Design, performance and wavelength assignment of a wavelength
division multiaccess protocol for optical fibre ring networks 1

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Abstract

This paper presents a multiaccess strategy for use over optical fibre ring networks employing two counter rotating rings, and using wavelength division multiplexing. Transmitters employ tunable lasers, while receivers employ one or more fixed wavelength filters. The paper introduces an algorithm for the optimal assignment of the receivers to the channels, such that the possibility of finding an unused channel leading to a certain receiver is maximized. The paper contains a performance study of the network protocol. © 1999 Elsevier Science B.V. All rights reserved.

Keywords: Ring networks; Wavelength division multiplexing (WDM); Medium access control protocols; Wavelength assignment; Optimization; Performance

1. Introduction

The continuous advances in computing equipment, and the prevalent trend in their interconnection through networks compounded with the introduction of bandwidth-hungry applications [6,7,14,32–34,38], have contributed to the increasing need for high-speed network operation. In such networks, the optical fibre is the natural transmission medium. Networks based on fibres can be configured according to a number of topologies, e.g., the bus, the star, and the ring topology [22]. In all such topologies, nodes transmit and receive through optical taps, which are either of the passive or active type. Because of the disparity between the speed of the electronics and the fibre’s bandwidth, it is practically impossible for a single transmitter to fully utilize the bandwidth of the fibre. This is referred to as the electronic bottleneck [22].

The most practical approach to circumvent the electronic bottleneck problem is to use dense Wave-length Division Multiplexing (WDM) [4,19]. In this approach, the fiber bandwidth is accessed in the wavelength domain by using several wavelengths, where the spacing between the distinct wavelengths is on the order of 1 nm. Multiple transmissions and receptions may proceed simultaneously and independently using this approach.

Even after circumventing the electronic bottleneck problem, there still remains two intertwined issues. The first is the medium access protocol, which can be a very important factor in determining the net-
work capacity [18,36]. The second is the transmitter/receiver coordination issue.

Transmitters and receivers can be either tunable over a range of wavelengths, or fixed-tuned to a certain wavelength [4,11]. With fixed transmitters and receivers, the number of such devices determines the coordination approach, as well as the addressing method. Through the use of a large number of fixed transmitters and receivers, it may be possible to avoid contention [11]. On the other hand, and with fewer devices, channel collisions may occur which may be resolved using a backoff method similar to that used in CSMA and ALOHA [39], or using a reservation approach.

The above methods are primarily designed for the single hop approach. With the number of transmitters and the number of receivers per node being less than the total number of nodes, a multi-hop approach must be used [1,2]. This approach requires full addressing to be contained with the packet transmissions, and also increases the packet delay by a factor of $O(\log_p N)$ on average, where $P$ is the number of transmitters and the number of receivers at each node, and $N$ is the total number of nodes.

In order to limit the number of devices, and consequently the cost, tunable transmitters and/or receivers may be used. Tunable devices are usually more expensive than fixed wavelength devices. In addition, the tuning time may be a source of bandwidth wastage, and may also lead to channel and receiver collision. To avoid this bandwidth wastage, coordination between the transmitters can be implemented using either reservation [5,17], or collision-avoidance [24,28].

In this paper we consider ring networks using WDM, and implemented using two counter rotating rings, as shown in Fig. 1. Very few studies of such networks have appeared in the literature e.g., [3,8,9,11,15,27]. The protocols proposed in Refs. [29,31] have been designed for unidirectional rings, although they can be easily extended to bidirectional rings. One of the disadvantages of such topologies is that the power loss due to the linear tapping pattern severely limits the number of nodes which can be connected to such a network [22]. However, with the recent advances in optical amplifier technology, interest in such topologies has been revived. The objective of this paper is to introduce a strategy for multiple access over slotted ring networks using WDM, and to also formulate and solve the associated wavelength assignment problem. The strategy should enable the resolution of conflicts between transmitters and receivers without introducing any added node latencies, or being a source of bandwidth wastage due to node coordination or device tuning. The approach that we take in this paper is to use tunable transmitters and fixed-tuned receivers. However, each receiver device may have multiple optical receivers and may therefore receive on multiple wavelengths. The choice of such devices is based on the observation that due to the serial nature of packet arrivals from the node's host, usually a node is transmitting a single packet. However, a node may be receiving multiple packets transmitted by several nodes. This approach has the advantage of reducing the probability of packet loss due to busy receivers. However, it may potentially lead to bandwidth wastage due to the packet header processing time, and the transmitter tuning time. We overcome this problem by splitting the packet header into two parts. The first part consists of the busy bit and the destination address. This is transmitted on a common low-speed control channel using the field encoding technique in Ref. [16]. The second part consists of the source address, as well as the rest of the packet, which are transmitted on one of the high-speed data channels. In this case, the processing of the header required for packet transmission and reception can be done at a speed which is much lower than that required for the transmission and reception of data.
In order to maximize bandwidth usage, the network also employs a bandwidth reuse strategy. This strategy is implemented in two dimensions, namely, slot reuse and wavelength sharing. In slot reuse, a slot is emptied after it is read by the destination node and does not necessarily have to return to its source to be emptied. In order to keep the network latency at a reasonable value, and in order to simplify the node design and allow the use of passive taps, the task of slot release is implemented through the use of multiple erasure nodes similar to those employed in DQDB [37,13]. Wavelength sharing is also implemented in two orthogonal directions. First, a wavelength can be used to address several receivers. For example, node 1 in Fig. 1 can use wavelength $\lambda_j$ to transmit to nodes 2, 3 and 4 on the clockwise ring. We call this strategy wavelength co-use. Second, since in the double ring network a packet is transmitted using the ring providing the shortest route to the destination, a node that is a member of the set of nodes which can be reached using a certain wavelength on a certain ring can be replaced by another node in the same set if the wavelength is used downstream from this node. We call this strategy wavelength reallocation and is explained in detail in Section 5. The assignment of the receivers to the different wavelength channels has been formulated as a binary linear program that minimizes the number of interferences between the receivers on the different channels, where the separation between adjacent channels is on the order of 1 nm. The single channel bandwidth can be calculated to be on the order of several giga bits per second. One of the channels on each ring is designated as the control channel, while the rest of the channels are divided into $G$ groups of channels. Each group consists of $B$ channels, and each channel is divided into slots such that each slot can hold exactly one packet. The total number of channels on each ring is therefore equal to $GB + 1$ channels. For example, a total of 13 channels can be divided into 3 groups, with each group consisting of four channels, in addition to one control channel (see Fig. 2). Within each group, the start of slots on all $B$ channels is synchronized. Additionally, the groups of channels are skewed in time, as shown in Fig. 2, and the amount of time skew is equal to the maximum of the slot time $G$, and the worst case transmitter tuning time. The purpose of skewing is to allow the transmitters ample opportunity to use slots, as will be explained in the next section. The control channel is also divided into slots which are divided in turn into GB fields, with each field pertaining to one data channel. Each of the fields contains an Empty/Busy bit that indicates the status of the corresponding data channel, and a destination address field which is used only if the data slot is busy.

2. Network architecture

The network consists of two counter rotating rings to which a total of $N$ nodes are connected (see Fig. 1 for an example with $N = 6$). Each of the two rings can be implemented using a single mode fibre, which would allow a total optical bandwidth of more than 30 THz. Each node has two optical interfaces, one to each ring. The purpose of using two rings is twofold. First, to increase the reliability of the system which guarantees the existence of a path between each pair of nodes even if one of the rings fails. Second, to allow a short packet transit time under normal operation. In order to achieve the latter, each node transmits on the ring that provides the shortest distance from the transmitter to the receiver. For example, in Fig. 1 node number 1 transmits to node 2 on the clockwise ring, while node 3 transmits to node 2 on the counter clockwise ring. It has been shown in Refs. [10,26] that with this approach and under the uniform source destination distribution, a system capacity of 8 can be achieved if slots are erased by their destinations.

On each ring, wavelength division multiplexing is used. Therefore, the low loss region on each ring, which is between 1.2 to 1.6 $\mu$m, is optically divided into a number of channels, where the separation between adjacent channels is on the order of 1 nm. The single channel bandwidth can be calculated to be on the order of several giga bits per second. One of the channels on each ring is designated as the control channel, while the rest of the channels are divided into $G$ groups of channels. Each group consists of $B$ channels, and each channel is divided into time into slots such that each slot can hold exactly one packet. The total number of channels on each ring is therefore equal to $GB + 1$ channels. For example, a total of 13 channels can be divided into 3 groups, with each group consisting of four channels, in addition to one control channel (see Fig. 2). Within each group, the start of slots on all $B$ channels is synchronized. Additionally, the groups of channels are skewed in time, as shown in Fig. 2, and the amount of time skew is equal to the maximum of the slot time $G$, and the worst case transmitter tuning time. The purpose of skewing is to allow the transmitters ample opportunity to use slots, as will be explained in the next section. The control channel is also divided into slots which are divided in turn into GB fields, with each field pertaining to one data channel. Each of the fields contains an Empty/Busy bit that indicates the status of the corresponding data channel, and a destination address field which is used only if the data slot is busy.
The node architecture is shown in Fig. 3. The transmission channel wavelength is $\lambda_i$, and the node is assumed to be able to receive on wavelengths $\lambda_1, \lambda_2, \ldots, \lambda_C$. The control channel is $\lambda_0$. To read from and write to the control channel each node is equipped with a fixed filter and a fixed laser tuned to the control channel wavelength. The output of this filter is converted to an electrical signal which is used by the control logic. The operation of the control channel laser is also controlled by the same logic. The transmitter section of each station is equipped with one tunable laser. The tuning range is assumed to be over the entire wavelength range. The receiver section of each station has $C$ fixed receivers, where $1 \leq C \leq G$. This is necessary since each destination station is assumed to be reachable on $C$ wavelengths, such that the destination is reachable on at most one wavelength per group. Notice
that since the number of such fixed receivers is expected to be small, e. g., 2 or 3, the added cost of such a strategy is small compared to the expected gain in performance. The outputs of these filters are decoded and fed to a common receiver queue if the slots contain any packets destined to the station. Since a node completes the reception of different packets at different points in time (because of the single channel per group condition and the group skew arrangement), then it is guaranteed that no conflicts in packet queueing at the receiver will take place. This added cost, and slight complexity can be justified by the performance gain. The employment of multiple receivers per destination reduces the head-of-line blocking since a source now has a greater chance of transmitting to destinations. Not only that, but in the case of unbalanced traffic, and especially if one of the destinations is a hot-spot, the adverse effect of heavy traffic generated by upstream nodes will be offset by the availability of other receiver channels for the other sources to transmit on.

The purpose of the erasure nodes is to erase the slots which have already been read by their respective destinations in order to allow these slots to be reused by downstream sources. For example, in Fig. 4 in which there are four such erasure nodes, $M_0$, $M_1$, $M_2$ and $M_3$, and twelve normal nodes, nodes 9, 10, 11, 0 and 1 may use a certain wavelength to send to node 2. Since such a slot will be erased by $M_1$, then it can be used by nodes 3, 4, 5, 6, 7 and 8. This is an example of slot reuse. At the same time, a wavelength used by station 0 to transmit to stations 1, 2, ..., 5 can also be used by station 1 to transmit to stations 2, 3, ..., 6. This is an example of wavelength sharing.

Erasure nodes function by inspecting the control channel and finding out whether a slot is used or not. If a slot is used, the erasure node also inspects the destination address (which is also transmitted on the control channel). Once the erasure node concludes that the slot has been read (based on the destination location with respect to the erasure node), it resets the busy bit and the destination field on the control channel, and erases the data on the corresponding data channel. The erasure function can be implemented by using a set of $2 \times 2$ switches whose settings are determined according to the required function. The implementation of these erasure nodes can be done either in a pure optical manner, using wavelength selective dividers and combiners as well as optical switches [36], or can be implemented electronically. The latter requires the use of optical-to-electrical and electrical-to-optical converters. The erasure node may also act as an amplifier, which is a much needed function if such linear topologies are used [15].

3. Protocol description

The network protocol is based on the empty slot approach employed in Refs. [21,12,26]. That is, a node that wants to transmit in a slot must find out if the slot is empty or not. If so, the node marks the slot as full and starts writing its information into the slot. If not, it looks for another slot.

Marking the slot as either empty or full is done over the control channel. Therefore, at the input to the node hardware, the control channel data is filtered and read by the control logic, just prior to being written with a 1 if the node wanted to use it. Based on the status of the bit corresponding to the channel under consideration, if the bit was already 1, then the channel is in use, while if it was a 0, then the channel is available for transmission. In the latter

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Fig. 4. Example of a ring with four erasure nodes.
Assignment[0..N-1,0..G-1];

Group := CurrentGroup;

repeat
    begin
        Group := (Group+1) mod G;
        Channel := Assignment[Destination,Group];
        if Channel <> Nil then begin
            Status := ReadStatus(Group,Channel);
            if Status := 0 then begin
                SetStatus(Group,Channel);
                Tune(Group, Channel);
                Transmit(Group, Channel, Packet);
            end;
        end;
    end;
until Status = 0;

Fig. 5. Transmission procedure.

case, the station sets this bit to 1, and follows it by the destination address. At the same time, the station tunes its laser to the channel’s corresponding wavelength and starts transmitting. The transmitter starts by writing its own (source) identity followed by the rest of the packet. Since each receiver station is assigned a number of channels, such that there is at most one channel per group, a source that finds one such channel in a certain group to be already occupied, tries to find another channel in the following group. It therefore checks the control channel for the status of that next channel, and keeps on repeating this process until the packet is finally transmitted. The procedure that implements the transmission protocol is shown in Fig. 5.

An example of channel assignment is shown in Fig. 6 in which \( G = 3, \ B = 2, \ C = 2 \) and \( N = 24 \). The channel assignments on the clockwise ring, as seen by station 0, are shown in the figure. In the next section we will explain why these assignments will change from station to station. According to this example, if station 0 would like to transmit to station 6, it uses the clockwise ring since it provides the shortest distance. Noting that station 6 receives on two channels, namely channels 1 and 3, station 0 hunts for an empty slot on these two channels. If station 0 inspects channel 1 first, and finds the slot on that channel to be occupied, it tries the slot on channel 3. If channel 3 is also found to be occupied, station 0 keeps on inspecting channels 1 and 3 alternately, until a slot is found empty on either of

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<td>1, 2, 3, 4</td>
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<tr>
<td></td>
<td>1</td>
<td>5, 6, 7, 8</td>
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<tr>
<td>1</td>
<td>2</td>
<td>1, 5, 9, 10</td>
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<td></td>
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Fig. 6. Example of channel assignment for the transmissions of node 0 on the clockwise ring in a network with \( N = 24, \ G = 3, \ B = 2 \) and \( C = 2 \).
these two channels. Station 0 then uses this slot for transmission to station 6.

The receiver protocol is very simple and follows directly from the description of the node architecture (see Fig. 3). Receivers are equipped with C fixed wavelength filters, which are tuned to the wavelengths of their assigned channels. The received slots are decoded into electronic form, and if the slot is found to contain a packet destined to the station (based on the contents of the destination address field in the control slot corresponding to the data channel), then it is relayed to a queue for further processing by the station. Otherwise, i.e., if the slot did not contain a packet destined to the receiver, the receiver logic ignores the packet. Notice that since a slot can be used for transmission to multiple receivers, then detecting the status of the packet in a slot requires the receiver to inspect the destination address.

Due to the employment of destination (or erasure node) release of slots, unfairness in slot access may result. Since it is not really the objective of this paper to investigate fairness control mechanisms, we have decided to employ one of the fairness protocols which have been proposed in the literature for ring networks. The most two prominent such protocols are the Metaring protocol [10], and the ATM Ring protocol [26]. Ref. [30] has considered the implementation of the Metaring approach in the multichannel environment. However, we have decided to employ the ATM Ring approach in this paper.

The ATMR access protocol employs a cycle-based global fairness mechanism, which is independently applied to each of the two rings. This mechanism is an enhancement of a fairness mechanism originally introduced for the Orwell ring [12]. Under this fairness scheme, each node is allowed to transmit a maximum number of cells which is equal to a prescribed window size ($W_n$) within a given cycle. The duration of the cycle is determined as follows. A special busy field is inserted in the header of each slot. At the start of a new cycle, each active node persistently writes its own address in the busy address field of every incoming slot. A node becomes inactive either when it has exhausted its permitted window size, or when there are no cells queued for transmission at the node. Once a node becomes inactive it ceases to write its own address into busy address fields of subsequent slots. Whether a node is active or not, whenever it detects its own address appearing in the busy address field of an incoming slot, it concludes that all other nodes have completed their transmissions. At this time, it issues a reset (cycle restart) signal. The reset signal circulates around the ring network to inform other nodes that a new cycle is to start. When employing this fairness mechanism, one has to decide on the number of channels that should be controlled by a window. That is, disjoint groups of channels can be controlled by independent windows. In this paper we have chosen to have a single window controlling all the channels. The need for multiple windows does not arise until one considers unbalanced traffic.

4. The wavelength assignment problem

In describing the system we have made the assumption that channels are assigned to receivers according to certain criteria. In this section we discuss these criteria.

(1) First, it should be noted that in order to allow receivers to queue multiple received packets without intervention, the packet queueing times should be distinct. Therefore, restricting the receiver to at most one channel per group, along with the group skewing arrangement, guarantees that multiple packet receptions will not occur at the same instant of time. This means that the maximum number of channels that a station can be assigned is $G$. This also makes it simpler to design the transmitter since the transmitter, while inspecting the control field corresponding to a target channel, can be tuned to the channel’s wavelength in preparation for using that wavelength if it was available. It should be noted that stations usually do not require the use of too many channels. This follows since allowing multiple receptions is congruent with the concept of output queueing which has been shown to require only a few buffers compared to the number of input stations [25].

(2) Second, since the total number of channel assignments is equal to $NC$, where $N$ is the number of stations in the system, which is usually greater than the total number of channels in the system, $GB$, then at least one channel will be assigned to more
than one destination station. Notice that since a channel can be used to carry packets to several receivers, then the number of destination stations assigned to the same channel should be minimized. That is, let destination \( i \), \( i \in \{1,2,\ldots,N/2\} \) be reachable from node 0 on \( C \) channels, such that \( C \leq G \), and no more than one channel belongs to any group, and define the set of channels on which destination \( i \) is reachable as \( \Theta_i \). Similarly, let destination \( j \) satisfy similar conditions, and let the corresponding set of channels be \( \Theta_j \). Then, our objective is to minimize \( \sum_{i,j<i} |\Theta_i \cap \Theta_j| \). This is referred to as the sum of interferences.

The channel assignment that minimizes the sum of interferences is an assignment in which the difference between the number of destinations assigned to the different channels should be minimized. This follows from the following theorem:

**Theorem 1.** Given \( N \) destinations that are to be assigned to \( M \) channels, \( \sum_{i,j<i} |\Theta_i \cap \Theta_j| \) is minimal if and only if:

(a) \( N \mod M \) of the channels are assigned \( \lceil N/M \rceil \) destinations, each.

(b) The remaining \( M - N \mod M \) channels are assigned \( \lfloor N/M \rfloor \) destinations, each.

**Proof.** In Appendix A.

This means that each channel should be assigned a number of destinations that is between \( \lfloor NC/(G) \rfloor \) and \( \lceil NC/(G) \rceil \). It is to be noted that this assignment also balances the load on all channels.

(3) In addition to the above, we would also like to minimize the number of times two destination stations are assigned to the same channel. The objective of this criterion is to prevent bandwidth starvation by stations trying to transmit to a destination station sharing a channel with a hot spot. Notice that this minimization is different from the minimization in criterion number 2. To illustrate the difference, assume that there are two groups, each of which contains two channels. Station 0 would like to reach destination stations 1, 2, \( \ldots \), 6. In Fig. 7, we show two different assignments. In part (a) of the figure, the assignment minimizes the sum of interferences, which is equal to 12 in this case. However, if \( \Theta_i \cap \Theta_j \) is not empty, then \( |\Theta_i \cap \Theta_j| = 2 \). This assignment does not implement the minimization required for the current criterion. However, the assignment shown in part (b) results in two interferences between stations 1 and 5, and between 3 and 6 only. However, the total number of interferences is equal to 13.

In order to formulate an optimization problem for the entire system, we let the \( F \)th interference between two destination stations incur a cost of \( F \). Therefore, if there is a total of \( F \) interferences between two destinations, the total cost of interference will be \( F(F + 1)/2 \).

A binary integer programming (BIP) characterization of the channel assignment according to the interference minimization criterion is shown in Fig. 8. In this BIP, \( X_{ki} \) is an indicator function which is 1 if and only if station \( i \) is reachable on channel \( k \) within group \( g \). \( Y_{gij} \) is an indicator function which

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(b)

Fig. 7. Example to illustrate the difference between the two minimization criteria.
$X_{kgi} = \text{indicator function which is 1 if and only if station } i \text{ receives on channel } k \text{ within group } g.$

$Y_{kij} = \text{indicator function which is 1 if and only if both stations } i \text{ and } j \text{ receive on channel } k \text{ within group } g.$

minimize the objective function $\sum_i \sum_{j>i} \sum_{l=0}^{C-1} Z_{lij} \cdot d_l$

subject to

1. $Y_{kij} \geq X_{kgi} + X_{kgj} - 1 \quad \forall i, j$
2. $\sum_{l=0}^{C-1} Z_{lij} = \sum_k \sum_g Y_{kij} \forall i, j, i < j$
3. $Z_{lgi} \leq Z_{(l-1)ij} \forall i, j, l > 0$
4. $\sum_g \sum_k X_{kgi} = C \quad \forall i$
5. $\sum_k X_{kgi} \leq 1 \quad \forall i, g$
6. $\left\lfloor \frac{NG}{GB} \right\rfloor \leq \sum_i X_{kgi} \leq \left\lceil \frac{NG}{GB} \right\rceil \quad \forall k, g$
7. $Z_{lij} \in \{0, 1\} \quad \forall l, i, j$
8. $Y_{kij} \in \{0, 1\} \quad \forall k, g, i, j$
9. $X_{kgi}, X_{kgj} \in \{0, 1\} \quad \forall k, g, i, j$

Fig. 8. Binary linear program used in the channel assignment problem.

is 1 if and only if both stations $i$ and $j$ are reachable on channel $k$ within group $g$; otherwise, it is equal to 0. These values of $Y_{kij}$ are guaranteed by restrictions 1 and 8, together with the minimization process of the objective function. Notice that in this case $\sum_i \sum_j Y_{kij}$ is equal to the total number of interferences between destinations $i$ and $j$. Although this last summation can be used in the objective function, it will lead to a non-linear equation. Instead, we use a mapping that results in a linear objective function. The binary variables $Z_{lij}$ for $l = 0, 1, \ldots, C-1$ are used for this purpose, and they provide another representation for this sum of interferences. The total number of interferences is given by $\mathcal{I}$, then $Z_{ij} = 1$ for $l = 0, 1, \ldots, \mathcal{I} - 1$, and $Z_{ij} = 0$ for $l = \mathcal{I}, \mathcal{I} + 1, \ldots, C - 1$. This representation is enforced by restrictions 2, 3 and 7. $d_l$ in the objective function is the cost of the $i$th interference. Its value \textsuperscript{4} is $i + 1$.

\textsuperscript{4} For consistency, we have chosen indexing to start from 0. This means that the interference with index $i$ actually corresponds to the $(i+1)$st interference.
Restriction 4 was imposed since each destination should be reachable on exactly $C$ channels. Restriction 5 was imposed since each destination should be reachable on no more than one channel per group, while restriction 6 serves to guarantee that the minimization process in criterion 2 is satisfied. According to this procedure, the objective function corresponding to the assignment in Fig. 7(a) has a value of 18, while that corresponding to Fig. 7(b) is 14.

This BIP can be solved using a method such as the branch-and-bound [20]. However, it is well-known that such a solution is NP-complete [35].

In special cases, linear time algorithms can be found for the channel assignment problem, such that the intersection is minimal, such as the case in which $C = 2, G \geq 2,$ and $B \geq 1$. In this case, the maximum number of destination nodes that can be assigned such that the objective function in Fig. 8 is minimal and has the same value of $\sum_{i,j} |\Theta_i \cap \Theta_j|$ resulting from Theorem 1, is equal to $\binom{G}{2}$. The number of destination nodes per channel, $n$, in this case is equal to $(G - 1)B$. This can be proven in the following lemma:

**Lemma 1.** If the maximum number of interferences between any pair of destination nodes is to be 1, then $n \leq (G - 1)B$. 

**Proof.** In Appendix B. \hfill $\square$

Based on the above, we introduce an algorithm in Fig. 9 performing the channel assignment for the source station 0 on the clockwise direction in exactly $2N$ steps. The channel assignment in the example in

![Assignment algorithm used for $C = 2$.](image-url)
Fig. 6 has been produced using this algorithm. The algorithm is based on considering the destination nodes of groups of \((G - 1)GB^2/2\) and assigning them to channels such that they exhaust all the \(\binom{G}{2}\) permutations.

In the algorithm of Fig. 9, it is assumed that channels are numbered from 0 to \(B - 1\) within each group. That is, channel \(i\) belongs to group \(\left[ i/G \right]\), and its position within the group is \(i \mod B\). \(S_{nm}\) in the algorithm represents the set of stations reachable by station 0 using channel \(n\) within group \(m\). In the algorithm, channels are assigned to destination stations 1,2,\ldots,\lfloor N/2\rfloor sequentially, such that station 1 is assigned to the first and second channel, station 2 is assigned to the third and fourth channels, and station \(i\) is assigned to the \((2 \cdot i - 1)\)th and \((2 \cdot i)\)th channels. To do so, the channels are accessed in rounds, where in the first round the channels are accessed according to the order 5: 

\[C_{0,0}, C_{1,0}, \ldots, C_{G-1,0}, C_{0,1}, C_{1,1}, \ldots, C_{G-1,1}, \ldots, C_{0,B-1}, C_{1,B-1}, \ldots, C_{G-1,B-1}\]

Each following round is a cyclic permutation of the preceding round.

(4) The fourth factor that influences channel assignment is wavelength sharing. To illustrate this issue let us consider a ring network with 24 stations that are numbered sequentially from 0 through 23. Notice that each source station will transmit to a certain destination station using the ring with the direction that provides the shortest possible route. In this example, stations 1 through 11 will transmit to station 12 using the clockwise ring while stations 13 through 23 use the counter clockwise ring to reach the same station. Station 0 can use either ring. If stations 0 through 11 use a certain wavelength to transmit to station 12 in the clockwise direction, then this wavelength, after passing station 12 in the same direction, will not be used for transmission to station 12 once again until it reaches station 0. In this case, the same wavelength can be used by stations 12 through 23 to transmit to station 0 in the clockwise direction. The wavelength used by stations 13 through 0 to transmit to station 12 in the counter clockwise direction can also be used by stations 1 through 12 to transmit to station 0 in the same direction.

Based on this example, we introduce the concept of station pairing. A station pair with respect to a certain ring are two stations that are separated by \([N/2]\) stations on the direction of flow of the considered ring. For example, stations \(i\) and \((i + [N/2])\) mod \(N\) form a station pair, such as (0,12), (1,13), (2,14), etc, in the example. For such a station pair, a wavelength which is used for transmission by stations \((i - [N/2])\) mod \(N\) through station \((i - 1)\) mod \(N\) to station \(i\) in the clockwise direction can also be used to carry transmissions from stations \(i\) through \((i + [N/2] - 1)\) mod \(N\) to station \((i + [N/2])\) mod \(N\) in the same direction. Note that while in a ring network with an even number of stations the station pairs in both the clockwise and the counter clockwise directions are the same, in a ring with an odd number of stations they are not the
same. With the assignment produced by this algorithm is optimal according to criteria 2 and 3, provided that \( C \cdot [N/2] \leq (G \cdot B)^2 \).

Finally, it should be noted that if the farthest station reachable by station \( i \) on a certain direction, e.g., the clockwise direction, is \((i + [N/2]) \mod N\), and if station \( i \) uses wavelength \( \lambda_j \) for transmission to station \((i + 1) \mod N\) in the same direction, then station \((i + 1) \mod N\) may use wavelength \( \lambda_j \) to transmit to station \((i + [N/2] + 1) \mod N\) in the same direction. This is the basis for constructing the channel assignment for other stations once the channel assignment for the source station 0 has been determined. The example in Fig. 10 expands the channel assignment for the source station 0 given in Fig. 6 to source stations 0 through 6. The complete channel assignment can be obtained by employing the concept of station pairing introduced above. In order to illustrate the construction of this table, we consider an example. Let source 0 be capable of reaching the sets of destinations given in the third column of Fig. 10 using the indicated channels in the clockwise direction. (This is the same assignment given in Fig. 6 and is optimal according to criteria 3 and 4.) Source 1 need not reach destination 1. Since the pair \((1, 13)\) is a station pair, source 1 can use the same assignment used by station 0 after replacing destination 1 by destination 13 in the sets reachable on channels 0 and 2. Similarly, source 2, instead of reaching destination 2 on the same channels, reaches the other destination that pairs with 2, viz., destination 13.

5. Performance

In this section we provide simulation results of the above described network in order to be able to assess its performance.

The simulation model used in this study consists of 24 stations connected by a bidirectional ring. Each station is equipped with a buffer that is large enough that overflow will never occur. Each station has a tunable transmitter, and one or more fixed receivers (the number of receivers will be varied in the examples). The transmission rate on each of the data channels is assumed to be 1 Gb/s, while the transmission rate on the control channel is assumed to be much lower. We assume that the ring operates in the local area, and that the stations are evenly separated by a distance of 100 meters. The packet size is determined so as to be able to accommodate a single ATM cell (53 bytes), in addition to the MAC layer overhead. As such, a 64-byte packet size is assumed. Several parameters will be varied in the simulation study. These include the number of receivers per station, the number of erasure nodes, the window size and the number of channels on the ring.

Our interest in this section is mainly in the network capacity. We therefore assume that the transmitters have an endless supply of messages, with each message fitting in exactly one slot. In the simulation model we considered one ring only, and therefore the destinations of the messages are uniformly chosen from the stations reachable on the considered ring (half of the total number of stations). The performance measure of interest here is the throughput which is defined as the total number of transmitted messages per time unit per ring. It is also of interest to compare the normalized throughput which is the throughput per wavelength channel. A greater normalized channel throughput does not necessarily mean a greater overall throughput because the latter depends on the total number of channels in the network.

Before we conduct the performance experiments, we should mention that given a certain number of channels per ring, there are several factors which affect the throughput, namely, the number of erasure nodes, the window size used by the fairness mechanism, and the number of receivers per station. The effects of the first two factors have been studied extensively in the literature. For example, it was shown in Refs. [37, 13] that with only a few erasure nodes most of the improvement in the throughput can be achieved. In the examples, we have used different numbers of erasure nodes. As will be shown in the examples, one can achieve a significant improvement in the throughput by using a number of erasure nodes that is fewer than the number of stations. For example, instead of making all the stations act as erasure nodes, only half of them act as such and the reduction in the maximum achievable throughput does not exceed 10%. It was also shown in Ref. [26] that increasing the window size increases...
the throughput, but there is a limit on the window size after which the improvement in the throughput becomes insignificant. In this paper we concentrate on the effect of the number of receivers per station.

We consider first the case in which each station is equipped with a single receiver, with each destination station being assigned a unique wavelength. For this purpose, and because of the sharing of wavelengths, we only require 12 wavelength channels. This case is considered as a baseline in order to assess the merits of the proposed network. Table 1 shows the total achievable throughput (for a single ring only) when different numbers of erasure nodes are used (namely, 3, 6, 12 and 24 — destination release), and the window size is 50 and 200 slots. It is shown that increasing the number of erasure nodes beyond a certain limit does not result in a significant increase in throughput, which is consistent with the observations in Refs. [37,13]. When the window size is increased from 50 to 200 a greater increase in throughput can be seen, which can be as large as 2. Increasing the window size to larger values only increases the throughput marginally.

Now assume that the number of wavelength channels is equal to 6, which is fewer than the number of destination nodes per ring for each source node. The channels must therefore be shared among nodes. We first consider the case in which each destination station is equipped with a single buffer. This means that each channel is used by a source to transmit to two destinations. It is seen in Table 2 that the achievable throughput drops significantly by about 25% due to this channel sharing.

We now turn our attention to the case in which each station is equipped with multiple (two) receivers. We start with the case of twelve channels, and divide them into three groups, with four channels per group, and allow each station to receive on two channels. The achievable throughput is shown in Table 3. As can be observed from the table, the system capacity increases significantly, just by adding a second receiver at each destination. The increase can be as large as 50%. It can be concluded that the multiplicity of the receivers increases the system throughput by overcoming the head-of-line blocking phenomenon.

### Table 1
<table>
<thead>
<tr>
<th>Number of Erasure Nodes</th>
<th>Window Size in Slots</th>
<th>Achievable Throughput</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>50</td>
<td>200</td>
</tr>
<tr>
<td>3</td>
<td>9.421 (0.785)</td>
<td>10.420 (0.8683)</td>
</tr>
<tr>
<td>6</td>
<td>11.085 (0.924)</td>
<td>12.527 (1.044)</td>
</tr>
<tr>
<td>12</td>
<td>12.006 (1.0005)</td>
<td>13.78 (1.1483)</td>
</tr>
<tr>
<td>24</td>
<td>12.475 (1.03958)</td>
<td>14.58 (1.215)</td>
</tr>
</tbody>
</table>

### Table 2
<table>
<thead>
<tr>
<th>Number of Erasure Nodes</th>
<th>Window Size in Slots</th>
<th>Achievable Throughput</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>50</td>
<td>200</td>
</tr>
<tr>
<td>3</td>
<td>6.405 (1.068)</td>
<td>6.892 (1.149)</td>
</tr>
<tr>
<td>6</td>
<td>7.894 (1.315)</td>
<td>8.671 (1.445)</td>
</tr>
<tr>
<td>12</td>
<td>8.913 (1.4855)</td>
<td>9.992 (1.6653)</td>
</tr>
<tr>
<td>24</td>
<td>9.426 (1.571)</td>
<td>10.769 (1.7948)</td>
</tr>
</tbody>
</table>

### Table 3
<table>
<thead>
<tr>
<th>Number of Erasure Nodes</th>
<th>Window Size in Slots</th>
<th>Achievable Throughput</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>50</td>
<td>200</td>
</tr>
<tr>
<td>3</td>
<td>12.502 (1.042)</td>
<td>13.927 (1.161)</td>
</tr>
<tr>
<td>6</td>
<td>15.228 (1.269)</td>
<td>17.238 (1.437)</td>
</tr>
<tr>
<td>12</td>
<td>16.910 (1.409)</td>
<td>19.592 (1.633)</td>
</tr>
<tr>
<td>24</td>
<td>17.958 (1.4965)</td>
<td>21.109 (1.759)</td>
</tr>
</tbody>
</table>

### Table 4
<table>
<thead>
<tr>
<th>Number of Erasure Nodes</th>
<th>Window Size in Slots</th>
<th>Achievable Throughput</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>50</td>
<td>200</td>
</tr>
<tr>
<td>3</td>
<td>8.119 (1.353)</td>
<td>8.777 (1.463)</td>
</tr>
<tr>
<td>6</td>
<td>10.376 (1.729)</td>
<td>11.419 (1.903)</td>
</tr>
<tr>
<td>12</td>
<td>11.650 (1.94)</td>
<td>13.121 (2.187)</td>
</tr>
<tr>
<td>24</td>
<td>12.602 (2.100)</td>
<td>14.415 (2.403)</td>
</tr>
</tbody>
</table>
Table 5
Achievable throughput with 12 channels and three receivers per station

<table>
<thead>
<tr>
<th>Number of erasure nodes</th>
<th>Window size in slots</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>50</td>
</tr>
<tr>
<td>3</td>
<td>14.460 (1.205)</td>
</tr>
<tr>
<td>6</td>
<td>18.093 (1.508)</td>
</tr>
<tr>
<td>12</td>
<td>20.398 (1.699)</td>
</tr>
<tr>
<td>24</td>
<td>21.690 (1.807)</td>
</tr>
</tbody>
</table>

In the case of a system with six channels and two receivers per station, the channels are divided into three groups, where each group consists of two channels. The channel assignment is as shown in Fig. 10. The achievable throughput is shown in Table 4. As can be seen from this table, the achievable throughput increases with the employment of two receivers per destination and becomes very close to that achievable under the one destination per channel strategy (Table 1). That is, the reduction in throughput due to the sharing of channels between destinations can be offset by increasing the number of receivers per destination node in order to overcome the head-of-line blocking. It should be noted that in Refs. [29,31] another approach was taken to overcome this blocking; namely, the use of one queue per destination at the transmitter side. The scheduling algorithm, although efficient, requires several computations, and it is not sure whether it can be executed efficiently within the short slot time.

Furthermore, we consider the case in which each station is equipped with three receivers under the two conditions of having a total of twelve and six channels in the network; the results are shown in Tables 5 and 6, respectively.

Table 6
Achievable throughput with 6 channels and three receivers per station

<table>
<thead>
<tr>
<th>Number of erasure nodes</th>
<th>Window size in slots</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>50</td>
</tr>
<tr>
<td>3</td>
<td>8.744 (1.457)</td>
</tr>
<tr>
<td>6</td>
<td>11.460 (1.910)</td>
</tr>
<tr>
<td>12</td>
<td>13.302 (2.217)</td>
</tr>
<tr>
<td>24</td>
<td>14.439 (2.407)</td>
</tr>
</tbody>
</table>

Again, the improvement in the achievable throughput is evident through the employment of more receivers per station in both cases. However, we notice that the incremental increase in the bandwidth by adding a third receiver is smaller than that achieved by adding a second receiver per station.

Our final experiment with the investigation of the system throughput shows the effect of increasing the number of nodes on the ring throughput, as we increase the number of receivers per node from one to two. The results are shown in Fig. 11. It is assumed that the window size is equal to 200, and we consider two cases in which the number of erasure nodes per ring are equal to 2 and 8 erasure nodes. The number of channels on the ring is equal to 8. As expected, increasing the number of erasure nodes increases the achieved throughput per ring. Given a certain number of erasure nodes, increasing the number of nodes on the ring also increases the throughput slightly, but the differential improvement starts to diminish as the number of nodes increases. This can be justified by the more efficient sharing of the bandwidth, and the reduction in the fairness mechanism cycle resetting overhead. Also, as we increase the number of receivers from one to two, given a certain number of erasure nodes, the achievable throughput improves. As the figure shows, the improvement is almost independent of the number of nodes.

We also study the mean message transfer delay defined as the mean time measured from the instant the message is generated to the instant the message is received.
is delivered to its destination. This delay is normalized with respect to the slot transmission time, and is therefore measured in terms of slot times. We consider the six cases shown in Fig. 12, namely a network with 12 channels, and with one, two and three receivers per destination, and another network with 6 channels, and again with one, two and three receivers per destination. The mean transfer delay is plotted against the total offered load per ring in Erlangs. As expected, increasing the number of channels per ring reduces the mean delay, especially at medium to heavy load. Further, increasing the number of receivers per destination on the same ring reduces the delay further as it increases the ring capacity.

Finally, we consider the behaviour of the network under unbalanced traffic. We consider the two cases of the rings with 6 and 12 channels per ring, and in each case we consider destinations with 2 and 3 receivers. Each ring is equipped with six erasure nodes, and the window size employed is 200. We assume that all nodes generate the same amount of traffic. We further assume that one of the destination nodes, namely node number 12, acts as a hot spot where on each ring, each of the preceding 12 nodes sends half of its generated traffic to node 12, and the remaining half is destined to the remaining reachable destinations in a uniform manner. In the case of the ring with 6 channels per ring, we assume that the total offered load per ring is equal to 4 Erlangs, while in the case of the ring with 12 channels per ring, we assume that the total offered load is 6 Erlangs. We show the throughput achieved by each

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6 The following 12 nodes will use the other ring to transmit to the hot spot. Therefore, in the present scenario they will not compete for transmission to the hot spot.

7 In the case of a ring with 12 channels, and the hot spot scenario described above, it can be easily concluded that the maximum amount of traffic the ring can carry is 8 Erlangs when the number of receivers per destination is 2. That is why we limited the total traffic per ring to 6 Erlangs.
of the nodes in each of the above four cases in Fig. 13. From this figure, it is noticed that for each of the considered cases, the source nodes will receive similar throughput quotas. This is guaranteed by the employed throughput fairness mechanism. However, when we plot the mean transfer delay for all four cases, which is shown in Fig. 14, it is noticed that the mean transfer delay differs from node to node. For nodes which do not transmit to the hot spot on the considered ring (nodes 12 through 23), the mean transfer delay is almost the same under all scenarios. For the other nodes which compete for slots leading to the hot spot, it is noticed that nodes farther from the hot spot, e.g., node 0, will encounter a greater average transfer delay when compared to nodes closer to the hot spot. This can be expected since the propagation delay from the source to the destination is a component of the total mean transfer delay. However, if we measure the mean access delay, it can be shown that the farther nodes will encounter a slightly smaller mean access delay as compared to nodes which are closer to the hot spot (as an example, when 6 channels are used with 2 receivers per node, the mean access delay figures for nodes 0 and 11 are about 4 and 5 slot times, respectively). For the case of the ring with 12 channels and 2 receivers per destination, the mean transfer delay exhibits a convex shape as we approach the hot spot. This is expected since under this scenario the load on the channels leading to the hot spot is significant. In order to get an idea of how this delay varies with the node location, we also plot the square of the peakedness of the transfer delay in Fig. 15, which is defined as the ratio between the variance and the mean of the delay. For nodes upstream from the hot spot, the peakedness measure has a convex shape. This can be justified by the fact that for the upstream nodes the variance (and also the mean) of the propagation delay is large and decreases as one approaches the hot spot node, while the access delay mean and variance increase as we get closer to the hot spot node. This has been verified by inspecting the mean

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The variance of the propagation delay is minimal at node 6.
and the variance of the different components of the transfer delay.

To establish the merit of the proposed protocol, we compare it to a simple protocol in which each station employs one receiver. In this protocol, several packets at the head of the queue are inspected in every slot. This inspection continues until either a packet is scheduled for transmission in the slot, or a limit on the number of inspected packets is reached. We consider two cases in which the limit on the number of inspected packets is two and three, respectively. In Table 7 we consider the same network with 12 channels that was considered in Tables 1, 3 and 5, but with the added provision of inspecting a few packets at the head of the queue. It is evident that this provision enhances the system throughput. However, the increase in the throughput is still smaller than that which can be achieved by the introduced protocol. We repeat the same experiment for the case of the network with 6 channels that was considered in Tables 2, 4 and 6. The results for the network with the packet inspection mechanism are shown in Table 8. Similar observations hold for this case also.

It is to be noted that although the packet inspection mechanism is a simple one that results in a capacity enhancement, and that it does not require any added receiver hardware, it suffers from a major drawback that the proposed protocol overcomes. This drawback is shared by all other protocols in which each of the destinations is equipped with a single receiver. In the case of heavy traffic being directed to a certain destination station (hot spot), and if all stations employ a single receiver, source stations wanting to use the same channel leading to the hot spot, and which are located downstream from other source stations will be at a disadvantage. This will, most importantly, increase the delay variance among source stations. In the proposed protocol, the multiplicity of the receivers in addition to the wavelength assignment criteria, especially criterion 3, plus the time skewing of the channel groups will minimize the interference and will give stations several access opportunities which are disjoint from the access opportunities of the upstream sources.

6. Conclusions

This paper has introduced a protocol for ring networks employing wavelength division multiplexing. The protocol has the following merits:

- The transmitters do not encounter channel collision due to their coordination through a control channel.
- There are also no receiver collisions. A maximum of \( C \) transmissions to a receiver is supported.
- The receiver packet queueing instants are distinct, since a receiver can only receive one packet per group, and groups are skewed.
- The protocol lends itself to possible all-optical implementation.
- Any fairness algorithm used in slotted rings such as the Orwell, the ATM Ring, the FECCA or the Metaring algorithms, can be employed.
The paper has also considered the problem of optimally assigning wavelength channels such that interference between nodes is minimized, and has introduced a binary linear programming formulation to this problem. A linear time algorithm was introduced for a special case of the wavelength assignment.

Acknowledgements

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Appendix A

In this Appendix we prove Theorem 1. We first prove the implication by proving its contrapositive. That is, if the channel assignment is different from the one shown in the theorem, then the sum of interferences is not minimal. We prove this by contradiction. Assume that the channel assignment is different from the one in the theorem, and assume that the sum of interferences is minimal. Let the set of destinations assigned to channel $m$ be $\Omega_m$. Then, there must be two channels, $m$ and $n$, such that $|\Omega_m \cap \Omega_n| > 1$. Without loss of generality, assume that $|\Omega_m| > |\Omega_n|$. (A.1)

Therefore, there exists a destination node, $i, i \in \Omega_m$, and $i \notin \Omega_n$. We can deassign destination node $i$ from channel $m$, and assign it to channel $n$. This results in reducing the sum of interferences by $|\Omega_m| - 1$, and increasing the same sum by $|\Omega_n| - 1$, respectively. Using Eq. (A.1), this results in an overall reduction in the sum of interferences, which contradicts the assumption that the channel assignment results in a minimal sum of interferences. This proves the implication.

To prove the converse, we use mathematical induction on $N$, for $N \leq M$.

Basis Step: Let $N = M$. In this case each channel is assigned exactly one destination node and $\Sigma_{i,j,i < j} |\Omega_i \cap \Theta_j| = 0$, which is minimal.

Inductive Step: Assume that under the given channel assignment for $N = K \leq M$, the sum of interferences is minimal. When $N = K + 1$, we have two cases:

1. $K \mod M = 0$. In this case the $K + 1$st node can be assigned to any channel since this will result in increasing the sum of interferences by $K$, and this sum is minimal in this case.

2. $K \mod M \neq 0$, which leaves us with two options to consider:

   2.1. Add the $K + 1$st node to any of the $K$ mod $M$ which are assigned $\lceil \frac{K}{M} \rceil$ nodes, each. This results in increasing the sum of interferences by $\lceil \frac{K}{M} \rceil$.

   2.2. Add the $K + 1$st node to any of the $M - (K \mod M)$ which are assigned $\lceil \frac{M}{M} \rceil$ nodes, each. This results in increasing the sum of interferences by $\lceil \frac{M}{M} \rceil$.

The second option results in a smaller increase in the sum of interferences. From the above, the given channel assignment under $N = K + 1$ also results in a minimal value for the sum of interferences.

The above proves the converse.

Appendix B

In this Appendix we prove Lemma 1 by contradiction. Suppose that the maximum number of interferences is 1, and assume that at least one channel, $c_i$, has $n > (G - 1)B$. One of the destination nodes assigned to this channel can be also assigned to one of $(G - 1)B$ other channels. However, since there is at least $(G - 1)B$ other nodes by supposition, then this node must interfere again with at least one of the other nodes assigned to channel, $c_i$, which contradicts our assumption. Therefore, the maximum number of nodes per channel is $(G - 1)B$.

References


[27] G.N.M. Sudhakar, M. Kavehrad, N.D. Georganas, Access...
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