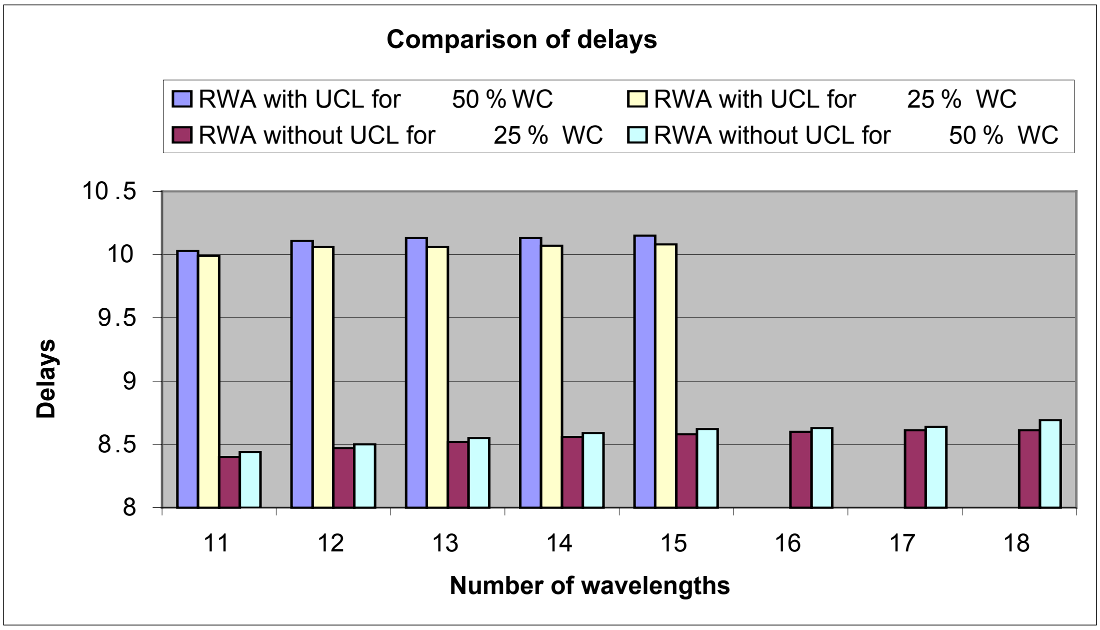

Figure 7. Delays comparison between UCL and Non-UCL.

An important insight into the effect of increasing wavelength conversion capability can be obtained from Figure 8. For a given traffic load, the achievable benefit in network throughput by using more wavelength converters starts to be significant and then gradually levels off after a certain threshold. In this case, before getting 37.5% of wavelength conversion capability, the network throughput has been steadily increasing. After that, the gain drops sharply and barely changes. For this particular case, around 37% conversion capability is good enough and cost-efficient. Such an observation implies that a careful selection on the number of wavelength converters in optical networks is a must. More research work should be done on finding the most cost-effective combination of the number of wavelengths, the number of converters, network gains and associated network costs.

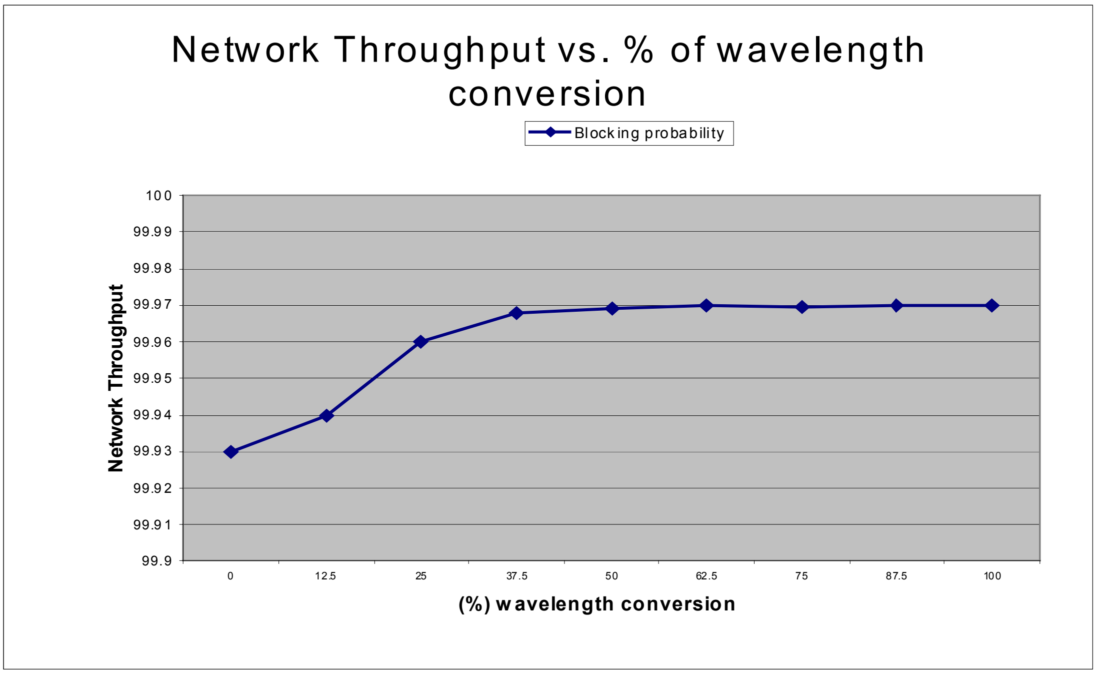

Figure 8. Network throughput vs. the percentages of wavelength converters.

5. Summary

The performance of a wavelength-convertible optical network is closely related to the architecture of the optical switch nodes, the traffic load, the network topology and the RWA algorithms. Therefore, a study on an All-optical network must carefully take into consideration all these correlated factors. Moreover, the interleaving influence between those factors shall be studied.

The proposed X% wavelength-convertible switch architecture is an innovative idea to explore the most cost-efficient way to gain network performance enhancements. It works in conjunction with the new G-RWA algorithm to smartly do network configuration, lightpath establishment and fully use the wavelength resources. In such a way, wavelength-convertible switches can truly bring to the next generation All-optical networks more robust capabilities at as little cost as possible. In G-RWA, the waveband routing method for large-scale traffic is a cost-effective, simple-controlled and easy-implemented solution. Further detailed research will use WACOSOD to study the role of wavelength converters in large-scale traffic by means of analyzing the network throughput enhancement due to wavelength converters, change in average traffic delay vs. traffic load, and network cost variance due to the change in wavelength converter deployment.

6. Acknowledgement

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