Solutions of Routing and Wavelength Assignment in Wavelength Division Multiplexing Optical Network: A Survey

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ABSTRACT
Routing and Wavelength Assignment (RWA) is the problem of setting up light paths by routing and assigning a wavelength to each connection in wavelength-routed optical WDM networks. There are two types of RWA problem based on the type of connection requests. These are: static and dynamic. This paper reviews different solutions for RWA problems concerning static and dynamic connection requests under the wavelength-continuity constraints, which are proposed in the literature. Most of these solutions are for static RWA.

Keywords: Optical Network, Wavelength Division Multiplexing, Routing and wavelength assignment, Static and Dynamic RWA

1. INTRODUCTION
Nowadays, different applications such as World Wide Web (WWW) browsing, Java applications and video-conferencing require more bandwidth usage and there is a need for high-speed networks that allow users to access information quickly. Optical networks are the best solution to meet these needs due to the fact that they make use of fiber-optic technology which has many advantages including low signal attenuation, low power requirements, small space requirements, huge bandwidth [nearly 50 terabits per second (Tb/s)], low cost, low signal distortion and low material usage [1].

The architectures of optical networks are evolving from traditional opaque networks towards all-optical (transparent) networks. When the transmission achieves an optical signal without any regeneration, the regeneration process will simply improve the quality of the signal by re-amplifying and re-shaping it. There is an optical-electronic-optical (OEO) conversion at each switching (or routing) node in the opaque networks to enable the optical signal to achieve long distances, but OEO conversions add extra cost, involve more power consumption, require more space and have higher maintenance costs [2]. Translucent (or optical-bypass) networks consist of intermediate optical network architectures between opaque and all-optical networks. A set of sparsely but strategically selected regenerators are deployed in translucent networks to maintain the acceptable level of quality in the transmission (QoT) of signals. This solution, in fact, eliminates most of the OEO nodes, and allows a signal to remain in the optical domain for much of its path, from its source to its destination. Regenerations are eliminated in all-optical networks [2].

Optical networks use Wavelength Division Multiplexing (WDM) technology which has an architecture entitled Wavelength Routed (WDM) networks that allow users to communicate with each other via light paths, which are used to support connections by spanning multiple fiber links of the same wavelength to achieve wavelength-continuity constraints.

Routing and Wavelength Assignment (RWA) problems occur in WDM networks due to the limited number of available wavelengths [3].

The rest of this paper is arranged as follows: Section 2 introduces the RWA problem; Section 3 introduces the existing solutions for the RWA problem; Section 4 offers a conclusion.

2. ROUTING AND WAVELENGTH ASSIGNMENT (RWA)
Routing and Wavelength Assignment (RWA) is the problem of setting up light paths by routing and assigning a wavelength to each connection. The solution to this problem involves assigning wavelengths and route light paths by finding a way to minimize the amount of consumed network resource, and ensuring that no two light paths use the same wavelength on the same link [4]. There are two types of connection requests - static and dynamic [5]. The RWA problem operates under the wavelength-continuity constraint, i.e. a light path must occupy the same wavelength on its route between each fiber link. This constraint applies in the absence of wavelength conversion devices [4].

2.1 RWA Formulation
The RWA problem can be formulated as a graph coloring problem. G is the directed graph which corresponds to the physical topology of the network, and I is called an instance which is a set that contains q source-destination pairs (si, di) where si(di) is the source (destination) of the ith communication request and 1 ≤ i ≤ q. So G and I are inputs to this formulation. There are many routes in G to any pair of sources and destinations (si, di) ∈ I such as routes from si to di in G are p1i, p2i..., pni, where n is the number of routes from si to di and its value may be large. Only a single route pi, which is the shortest route from si to di, must be selected for the pair (si, di), for all i, 1 ≤ i ≤ q. R is a set of selected routes R= {p1, p2, . . . , pq} [6]. Figure 1 shows the physical network.
Fig 1: The physical Network [6].

Suppose that there are four requests for light paths including:

a. L1 from E1 to E2
b. L2 from E1 to E4
c. L3 from E3 to E4
d. L4 from E3 to E4

So the \( I = \{(E1, E2), (E1, E4), (E3, E2), (E3, E4)\} \) and \( R = \{E1 \rightarrow R1 \rightarrow R2 \rightarrow E2, E1 \rightarrow R1 \rightarrow R3 \rightarrow R4 \rightarrow E4, E3 \rightarrow R3 \rightarrow R4 \rightarrow R2 \rightarrow E2, E3 \rightarrow R3 \rightarrow R4 \rightarrow E4\} \) as shown in figure 2 [6].

Fig 2: Routes for four light paths on the network shown in figure 1 [6].

A conflict graph will then be built to specify the number of wavelengths that will be used for the routed light paths. In the conflict graph, there is an edge between two routes if they share the fiber link in G as shown in figure 3 [6].

Fig 3: Conflict graph for the light paths shown in Figure 2 [6].

Finally, any two routes that do not have a shared edge will use the same wavelength. So, the chromatic number of the conflict graph is equal to 3, which gives the total number of wavelengths that are needed, as shown in figure 4 [6].

Fig 4: The chromatic number of the conflict graph [6].

2.2 RWA Types

There are two types of RWA problem based on traffic assumptions. These are the static RWA problem and the dynamic RWA problem. The static RWA problem applies in a case when the set of connections is known in advance and for each connection a light path must be established, whereas the set of connections arrive dynamically at the network, and remain for some time before they depart [4].

2.2.1 RWA for Static Light path Establishment

In static traffic, the entire set of connections is known in advance, and the problem is knowing how to set up light paths for these connections while minimizing network resources such as the number of fibers in the network, and the number of wavelengths. The Static Light path Establishment (SLE) problem is the RWA problem for static traffic [5].

2.2.2 RWA for Dynamic Light path Establishment

Routing and wavelength assignment decisions must be made when the connection requests arrive at the network. Then the light paths are established and taken down dynamically. The connection requests will be
2.3 Solutions for each sub-problem

The RWA problem is divided into two sub-problems - the routing problem and the wavelength assignment problem. Different solutions are proposed in the literature for each sub-problem. This subsection presents these solutions.

2.3.1 Routing sub-problem

There are three basic approaches for the routing sub-problem in the literature, including fixed routing, fixed-alternate routing, and adaptive routing. Among these approaches, adaptive routing gives the best performance while fixed routing is the simplest [5].

a. Fixed Routing

This is the simplest routing approach in terms of routing a connection. For source-destination pairs this approach is to choose the same fixed route. Fixed shortest-path routing is an example of this approach and is calculated off-line for each source-destination pair by using standard shortest-path algorithms such as the Bellman-Ford algorithm or Dijkstra's algorithm, and any connection is established using the pre-determined route between a specified pair of nodes [7].

This approach has disadvantages such as if wavelengths are tied up along the path, it can lead to a large number of wavelengths that are used in the static case or high blocking probabilities in the dynamic case. It also does not handle faulty situations if the links in the network fail [7].

b. Fixed-Alternate Routing

This is a routing approach that involves multiple routes. A routing table that contains an ordered list of a number of fixed routes to each destination node is maintained by each node in the network in this approach.

The first route in the list of routes to the destination in the routing table at the source is called a primary route that runs between the source and destination node, while an alternate route is any route that does not share a link with the primary route in the source's routing table. In general, all routes between the source and destination node (even the primary route) are called alternate routes [7].

The source node attempts to establish the connection on each of the routes from the routing table sequentially if a connection request arrives, until it finds a route with a valid wavelength assignment. However, the connection request is blocked and lost if the source node does not find an available route from the list of alternate routes [2-n]. In most cases, the routing tables are ordered by the number of hops to the destination at each node. Therefore, the first route in the routing table will be the shortest path to the destination. Simplicity of control for setting up and tearing down light paths is provided by this approach. Some degree of fault tolerance upon link failure is also provided by this approach. The probability of connection blocking is reduced by applying this approach compared to fixed routing [7].

c. Adaptive Routing

This approach chooses the route dynamically from a source node to a destination node based on the state of the network which is determined by the set of current progressed connections [7]. When the adaptive routing wants to update continuously the routing tables at the nodes, it requires extensive support from the control and management protocols. The advantage of this approach is that the blocking of the connection in the adaptive routing is lower than fixed and fixed-alternate routing. There are two forms of this approach which are adaptive shortest-cost-path routing which is used in wavelength-converted networks and least-congested-path (LCP) routing [5].

In adaptive shortest-cost-path routing, the cost of each unused link in the network is 1 unit, the cost of each wavelength-converter link is c units and the cost of each used link in the network is $\infty$, but c will be equal to $\infty$ when the wavelength conversion is not available. When a connection arrives, this approach determines the shortest-cost path between the source node and the destination node. One path is chosen randomly if there are multiple paths with the same distance. A connection is blocked in this approach if there is no route from the source node to the destination node in the network [5].

LCP routing is similar to alternate routing, a sequence of routes for each source-destination pair is predetermined. When a connection request arrives, this approach chooses the least-congested path among the pre-selected routes. The number of wavelengths available on a link is used to measure the congestion on the link. If there are few available wavelengths on the link, then this link is considered to be more congested. Computational complexity for LCP is a disadvantage with LCP. It also needs to examine all links on all candidate paths when choosing the least-congested path, but it performs much better than fixed-alternate routing [5].

2.3.2 Wavelength Assignment sub-problem

There are a number of heuristics that have been proposed in the literature for the wavelength assignment sub-problem including Random Wavelength Assignment, First-Fit, Least-Used/SPREAD and Most-Used/PACK [5]. These heuristics can be implemented as online algorithms and combined with different routing approaches. These schemes attempt to reduce the overall
blocking probability for new connections [7]. These heuristics are applied to the static wavelength-assignment problem and the dynamic wavelength-assignment problem.

a. Random Wavelength Assignment

This scheme is applied by searching the entire wavelength space for the set of wavelengths that are available on the required route and choosing one of these lists in a random way [7].

b. First Fit

When searching for available wavelengths that are numbered in this scheme, a lower-numbered wavelength is considered before a higher-numbered wavelength. Then it selects the first available wavelength and this scheme does not require global information. The computation cost of this scheme is lower than random wavelength assignments because there is no need to search the entire wavelength space for each route. This scheme is preferred in practice due to its small computational overheads and low complexity. There is a communication overhead in this scheme like Random because it does not require global knowledge [7].

c. Least-Used (LU)/SPREAD

This scheme selects the least used wavelengths in the network for achieving the balance in the load along all the wavelengths. This scheme serves only connection requests that traverse a small number of links in the network. The performance of this scheme is worse than Random. There is an additional communication overhead due to the computation of the least-used wavelength which requires global information. This scheme is not preferred in practice since it has additional storage and computation costs [7].

d. Most-Used (MU)/PACK:

This scheme is the opposite of LU and outperforms LU. The most-used wavelength in the network is selected in this scheme. There are similarities between this approach and LU in computation cost, communication overheads and storage [7].

3. EXISTING SOLUTIONS FOR RWA PROBLEMS

This section presents various solutions for the RWA problem whether static or dynamic in the case of absence of wavelength conversion.

3.1 Solutions for Static RWA problem

One of the static RWA solutions to assign wavelength and routes to a set of light paths is Greedy Edge Disjoint Path (EDP). The inputs for this algorithm are in the graph of the physical network (G) and set of light paths (T) and the total number of wavelengths that will be assigned for all light paths as output for the algorithm as shown in figure 5 [8].

Algorithm Greedy_EDP_RWA(G,T)

\[
\text{Begin} \\
\text{d} = \text{max} (\text{diam}(G), \sqrt{|E|}) \\
X = 0 \\
\text{While} (T \neq \Phi) \text{ do} \\
\quad X = X + 1 \\
\quad \text{BGA for EDP}(G,T,d) \\
\quad \text{Assign} X \text{ to all paths } P_i \in P \\
\quad T = T - \{G,T\} \\
\text{End While} \\
\text{End}
\]

Fig5: Greedy EDP Algorithm [8].

It uses a bounded greedy algorithm for the maximum EDP. The inputs to the algorithm are a set of light paths (T), the graph of the physical network (G) and the upper bound for edges in the chosen path by algorithm (d), while the output is light paths which are routed and their physical paths are shown in figure 6 [8].

Algorithm BGA for EDP(G,T,d)

\[
\text{Begin} \\
k = \text{Number of light paths to be routed} \\
\alpha(G,T) = \Phi; \ P(G,T) = \Phi \\
\text{Randomly permute elements of } T \\
\text{For } i = 1 \text{ to } k \\
\quad \text{Find shortest path } P_i \text{ for } T_i \\
\quad \text{If } ((\text{path length of } P_i) < d) \text{ then} \\
\quad \quad \text{Select path } P_i \text{ for } T_i \\
\quad \quad \alpha(G,T) = \alpha(G,T) \cup T_i \\
\quad \quad P = P \cup (T_i, P_i) \\
\quad \quad \text{Delete edges in path } P_i \text{ from } G \\
\text{End If} \\
\text{End For} \\
\text{End}
\]

Fig6: BGA for EDP algorithm [8].

Suppose there is a physical topology of a network that has ten nodes and a set of light paths \( T = \{(1,8), (4,6), (1,8), (6,9)\} \), the total number of wavelengths after the running of this algorithm is 2. Wavelength 1 is assigned for (1,8) and (4,6), while wavelength 2 is assigned for (1,8) and (6,9) as shown in figure 7 [8].

Fig7: The total number of wavelengths after running this algorithm [8].

This algorithm is simple and more effective in the case of deploying topology that requires a number of
wavelengths, compared with the more complex solution methods depending on integer linear programming and graph coloring [8].

Another solution is the Lookup Table Based RWA Algorithm. The inputs for this algorithm are G, which is a network topology, and D, which is a demand set, while the output is the total number of wavelengths for D as shown in the figure 8 [9].

![Fig8: Lookup Table Based RWA Algorithm [9].](image)

This algorithm uses Demand Based Maximum EDP Algorithm DB_MAX_EDP. The inputs for DB_MAX_EDP are D and G while the outputs are Lookup Table and Weight matrix of the edges as shown in figure 9 [9].

![Fig9: DB_MAX_EDP algorithm [9].](image)

By applying this solution to the same example as the previous solution, the result will be one as the total number of wavelengths used for all light paths as shown in the figure 10 [9].

![Algorithm 1LTB_RWA (G,D).
Input: Network topology G and a demand set D.
Output: Total number of wavelength X used for D.
While (the same G) do
  Retrieve a new D
  DB_MAX_EDP(G,D)
  X=0
  While (D≠Φ) do
    Gi=G
    X=X+1
    For j=1 to |D| do
      If P(s,j,i) with the smallest W is available in G* then
        Assign P(s,j,i) and X to (s,j,i)
        D=D–(s,j,i)
        Delete edge(s) in P(s,j,i) from G*
      End if
    End for
    In Return X
    End while
End while
End while
Fig10: The total number of wavelengths after running this algorithm [9].

As a result, this algorithm outperforms the previous solution by minimizing the number of wavelengths needed and it runs in a shorter time than the previous solution [9].

De et al. [10] proposed a new polynomial time heuristic that depends on the concept of clique partitioning for wavelength assignments while the Dijkstra’s algorithm is used for routing. The inputs for this algorithm are the compatibility graphs for a set of given connection requests, while the outputs are the number of cliques with numerous wavelengths required to set up all the connection requests as shown in the figure 11.

![Algorithm 2DB_MAX_EDP(G,D).
Input: G is a network topology and D is a demand set.
Output: Total number of wavelength X used for D.
While (the same G) do
  Retrieve a new D
  DB_MAX_EDP(G,D)
  X=0
  For i=1 to |D| do
    If P(s,i) with the smallest W is available in G* then
      Assign P(s,i) and X to (s,i)
      D=D–(s,i)
      Delete edge(s) in P(s,i) from G*
    End if
  End while
End while
Fig11: The new polynomial time heuristic algorithm [10].
Suppose that there are six connection requests and the physical topology that consists of six nodes. Then the compatibility graph is constructed which has connection requests as nodes and there is an edge between the two connection requests if they do not share the same fiber link in physical topology as shown in the figure 12 [10].

![Fig12: The commutability graph for connection requests](image)

As a result, there will be two cliques in CLIQUE where each clique consists of three connection requests and each clique has a distinct wavelength as shown in the figure 13 [10].

![Fig13: The total number of wavelengths after running this algorithm](image)

This algorithm outperforms other algorithms for assigning wavelengths, such as the First Fit (FF) algorithm and the Longest First Fixed Path (LFFP) algorithm, by conducting simulations [10].

The last solution for the static RWA problem is Ant Colony Optimization (ACORWA). The inputs for this algorithm are the physical topology of the network as graphs and the list of connection requests, whereas the output in each light path is routed and assigned wavelengths as shown in the figure 14 [11].

![Fig14: ACORWA algorithm](image)

For each light path a colony of artificial ants is established. Each ant starts from the source of the light path, and decides to choose the next node based on the probabilities. When the ant reaches its destination, it chooses the free wavelength on its path because it has a memory, unlike real ants. Then it will die, and a new ant will be born at the source node. Due to the light path it may be established by long paths in the first iteration of the program, the algorithm is adjusted by adding parameter S that is predefined by the user for removing unfavorable light paths that are established based on the value of S. The simulation proved that the proposed algorithm outperforms other heuristic algorithms [11].

3.2 Solutions for Dynamic RWA problem

Ngo et al. [12] proposed a very flexible ant-based algorithm for the dynamic RWA problem under the constraints of wavelength continuity. It not only developed a new routing table, but also a way to adapt the routing table according to the network state. It used a sufficient number of ants to continuously exploit the network. This new algorithm is beneficial because the path for a connection request is determined immediately upon arrival, based on the adapting routing table, so the
setup delay time is very much reduced when compared to the fixed routing scheme. The simulation proved that the proposed algorithm outperforms the fixed routing algorithm by achieving lower blocking probability.

4. CONCLUSION

Routing and Wavelength Assignment (RWA) continues to be a critical problem in optical networks. This paper focuses particularly on the static RWA problems rather than the dynamic ones under the wavelength-continuity constraints, by presenting different solutions from the literature. The future work will be focused on proposing different solutions for the dynamic RWA problem and finding new solutions.

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