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COLLISION-FREE FAULT TOLERANT MULTISTAGE INTERCONNECTION NETWORKS BASED ON WAVELENGTH DIVISION MULTIPLEXING

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ABSTRACT

In this paper, the performance of the extra stage Omega (ESO) networks based on wavelength division with limited number of buffers and wavelength converters was analyzed. Since the ESO networks suffer from the problem of internal blocking, therefore, the goal is to minimize the dropping probability by utilizing the available buffers and wavelength converters in the central controller of these networks. The advantage of ESO over the Omega networks is that there is a redundant path from any source to any destination. Having an additional path gives packets more flexibility, thus reducing the probability of packet buffering or dropping.

Keywords: *Multistage Interconnection Networks, Omega Networks, Internal Blocking, Buffering, Wavelength Conversion, Wavelength Division Multiplexing.*

1. INTRODUCTION

Multistage Interconnection Networks (MINs) have been exploited widely in many important applications in fields such as telecommunications and parallel computing in the past decades [1]. MINs are among the most efficient switching architectures in terms of the number of switching elements (SEs) used. MINs consist of a few stages of a number of smaller SEs. For example, by using 2×2 SEs, only $\log_2 N$ stages are required to achieve full access capability in an $N\times N$ switch, and in each stage, there are $N/2$ of 2×2 SEs [2]. Many types of MINs have been investigated, such as the baseline, delta, indirect binary n-cube, and Omega networks. It has been proven that these types of MINs are topologically equivalent [3].

MINs with only a few stages suffer the problem of *internal blocking*. Packets collide within a switch when more than one cell tries to use the same internal link, even though they are destined for different outputs. Using 2×2 switching elements, data might go through some unwanted changes when the two input channels try to access an internal channel simultaneously [4].

The extra stage MINs, a fault-tolerant structure, is constructed by adding of one stage of switching elements to the regular multistage interconnection network. It is shown that the extra stage MINs provides fault tolerance for any single failure [5]. Tolerating any number of switch faults was demonstrated with in optimal performance [6].

Recently, significant developments have been made in photonic switching based on *Wavelength Division Multiplexing* (WDM). By modifying MINs to be based on WDM, it is possible that two or more packets share the internal channel provided that they use different wavelengths. Therefore, a 2×2 switching element with additional configurations was introduced, namely the upper and lower mergers, and the upper and lower splitters [7]. The internal blocking is redefined as two or more packets with the same wavelength trying to access an internal channel simultaneously. This problem can be eliminated by increasing the number of switching elements, the number of stages, or the size of the switching element. However, all these techniques increase the cost and delay of such networks. Therefore, in this paper, utilizing the same few switching elements while maintaining full accessibility is attempted.

To alleviate the problem of internal blocking in MINs based on WDM, buffers or wavelength converters [8] are used. The advantage of wavelength conversion over buffering is the ability to utilize the available channel bandwidth and to send a packet to its destination without waiting for the next switching cycle. Once the central controller of MIN resolves the internal blocking by buffering, wavelength conversion, or dropping of the packets, it directs the packets through the network without any collision.

The scope of this paper is to investigate the performance of the extra stage Omega (ESO) networks based on wavelength division multiplexing. The goal is to minimize the dropping probability by utilizing the available buffers and wavelength converters in the central controller of the network. The paper is structured as follows: Section II surveys some of the related work. A brief overview of ESO is given in section III. ESO with buffering and wavelength conversion is discussed in section IV. The performance of ESO networks is evaluated by simulation in section V. The final section concludes the paper.

2. RELATED WORK

In [7], several architectures and algorithms were introduced to alleviate the problem of internal blocking in WDM-based Omega networks. The first architecture was a collision-free Omega network based on buffering, the second one uses wavelength converters and buffering, and the last one considers look-ahead wavelength conversion which eliminates unnecessary wavelength conversions in case of using larger networks with arbitrary connections. It is shown that a few buffers and look-ahead wavelength converters will considerably improve the system performance. In [6], fault tolerance capabilities of multistage interconnection networks were investigated. The fault model that is used is the stuck-in straight model and the fault tolerance criterion is to guarantee point-to-point and broadcast connections. Fault-tolerant multistage interconnection network that is optimal in the number of redundant stages was constructed. In addition, the general condition that is both sufficient and necessary for MINs to achieve this optimal performance in tolerating switch faults was proven.

In [8], an irregular fault-tolerant multistage interconnection network named as Irregular modified baseline network (IMABN) was proposed and analyzed. IMABN is dynamically re-routable and provides multiple paths of varying lengths between source and destination pairs. The number of switching elements encountered is varying, depending on the path chosen which makes the average rate of failure of the network to be lesser for the irregular MINs as compared to that of regular MINs. In [9], an attempt has been made to analyze the characteristics IMABN. It was shown that IMABN can provide *full access* capability in presence of multiple faults.

In [10], node-disjoint paths routing is an approach to solve the crosstalk problem on both links and switches of all-optical networks. The results suggest that the required node-disjointness on all-optical MINs may not be a bottleneck. An interesting open problem is to find a tight bound on the number of wavelengths for any partial permutation by node-disjoint paths with respect to the minimum number of passes for the same permutation by edge-disjoint paths on the MINs. Heuristic algorithms for finding the wavelength assignment for arbitrary permutations on all-optical MINs and efficient algorithms for finding the wavelength assignment for permutations on extra-stage all-optical MINs were considered to be investigated.

In [11], a new fault-tolerant Banyan (FTB) network design was proposed. The rules to add extra hardware and links to the regular Banyan network in order to get the new FTB network were presented. The work includes a modular design for a new 2×2 switching element that can be configured in different well-defined modes. In case an error occurs in the function of a switch in the FTB network, the switch can be bypassed and other switch in the network replaces its role. The most attractive feature of the new design is that it can maintain the regular Banyan topology in the presence of faults. Consequently, the system performance will not be affected due to the occurrence of tolerable faults in the interconnection network. Moreover, multiple faults can be tolerated in the proposed FTB network. The FTB network can be very powerful in critical systems and applications where error can lead to catastrophic events.

3. EXTRA STAGE OMEGA NETWORKS

An $N \times N$ Omega network is a multistage interconnection network which consists of $\log_2 N$ identical stages, and in each stage, there are $N/2$ of 2×2 switching elements. The outputs from each stage are connected to the inputs of the next stage using a *perfect shuffle* link interconnect. This means that the connections at each stage simply represent the division of the N channels into two halves, which are then interleaved perfectly. In terms of binary representation of the N input channels, each stage of the perfect shuffle can be thought of as a cyclic logical left shift; each bit in the address is shifted once to the left, with the most significant bit becoming the least significant bit.

The extra stage Omega (ESO) network is formed from the Omega network by adding an extra stage of switching elements along with a number of multiplexers and demultiplexers as shown in Fig. 1. Therefore, ESO has relatively low incremental cost over the Omega network.

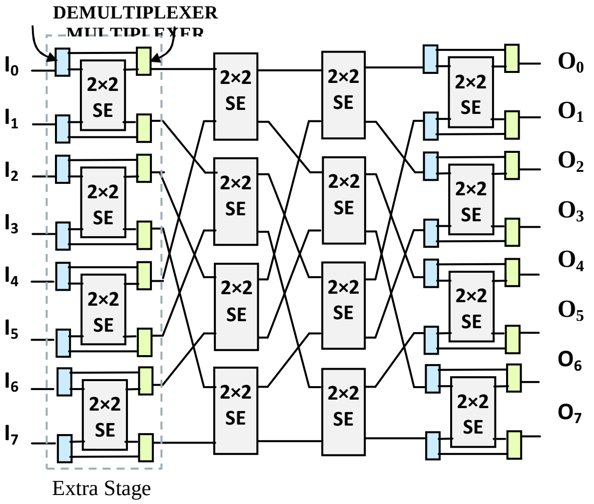


Fig. 1 The Extra Stage Omega Network with N=8

The ESO gets its fault-tolerant abilities by having redundant paths from any source to any destination. This allows continued communication between source and destination. ESO has two paths which are sufficient to provide tolerance to single faults for one-to-one connections. In ESO, the failure of any switching element in the inner stage can be resolved by choosing the redundant route provided as shown in Fig. 2.

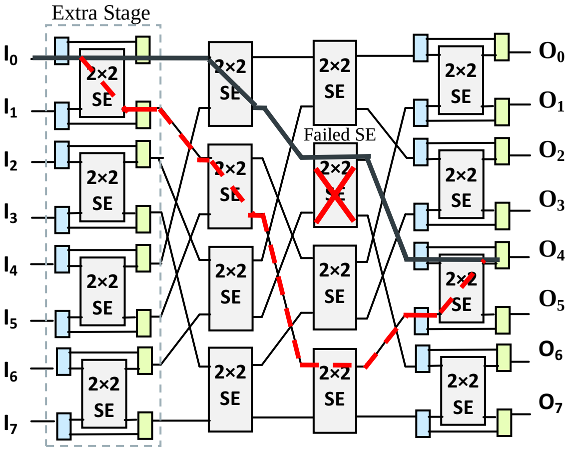


Fig. 2 The Extra Stage Omega Network with N=8

However, failure of any switching element in the first and last stages will cause the MIN to lose its full accessibility. Therefore, a number of multiplexers and demultiplexers are used to overcome this problem. The first and last stages can each be either enabled or disabled (bypassed). A stage is enabled when its switching element are being utilized to provide interconnection. It is disabled when its switching element are being bypassed [1]. Enabling and disabling the first and last stages is accomplished with a demultiplexer at each input and a multiplexer at each output. The demultiplexer and multiplexer are configured such that they either both enabled or disabled as shown in Fig. 3(b) and 3(c), respectively.

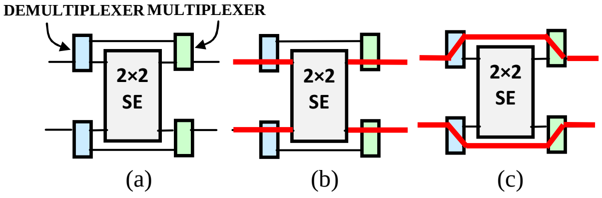


Fig. 3 (a) Detail of SE with Demultiplexer and Multiplexer. (b) Enabled SE. (c) Disabled SE (Bypassed).

Since the ESO network considered in this paper is based on WDM, and each input link can carry at most w packets, each with a different wavelength from the set of available wavelengths, $\Lambda = (\lambda_1, \lambda_2, \ldots, \lambda_{w-1}, \lambda_w)$, one may merge both inputs of a 2×2 switching element and forward them to either the upper or lower output link when the sets of wavelengths on both input links are disjoint. Therefore, two configurations are to be considered, namely, *upper merger* and *lower merger* as illustrated in Fig. 4(c). Note that these two configurations would have been considered as internal blocking in an ordinary Omega networks. Moreover, two additional configurations are required, namely, the *upper splitter* and *lower splitter* as illustrated in Fig. 4(d) to satisfy the requirements of one-to-one mapping.

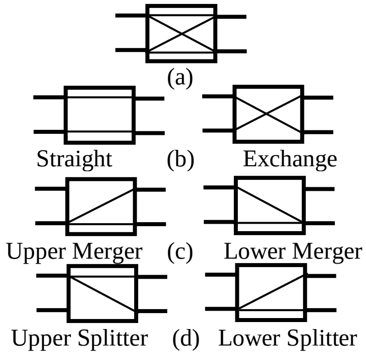


Fig. 4 Configuration of a 2 × 2 Switching Element

The set of permutations realizable by an Omega network is characterized by having *n-1* windows, where $n=log_2N$, and each of them is a permutation. To understand this concept, concatenate the binary representation of all sources, $s_{n-1}s_{n-2}\ldots s_1s_0$, and the binary representation of the corresponding destinations, $d_{n-1}d_{n-2}\ldots\ldots d_1d_0$. This generates a table with N rows and $2\times n$ columns, and which can be represented by $(d_{n-1}d_{n-2}\ldots\ldots d_1d_0\ s_{n-1}s_{n-2}\ldots s_1s_0)$. Now, *n-1* windows can be defined as,

W_1 : $\boldsymbol{s}_{n-2}\ldots s_2s_1s_0d_{n-1}$

W_2 : $\boldsymbol{s}_{n-3}\ldots s_ns_{n-1}d_{n-2}$

...

W_i : $s_{n-i-1}s_{n-i-2}\ldots\ s_1s_0d_{n-1}d_{n-2}\ldots d_{n-i}$

...

W_{n-1}: $\boldsymbol{s}_0d_{n-1}d_{n-2}\ldots d_2d_1$

A window W_i has N rows, each with log_2N bits. If W_i is a permutation, i.e., no two rows in W_i are equal, then, it is guaranteed that there is no internal blocking in any switching element in stage *i*; otherwise, there is at least one switching element in stage *i* with both of its inputs competing on the same output link, which causes internal blocking in the ordinary Omega network. Since WDM is used, the switching element can be configured to either upper merger or lower merger. However, if the sets of wavelengths on both inputs of that switching element are disjoint, then there will be no internal blocking; otherwise, there will be internal blocking, and it can be resolved by packet buffering, wavelength conversion, or packet dropping. The concept of internal blocking detection in ESO is illustrated in Fig. 5.

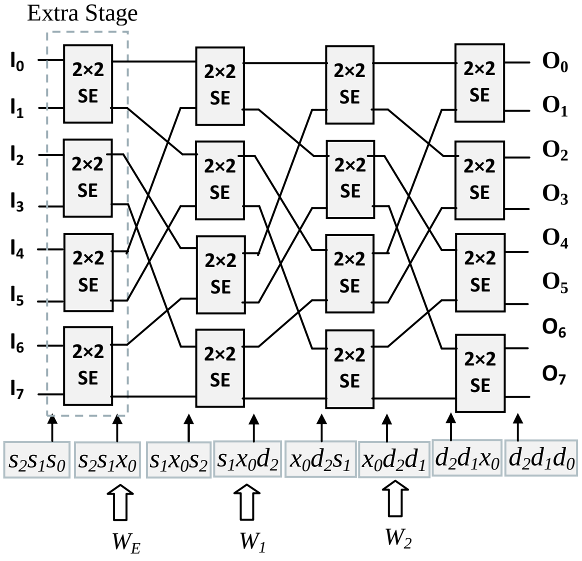


Fig. 5 Internal Blocking Detection in ESO

4. COLLISION-FREE 8X8 OMEGA NETWORKS WITH BUFFERING AND WAVELENGTH CONVERSION

In this section, *buffers* and *wavelength converters* are included in the central controller of the ESO as illustrated in Fig. 6. The purpose of a wavelength converter is to convert the wavelength λ_i of a packet to another wavelength λ_j, with λ_i not equal to λ_j. Therefore, if there is internal blocking, and wavelengths of packets that cause the internal blocking are converted, then the number of packets to be buffered or dropped by the central controller can be reduced, and the performance of the network will improve. Note that a packet can have at most one wavelength conversion and this happens inside the central controller. The number of packets which can have their wavelengths converted is limited by the number of available converters. Packets which will cause internal collision and cannot be wavelength converted are buffered. If no more buffers are available, packets are dropped.

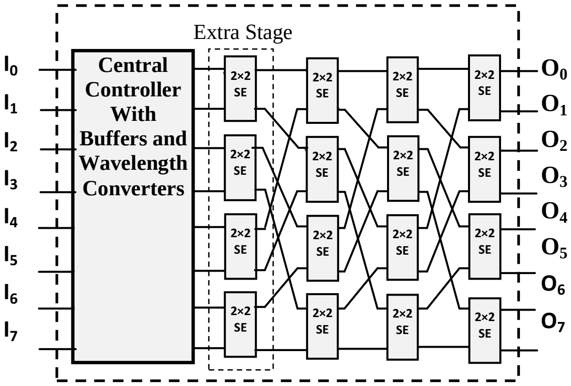
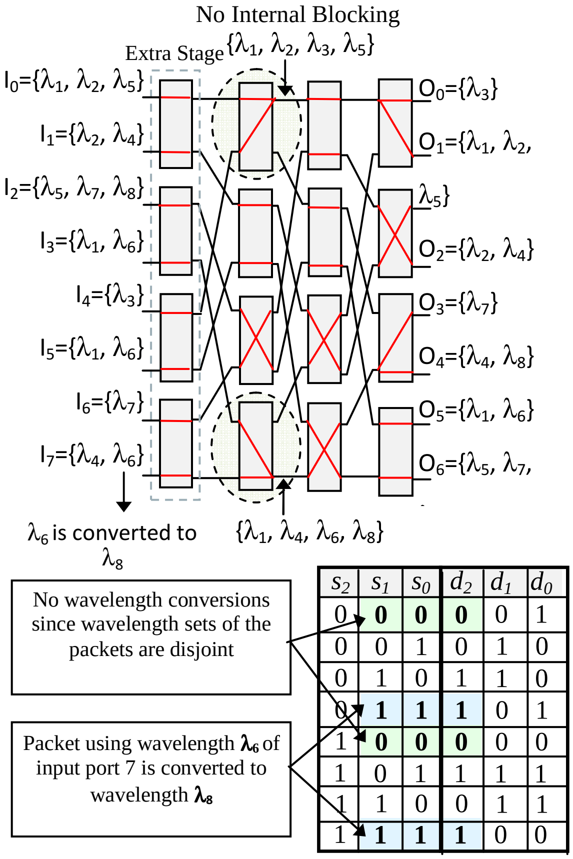


Fig. 6 Architecture of a Collision-Free Omega Network

Fig. 7 illustrates an example of a collision-free extra stage Omega network. Assuming that the arriving set of packets to the input port (I_0) uses wavelengths $\{\lambda_1, \lambda_2, \lambda_5\}$, and the arriving packet to the input port (I_4) uses wavelength $\{\lambda_3\}$, and both are sent simultaneously to the same output port, then there will be no internal blocking since wavelength sets of the packets are disjoint. Considering the other case, the arriving set of packets to the input port (I_3) uses wavelengths $\{\lambda_1, \lambda_6\}$, and the arriving packet to the input port (I_7) uses wavelength $\{\lambda_4, \lambda_6\}$, and both are sent simultaneously to the same output port, then there will be internal blocking by the packets that use wavelengths λ_6. However, if the wavelengths λ_6 of one of the packets is converted to λ_8, then there will be no internal blocking at that switching element, and its output port can forward the set of packets with wavelengths $\{\lambda_1, \lambda_4, \lambda_6, \lambda_8\}$ to the next stage.



s_2	s_1	s_0	d_2	d_1	d_0
0	**0**	**0**	**0**	0	1
0	0	1	0	1	0
0	1	0	1	1	0
0	**1**	**1**	**1**	0	1
1	**0**	**0**	**0**	0	0
1	0	1	1	1	1
1	1	0	0	1	1
1	**1**	**1**	**1**	0	0

Fig. 7 Example of a Collision-Free ESO Network

5. Performance Results

This section presents the performance of an 8×8 ESO network with one-to-one connections. To generate the performance parameters of this network such as packet dropping probability, buffering probability, and wavelength conversion probability, a simulator program was created to simulate the behavior of an 8×8 Omega network and an 8×8 extra stage Omega network. The simulator considers a variable number of buffers and wavelength converters available in the central controller.

The simulator performs the following tasks:

- It randomly creates 10,000 one-to-one connections.
- For each permutation, it creates a set of inputs, which has at most 8 random packets with different wavelengths, for each input channel of an 8×8 ESO network. The arriving set of packets on each input channel is assumed to be independent, and has a Uniform distribution.
- It generates the performance parameters such as packet dropping probability, buffering probability, and wavelength conversion probability.

Fig. 8 illustrates the probability of packet dropping versus the arrival load for the ESO network with variable number of buffers. It is shown that the packet dropping probability decreases with the increasing number of buffers. For example, the packet dropping probability is reduced by almost 6% when using 10 buffers at the arrival rate 70% compared with the same network except without buffers.

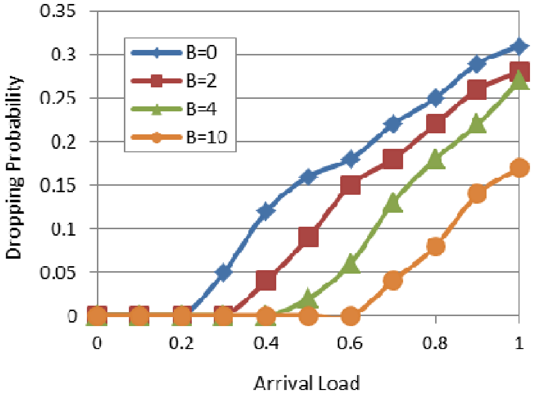


Fig. 8 Packet Dropping Probability versus Arrival Load (Limited Buffers and No Wavelength Conversion)

The buffering probability is defined as follows: It is a ratio that a random packet is to be buffered when the packet arrives to the network. Fig. 9 illustrates the buffering probability versus arrival load. Initially, probability of buffering for different number of buffers increase linearly with the network load because the load of the network is satisfied with the available buffers. However, at some point these curves start to saturate and then go down. The reason is that the number of packets in the network becomes very large with respect to the available buffers, and therefore, the network cannot carry the offered traffic and many of the packet will be dropped. Also, it is shown that the point of saturation moves to the right with the increase of buffers. For example, the network with 10 buffers will saturate when the arrival load is almost 70% while this network with no buffers will saturate when the arrival load is almost 30%.

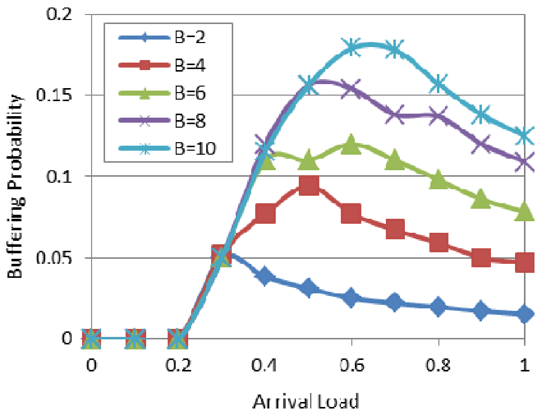


Fig. 9 Buffering Probability versus Arrival Load (Limited Buffers and No Wavelength Conversion)

Fig. 10 illustrates the packet dropping probability versus arrival load when using a variable number of wavelength converters. It shows that a network with a few wavelength converters can improve the network performance. The packet dropping probability decreases with the increasing number of wavelength converters. For example, the packet dropping probability is reduced by almost 6% when using 10 wavelength converters at the arrival rate 70% compared with the same network except without wavelength converters. At arrival load of 80% and higher, the packet dropping probability will have no improvement compared with different number of wavelength converters since almost all wavelengths are utilized and none of them are available for conversion.

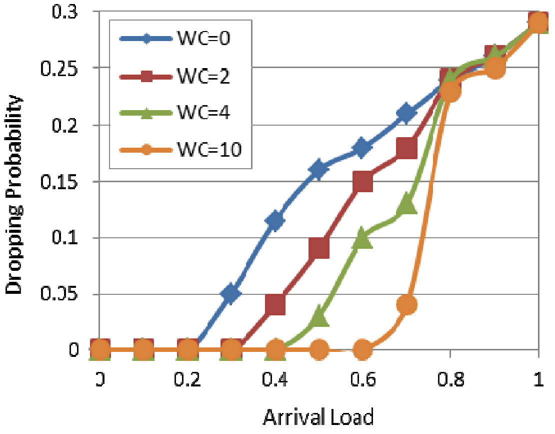


Fig. 10 Packet Dropping Probability versus Arrival Load (Limited Wavelength Converters and No Buffering)

The wavelength conversion probability is defined as follows: It is a ratio that a random packet is to be wavelength converted when the packet arrives to the network. Fig. 11 illustrates the wavelength conversion probability versus arrival load. The wavelength conversion probability will increase with the increase of wavelength converters. Initially, when the arrival load is low, there is no need for wavelength conversion. Then all curves starts to increase linearly because the system is satisfied with the available wavelength converters. Later, the curves start to saturate, and the wavelength conversion probability starts to decrease till reach to 0 at the higher arrival load since all the wavelengths are utilized and it is impossible to convert the wavelength of a packet.

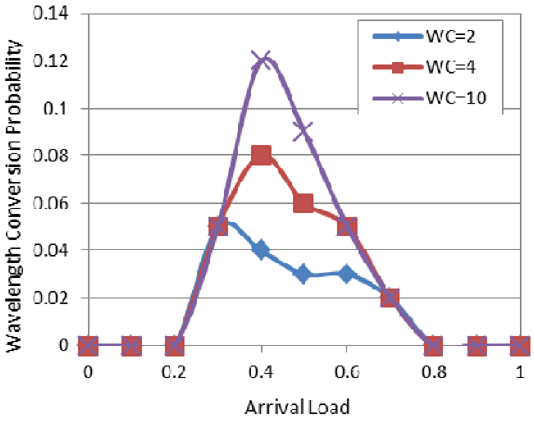


Fig. 11 Wavelength Conversion Probability versus Arrival Load (Limited Wavelength Converters and No Buffering)

Fig. 12 shows a comparison among ESO networks with different configurations. It shows that at the arrival load of higher than 60%, the packet dropping probability for a network with 2 buffers is better than a network with 2 wavelength converters since the wavelength converter might be available but at that time all wavelengths are utilized and it is impossible to convert the wavelength of a packet. It can be noticed that when the load of the network is low to medium, the performance can be improved by increasing the number of available wavelength converters with a constant number of buffers. This improvement represents a load of packets that have been transmitted through the network in the current switching cycle, rather than buffering or even dropping them.

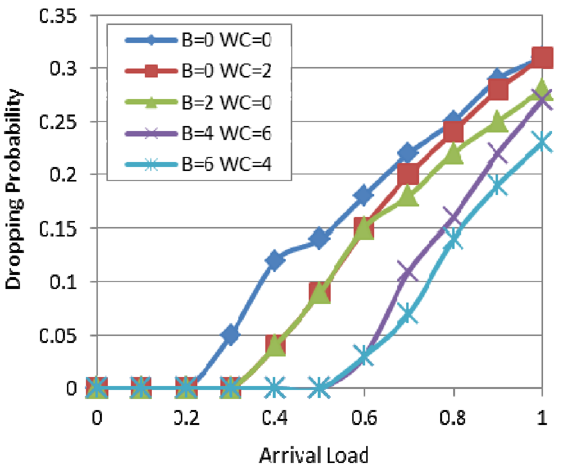


Fig. 12 Packet Dropping Probability (Limited Buffers and Wavelength Converters)

Fig. 13 illustrates the packet dropping probability versus arrival load for the ESO and Omega networks. The ESO network provides a better performance compared with the Omega network. The reason for the performance advantage of the ESO network can be attributed to the extra stage, which provides a redundant path from any source to any destination. Having an additional path will allow packets to have more flexibility, thus reducing the probability of packet dropping.

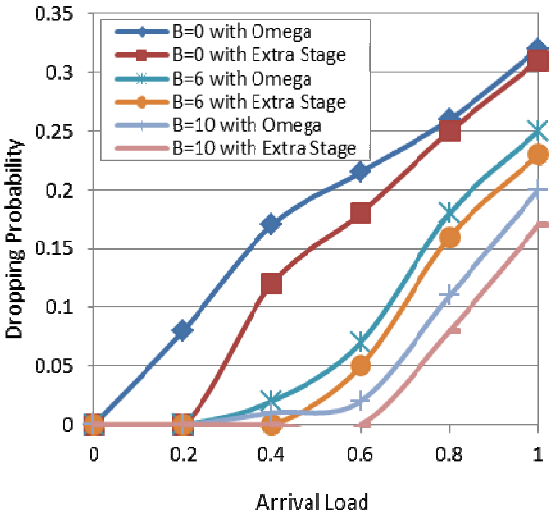


Fig. 13 Packet Dropping Probability versus Arrival Load (Limited Buffers and No wavelength Conversion)

Fig. 14 illustrates the buffering probability versus arrival load for the ESO and Omega networks. Initially, the buffering probability for different number of buffers increases linearly with the network load because the load of the network is satisfied with the available buffers. However, at some point in time these curves start to saturate and then go down. The reason is that the number of packets in the network becomes very large with respect to the available buffers and some of them are dropped. It is noticed that the buffering probability of Omega network is higher than the ESO network for the same number of buffers since there is a redundant path from any source to any destination. Having an additional path gives packets more flexibility, thus reducing the probability of packet buffering.

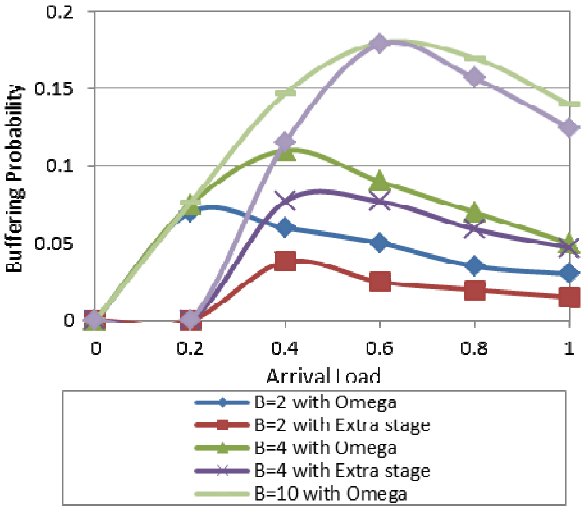


Fig. 14 Packet Buffering Probability versus Arrival Load (Limited Buffers and No Wavelength Converters)

Fig. 15 illustrates the packet dropping probability versus arrival load for the ESO and Omega networks. It is shown that the dropping probability of the ESO network is lower than the dropping probability of the Omega network for the same number of wavelength converters since there is a redundant path from any source to any destination.

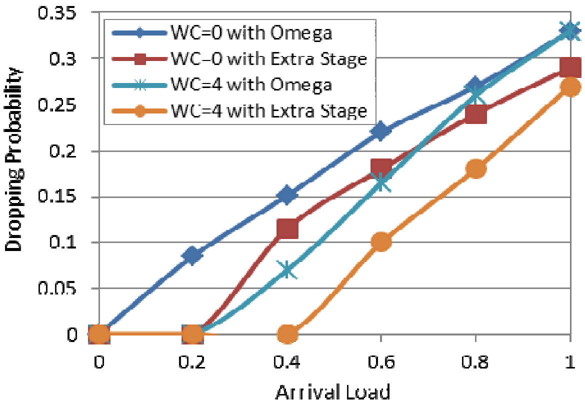


Fig. 15 Packet Dropping Probability versus Arrival Load (Limited Wavelength Converters and No Buffering)

Fig. 16 Illustrates wavelength conversion probability versus arrival load for the ESO and Omega networks. The wavelength conversion probability will be decreased in the ESO network more than the Omega network for the same number of wavelength converters.

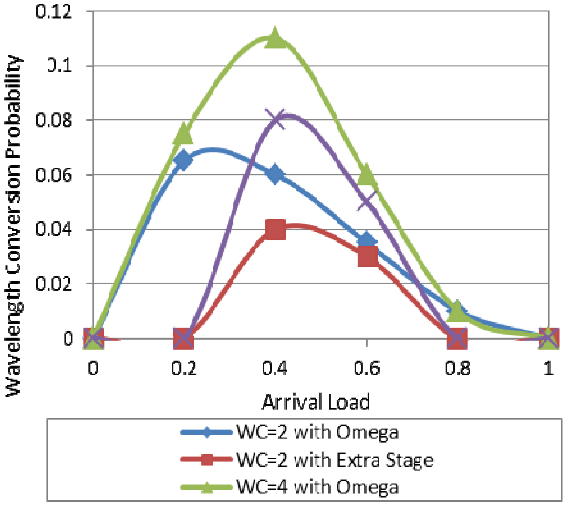


Fig. 16 Wavelength Conversion Probability versus Arrival Load (Limited Wavelength Converters and No Buffering)

Fig. 17 shows a comparison between the ESO and Omega networks with different configurations. It shows that the packet dropping probability of the ESO is better than the Omega network with the same configuration.

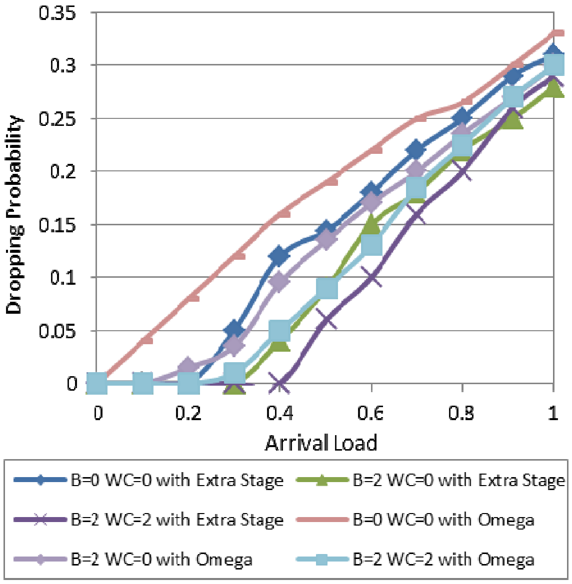


Fig. 17 Packet Dropping Probability (Limited Buffers and Wavelength Converters)

6. CONCLUSION

In this paper, the performance of the extra stage Omega (ESO) networks based on wavelength division was analyzed in terms of packet dropping probability, buffering probability, and wavelength conversion probability. The goal is to minimize the dropping probability by utilizing the available buffers and wavelength converters in the central controller of the network.

It is shown that the packet dropping probability decreases with the increasing number of buffers or wavelength converters. However, at higher arrival load, the wavelength converters become inactive since all the wavelengths are utilized and it is impossible to convert the wavelength of a packet. It can be noticed that when the load of the network is low to medium, the performance can be improved by increasing the number of available wavelength converters with a constant number of buffers. This improvement represents a load of packets that have been transmitted through the network in the current switching cycle, rather than buffering or even dropping them.

It is shown that the dropping probability of the ESO network is lower than the dropping probability of the Omega network for the same number of wavelength converters or buffers since there is a redundant path from any source to any destination. Having an additional path gives packets more flexibility, thus reducing the probability of packet buffering or dropping.

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