Wide-Sense Nonblocking Multicast in WDM Optical Linear Array and Ring Networks with 2-Length Extension under Index Based Routing

M. SABRIGIRIRAJ[1] K. MANOHARAN[2] R.KARTHIK[3],
[1]Department of ECE, SVS College of Engineering, Coimbatore, 642 109, Tamilnadu, India
[2]Department of ECE, SNS College of Technology, Coimbatore, 641 035, Tamilnadu, India.
[3]Department of ECE, Sri Krishna College of Technology, Coimbatore, 641042, Tamilnadu, India.

Abstract: - Multicast communication is the concurrent transmission of data from one source node to many destination. It is widely deployed in high performance computing and communication networks.In this paper, a linear array and ring networks are extended by directly linking all nodes which are separated by one intermediate node with additional fibers which is referred as linear array and ring network with 2-length extension and wide sense nonblocking multicast is studied. The wavelength allotment methods are proposed to realize one-to-many communication over wavelength division multiplexing optical linear array and ring with 2-length extension under index-based routing and the minimum wavelength number needed is determined. The minimum wavelength number needed to support for the extended linear array and ring topologies is reduced approximately by half when compared with that of a linear array network and ring network.

Key-Words: -Wavelength division multiplexing (WDM), Multicast communication, WDM Optical Network, Wavelength Assignment, Modified Linear Array

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1. Introduction

The modern scientific developments in optical networks based on wavelength division multiplexing (WDM) are more attractive to satisfy the high bandwidth necessities of the internet infrastructure. Additionally, they promise to satisfy the future bandwidth needs.WDM optical networks act as the backbone for telecommunication and high-performance networks. An optical network is a communication system that uses light signals to transmit information between two or more points. Optical networks are based on optical technologies and components, and are used to route, groom, and restore wavelength levels and wavelength-based services.

Multicast communication is the concurrent transmission of data from one source node to many destination nodes.It is widely deployed in high performance computing andcommunication networks. Multicast assignment [1,2] is a well-defined type of multicast communication and is widely used in traffic analysis. Multicast assignment involves establishing connections between various nodes of a network in such a way that each destination node is connected to only one source node, whereas each source node may be connected to one or more destination nodes. All forms of multicast communication can easily be broken down into multiple multicast assignments. Due to the absence of optical buffering at the nodes in an optical network, it is preferred to have a nonblocking network. Otherwise, data would be lost with blocked connections. An optical network can be termed as nonblocking, if it is possible to establish all the connections of the given multicast communication without removing or rerouting any of the existing connections. Such networks are said to be wide-sense nonblocking [1], if the connections are established by a definite routing algorithm.Wide-sense nonblocking multicast is studied in electronic switching networks and network topologies namely linear array, ring, torus, mesh and hypercube [1].Wide-sense nonblocking multicast and strict-sense nonblocking multicast is studied for clos networks [3] and elastic optical switch [4]. Multicast communication is alsostudied for various optical networks namely clos network,benes network, elastic optical networks and for general network topologies [5–10].

Linear array [11-15] and ring networks [16-20] are the basic network topologies suitable for interconnection networks and for LAN /WAN and are well investigated. The linear array and ring networks are widely adopted for LAN, MAN and WAN and also used ininterconnection networks due to its regularity and small node degree. The results obtained in this paper can be applied for practical long-haul networks like mesh network, since mesh network can be decomposed into multiple linear array and/or ring networks.

Multicast communication is investigated well under different scenarios [21-26] in WDM networks. Wide-sense nonblocking Multicast communication in linear array with 2-length extension and unidirectional ring and bidirectional ring with 2-length extension networks are studied under longest link first routing is studied already [24]. In this paper, for the same topologies, index-based routing strategy is employed to route the connections based on the index of the source and/or destination nodes. Particularly, the most important attention is over the determination of the necessary and sufficient condition over the minimum wavelength number needed for the network to be wide sense nonblocking. Explicit wavelength allotment techniques are also proposed for each of the network topologies.

Section 2 gives preliminaries needed to analyze wide-sense nonblocking multicast problem in linear array, unidirectional ring and bidirectional ring networks with 2-length extension under index-based routing is discussed. Section 3, the necessary and sufficient condition on the minimum wavelength number required to realize wide-sense nonblocking multicast under index-based routing is derived and explicit wavelength allotment techniques are also given. Section 4, discusses the result obtained for the 2-length extension networks. Finally, section 5 completes the paper highlighting future research avenues.

2. Preliminaries

Figure 1(a) and 1(b) shows a 8-node basic linear array network and a linear array network with 2-length extension respectively. A linear array network with 2-length extension is obtained by additionally connecting the alternate nodes of the linear array. Each node in the linear array is additionally connected to an alternate node. At each node, data can move from node x to node x+1 and also directly to node x+2, if such nodes exist and also vice-versa.

Figure 1 (a) An 8-node basic linear array

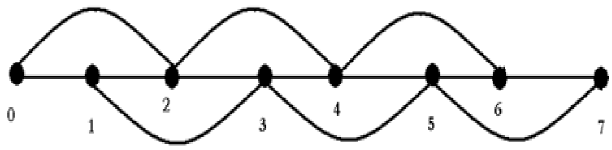

Figure 1 (b) An 8-node linear array with 2-length extension

Figure 2(a) and 2(b) shows an 8-node basic ring network and an 8-node ring network with 2-length extension respectively. A ring network with 2-length extension is obtained by additionally connecting the alternate nodes of the basic ring. Each node in the ring is additionally connected to an alternate node. At each node, data can move from node x to node (x+1) mod N and also directly to node (x+2) mod N.

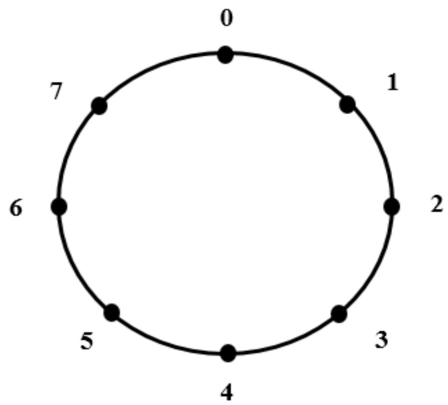

Figure 2 (a) An 8-node basic ring

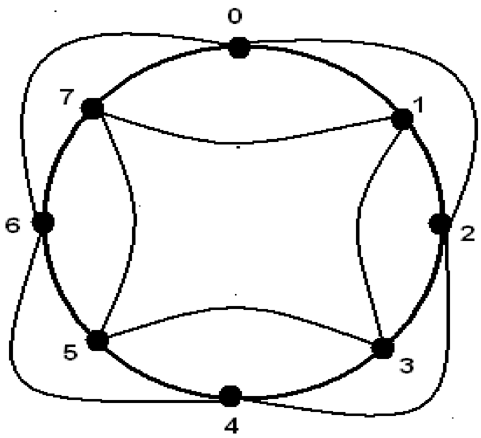

Figure 2 (b) An 8-node ring with 2-length extension

Definition 1: A link that joins two nodes $x$and $x \oplus 1$ (where $x \oplus 1$denotes$x \oplus 1$mod N) is called a shorter link. For example, in Figure 2,the link that joins node 0 with node 1 is a shorter link.

Definition 2: A link that directly joins two nodes, both labeled with even index is termed as an 'even link'. For example, in Figure 2,the link that directly joins node 2 with node 4 is aneven link.

Definition 3: A link that directly joins two nodes, both labeled with odd index is termed as an 'odd link'. For example, in Figure.2,the link that joins node 1 with node 3 is an odd link.

Definition 4: A connection (x, y) is defined as the set of all links that joins source node *x* with destination node *y* under a prescribed routing method.

3. Main Results

Wavelengths are scarce resources in an optical networks and its usage need to be minimized to reduce the cost and complexity of the network. In this section, the sufficient and necessity condition on the minimum wavelength number required for the network to be wide-sense nonblocking is derived for linear array and unidirectional ring networks with 2-length extension under index-based routing technique.

3. 1 Linear Array with 2-length extension

Figure 1(b) shows an 8-nodelinear array with 2-length extension. The following assumptions are made to reduce the wavelength number under index-based routing. If the index of both source and destination are even, then such lightpaths are routed only using even links. If the index of both source and destination are odd, then such lightpaths are routed only using odd links. All other lightpaths are routed using shorter links only. Theorem 1 is proved based on this assumption.

Theorem 1:The sufficient and necessary condition on the wavelength number for a N node linear array with 2-length extension to be wide-sense non-blocking is$\lfloor N/2 \rfloor$.

Proof: sufficiency: It is to be noted that all the lightpaths between various sources and destinations are routed either in rightward direction or in leftward direction. For a lightwave network, a particular wavelength can be allotted for multiple lightpaths as long as they do not overlap with one another. A wavelength released by a current lightpath during its termination can be again used to allot for a new lightpath establishment. It can be noted that out of N multicast lightpaths, there can be atmost $N-1$lightpaths either in rightward direction or in leftward direction. Out of these $N-1$lightpaths, there can be a maximum of $\left\lfloor \frac{N}{2} \right\rfloor$lightpaths (first set) established only on the shorter links whereas the remaining lightpaths (second set) are established only on the longer links. So, these two sets of lightpaths can be on the same set of wavelengths and so needs $\left\lfloor \frac{N}{2} \right\rfloor$ wavelengths. Reusing any one of these $\left\lfloor \frac{N}{2} \right\rfloor$ wavelengths, the remaining lightpath in the opposite direction can be established. So, $\left\lfloor \frac{N}{2} \right\rfloor$ wavelengths are sufficient to route all the multicast lightpaths.

Necessity: Consider a worst-case multicast assignment of the form with 0 as the source and all other nodes as its destinations along with another connection with 0 as destination for any arbitrary source. Among those $N-1$ lightpaths whose source index is 0, there can be almost$\left\lfloor \frac{N}{2} \right\rfloor$lightpaths established using only shorter links. These $\left\lfloor \frac{N}{2} \right\rfloor$lightpaths (first set) share the link connecting nodes 0 with 1 and so each of these lightpaths needs a unique wavelength. So, $\left\lfloor \frac{N}{2} \right\rfloor$ wavelengths are needed to establish the above lightpaths.All the remaining lightpaths (second set) whose source index is 0 are established on the even links only. Since the first set of lightpaths and second set of lightpaths don't share any link in the same direction, and they can be established using the same set of $\left\lfloor \frac{N}{2} \right\rfloor$wavelengths. Also, the lightpath whose destination index is 0 is routed in opposite direction to all the above lightpaths and can be established on any one of the already used$\left\lfloor \frac{N}{2} \right\rfloor$wavelengths. Hence, the wavelength number requirement is$\left\lfloor \frac{N}{2} \right\rfloor$. Therefore, $\left\lfloor \frac{N}{2} \right\rfloor$wavelengths are the sufficient and necessary condition on the wavelength number.

Wavelength allotment technique

Let the tables$T_{RE}$and T_{LE}be used for managing lightpaths whose source and destination are even indexed and routed in rightward direction and leftward direction respectively.

Let the tables T_{RO} and T_{LO}be used for managing lightpaths whose source and destination are odd indexed and routed in rightward direction and leftward direction respectively.

Let the tables T_R and $T_L$be used for managing lightpaths of all other connections routed in rightward direction and leftward direction respectively.

Let all the above tables be initially empty.

Let T_W be used for storing the available $\left\lfloor\frac{N}{2}\right\rfloor$ wavelengths namely $\lambda_1, \lambda_2, \lambda_3, \dots, \lambda_{\left\lfloor\frac{N}{2}\right\rfloor}$.

Let x and y be the index of source and destination node respectively.

The step-by-step procedure is described as follows,

Step 1: If x and $y$are both even and $x < y$,allot a wavelength that is not available in T_{RE}but available in T_W.Then include this wavelength in T_{RE}.

Step 2: Else Ifx and $y$are both even and $x > y$,allot a wavelength that is not available in T_{LE}but available in T_W.Then include this wavelength in T_{LE}.

Step 3: Else If x and $y$are both odd and $x < y$,allot a wavelength that is not available in T_{RO}but available in T_W.Then include this wavelength in T_{RO}.

Step 4: Else If x and $y$are both odd and $x > y$,allot a wavelength that is not available in T_{LO}but available in T_W.Then include this wavelength in T_{LO}.

Step 5: Else If $x > y$,allot a wavelength that is not available in $T_R$but available in T_W.Then include this wavelength in T_R.

Step 6: Else allot a wavelength that is not available in $T_L$but available in T_W.Then include this wavelength in T_L.

3. 2 Unidirectional ring with2-length extension

Figure 2(b) shows an 8-node ring with 2-length extension. The routing of lightpaths is assumed to be in clockwise direction without loss of generality. The following assumptions are made to reduce the wavelength number when N is even. If the index of both source and destination are even, then such lightpaths are routed only using even links. If the index of both source and destination are odd, then such lightpaths are routed only using odd links. All other lightpaths are routed using shorter links only. Theorem 2 is proved based on this assumption.

Theorem 2:When N is even, the sufficient and necessary condition on the wavelength number for a N node unidirectional ring with 2-length extension to be wide-sense non-blocking is$\lfloor N/2 \rfloor$.

Proof: Sufficiency: It is to be noted that all the lightpaths between various sources and destinations are routed only in clockwise direction without loss of generality. For a lightwave network, a particular wavelength can be allotted for multiple lightpaths as long as they do not overlap with one another. A wavelength released by a current lightpath during its termination can be again used to allot for a new lightpath establishment. It can be noted that out of N multicast lightpaths, there can be atmost$N-1$lightpaths originating from the same sourcex. Out of these $N-1$ lightpaths originating from the source x, there can be almost$\left\lfloor\frac{N}{2}\right\rfloor$lightpaths (first set) sharing the link joining the source node x with$x \oplus 1$.These lightpaths use only shorter links from the source to the corresponding destination. The other lightpaths (second set) with the same source index $x$uses only longer links and do not share any link in the same direction with the first set of lightpaths. The remaining lightpath whose destination is xdo not share any link with the lightpath already established between the nodes$x$ and$x \oplus 1$, and they can be on the same wavelength. So,$\left\lfloor\frac{N}{2}\right\rfloor$ wavelengths are sufficient to route all connections.

Necessity: Consider a worst-case multicast assignment of the form with 0 as the source and all other nodes as its destinations along with another lightpath with 0 as the destination for an arbitrary source. Among those lightpaths (first set) whose source index is 0, there can be almost$\left\lfloor\frac{N}{2}\right\rfloor$lightpaths sharing the link joining the nodes 0 with 1. So, each of these $\left\lfloor\frac{N}{2}\right\rfloor$lightpaths needs a unique wavelength. The other$\left\lfloor\frac{N}{2}\right\rfloor$lightpaths (second set) whose source index is 0 (second set) are all established only on the even links. Since the first set of lightpaths and second set of lightpaths do not share any link in the same direction, they can be established on the same set of wavelengths. The remaining lightpath whose destination index is 0 for an arbitrary source may be allotted the same wavelength that is already allotted for the lightpath (0, 1). Hence, the wavelength number requirement is$\left\lfloor\frac{N}{2}\right\rfloor$. Therefore, $\left\lfloor\frac{N}{2}\right\rfloor$wavelengths are the sufficient and necessary condition on the wavelength number.

Wavelength allotment technique

Let the table T_{CE} be used for managing lightpaths whose source and destination are even indexed and routed in clockwise direction.

Let the tableT_{CO} be used for managing lightpaths whose source and destination are odd indexed and routed in clockwise direction.

Let the tables T_S be used for managing lightpaths of all other connections routed through shorter links only.
Let all the above tables be initially empty.
Let T_W be used for storing the available $\left\lfloor \frac{N}{2} \right\rfloor$ wavelengths namely $\lambda_1, \lambda_2, \lambda_3, \ldots, \lambda_{\left\lfloor \frac{N}{2} \right\rfloor}$.
Let x and y be the index of source and destination node respectively.

The step-by-step procedure is described as follows,
Step 1: If x and $y$are both even, allot a wavelength that is not available in T_{CE}but available in T_W.Then include this wavelength in T_{CE}.

Step 2: Else If x and $y$are both odd, allot a wavelength that is not available in T_{CO}but available in T_W.Then include this wavelength in T_{CO}.

Step 3: Else allot a wavelength that is not available in $T_S$but available in T_W.Then include this wavelength in T_S.

Now the following assumptions are made to reduce the wavelength number when N is odd.

- Let a flag be established for each node and let it be zero initially.
- Let x and y be the index of the source and destination respectively.
- If no intermediate node is present in between x and y along the primary ring (primary ring is the basic ring network without modification) in the clockwise direction, then the lightpath between x and yis established using the shorter link only.
- If only one intermediate node is present in between x and y along the primary ring in the clockwise direction, then the lightpath between x and y is established using the longer link only.
- If two or more intermediate nodes are present in between x and y along the primary ring in the clockwise direction, and if $F_x = 0$,then the lightpath is routed first from source xto next node$x \oplus 1$. From the node$x \oplus 1$, the lightpath is routed using the longest link first routing.
- If two or more intermediate nodes are present in between x and y along the primary ring in the clockwise direction, and if $F_x = 1$,then the lightpath is routed using the longest link first routing.
- Theorem 3 is proved based on this assumption.

Theorem 3:When N is odd, the sufficient and necessary condition on the wavelength number for a unidirectional 2-length extension ring with N nodes to be wide-sense non-blocking is$\left\lfloor \frac{N}{2} \right\rfloor$.

Proof: Sufficiency: It is to be noted that all the lightpaths between various sources and destinations are routed only in clockwise direction without loss of generality. For a lightwave network, a particular wavelength can be allotted for multiple lightpaths as long as they do not overlap with one another. A wavelength released by a current lightpath during its termination can be again used to allot for a new lightpath establishment. It can be noted that out of N multicast lightpaths, there can be atmost $N-1$ lightpaths originating from the same sourcex. Out of these $N-1$ lightpaths, there can be almost$\frac{N-1}{2}$lightpaths (first set) sharing the link joining the source node x with$x \oplus 1$. So, each of these $\frac{N-1}{2}$lightpaths needs a unique wavelength and $\frac{N-1}{2}$ wavelengths are needed to route all the lightpaths in the first set. The other$\frac{N-1}{2}$lightpaths (second set) from the same source x are established using the longer link joining the nodes x with$x \oplus 2$. So, each of these $\frac{N-1}{2}$lightpaths needs a unique wavelength and $\frac{N-1}{2}$ wavelengths are needed to route all the lightpaths in the second set. However, all the lightpaths of the first set do not share any link with any of the lightpaths of the second set. So, these two set of lightpaths can be established on the same set of wavelengths. The remaining lightpath whose destination is xdo not share any link with the lightpath already established between the nodes x and $x \oplus 1$and they can be on the same wavelength. So, $\frac{N-1}{2}$ wavelengths are sufficient to route all connections.

Necessity: Consider a worst-case multicast assignment of the form with 0 as the source and all other nodes as its destinations along with another lightpath with 0 as the destination for an arbitrary source. Among those lightpaths (first set) whose source index is 0, there can be atmost$\frac{N-1}{2}$lightpaths sharing the link joining the nodes 0 with 1 ($F_0 = 0$). So, each of these $\frac{N-1}{2}$lightpaths needs a unique wavelength. The other lightpaths (second set) with the same source index 0 (second set) are all established mostly on the even links ($F_0 = 1$). Since the first set of lightpaths and second set of lightpaths do not share any link in the same direction, they can be established on the same set of wavelengths. The remaining lightpath whose destination index is 0 may be allotted the same wavelength that is already allotted for the lightpath (0, 1). Hence, the wavelength number requirement is $\frac{N-1}{2}$. Therefore, $\frac{N-1}{2}$ wavelengths are the sufficient and necessary condition on the wavelength number.

Wavelength allotment technique

In this technique, two tables namely T_R for rightward direction and T_L for leftward direction are used for managing wavelength allotment for the lightpaths.

Let all the tables be initially empty

Let T_W be used for storing the available $\frac{N-1}{2}$ wavelengths namely $\lambda_1, \lambda_2, \ldots, \lambda_{\frac{N-1}{2}}$.

Let $F_A = 0, 0 \leq A \leq N-1$.

Let x and y be the index of the source and destination respectively.

The step by step procedure is described as follows,

Step 1: If $y > x, y - x \leq 2$, then the lightpath is established using the wavelength λ_1.

Step 2: Else if $x > y, N - x + y \leq 2$, then the lightpath is established using the wavelength λ_1.

Step 3: Else if x is even and $F_x = 0$, assign a wavelength that is in T_W but not in T_R. Add this wavelength to T_R and make $F_x = 1$.

Step 4: Else if x is odd and $F_x = 1$, assign a wavelength that is in T_W but not in T_R. Add this wavelength to T_R and make $F_x = 0$.

Step 5: Else if x is even and $F_x = 1$, assign a wavelength that is in T_W but not in T_L. Add this wavelength to T_L and make $F_x = 0$.

Step 6: Else assign a wavelength that is in T_W but not in T_L. Add this wavelength to T_L and make $F_x = 1$.

3. 3 Bidirectional ring with2-length extension

Figure 4 shows an 8-node ring with 2-length extension. The routing of lightpaths is assumed to be in shortest path direction. If the length of the lightpath is same in both clockwise and anticlockwise direction, then clockwise direction is always followed. The following assumptions are made in the routing procedure: If the index of destination is odd, then the lightpath is established using longest link first routing. If the index of destination is even, then the lightpath is established using only shorter links. Theorem 4 is proved based on this assumption.

Theorem 4: The sufficient and necessary condition on the wavelength number for a N node bidirectional ring with 2-length extension to be wide-sense non-blocking is $\left\lceil\frac{N}{2}\right\rceil$.

Proof: Sufficiency: All the lightpaths between various sources and destinations are routed only in the shortest path direction. If the length of lightpath is same in both clockwise and anticlockwise direction, then clockwise direction is always followed. For a lightwave network, a particular wavelength can be allotted for multiple lightpaths as long as they do not overlap with one another. A wavelength released by a current lightpath during its termination can be again used to allot for a new lightpath establishment. It can be noted that a multicast lightpath spans up to a maximum of $\left\lceil\frac{N}{2}\right\rceil$ longer links. Since, there are Nlonger links present in a ring network, two multicast lightpaths which do not share any link in the same direction can be on the same wavelength. So, $\left\lceil\frac{N}{2}\right\rceil$ wavelengths are sufficient to route all multicast lightpaths.

Necessity:

Consider a worst-case multicast assignment of the form $\left(x,\ x \oplus \frac{N}{2}\right)$, for $0 \leq x \leq N-1$. If N is even, then for every integer i such that $0 \leq i \leq \frac{N}{2} - 1$, lightpaths of the form $\left(i,\ i \oplus \frac{N}{2}\right), \left(i \oplus \frac{N}{2},\ i\right)$ can be allotted a unique wavelength as they do not share any link. This necessitates $\frac{N}{2}$ wavelengths. If N is odd, then for every integer i such that $0 \leq i \leq \frac{N-1}{2}$, lightpaths of the form $\left(i, i \oplus \frac{N-1}{2}\right), \left(i \oplus \frac{N-1}{2},\ i \oplus N-1\right)$ can be allotted a unique wavelength as they do not share any link. This necessitates $\frac{N-1}{2}$ wavelengths. The remaining connection of the form $\left(N-1,\ N-1 \oplus \frac{N-1}{2}\right)$ may be allotted another unique wavelength. Hence, $\left\lceil\frac{N}{2}\right\rceil$ wavelengths are sufficient to route all multicast lightpaths irrespective of whether N is even or odd.

Wavelength allotment technique

Let x and y be the index of source and destination node respectively.

Step 1: When N is even, and if $y \le \frac{N}{2} - 1$, allot the wavelength Wy for this lightpath. Else if $y > \frac{N}{2} - 1$, allot the wavelength $W_{\left(y-\frac{N}{2}\right)}$ for this lightpath.

Step 2: When N is odd, and if $y \le \frac{N-1}{2}$, allot the wavelength Wyfor this lightpath. Else if $y > \frac{N-1}{2}$, allot the wavelength $W_{\left(y-\frac{N-1}{2}\right)}$ for this lightpath.

4. Results and Discussion

Table1 shows the comparison between basic network topologies and network topologies with 2-length extension under longest link first routing and index-based routing in terms of the number of wavelengths required to support wide-sense nonblocking multicast communication. The results were obtained in the previous section for network topologies with 2-length extension under index-based routing. From Table 1, it can be observed that the wavelength number needed to support wide-sense nonblocking multicast is reduced approximately by half for linear array and unidirectional ring with 2-length extensions under index-based routing when compared with corresponding network topologies under longest link first routing. However, it is observed that there is no change in wavelength requirement for a bi-directional ring with 2-length extension. In addition to LAN, WAN and MAN, the results obtained in this work can be used to analyze the practical long-haul networks like mesh network (both regular and irregular), since mesh network can be decomposed into a combination of basic networks and networks with 2-length extension.

5. Conclusion and future work

In this work, wide-sense nonblocking multicast communication is studied for WDM optical linear array and unidirectional and bidirectional ring with 2-length extensions under index-based routing. The sufficient and necessary condition on the minimum wavelength number needed for the network to be wide-sense nonblocking is derived for each of the above network topologies. The results found in this work are then compared with their corresponding network topologies under longest link first routing. The wavelength number needed to support wide-sense nonblocking multicast in linear array and unidirectional ring is reduced approximately by half when compared with corresponding network topologies under longest link first routing. However, it is observed that there is no change in wavelength requirement for a bi-directional ring with 2-length extension.Future work includes extending this study of wide-sense nonblocking multicast communication for WDM optical linear array and unidirectional and bidirectional ring with 3-length and higher length extensions.

Table 1. Comparison of wavelength requirement between basic network topologies and network topologies with 2-length extension

Network Topology	Conventional[1]	2-length extension with longest link first routing[24]	2-length extension with index-based routing
N-node Linear Array	N-1	N-2	$\left\lfloor \frac{N}{2} \right\rfloor$
N-node Unidirectional ring	N	N-2	$\left\lfloor \frac{N}{2} \right\rfloor$
N-node Bidirectional ring	$\left\lceil \frac{N}{2} \right\rceil$	$\left\lceil \frac{N}{2} \right\rceil$	$\left\lceil \frac{N}{2} \right\rceil$

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