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Wavelength assignment for all-to-all broadcast in WDM optical linear array with limited drops

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ABSTRACT

All-to-all broadcast is to disseminate a unique message from each node to every other node. This is a fundamental problem in multiprocessor systems and telecommunication networks that need to collect information about other nodes in the network regularly in order to manage network resources efficiently. In this paper, a novel wavelength assignment method is proposed to establish all-to-all broadcast in a linear array network. The network model is an all-optical network, in which a message from source node can be dropped (or split) only at a limited number of destination nodes along a light path due to power loss of dropping optical signals. The minimum number of wavelengths required to establish all-to-all broadcast is also derived for a linear array network.

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1. Introduction

Optical networks have the potential of interconnecting hundreds to thousands of users covering local to wide area networks. It provides capacities of the order of gigabits per second to each user. There has been an increasing demand for higher channel bandwidth and lower communication latency in high-performance computing and communication applications. Recent advances in electro-optic technologies have made optical communication a promising network choice to meet the above demands. Wavelength division multiplexing (WDM), by means of which a single physical link can have several logical channels (i.e. wavelengths), provides an economical way of utilizing the huge bandwidth of the fiber. Under WDM, the spectrum is divided into multiple wavelength bands, with each wavelength supporting a single communication channel operating at peak electronic rate.

An optical WDM network consists of routing nodes interconnected by point-to-point fiber links, which can support a certain number of wavelengths. Each link in the network is bidirectional and actually consists of pair of unidirectional links with one link in each direction. The routing nodes are assumed to be equipped with "tap-and-continue" facilities. A tap-and-continue node [1–4] "taps" the information from the wavelength channel, which is then forwarded by the node. The local node may use the tapped optical power. A light splitter is an optical device that can split the incoming light signal from a fiber into two or more fibers. A tap-and-continue node is similar to a local node split with the main difference being that the tapping function taps only a small amount of power. A connection or a lightpath in a WDM network is an ordered pair of nodes (x,y) corresponding to a transmission of a packet from source x to destination y. An optical signal transmitted at a source node has a fixed amount of power. However, due to the power loss when an optical signal drops off at a destination along the path, there is a limit on the maximum number of destinations at which a signal from the source can be dropped on a path. Therefore, the route of each broadcast connection consists of multiple lightpaths, each of which contains a limited number of destinations. The wavelength conflict rule defines that two lightpaths will use different wavelengths if they share a common link. Wavelengths are scarce resources in optical networks and hence it is desirable to assign a minimum number of wavelengths to all the connections in a network without any color clash. Wavelength assignment can be seen as a problem of coloring the lightpaths of the network without color clash [5].

All-to-all broadcast [6–9] is to disseminate a unique message from each node to every other node. This is a fundamental problem in multiprocessor systems and telecommunication networks that need to collect information about other nodes in the network regularly in order to manage network resources efficiently. The need also arises in many form of parallel and distributed computing including many scientific computations and database management

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[10,11]. All-to-all broadcast communication is needed in many applications such as matrix multiplication, LU-factorization, Householder transformations, and basic linear algebra operations [12]. In this paper, we have studied wavelength assignment for all-to-all broadcast in a linear array network and derived the minimum number of wavelengths required. The linear array network is popular and finds application in any form of network including WAN, MAN and LAN. Owing to its small node degree and regularity it also finds application in interconnection networks [13]. Though lot of research has gone into the study of optical linear array network [6–8,14–16], to the best of our knowledge, this is the first paper to study all-to-all broadcast communication in a linear array network that permits some specified maximum number of drops, d, per transmission. The value of d is dictated by the power budget [16–18], and henceforth d is referred to as the split degree. In all-to-all broadcast, as all the connection requests are known well in advance, it corresponds to static traffic and can be realized as a simple case, with the architecture of light-trail [19] or optical hyperchannel [20].

The problem investigated in this paper can simply be stated as follows: "Find a suitable wavelength assignment to establish all-to-all broadcast in a linear array network that reduces the number of wavelengths required". The results obtained show that there is a large reduction in the number of wavelengths when split degree increases from one to two, but the rate of reduction diminishes for subsequent increase in the number of splits. The remainder of the paper is organized as follows. In Section 2, we introduce the preliminaries needed to prove the results of this paper. In Section 3, we derive the minimum number of wavelengths required to support all-to-all broadcast in a linear array. Section 4 concludes the paper and points out some future work.

2. Preliminaries

In this section, we introduce a term called *Connection set* to prove our results. A connection set is defined as a group of connections where a single source node transmits a message on a unique wavelength to a group of at most d consecutive destination nodes along a light path. Let the connection set denoted by $(x,\{y_1,y_2,\ldots,y_d\})$ refer to a source node x transmitting a message to d consecutive destination nodes $y_1,y_2,\ldots,y_d$ on a unique wavelength. The results of this paper are obtained through the following four steps: (i) grouping of connections into a connection set under multi-drop lightpath model, (ii) mapping of non-overlapping connection sets on a common wavelength, (iii) determining the number of such wavelengths required and (iv) establishing the number obtained as the minimum number. The link load of a network is defined as the maximum number of lightpaths that share a common link. For any network, it can be intuitively observed that the minimum number of wavelengths required to support all connections is greater than or equal to the link load. An illustrative example is shown below.

Example 1. Wavelength allocation for all-to-all broadcast in an 8-node linear array with split degree $d = 3$. Consider an 8-node linear array network shown in Fig. 1.

We consider only connections going in rightward direction for reasons described in next section. First of all, the connection sets for all sources are formed as shown below for the above network.

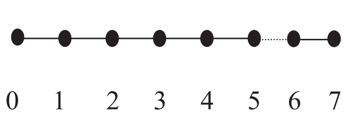

Fig. 1. An 8-node linear array network.

$(0,\{1,2,3\}),(0,\{4,5,6\}),(0,\{7\}),$
$(1,\{2,3,4\}),(1,\{5,6,7\}),$
$(2,\{3,4,5\}),(2,\{6,7\}),$
$(3,\{4,5,6\}),(3,\{7\}),$
$(4,\{5,6,7\})$
$(5,\{6,7\}),$
$(6,\{7\}).$

Secondly, non-overlapping connection sets are mapped on a unique wavelength as shown below.

$\{(0,\{1,2,3\}),(3,\{4,5,6\}),(6,\{7\})\}\rightarrow\lambda_1,$
$\{(1,\{2,3,4\}),(4,\{5,6,7\})\}\rightarrow\lambda_2,$
$\{(2,\{3,4,5\}),(5,\{6,7\})\}\rightarrow\lambda_3,$
$(0,\{4,5,6\})\rightarrow\lambda_4,$
$(0,\{7\})\rightarrow\lambda_5,$
$(1,\{5,6,7\})\rightarrow\lambda_6,$
$(2,\{6,7\})\rightarrow\lambda_7,$
$(3,\{7\})\rightarrow\lambda_8$

Thus, it is noted from the above example that all-to-all broadcast for an 8-node linear array with at most 3 drops can be performed with eight wavelengths.

Now consider the link joining node 3 and node 4. It is easy to observe that each node before node 4, uses the above link twice to transmit message to all the nodes after node 3. Since there are four such nodes, the number of connection sets sharing the above link is $4\times2 = 8$. Since all overlapping connection sets must be assigned different wavelength, the number of wavelengths needed is eight. Hence, eight wavelengths are required to support all-to-all broadcast in an 8-node linear array considering split degree 3.

3. Generalization to a linear array

Consider an N-node linear array network whose nodes are numbered from 0 to $N-1$. In a linear array network, all-to-all broadcast connections consist of two sets of connections, one set of connections going left and the other going right. These two sets of connections do not share any physical fiber since bidirectionality is implemented with separate fiber links for either direction. Therefore, these two sets of connections can be assigned the same wavelength. So, in our analysis, without loss of generality, we consider only connections going rightward direction.

Let i be a positive integer. Then, for $x = 0,1,2,\ldots,N-2$, we form connection sets as

$$S(d,x,i)=\begin{cases}\{(x,y):x+d(i-1)+1\leqslant y\leqslant x+di\}, & i=1,2,\ldots,\left\lfloor\frac{N-1-x}{d}\right\rfloor,\\ \{(x,y):x+d(i-1)+1\leqslant y\leqslant N-1\}, & i=\left\lfloor\frac{N-1-x}{d}\right\rfloor+1,\end{cases}$$

where x and y refer to the index of source node and destination node, respectively, and d is the split degree.

Remark 1. $\{\{(x,y):x+d(i-1)+1\leqslant y\leqslant N-1\},i=\left\lfloor\frac{N-1-x}{d}\right\rfloor+1\}$ is empty when d divides $N-1-x$.

If d divides $(N-1-x)$, then the connection sets of interest are $S(d,x,1),S(d,x,2),\ldots,S(d,x,\frac{N-1-x}{d})$. If d do not divide $(N-1-x)$, then the connection sets of interest are $S(d,x,1),S(d,x,2),\ldots,S(d,x,t)$ where $t=\left\lfloor\frac{N-1-x}{d}\right\rfloor+1$. Also $\frac{N-1-x+1}{d}\leqslant\left\lfloor\frac{N-1-x}{d}\right\rfloor+1\leqslant\frac{N-1-x+d-1}{d}$ and so $t\in\{\frac{N-x}{d},\frac{N-x+1}{d},\ldots,\frac{N-x+d-2}{d}\}$.

Through out this section, the number of nodes in the linear array is expressed by $N = 2dm + h$ where $m\geqslant0$ and $0\leqslant h\leqslant(2d-1)$ are integers. The values of m and h are determined by the values of N and d.

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