

Wide Sense Nonblocking Multicast in an Augmented Linear Array

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Abstract: - Multicast communication refers to the transmission of information from a single source node to multiple destination nodes at the same time. This type of communication is used in applications such as video streaming, online gaming, and content distribution, where the same data must be delivered to many users simultaneously. Wavelength Division Multiplexing (WDM) optical networks are suitable for such applications because they can transmit large amounts of data over long distances with very low signal loss. In this work, the linear array network is modified by connecting terminal nodes that have a fixed index difference. The resulting structure is called an augmented linear array network. The study focuses on wide-sense nonblocking multicast communication and derives the necessary and sufficient conditions for wavelength requirements in the augmented linear array network.

Key-Words: - Wide-sense nonblocking, Multicast, WDM, Wavelength Assignment, Augmented Linear Array, Linear Array, Multicast Switching, Routing Algorithms, Network Topology.

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1 Introduction

Multicast communication involves transmitting information from a single source node to a group of destination nodes simultaneously. This communication model differs from unicast and broadcast communication. In unicast communication, data is transmitted from one sender to one receiver, whereas broadcast communication involves sending data from one source to all nodes in the network. Multicast communication, however, delivers data only to a selected group of nodes, which helps avoid unnecessary data duplication. This communication model is useful for applications such as barrier synchronization, clock synchronization, and data replication [1]. Multicast communication is widely used in applications such as video streaming, online gaming, and content distribution, where the same data must be delivered to multiple users at the same time [2]. Multicast communication sends the same data from one source to many receivers at the same time. This avoids repeated transmissions and makes better use of the available bandwidth. As a result, it reduces network congestion and improves overall network efficiency.

Because of these benefits, multicast communication is widely used in modern networking systems, including IP networks and distributed computing environments.

Wavelength Division Multiplexing optical networks are suitable for multicast communication because they can carry large amounts of data over long distances with low signal loss. However, multicast communication in WDM optical networks is more complex than in electronic networks. In these networks, it is not enough to select only the route. A suitable wavelength must also be assigned for the transmission [3]. Therefore, routing and wavelength assignment must be handled together. This helps reduce wavelength usage and avoids conflicts between different multicast sessions. The efficiency of multicast communication in optical networks depends on the number of multicast sessions, the available wavelengths, and the network topology [2], [3]. Multicast grooming can help by allowing more than one multicast session to share the same wavelength. Dynamic wavelength assignment can also improve wavelength use by adapting to current network conditions. These

methods help improve network performance and support reliable multicast communication.

The need for wide-sense nonblocking multicast communication is increasing because many modern applications require continuous and high-bandwidth data transmission. These applications include content delivery networks, video streaming, online gaming, telecommunications, virtual collaboration, smart manufacturing, data centers, broadcasting, online education, and medical imaging. Therefore, improving multicast methods in optical networks is important for reducing delay, using bandwidth efficiently, and maintaining reliable communication.

The linear array network is commonly used in Local Area Networks, Wide Area Networks, and interconnection network architectures because it has a simple and uniform structure [3], [4]. However, when traffic demand increases, the basic linear array structure may not be enough. It needs suitable modifications, similar to the improvements used in ring topologies [5]. One such improvement is to add extra links between alternate terminal nodes in the linear array network [6]. These added links create alternative paths for communication. They also reduce the number of hops needed for transmission and lower the overall wavelength requirement.

Several studies have examined linear array networks and multicast transmission, mainly focusing on network design and performance analysis. However, modern applications and traffic patterns require improved network structures with better performance and scalability. Many advanced network topologies can be constructed using multiple basic or modified linear arrays as building blocks [3], [4]. Earlier studies have shown that modified ring topologies perform better than traditional ring networks in terms of scalability and efficiency. In this work, a similar concept is applied to linear array networks by introducing additional links to improve performance and adaptability to modern network requirements. Wide-sense nonblocking multicast communication has been studied extensively [7], [8], [9], [10], [11], [12], [13], [14] and the number of wavelengths required for linear array and ring networks has been analyzed under various scenarios [7], [8], [9], [10], [11]. Several switching architectures and wavelength-space-wavelength (WSW) node designs have also been studied for wide-sense and strict-sense nonblocking communication in optical networks [12], [13], [14]. Routing and wavelength assignment problems in optical networks continue to be important research areas, especially in elastic optical networks and multicast communication systems [15], [16], [17], [18], [19], [20], [21].

Despite these advancements, the issue of nonblocking multicast in variants of popular network networks, which are widely used in networking, remains unexplored. To address this gap, the authors investigate this problem within the context of an augmented linear array network. The outcomes of this study can serve as a foundation for evaluating similar challenges in more complex and irregular networks used in long-haul applications. Notably, irregular network structures can often be partitioned into multiple regular sub-networks, including linear arrays and/or their variant structures, facilitating their analysis and optimization.

The main contribution of this work is the analysis of wide-sense nonblocking multicast communication in an augmented linear array network topology and the derivation of necessary and sufficient conditions for the minimum number of wavelengths required under shortest path routing. In addition, a wavelength allotment algorithm suitable for multicast communication in augmented linear arrays is proposed. The results demonstrate that the augmented linear array requires significantly fewer wavelengths compared to traditional linear array networks, making it suitable for high-capacity optical multicast communication.

The organization of this document is as follows: Section II provides a synopsis of the foundational concepts necessary to understand the main results, with a focus on multicast assignment and routing within the augmented linear array network topology. In Section III, the necessary and sufficient conditions on the minimum number of wavelengths required to achieve wide-sense nonblocking multicast in an augmented linear array network are derived. Section IV compares the results of the augmented linear array with other commonly used network topologies. Section V concludes the article and outlines possible directions for future research.

2 Preliminaries

Multicast assignment [4], [5] is a form of multicasting used in traffic analysis for communication networks. In this method, each destination node is connected to one source node, while one source node may serve several destination nodes. A typical multicast assignment scenario is shown in Figure 1.

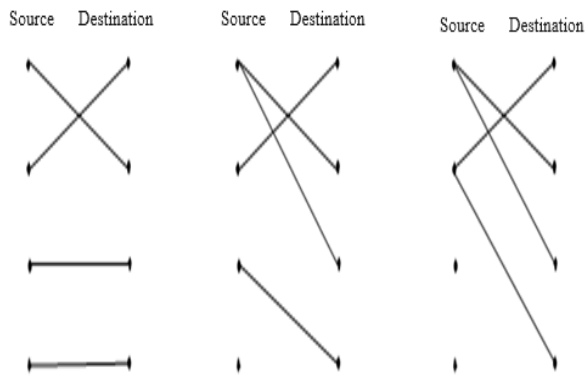


Fig. 1: Typical multicast assignment scenarios
Source: Adapted from [3]

In optical networks, data loss can occur when connection requests are blocked. This mainly happens because intermediate nodes usually do not have buffering capability. To reduce such losses, nonblocking network structures are used. A nonblocking optical network is designed to enable the establishment of all required multicast connections without the need to remove or reroute existing connections. When this property is achieved using a predetermined routing algorithm, the network is classified as wide-sense nonblocking.

Figure 2 displays a 10-node linear array and its augmented version. In an augmented linear array, terminal nodes are interconnected in a specific way to enhance communication efficiency. Along with the standard linear connections, each terminal node is linked to another terminal node whose index differs by, where N is the total number of terminal nodes. This means data can directly hop not only to adjacent terminal nodes but also to terminal nodes separated by, provided they exist. These additional connections create alternative pathways between terminal nodes, reducing the number of hops needed for data transfer and minimizing network wavelength demands

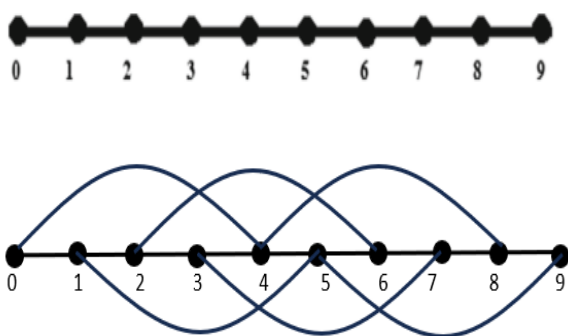


Fig. 2: A 10-node linear array and its augmented version

Source: Adapted from [6] & Created by the authors

In the augmented linear array shown in Figure 2, each node is connected to its immediate neighbor through shorter links and also connected to another node whose index differs by $[N/2]$ through longer links. For a 10-node array, node 0 is connected to node 5, node 1 to node 6, node 2 to node 7, node 3 to node 8, and node 4 to node 9. These additional links reduce the network diameter and provide alternative routing paths for multicast connections. Because of these additional paths, the number of hops required for communication is reduced, which in turn reduces wavelength requirements and improves network efficiency. The following definitions are used to explain the key concepts discussed in this paper.

Definition 1: A lightpath, also called an optical connection, is defined as a sequence of links that connects a source node to a destination node according to a given routing strategy. The notation (u, v) represents the transmission of a data packet from source node u to destination node v along the established lightpath.

Definition 2: The constraint on wavelength continuity mandates that a lightpath must be on the same wavelength across all the links from the source to the destination in the absence of wavelength conversion at intermediary nodes. Additionally, multiple lightpaths may share the same wavelength, provided they do not traverse the same link in the same direction.

Definition 3: A lightpath or connection is classified as rightward if the index of the destination terminal node is greater than the index of the source terminal node. Conversely, a connection is classified as leftward if the index of the destination terminal node is smaller than that of the source terminal node.

Definition 4: Consider two terminal nodes, a as the source and b as the destination. The length of the connection between these nodes is defined as the total number of edges traversed to move from the source node to the destination node.

Definition 5: A link joining two nodes whose index difference is unity is said to be a shorter link. A link directly joining two nodes whose index difference is $[N/2]$ is said to be a longer link.

In this study, shortest path routing is adopted for multicast transmission in the augmented linear array network. For any source–destination pair, the routing path is selected such that the number of hops between the nodes is minimized. In the augmented linear array, two types of links are available: shorter links connecting adjacent nodes and longer links connecting nodes separated by $[N/2]$. Based on the source and destination indices, the routing may use

shorter links, longer links, or both. This helps choose the shortest possible path and reduces the number of wavelengths needed. This is important for wide-sense nonblocking multicast communication.

3 Main Results

This section derives the necessary and sufficient conditions for finding the minimum number of wavelengths required to achieve wide-sense nonblocking in an augmented linear array. The routing method applied for the analysis is shortest path routing under the assumption that all links in the augmented linear array are of equal length. The analysis focuses on identifying the wavelength resource requirements needed to maintain wide-sense nonblocking communication within an augmented linear array network.

Theorem 1: For an augmented linear array with N nodes, the sufficient and necessary condition on the minimum wavelength number required to be wide-sense nonblocking is $\lceil N/2 \rceil$ under shortest path routing.

Proof:

Sufficiency: The technique dealt with here involves the effective utilization of wavelengths within an augmented linear array network by reassigning a single wavelength to multiple lightpaths where there is no overlap. The release of a wavelength upon the termination of a current lightpath allows for its reuse in establishing new lightpaths. Notably, in a multicast scenario with N lightpaths (the number of lightpaths equal to the number of nodes in an augmented linear array under a worst-case multicast scenario), $N-1$ lightpaths can originate from the same source node. When accommodating a new connection request, it is to be observed that a maximum of $\lceil N/2 \rceil$ lightpaths may already share one of the outgoing links, and a maximum of another $\lceil N/2 \rceil - 1$ lightpaths may share another outgoing link in the same direction. To accommodate the new connection request, one additional wavelength is required along the optical link that already hosts $\lceil N/2 \rceil - 1$ lightpaths. Consequently, it is deduced that $\lceil N/2 \rceil$ wavelengths are required to effectively route all multicast connections.

Necessity: Consider a worst-case multicast assignment scenario, where the terminal node labeled 0 acts as the source and every other node acts as a destination, accompanied by another connection whose origination is any arbitrary node but whose destination is node 0. In such a situation, one set of connections of the form $(0, x)$, where x is

such that $0 < x < \left\lfloor \frac{N}{2} \right\rfloor + 1$ share the link connecting nodes 0 and 1, and hence $\lceil N/2 \rceil$ wavelengths are needed. The remaining set of connections shares the longer link connecting nodes 0 and $\lceil N/2 \rceil$ and hence does not overlap with the connections of the previous set. Hence, $\lceil N/2 \rceil$ wavelengths are sufficient to route all multicast connections.

Wavelength Allotment Technique

A wavelength allotment technique utilizing three tables, T_A , T_1 , and T_2 , where T_A contains available wavelengths, namely, $\lambda_1, \lambda_2, \dots, \lambda_{\lceil N/2 \rceil}$, and both T_1 and T_2 are initially empty. The assignment process follows the steps given below:

Step 1: If the source index is greater than the destination index and the destination index is even, route the lightpath using either shorter links in the forward direction or longer links in the reverse direction or both. For this lightpath, assign a wavelength that is in T_A but not in T_1 .

Step 2: If the source index is smaller than the destination index and the destination index is odd, route the lightpath using either shorter links in the forward direction or longer links in the reverse direction or both. For this lightpath, assign a wavelength that is in T_A but not in T_1 .

Step 3: If the source index is smaller than the destination index and the destination index is even, route the lightpath using either shorter links in the reverse direction or longer links in the forward direction or both. For this lightpath, assign a wavelength that is in T_A but not in T_2 .

Step 4: If the source index is greater than the destination index and the destination index is odd, route the lightpath using either shorter links in the reverse direction or longer links in the forward direction or both. For this lightpath, assign a wavelength that is in T_A but not in T_2 .

Step 5: Upon the release of an existing connection, remove the corresponding wavelength from T_1/T_2 .

The computational complexity of the wavelength allotment algorithm mainly depends on the process of selecting an available wavelength from the table T_A while ensuring that it is not already present in T_1 or T_2 . Let W denote the number of available wavelengths, where $W = \lceil N/2 \rceil$. For each incoming connection request, the algorithm checks wavelength availability in either T_1 or T_2 , which requires at most $O(W)$ time. Therefore, the complexity of assigning a wavelength for a single connection request is $O(N)$. For M connection requests, the overall computational complexity becomes $O(MN)$. Since wavelength assignment

operations involve only table lookup and update operations, the algorithm is computationally efficient and suitable for real-time multicast communication in optical networks.

Example 1: Wavelength assignment in an augmented linear array with 10 nodes and for some 7 random connection requests.

Solution: Initially, $T_A = \{\lambda_1, \lambda_2, \dots, \lambda_5\}$, $T_1 = \{\}$, $T_2 = \{\}$.

The step-by-step assignment of wavelengths to the incoming connection requests (generated randomly) is shown below:

Incoming Connection (randomly generated Source – destination pairs)	Wavelength assigned for the requested connection in column 1	Released connection, if any (randomly selected for release)	T_1	T_2
(0,5)	λ_1	-	-	λ_1
(3,7)	λ_2	-	-	λ_1, λ_2
(4,6)	λ_1	-	λ_1	λ_1, λ_2
(0,9)	λ_3	-	λ_1	$\lambda_1, \lambda_2, \lambda_3$
(1,8)	λ_2	(3,7)*	λ_1, λ_2	λ_1, λ_3
(4,7)	$\lambda_{2^{**}}$	-	λ_1, λ_2	$\lambda_1, \lambda_2, \lambda_3$
(1,0)	λ_3	-	$\lambda_1, \lambda_2, \lambda_3$	$\lambda_1, \lambda_2, \lambda_3$

** Wavelength reuse due to the release of an *existing connection.

Source: Created by the authors

4 Results and Discussion

Table 1 presents a comparative analysis of fundamental network topologies, specifically focusing on the count of wavelengths needed to facilitate wide-sense nonblocking multicasting. Table 2 presents Comparison between the wavelength requirement of Linear Array, Modified Linear Array and Augmented Linear Array

Table 1. Wavelength COUNT Comparison for Wide-Sense Nonblocking Multicasting in popular architecture

Network Topology	Wavelength Count Required
N node Linear Array [3]	N-1
N node Unidirectional ring [3]	N
N node Bidirectional ring [3]	N/2
p*q Torus [3]	p*(q/2)
p*q Mesh [3]	p*(q-1)
n-dimensional Hypercube [3]	2 ⁿ -1
N node modified linear array [9]	N-3

Network Topology	Wavelength Count Required
N node modified Unidirectional ring [9]	N-3
N node modified Bidirectional ring [9]	(N-4)/2
Binary Tree of height h [7]	2 ^{h+1} - 2
N node Augmented linear array	[N/2]

Source: Adapted from [3],[9],[7] & Created by the authors

Table 2. Comparison between Linear Array and Augmented Linear Array

Network	Diameter	Wavelength Requirement
Linear Array	N-1	N-1
Modified Linear Array	N-3	N-3
Augmented Linear Array	[N/2]	[N/2]

Source: Adapted from [3],[9] & Created by the authors

Table 3. Simulation Results

N	Linear Array	Modified Linear Array	Augmented Linear Array
8	7	5	4
10	9	7	5
12	11	9	6
16	15	13	8

Source: Adapted from [3],[9] & Created by the authors

To further validate the analytical results obtained in this study, simulation experiments were conducted for augmented linear array networks with different numbers of nodes. Random multicast connection requests were generated, and shortest path routing was applied along with the proposed wavelength allotment algorithm. The simulation measured the minimum number of wavelengths required to support wide-sense nonblocking multicast communication. Table 3 compares the wavelength requirements for linear array, modified linear array, and augmented linear array networks for different network sizes. From the table, it can be observed that the augmented linear array requires fewer wavelengths than both the linear array and the modified linear array networks. The simulation results are consistent with the theoretical results derived in this paper, which show that the minimum number of wavelengths required for wide-sense nonblocking multicast in an augmented linear array is [N/2]. This agreement between theoretical and simulation results supports the analytical model and shows that the augmented linear array topology reduces wavelength requirements.

The wavelength requirements derived for the augmented linear array are also presented along with

those of other commonly used network topologies. However, comparing wavelength requirements directly across different topologies may not always be fair. Each topology has its own strengths, limitations, and suitable application areas. To further verify the analytical results obtained in this study, simulation experiments were performed using randomly generated multicast connection requests for augmented linear array networks with different network sizes.

The simulation evaluated the number of wavelengths required under shortest path routing for various multicast scenarios. The results confirmed that the minimum number of wavelengths required to achieve wide-sense nonblocking multicast communication in an augmented linear array network is $\lceil N/2 \rceil$, which matches the theoretical result derived in this study. The simulation also showed that wavelength reuse significantly reduces overall wavelength usage compared to traditional linear array networks.

The key takeaway is that the results obtained for various standard network topologies, including the augmented linear array, are highly relevant when analyzing practical long-haul networks, which are often irregular in structure. Such irregular networks typically need to be decomposed into one or more basic topologies, among which the augmented linear array is almost invariably present. This decomposition facilitates the computation of multicast resource requirements in real-world long-haul networks, making the analysis both applicable and effective.

5 Conclusion and Future Work

This article presented an analysis of wide-sense nonblocking multicast in a WDM optical augmented linear array network. The study derived the necessary and sufficient conditions on the minimum number of wavelengths required to achieve wide-sense nonblocking in the network. Future research can extend this work in several directions. First, the analysis can be extended to strict-sense nonblocking multicast in augmented linear array networks. Second, the wavelength assignment strategy can be analyzed under different routing algorithms, such as longest link first routing and adaptive routing. Third, simulation studies can be conducted to evaluate blocking probability, wavelength utilization, and network throughput under dynamic traffic conditions. Another promising direction is the application of the augmented linear array topology to Optical Network-on-Chip (ONoC) and data center networks. Additionally, the augmented linear array concept can be extended to higher-dimensional networks such as torus, mesh, and

hypercube networks. Finally, machine learning and artificial intelligence techniques can be explored for dynamic wavelength assignment and traffic prediction in optical multicast networks.

Declaration of Generative AI and AI-assisted Technologies in the Writing Process

During the preparation of this work, the author(s) utilized artificial intelligence (AI) technologies solely for the purpose of linguistic refinement and grammatical correction. Following the application of these tools, the author(s) comprehensively reviewed, verified, and edited the resulting text. The author(s) maintain full accountability and responsibility for the accuracy, integrity, and final content of the publication.

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Contribution of Individual Authors to the Creation of a Scientific Article (Ghostwriting Policy)

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Conflict of Interest

The authors have no conflicts of interest to declare that are relevant to the content of this article.

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