# Routing and Wavelength Assignment in Optical Passive Star Networks with Non-uniform Traffic Load

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***Abstract*-This paper considers the problem of Routing and Wavelength Assignment (RWA) in optical passive star networks with non-uniform traffic load. The problem can be considered as designing a logical topology over an optical passive star physical topology with a given non-uniform traffic. The approach uses the bipartite graphs and the concept of Time and Wavelength Division Multiplexing (TWDM) embedding process to discuss the problem. The non-uniformity of the traffic load makes the logical design computationally hard and requires heuristic algorithms. Then, a linear program can solve the routing. We present an algorithm for effectively assigning a limited number of wavelengths among the access nodes of a WDM multi-hop network, which are connected via passive star topology. In this paper, the RWA problem for such a network with non-uniform traffic load is discussed for the first time. The idea is based on reducing the maximum load on each wavelength by using more wavelengths available. The proposed algorithm is tested on several traffic models, and results are given to show the improvement in the performance of the network using our algorithm.**

## I. INTRODUCTION

Possible bandwidths of the order of terabits per second make optical fiber an attractive choice for high-speed communications. Many schemes have been studied to efficiently utilize this high capacity. The most common approach is wavelength-division multiplexing (WDM), whereby the available spectrum is divided into channels.

One way to connect nodes in a WDM optical network is the *star topology*, where all the nodes exchange signals through a broadcast medium that can be achieved by a *passive star coupler*. In this architecture, each node can be equipped with transmitters and receivers that may be tunable or fixed tuned. For an efficient use of the bandwidth, tunability must be provided for at least one end (at the receiver side or transmitter side). However, tunability is an expensive option with some limitations and tuning delays. In this study, we assume that each node in the passive-star network is equipped with a *fixed wavelength transmitter* and a *fixed wavelength receiver.* The fixed wavelength devices are readily available in the current technology, cheaper than the tunable devices and are more reliable. We assume that time is slotted and the transmission time of each packet is equal to one time slot. We restrict our attention to schedules where collisions are avoided in the broadcast medium, i.e., two transmitters will not transmit in the same wavelength during any time slot. We also assume a non-uniform traffic that brings much complexity to the problem.

The problem of Routing and Wavelength Assignment (RWA) in optical passive star networks with non-uniform traffic load is a new topic and discussed here for the first time. The problem can be considered as to study the problem of designing a logical topology over an optical passive star physical topology with a given non-uniform traffic. There have been several studies on uniform traffic in optical passive star networks. However, the traffic load would usually not be as in this case and these designs cannot be extended to the non-uniform traffic case.

This study uses the bipartite graphs and the concept of TWDM embedding process to discuss the problem. The logical design is computationally hard and requires heuristic algorithms. Then, a linear program can solve the routing. The proposed algorithm of the problem is given in the paper.

The paper is organized as follows. In section 2, some previous works are discussed shortly. Section 3 gives the definition of the problem with all assumptions. In section 4, wavelength assignment algorithm is given. In Section 5, the proposed routing algorithm is given with discussions. In Section 6, some results obtained by using the proposed algorithm are given. Section 7 gives conclusion on the problem.

## II. PREVIOUS WORKS

The RWA problem in optical networks has been studied by many authors [1]-[7]. Several heuristic algorithms have been proposed and their performance has been quantified via simulation. In [4], an upper bound on the carried traffic of connections for any RWA algorithm is derived in a point-to-point network. Also, the amount of wavelength reuse is quantified. It is shown that the wavelength converters increase the amount of wavelength reuse.

Analysis of the performance improvement with wavelength converters is very important for the design of optical networks. Several authors studied benefits of wavelength conversion on different network topologies [5]-[7], [8]-[10]. [5] studied benefits of wavelength conversion on mesh networks with different routing and wavelength assignment algorithms. It is shown that LLR (Least–Loaded routing) algorithm, which jointly selects the least-loaded route-wavelength pair, achieves much better performance compared to fixed shortest path routing algorithm and produces larger wavelength conversion gains. In [6], it has been shown that the blocking probability with and without wavelength changers increase with the number of hops *H.* The effect is much more dramatic in networks without changers since the number of calls a given call shares some link with tends to increase with *H*. [7] discussed some wavelength assignment algorithms such as First Fit Algorithm and Random Assignment Algorithm and the effect of wavelength conversion on the wavelength assignment. It has been shown that First Fit algorithm performed much better than the random assignment at low

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loads, whereas the difference between the two algorithms is marginal at higher utilization.

The optical passive star topology is frequently suggested for implementing an optical network in which optical fibers are interconnected via an optical passive star coupler [11]-[15].

In [11], a new Media-Access protocol for WTDM optical passive star networks was presented. This protocol was based on a virtual Bus-Mesh topology. In [12], for a given number of nodes (stations) and the number of wavelengths that can be exploited, how the stations to receive on the same wavelength should be grouped was discussed. (Receiving graph model was introduced). Also, it discussed about the routing algorithms to even the network traffic load on each route or minimize the average packet delay, and then introduced a systematic way to design optimal WTDM network. Both [11] and [12] were based on that each station has only one fixed wavelength transmitter and one fixed wavelength receiver. In both papers, the traffic demand is assumed to be uniform, and the designs cannot be extended to the non-uniform case.

In [13], a reservation based collision-free media access protocol is proposed for optical star networks. In this scheme, if the number of requests is larger than the number of available channels, the call is blocked. Under high load conditions, the blocking probability will be very high. And also, it is assumed that each station may have many tunable transmitters and enough number of receivers.

## III. Definition Of The Problem

*The physical topology of the problem is Optical Passive Star* (Fig. 1). The problem uses WDM and then TDM within each wavelength channel. *Each node has only one fixed wavelength transmitter and receiver.* These devices are attached to optical fibers that connect to a passive star coupler such that the light signal from each transmitter is divided equally to reach all receivers. The receivers can filter the combined signal from all transmitters to receive only those packets transmitted on the receiver's wavelength. Packets on all wavelengths are always transmitted at the beginning of fixed length time slots. *The time slots are long enough to transmit a maximum sized packet.* The time slots are logically organized into repeating cycles. Each node gets to transmit within a cycle at a predetermined wavelength and time slot. We assume that the *number of nodes* connected through the passive star is $N$ and the *number of wavelengths available is* $W$ where $N \geq W$ (Number of nodes is greater than the number of wavelengths available). Also, *each fiber has only one channel*. The *traffic load for the network is given and is non-uniform*. The non-uniformity gives the problem uniqueness and makes better fit to the real world.

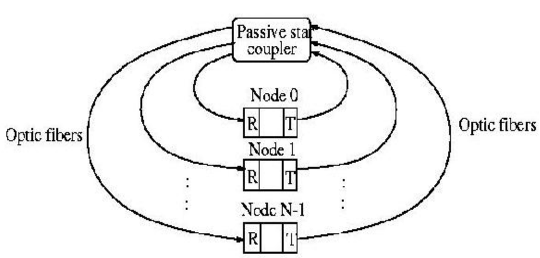


**Fig. 1.** Physical star topology based on an optical passive star coupler

The problem is to do Routing and Wavelength Assignment in Optical Passive Star Networks with Non-uniform Traffic Load. Having given a traffic pattern that is relative to traffic distribution among the source-destination pairs, *our objective* is to design the logical topology and the routing algorithm on that topology so as to minimize the maximum number of time slots in the transmission cycle on each wavelength, that is *to minimize the maximum load on each wavelength*.

## IV. Wavelength Assignment

The proposed approach uses TWDM embedding process. Having obtained the connection graph according to the traffic demand matrix, our aim is *to use more wavelengths in order to reduce the load on each wavelength*. First, we perform initial assignment of wavelengths to the connections and find the load on each wavelength. The wavelength assignment is done as follows: Suppose that the traffic matrix is given as $T=\{t_{ij}\}$ and the available wavelengths are in the set W=$\{w_k\}$. We begin from assigning wavelength $w_0$ to an arbitrary nonzero traffic link, say $t_{iojo}$, where $i_0$ denotes the transmitter of station $i_0$ and $j_0$ denotes the receiver of station $j_0$. Since all the stations are equipped with only one fixed wavelength transmitter and one fixed wavelength receiver, all receivers on stations to which station $i_0$ wants to talk and all transmitters on the stations that talk to station $j_0$ will also be assigned to use wavelength $w_0$. This process is continued until either all the links are assigned a wavelength to transmit on or none of the remaining nonzero traffic demand link, $t_{ij}$, can be assigned the same wavelength (that is, no receiver remained is expecting data from any of the previously wavelength-assigned transmitters or no transmitter remained has demands to send data to the previously wavelength-assigned receivers). Then, any of the remaining nonzero traffic links can be given another available wavelength (if any) to establish connection by repeating above procedure. After all assignments are done, the traffic demand matrix is divided into independent components – *A component is a group of stations receiving and/or transmitting on the same wavelength* –. The routing decision has also been made for this number of wavelengths.

## V. Substitution Of Links

Having the first wavelength assignment and routing completed, we will try to increase the number of wavelengths used (components in the traffic demand matrix). This can be accomplished either by increasing the number of transmitters/receivers on each node or by allowing multi-hop links to replace the one-hop links. Since we consider one fixed wavelength transmitter and one fixed wavelength receiver at each node, the solution to using more wavelengths in a connection graph could be the replacement of some of the links with multi-hop links, which may break the graph into separate sub-graphs (components) so that each can be assigned different wavelengths. On each wavelength, TDM will be used such that the more loaded links are given more time slots in the transmission cycle. While replacing a link, the load of the replaced link is added on to each of the links that used to substitute it.

For best understanding, we start with an example. Each station has only one fixed wavelength transmitter and one fixed wavelength receiver. Suppose that the number of available wavelengths is 3 and the number of stations is 4. Given a traffic load table, we can easily obtain the connection graph (Fig. 2). In this graph, if a station has nonzero traffic demand to some other station, we will connect its transmitter (T-end) with the destination's receiver (R-end). For instance, station A has some packets to send to B as well as C (see traffic demand table in Fig. 2). After all connections have been set using the algorithm given in section 4, we can only make use of one wavelength (remember that each station has only one transmitter and one receiver) according to the following constraint. Once a transmitter wavelength is decided, then the receiving wavelengths of all nodes connected to that transmitter wavelength are decided. Similarly, once a receiver wavelength is decided, then the transmitter wavelengths of all nodes connected to that receiver wavelength are decided. Therefore, by using only one wavelength, if we intend to satisfy each station according to the traffic demand table, we will need a transmission cycle of length 24 (assuming one packet per unit).

In this network, we might have a better solution by using more wavelengths. In order to do that, we can replace some one-hop links with multi-hop links, for example, use the two-hop route B→D→A to replace the connection B→A. The result is shown in Fig. 3. Since now we have two separate components, each can be assigned a different wavelength. The WDM is achieved and the longer transmission cycle is reduced to 17.

Traffic Demand Table

| | A | B | C | D |
|---|---|---|---|---|
| A | 0 | 7 | 2 | 0 |
| B | 1 | 0 | 0 | 3 |
| C | 0 | 0 | 0 | 4 |
| D | 5 | 2 | 0 | 0 |

Length of transmission cycle: 24

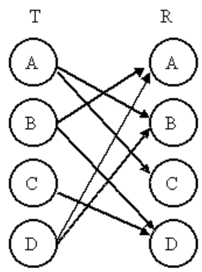


**Fig. 2.** Traffic Demand table and the corresponding connection graph.

Traffic Demand Table

| | A | B | C | D |
|---|---|---|---|---|
| A | 0 | 7 | 2 | 0 |
| B | - | 0 | 0 | 3+1 |
| C | 0 | 0 | 0 | 4 |
| D | 5+1 | 2 | 0 | 0 |

B-A => B-D-A

—— 7+2+6+2 = 17

········ 4+4 = 8

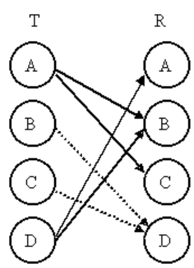


**Fig. 3.** 2-component graph and transmission cycle length for each component. Note that the traffic load on the removed link B-A is added onto the links replacing it.

We can continue this process and get better solution. In Fig. 4, for the packets sent from D→B, we use the route D→A→B, and divide the graph into 3 components, each using a different wavelength. The longest transmission cycle will then be 11 units only.

In the above example, we can observe: (1) Intuitively, the direct links (one hop links) with higher traffic load should be kept and those with less traffic demand might be substituted by multi-hop links, (2) To satisfy all the connection calls, we have to use TDM on each wavelength channel. The more the packets sending on a wavelength, the less the throughput will be, and (3) Because removing a direct link will cause the increase of traffic on other links, it seems the best choice of the links to be removed are those with less traffic demand.

Traffic Demand Table

| | A | B | C | D |
|---|---|---|---|---|
| A | 0 | 7+2 | 2 | 0 |
| B | 0 | 0 | 0 | 4 |
| C | 0 | 0 | 0 | 4 |
| D | 6+2 | - | 0 | 0 |

D-B => D-A-B

—— 9+2 = 11

········ 4+4 = 8

– – – 6+2 = 8

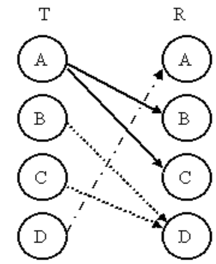


**Fig. 4.** 3-component graph and the transmission cycle lengths for each component.

Therefore, we are able to design an algorithm, which can divide the connection graph into several independent components so that each of them can be assigned a unique wavelength, and minimize the traffic load of the component with highest overall traffic demand. We propose an RWA algorithm to find the best routing and the number of wavelengths to be used. The algorithm uses the 2-hop links to replace the links starting with the replacement of links in the maximum loaded component. It can be extended to examine the use of all possible links in replacement, but for easier implementation, the 2-hop links is considered here.

Given a traffic matrix, wavelength assignment described in section 4 gives the number of wavelengths that can be used initially for the network. Next is to exploit more wavelengths to reduce the traffic load on each of them. Our algorithm can simply be described in 3 steps:

1. Determine the maximum loaded component in the connection graph.
2. In order to separate this component; find *the links to be replaced* in the component.
3. If the component is separated into independent components by the replacement of the links found above and the load is reduced, do the replacement and repeat steps 1 and 2. Otherwise, efficiency of TWDM of this network connection cannot be improved by exploiting more wavelengths.

In the above algorithm, the replacement of the links is not trivial. For the wavelength assignment algorithm, the complexity is $O(N^2)$ for a network with N stations. Links substitution algorithm, on the other hand, is an NP-hard problem. Given an N-station network, if there are 1/p non-zero entries in the table, at the beginning, there are $(1/p)N^2$ links that can be substituted, and for each link there are at most $(1/2)\times((1/p)\ N^2-1)$ replacements. After a link is substituted, the resulting graph has $((1/p)N^2-1)$ links, each having $(1/2)\times((1/p)N^2-2)$ replacement choices. Therefore, there are:

$$\left\{\left(\frac{1}{p}\right)N^2\times\frac{1}{2}\times\left[\left(\frac{1}{p}\right)N^2-1\right]\right\}\times\left\{\left[\left(\frac{1}{p}\right)N^2-1\right]\times\frac{1}{2}\times\left[\left(\frac{1}{p}\right)N^2-2\right]\right\}\times\ldots$$

possible choices to consider, which is expected to make the computation time grow very rapidly as the network size grows.

Searching for all possible replacements and comparisons makes RWA slow and undesirable. A fast solution requires a careful study of the traffic matrix eliminating some unuseful replacements and comparisons. The tradeoff between the fast and best routing is an important issue here.

After intensively studying on the attributes of various components in traffic matrices, we found that for some stations with relatively more incoming and outgoing links, it would be more difficult to re-route their links and separate the component. However, since they have more links, they might be used to re-route links of some other stations easily. Therefore, it gives us the inspiration of keeping a central structure and making other stations to be independent from this structure as much as possible. The central station method reduces the computation time in a great amount and is shown to give still a good solution.

## VI. RESULTS

We have tested our algorithms by randomly generated traffic matrices based on user-defined characteristics such as number of stations, maximum traffic demand, minimum traffic demand, and distribution of links. Also, we applied our algorithm on two realistic but unidentified traffic matrices given in [16].

The following are RWA results by our algorithms. In the Tables 1-3, there are 5 cases, which denote different traffic matrices. The original number of wavelengths that can be used before our algorithm is applied and the resulted number of wavelengths that can be used after our algorithm are given in the tables.

**TABLE 1.** 10 stations: 20% of stations talk to 4 stations, 30% talk to 2 stations, 10% talk to 3 stations, and the rest talk to only 1 station.

| **Case** | **1** | **2** | **3** | **4** | **5** |
|---|---|---|---|---|---|
| Original # of wavelengths | 2 | 1 | 2 | 2 | 3 |
| Original max load | 110 | 117 | 115 | 108 | 84 |
| Resulted # of wavelengths | 4 | 2 | 5 | 3 | 5 |
| Resulted max load | 62 | 113 | 68 | 77 | 63 |

**TABLE 2.** 15 stations: 20% of stations talk to 4 stations, 30% talk to 2 stations, 10% talk to 3 stations, and the rest talk to only 1 station.

| **Case** | **1** | **2** | **3** | **4** | **5** |
|---|---|---|---|---|---|
| Original # of wavelengths | 2 | 2 | 1 | 2 | 2 |
| Original max load | 169 | 176 | 170 | 148 | 196 |
| Resulted # of wavelengths | 4 | 3 | 2 | 6 | 4 |
| Resulted max load | 135 | 137 | 168 | 55 | 140 |

**TABLE 3.** 20 stations: 20% of stations talk to 4 stations, 30% talk to 2 stations, 10% talk to 3 stations, and the rest talk to only 1 station.

| **Case** | **1** | **2** | **3** | **4** | **5** |
|---|---|---|---|---|---|
| Original # of wavelengths | 5 | 5 | 5 | 2 | 4 |
| Original max load | 239 | 192 | 206 | 230 | 219 |
| Resulted # of wavelengths | 5 | 6 | 5 | 4 | 7 |
| Resulted max load | 239 | 178 | 206 | 135 | 129 |

The results of applying the RWA algorithm show that it is possible to improve TWDM scheme by exploiting more wavelengths. The results for 10 and 15 stations with 5 different traffic matrices are given in Tables 1-3. In the tables, the number of wavelengths used before and after using our algorithm is given. In Table-1, case 1 shows, by using two more wavelengths, the load on the maximum loaded component can be reduced from 110 to 62. Since the less the clock cycles needed for transmission, the shorter the length of transmission period will be, results show that we can improve the performance up to 45% for the network in case 1.

Now, the tradeoff of using a fast algorithm rather than using an exhaustive search (but slow) algorithm is given in Tables 4-5. The results are given for 3 different traffic matrices. The original maximum load before the use of algorithms, after using an exhaustive search algorithm, which is designed to be able to perform different depth searches, and the central station algorithm, which is designed to reduce the possible replacement choices are given in the following tables.

**TABLE 4.** 10 stations: 20% of stations talk to 4 stations, 30% talk to 2 stations, 10% talk to 3 stations, and the rest talk to only 1 station.

| **Case** | **1** | **2** | **3** |
|---|---|---|---|
| Original # of wavelengths | 2 | 3 | 3 |
| Original max load | 118 | 102 | 92 |
| Number of wavelengths by depth 3 search | 4 | 4 | 4 |
| Max. load by depth 3 search | 70 | 76 | 71 |
| Number of wavelengths by depth 5 search | 4 | 6 | 4 |
| Max. load by depth 5 search | 70 | 50 | 59 |
| Number of wavelengths by depth 7 search | 4 | 6 | 5 |
| Max. load by depth 7 search | 70 | 50 | 50 |
| Number of wavelengths by central station alg. | 3 | 4 | 4 |
| Max. load by central station alg. | 70 | 83 | 59 |

**TABLE 5.** 15 stations: 20% of stations talk to 4 stations, 30% talk to 2 stations, 10% talk to 3 stations, and the rest talk to only 1 station.

| **Case** | **1** | **2** | **3** |
|---|---|---|---|
| Original # of wavelengths | 5 | 1 | 2 |
| Original max load | 182 | 190 | 170 |
| Number of wavelengths by depth 3 search | 7 | 1 | 3 |
| Max. load by depth 3 search | 157 | 190 | 99 |
| Number of wavelengths by depth 5 search | 6 | 1 | 4 |
| Max. load by depth 5 search | 110 | 190 | 82 |
| Number of wavelengths by depth 7 search | 8 | 1 | 6 |
| Max. load by depth 7 search | 103 | 190 | 82 |
| Number of wavelengths by central station alg. | 7 | 1 | 4 |
| Max. load by central station alg. | 110 | 190 | 120 |

Comparing to the best routing algorithm, which search all possible combinations of replacements, the central station method can usually find good solutions (see Tables 4 and 5). Furthermore, the time takes for central station method is much faster (in terms of seconds) than the searching algorithm (several minutes to hours).

Note that in the discussions, we ignore the fact that there would be some physical delay in relaying packages. Also, multi-hop routes would increase the transmission time for some package delivery.

## VII CONCLUSION

In this paper, the problem of routing and wavelength assignment for optical passive star networks with non-uniform traffic load is studied for the first time. The algorithm for the problem is given with discussions. The results show that applying the RWA algorithm can improve TWDM scheme by exploiting more wavelengths. The following conclusion can be drawn for our method.

1. After the links substitution is done, routing decision is also made.
2. The maximum number of wavelengths to be used to give the best solution may not always be the number of all available wavelengths.
3. Removing a link from the most loaded component will be more efficient since reducing the maximum number of time slots in a cycle is the aim.
4. Replacing a link with least loaded traffic load will be more desired (Because the load on that link is added onto the replacing links). However, doing this may not give the best solution.
5. For some stations with relatively more incoming and outgoing links, it would be more difficult to re-route their links and separate the component. However, since they have more links, they might be able to re-route links of some other stations easily. Therefore, we may skip replacing links in this central structure and increase the usable wavelengths by keeping other stations unrelated to this structure. This can reduce the computation time in a great amount and is shown to give still a good solution. The results are given in section 6.

The discussion could be extended to the case in which the links might be replaced by multi-hop links (not necessarily to be 2-hops only). Furthermore, we can improve our design by using the following ideas.

Even if we cannot substitute any links or replace any links to get the graph separated, we can sometimes get better performance by having a zero traffic link that is already available in the connectivity to relay the load. This step might cause two original separate components become connected, i.e., it has potential hazard of reducing the wavelength that can be used (Lack of space, an example to this is not given in this paper.)

In case that the graph cannot be separated or a node is congested in transmitting or on receiving, we can add more receiver or transmitter, so that the graph might be separated or congestion is prevented. Of course, this changes the whole definition of the problem, but if the graph cannot be separated the congested nodes can be given more transmitter or receiver in order to handle their traffic and this could be an alternative solution to the component's separation.

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