# Wide-Sense Nonblocking Multicast in WDM Optical Linear Array and Ring Networks with 3-Length Extension

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*Abstract:* - The modern scientific growths in optical networks based on wavelength division multiplexing (WDM) are more attractive to satisfy the high bandwidth requirements of the modern internet infrastructure. Moreover, they have immense potential to satisfy the future bandwidth requirements.WDM optical networks act as the backbone for telecommunication and high-performance communication networks. Multicast communication is the simultaneous transmission of data from one source node to many destination nodes available in the network and can be implemented efficiently over a WDM optical network. It is extensively deployed in high performance computing and communication networks. In this article, a linear array and ring networks are extended by directly linking all nodes which are separated by two intermediate nodes with additional fibers which is referred as linear array and ring network with 3-length extension. The necessary and sufficient condition on the minimum wavelength number along with wavelength allotment methods are proposed to realize one-to-many communication over such a WDM optical linear array and ring with 3-length extension under longest link first routing techniques.

*Key-Words:* -Wavelength Division Multiplexing (WDM), Multicast, WDM Optical Network, Wavelength Assignment, Longest Link First Routing

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## 1 Introduction

The modern scientific growths in optical networks based on wavelength division multiplexing (WDM) are more attractive to satisfy the high bandwidth requirements of the modern internet infrastructure. Moreover, they have unlimited potential to satisfy the future bandwidth requirements. WDM optical networks act as the backbone for telecommunication and high-performance communication networks. An optical network is a most commonly and widely employed 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 and communication networks. Multicast assignment is a well-defined type of multicast communication and is used in this study. Multicast assignment involves establishing connections between various nodes of a network in such a way that each destination node should be 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 optical nodes, 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 [1-6], if the connections are established by a definite routing algorithm.

Wide-sense nonblocking multicast is studied in electronic switching networks [2] 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 [5] and elastic optical switch [6]. Multicast communication is alsostudied for various optical networks namely clos network,benes network, elastic optical networks and for general network topologies [3-4,7–12].

Linear array [13-17] and ring networks [18-22] are the basic network topologies suitable for interconnection networks and for LAN and WAN.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 wide-sense nonblocking multicast communication[23-33] in WDM networks such as linear array with 3-length extension and unidirectional ring with 3-length extension and bidirectional ring with 3-length extension networks are already studied under longest link first routing. 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. 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.

In Section 2, the preliminaries needed to analyse wide-sense nonblocking multicast problem in linear array, unidirectional ring and bidirectional ring networks with 3-length extension under longest link first routing is discussed. In Section 3, the necessary and sufficient condition on the minimum wavelength number required to realize wide-sense nonblocking multicast under longest link first routing is derived and explicit wavelength allotment techniques are given. Section 4, discusses the result obtained for the 3-length extension networks. Finally, section 5, the inference of this paper is presented highlighting future research direction.

## 2 Preliminaries

Figure 1 shows a 10-node basic linear array network. Figure 2 shows 16-node linear array network with 3-length extension. A linear array network with 3-length extension is obtained by additionally connecting all such nodes which are separated by two consecutive intermediate nodes of the linear array. Each node in the linear array is additionally connected to the node which is placed after 2 nodes away from it. At each node $x$, data can move from node $x$ to node $x$+1 and from node $x$ directly to node $x+3$, if such nodes exist and also vice-versa.

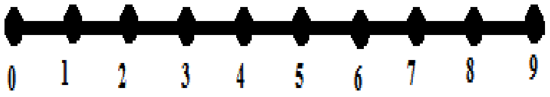

Figure 1. A 10-node basic linear array

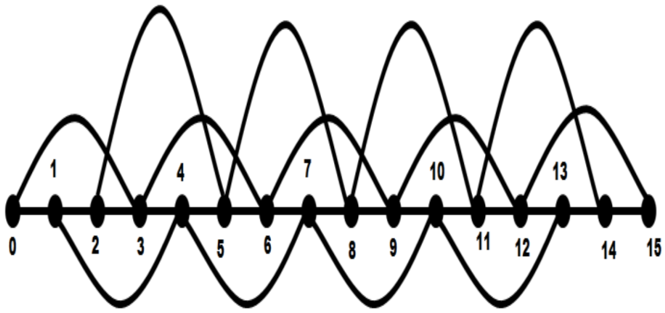

Figure 2. A 16-node linear array with 3-length extension

Figure 3 shows a 12-node basic ring network. Figure 4 shows a 12-node ring network with 3-length extension. A ring network with 3-length extension is obtained by additionally connecting each of the nodes with another node which is 2 nodes away from it in a basic ring. That is, each node in the ring is additionally connected to a node which is placed at the distance of 3 nodes away from it. At each node, data can directly move from node x to node$x \oplus 1$ and also directly from node x directly to node $x \oplus 3$ where $\oplus$ indicates modulo addition of $N$.

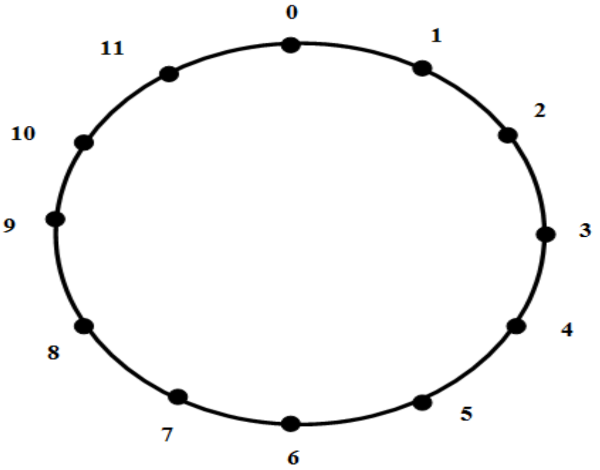

Figure 3. A-12 node basic ring

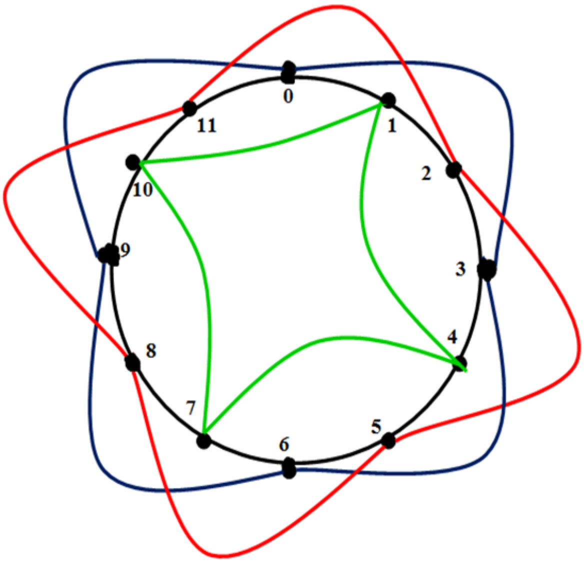

Figure 4. A-12 node ring with 3-length extension

Definition 1: A link that joins two nodes $x$ and $x \oplus 1$ (where $x \oplus 1$denotes$(x+1)$ mod $N$) is called a shorter link. A link that joins two nodes $x$and $x \oplus 3$ (where $x \oplus 3$ denotes$x \oplus 3$ mod N) is called a longer link.
For example, in Figure 2, the link that joins node 0 with node 1 is a shorter link. Similarly, the link that joins node 0 with node 3 directly (without passing through intermediate nodes1 and 2) is a longer link.

Definition 2: A lightpath (or optical connection) is characterized as the arrangement of all the links that joins source node with destination node under an endorsed routing technique. A connection (u, v) corresponds to a transmission of a data packet from source node u to destination node v through a lightpath.

Definition 3: A lightpath that chooses the longest link among all the accessible links at the source node and at each of the intermediate nodes to reach the destination node is said to follow as 'longest link first routing'.
For example, in Figure 4, under longest link first algorithm, a connection from node 0 to node 7 selects the links joining the node 0 with node 3, then node 3 with node 6, and node 6 with node 7.

## 3. Main Results

Wavelengths are costly resources in an optical network. The number of different wavelengths employed in a network increases the cost of the network besides complexity of the network. So, it is preferable to limit the usage of distinct wavelengths. The sufficient and necessary condition on the minimum wavelength number required for the network to be wide-sense nonblocking is derived for linear array, unidirectional ring and bidirectional ring networks with 3-length extension under longest link first routing technique.

### 3.1. Linear array with 3-length extension

Figure 2 shows a 16-node linear array with 3-length extension. The routing of lightpaths is either in rightward direction or in leftward direction. Lightpaths are built up under longest link first routing so as to use minimum number of hops for each connection. 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 3-length extension to be wide-sense non-blocking is $N-3$.

Proof: Sufficiency: It is to be noted that all the lightpaths between different sources and destinations are routed either in rightward direction or in leftward direction. For a lightwave network, a specific wavelength can be dispensed for numerous lightpaths as long as they do not overlap with each other. A wavelength released by a current lightpath during its termination can be again used to build up a new lightpath. It can be noted that out of $N$ multicast connections, there can be at most $N-1$ lightpaths either in rightward direction or in leftward direction. During a new connection request, it can be observed that there can be atmost N-4 already existing lightpaths sharing a particular link in the same direction. To establish the current connection request, one more lightpath is needed. So, $N-3$ wavelengths are sufficient to route all connection requests.

Necessity: Consider a worst-case multicast assignment of the form with 0 as the source and every other node as its destinations, alongside another connection with 0 as the destination for any arbitrary source. All lightpaths with destination node index greater than or equal to 3 utilize the link joining nodes 0 with 3. The aggregate number of such lightpaths is$N-3$which necessitates$N-3$wavelengths. The remaining lightpaths namely (0, 1), (0, 2) and (x, 0) where x ∈ {1, 2,…,N − 1} do not share any link in the same direction with the previous set of $N-3$ lightpaths and can be built up utilizing any of the already allotted wavelengths. Henceforth, the wavelength number requirement is$N-3$. Consequently, $N-3$ wavelengths are the sufficient and necessary condition on the wavelength number.

Wavelength allotment technique
In this technique, four tables namely $T_{R1}, T_{R2}$ for rightward connections and $T_{L1,}T_{L2}$ for leftward connections are used for managing wavelength allotment. Let $T_W$ contain all available $N-3$ wavelengths namely$\lambda_1, \lambda_{2,} \ldots \lambda_{N-3}$. Let the tables$T_{R1}, T_{R2}$ and $T_{L1,}T_{L2}$ be initially empty.
Let $x$ and $y$ be the index of source and destination node respectively. Then, the wavelength allotment procedure for a new connection request (x, y) is as follows:
Step 1: If $x < y,\ y - x > 2$,allot a wavelength that is not available in $T_{R1}$ but available in $T_W$. Then include this wavelength in TR1. Else if$y - x < 3$ allot the wavelengththat is not available in $T_{R2}$ but available in $T_W$. Then include this wavelength in TR2.

Step 2: If $y < x,\ x - y > 2$, allot a wavelength that is not available in $T_{L1}$ but available in $T_W$. Then include this wavelength in TL1. Else if $x - y < 3$ allot the wavelength that is not available in $T_{L2}$ but available in $T_W$.Then include this wavelength in TL2.

### 3.2. Unidirectional ring with 3-length extension

Figure 4 shows a 12-node ring with 3-length extension. The routing of lightpaths is assumed to be in clockwise direction without loss of generality. Lightpaths are established under longest link first routing to use minimum number of hops. Theorem 2 is proved based on this assumption.
Theorem 2: The sufficient and necessary condition on the wavelength number for an N node unidirectional ring with 3-length extension to be wide-sense non-blocking is $N - 3$.

Proof:
Sufficiency: It is to be noted that all the lightpaths between various sources and destinations are routed only in clockwise 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 at most $N - 1$ lightpaths originating from the same source. During a new connection request, it can be observed that there can be atmost N-4 already existing lightpaths sharing a particular link in the same direction. To establish the current connection request, one more lightpath is needed. So, $N - 3$ wavelengths are sufficient to route all connection requests.

Necessity: It is not hard to note that a worst-case multicast assignment can be of the form with 0 as the source and all other nodes are its destinations along with another lightpath with 0 as destination for an arbitrary source. All lightpaths with source index 0 and destination index greater than 2 use the longer link joining nodes 0 with 3. The total number of such lightpaths is$N - 3$. The remaining lightpaths namely (0, 1), (0,2)and (x, 0) where x ∈ {1, 2, . . ., N − 1} do not share any link with the previous N-3 lightpaths and can utilize any three wavelengths from the wavelengths assigned for previousN-3 lightpaths. Hence, the wavelength number requirement is$N - 3$. Therefore, $N - 3$wavelengths are the sufficient and necessary condition on the wavelength number.

Wavelength allotment technique
In this technique, two tables namely $T_{C1}$and $T_{C2}$are used for managing wavelength allotment to light-paths setup in clockwise direction. Let$T_W$be used for storing the available $N - 3$wavelengths namely$\lambda_1, \lambda_{2,} \ldots\ \lambda_{N-3}$. .
Let x and y be the index of source and destination node respectively. Then, the wavelength allotment procedure for a new connection request (x, y) is as follows:
Step 1: If $x < y,\ y - x > 2$, allot a wavelength that is not available in $T_{c1}$ but available in $T_W$. Then include this wavelength in Tc1. Else if $y - x < 3$ allot the wavelength that is not available in $T_{c2}$ but available in $T_W$. Then include this wavelength in Tc2.
Step 2: If $y < x,\ x - y > 2$, allot a wavelength that is not available in $T_{c1}$ but available in $T_W$. Then include this wavelength in Tc1. Else if $y - x < 3$ allot the wavelength that is not available in $T_{c2}$ but available in $T_W$. Then include this wavelength in Tc2.

### 3.3 Bidirectional ring with 3-length extension

Figure 4 shows a12-node ring with 3-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. Lightpaths are established under longest link first routing to use minimum number of hops. Theorem 3 is proved based on this assumption.

Theorem 3: The sufficient and necessary condition on the wavelength number for a N node bidirectional ring with 3-length extension to be wide-sense non-blocking is$\left\lfloor\frac{N-4}{2}\right\rfloor$.

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. During a new connection request, it can be observed that there can be atmost $\left\lfloor\frac{N-6}{2}\right\rfloor$ already existing lightpaths sharing a particular link in the same direction. To establish the current connection request, one more lightpath is needed. So, $\left\lfloor\frac{N-4}{2}\right\rfloor$ wavelengths are sufficient to route all connection requests.

Necessity:

Case i: N is even: Consider a worst-case multicast assignment of the form$(x,\ x\oplus i),\ 1\ \leq i\leq N/2$. The first group of lightpaths of the form $(x,\ x\oplus i)$, $3\leq i\leq\frac{N}{2}$ share the longer link joining the nodes x and $x\oplus 3$and hence each lightpath need to be assigned a unique wavelength. This necessitates $\frac{N-4}{2}$ wavelengths. The other group of lightpaths namely $(x,\ x\oplus 1)$ and $(x,\ x\oplus 2)$ does not share any link with any of the lightpaths of the previous group. Therefore, these two lightpaths can be assigned any two wavelengths from the wavelengths assigned from the first group. Hence,$\frac{N-4}{2}$wavelengths are required to route all the lightpaths of multicast assignment, if N is even.

Case ii: N is odd: Consider a worst-case multicast assignment of the form$(x,\ x\oplus i),\ 1\ \leq i\leq(N-1)/2$. The first group of lightpaths of the form $(x,\ x\oplus i)$, $3\leq i\leq\frac{N-1}{2}$ share the longer link joining the nodes x and $x\oplus 3$ and hence each lightpath need to be assigned a unique wavelength. This necessitates $\frac{N-5}{2}$ wavelengths. The other group of lightpaths namely $(x,\ x\oplus 1)$ and $(x,\ x\oplus 2)$ does not share any link with any of the lightpaths of the previous group. Therefore, these two lightpaths can be assigned any two wavelengths from the wavelengths assigned from the first group. Hence,$\frac{N-5}{2}$wavelengths are required to route all the lightpaths of multicast assignment, if N is odd.

Hence,$\left\lfloor\frac{N-4}{2}\right\rfloor$ wavelengths are necessary 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. Then, the wavelength allotment procedure for any connection request (x, y) is based on the index of the destination node which is mapped to a particular wavelength. The destination node index to wavelength index mapping is as given in table 1.

**Table 1** The destination node index to wavelength index mapping.

| Destination node index | Wavelength to be assigned |
|---|---|
| 0 | 0 |
| 1 | 1 |
| 2 | 2 |
| 3 | 3 |
| … | … |
| $\left\lfloor\frac{N-4}{2}\right\rfloor-1$ | $\left\lfloor\frac{N-4}{2}\right\rfloor-1$ |
| $\left\lfloor\frac{N-4}{2}\right\rfloor$ | 0 |
| $\left\lfloor\frac{N-4}{2}\right\rfloor+1$ | 1 |
| $\left\lfloor\frac{N-4}{2}\right\rfloor+2$ | 2 |
| $\left\lfloor\frac{N-4}{2}\right\rfloor+3$ | 3 |
| … | … |
| N-1 | $N-1-\left\lfloor\frac{N-4}{2}\right\rfloor$ |

## 4. Results and Discussion

Table 2 shows the comparison between basic network topologies and network topologies with 3-length extension 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 3-length extension. From Table 2, it can be observed that the wavelength number needed to support wide-sense nonblocking multicast is marginally reduced for linear array, unidirectional ring and bi-directional ring with 3-length extensions when compared with their basic counterpart.

**Table 2** Comparison of wavelength requirement for achieving wide-sense nonblocking multicast between basic network topologies and network topologies with 2-length and 3-length extension

| Network Topology | Conventional networks [1] | Networks with 2-length extension under longest link first routing [4] | Networks with 3-length extension under longest link first routing |
|---|---|---|---|
| N-node Linear Array | N-1 | N-2 | N-3 |
| N-node Unidirectional ring | N | N-2 | N-3 |
| N-node Bi-directional ring | $\left\lceil \frac{N}{2} \right\rceil$ | $\left\lceil \frac{N}{2} \right\rceil$ | $\left\lfloor \frac{N-4}{2} \right\rfloor$ |

## 5. Conclusion and future work

In this paper, wide-sense nonblocking multicast communication is studied for WDM optical linear array, unidirectional ring and bi-directional ring with 3-length extensions under longest link first 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 basic network topologies. The wavelength number needed to support wide-sense nonblocking multicast is marginally reduced for linear array, unidirectional ring and bi-directional ring with 3-length extensions when compared with their basic counterpart.

Future work includes extending this study of wide-sense nonblocking multicast communication for WDM optical linear array and unidirectional and bidirectional ring with 4-length and higher length extensions.

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