A Functional Classification of Routing and Wavelength Assignement Schemes in DWDM networks: Static Case

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Abstract

In this paper, we give an overview of well-known routing and wavelength assignment (RWA) algorithms, and develop a novel classification for some of their main features. The objective of this paper is to show functional aspects of routing and wavelength assignement algorithms in WDM routing networks. Based on this classification, we compare different solutions for each category. Several challenges and trade-offs are identified. Although no algorithm in our study is a clear winner, advantages and disadvantages of several functional characteristics are discussed in order to help a system developer make a reasonable choice among candidate algorithms. In this study, we only consider algorithms for the off-line model (static traffic condition).

Keywords

Routing and wavelength assignement protocol, Routing algorithm, Wavelength assignment algorithm, Static algorithm

I. Introduction

It is expected that Wavelength Division Multiplexing (WDM) routing networks will be deployed to meet the high bandwidth needs of Internet traffic, especially in backbone networks for nationwide or global coverage [1]–[3]. The advent of Dense WDM (DWDM) in optical networks has significantly increased the bandwidth available on a single fiber [4]. End-users are connected with one another via all-optical channels referred to as light-paths that require no processing or buffering at intermediate nodes and potentially no intermediate electric/optic conversion. Routing algorithms can optimize transmission bandwidth over fiber infrastructure so that DWDM network users can reap maximum throughput through optically multiplex channels.

A light-path is an optical path established between two nodes, created by the allocation of the wavelength throughout the path. The light-path provides a "circuit-switched" interconnection between two nodes which may be located "far" from each other in the physical fiber network topology. It is generally desirable to establish light-paths between every pair of nodes. However, in WDM routing networks, the number of wavelengths available on fiber links limits the number of end-to-end connections, since physical constraints such as wavelength channel spacing in fiber links, limited number and tunability of optical transceivers limit the number of channels. Moreover, each wavelength is assigned to one channel without considering the bandwidth requirement. The bandwidth granularity is restricted to the bandwidth utilization of one wavelength.

In this regard, WDM network imposes additional constraints on the wavelength assignment. If a switching/routing node is equipped with a wavelength converter facility, then the wavelength continuity constraint disappears and the routing problem is the same as in normal circuit-switched networks where the only limiting factor is the number of available channels on each link. However, if a light-path operates on the same wavelength across all fiber links that it traverses, the Routing and Wavelength Assignment (RWA) is said to satisfy the wavelength continuity constraint. This constraint leads to inefficient utilization of wavelength channels and results in higher blocking probability. For example, a request may have to be rejected even though a route is available because of the nonavailability of the same wavelength on all the links along the route. Therefore, the problem of RWA becomes critical in WDM routing networks where the goal is to maximize throughput by optimally assigning routes and wavelengths to a given traffic pattern.

RWA algorithms available in the literature also differ in their traffic assumptions and the performance metrics used. The traffic assumptions generally fall into one of the two categories: 1) static traffic, wherein a set of connections for source and destination pairs are given and 2) dynamic traffic, wherein connection requests arrive to and depart from the network one by one in a random manner. The performance metrics used generally fall under one of the following three categories: 1) number of wavelengths required, 2) connection blocking probability (or throughput) which is defined as the ratio between the number of blocked connections and the total number of connections arrived or given, or 3) number of fiber resources handled at the routing nodes (or fiber cost). For the class of algorithms with static traffic assumptions, the objective is to minimize the required number of wavelengths in order to accommodate a given set of connections or to maximize the number of connections accommodated if the number of wavelengths is limited. On the other hand, for the class of algorithms with dynamic traffic assumptions, the objective is to minimize the blocking probability. It is imperative that these algorithms be simpler and faster so that the dynamically arriving connection requests at some rate can be handled as quickly as possible.

Solving the RWA problem for a given network topology and traffic matrix is far from being trivial. RWA is a combinatorial problem known to be NP-complete [14] and routing and wavelength assignment problems are tightly linked together. Even though it is approximately divided into two sub-problems; routing and wavelength assignment, each sub-problem is still NP-complete [14]. Numerous algorithms have been proposed in the literature so far reducing computation complexity of each sub-problem. However, so far no study has addressed the functional classification or discussed any comparative evaluation among different algorithms. Recently, Yoo and Banerjee only describe a survey of some wide area all-optical networks [12]. They describe the design, implementation aspects and analysis of WDM routing algorithm.

In this paper, we give an overview of well-known RWA algorithms under static traffic condition, and develop a novel classification for some of their functional features. In this work, we classify RWA algorithms as a two-step process. In the first step, routes are computed and in the second step wavelengths are allocated. Each step is further broken into two components: (1) search and (2) selection. We classify these functions according to the algorithmic approaches; sequential or combinatorial. Based on this classification, we categorize different RWA algorithms and compare different solutions for each category. In this paper, we only consider RWA algorithms under the static traffic assumption called the off-line model (i.e., static RWA algorithms).

II. Functional Classification of RWA Algorithms

In what follows, a light-path is defined as an end-to-end connection request between two end nodes, which may span multiple links. A route is a selected path along the multiple optical fibers, which may be located far from each other in the physical network topology. A wavelength is a circuit-switched path for the route, that constitutes an interconnected routing path between two nodes. A message can be sent from one node to an other using a specific wavelength, without requiring any buffering and electro-optical conversion at the intermediate nodes.

Basically, a RWA problem can be formulated as follows. Given a set of light-paths that need to be established on the network, and given a constraint on the number of wavelengths, we need to determine the routes and the wavelengths that should be assigned to the light-paths so that the maximum number of light-paths may be established (or the minimum number of required wavelengths used or the minimum light-path blocking probability is achieved). The routing problem is solved by techniques based on the shortest path algorithm. The wavelength assignment problem is solved by graph coloring techniques for the selected routes. Hence, the RWA problem can be defined as an optimization problem in a number of ways using various cost functions. For example, (1) establish all light-paths using a minimum number of wavelengths, (2) establish all light-paths using a minimum number of paths length, (3) maximize the number of light-paths established subject to a constraint on the number of wavelengths and/or path lengths.

Fig. 1 shows a functional classification of RWA problems. The RWA problem is partitioned into two sub-problems; routing and wavelength assignment. We can further divide each routing and wavelength assignment problem into two components (1) search and (2) selection functions. Figs. 2–3 give example algorithms for solving each functional element described in the routing and wavelength assignment problems, respectively.

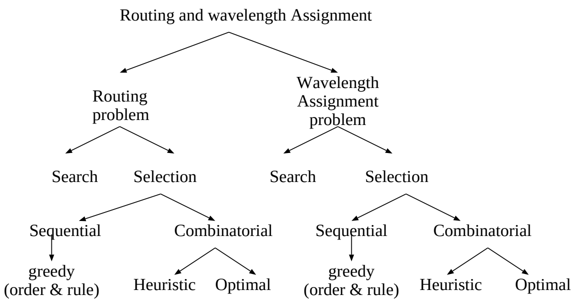

Fig. 1. Functional classification of routing and wavelength assignment algorithms.

<table>
<tr><th colspan="2">search</th><th colspan="2">selection</th><th colspan="2"></th></tr>
<tr><th>search method</th><th>search order</th><th>selection order</th><th>selection rule</th><th colspan="2"></th></tr>
<tr><td>Shortest path</td><td>——</td><td colspan="2" rowspan="2">——</td><td colspan="2" rowspan="2"></td></tr>
<tr><td>Weighted shortest path</td><td>largest traffic first
random</td></tr>
<tr><td rowspan="3">k-shortest path</td><td rowspan="3">——</td><td>Random
Fixed
longest-first
shortest-first</td><td>Random
First-fit
Probability
Minimum
-Weighted link</td><td colspan="2">Sequential algorithm (greedy)</td></tr>
<tr><td colspan="2">Random Rounding</td><td>Heuristic</td><td rowspan="2">Combina-torial algorithm</td></tr>
<tr><td colspan="2">Integer Linear Programming
(Multi-commodity flow problem)</td><td>Optimal</td></tr>
</table>

Fig. 2. Functional elements of routing algorithm.

A. Functional Elements of Routing Algorithms

In routing problems, taking into account all possible source and destination pairs is impractical because the number of state space is exponentially increased with the number of network nodes and links. Hence, the search function is usually performed by well-known techniques such as shortest-path algorithm and its variations. In k-shortest path algorithm (i.e., more than one route is available), the selection function is performed by either sequential or combinatorial optimization algorithms. Sequential algorithm (called greedy algorithm) is the simplest one in that the selection for each light-path is done sequentially. This technique does not change the results of the previous one, but it consider the results of the previous one. It requires two sub-functions; the selection order and the selection rule. The selection order is the selection sequence of light-paths to be routed (or to be assigned). The selection rule is a decision criterion to choose one of the available candidates. On the other hand, combinatorial selection techniques consider the inter-dependency of light-path routing.

The combinatorial methods are divided into two approaches; optimal and heuristic mechanisms. The optimal approaches use all possible combinations of the inter-dependency. Heuristic[1] methods reduce the combination space. The optimal selection achieves the best result, but, the cost of computational complexity becomes critical.

Fig. 2 illustrates functional elements for routing algorithm. The description of each function is as follows

- Shortest path (SP): Shortest path algorithms find the shortest route from a given source to a destination in a graph. The route is a path whose cost is less than any other route from the source to the destination. The cost function is often the sum of weights of the edges on the path. Typically, the weights on the graph are static and independent of the number of routes on the link. The shortest path algorithm generates one route and it is independent of other selections. Hence, SP does not require any search order/rule or selection functions.
- Weighted shortest path (WSP): Weighted shortest path algorithms are a shortest path algorithm, but the link cost may be dynamically changed depending on the number of routes established. Hence, it requires

[1] In mathematical programming, this usually means a procedure that seeks a solution but does not guarantee it will find one. This is used to guide the search as a human would do.

a search order. Some examples are as follows
- Largest traffic first schemes line up the light-paths to be routed starting the light-path with the largest traffic first in an attempt to search a route.
- Random schemes lines up the light-paths to be routed in random order.

However, this does not require any selection function since it also finds one route for each source and destination pair.

- k-shortest path (K-SP): k-shortest path algorithms find more than one route for each source and destination pair. K alternative paths provide the flexibility in route selection. However, the routing problem is transformed into a selection problem, where routes are selected to obtain a minimum cost (total number of hop or link cost) for all source and destination pairs.

The selection functions are as follows:
- Sequential selection (Greedy algorithm)
  - Selection order
    * Random schemes line up the light-paths to be routed in a random order in attempt to select routes.
    * Fixed schemes line up the light-paths to be routed in a given order (e.g., alphabetical order).
    * Longest-first schemes line up the light-paths to be routed as the longest (hop or cost) path first.
    * Shortest-first schemes line up the light-paths to be routed as the shortest (hop or cost) path first.
  - Selection rule
    * Random schemes randomly choose one route among candidates.
    * First-fit schemes choose the first matched one route among candidates.
    * Probability schemes choose one route among candidates with probability.
    * Minimum-weighted link first schemes choose the route on the link that includes minimum number of established routes.
- Combinatorial selection
  - For an optimal solution, a mixed integer program is used, which is modeled with the multi-commodity flow problem. This is extremely difficult in terms of computational complexity.
  - For a heuristic solution, a random rounding algorithm is proposed. In this approach, routing algorithm is repeatedly performed for different set of routes while the maximum number of links in all routes is decreased through an alternative selection of routes. The process is repeated until no further improvements are possible.

B. Functional Elements of Wavelength Assignment Algorithms

As shown in Fig. 3, the wavelength assignment problem can also be defined in terms of search and selection. The search is simple since any available wavelength can be assigned along the selected route. The remaining problem is the selection among available wavelengths, which can maximize the wavelength utilization. Selection is further classified into sequential and combinatorial approaches similar to that of routing algorithms. The sequential approach sorts routes to be assigned. Then, a wavelength is assigned to the sorted routes. On the other hand, combinatorial selection considers inter-dependency of each selection. It is further broken into optimal and heuristic approaches. The optimal approach is a well-known NP-complete problem which is difficult to apply to large networks. So, heuristic approaches are hard to reduce the search space to a smaller set of light-paths, although they may increase the number of wavelengths. A number of heuristic methods have been proposed. They are based on well-known graph coloring methods such as meta-heuristic mechanisms[2].

The descriptions of each functional element are as follows:
- Sequential selection (Greedy algorithm)
  - Selection order
    * Largest number of neighbor-first schemes sort the routes according to the number of neighbors at an attempt to assign an available wavelength.
    * Largest available wavelength-first schemes sort the routes in the order of available wavelengths.
    * Largest traffic-first schemes sort the routes in order of traffic requirement.

[2]This is a general heuristic framework for solving hard problems.

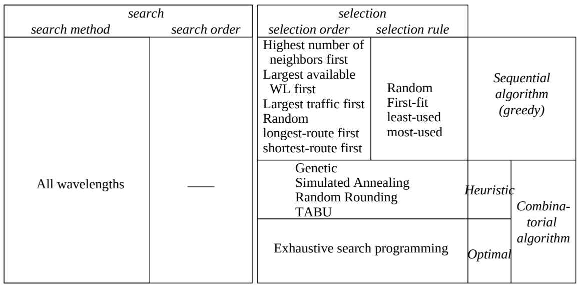

Fig. 3. Functional elements of wavelength assignment algorithm.

    * Longest path-first schemes sort routes in order of the number of hop counts for each route.
    * Shortest first schemes sort the routes with the shortest number of hop first.
    * Random schemes sort routes in a random order.
  - Selection rule
    * First fit schemes attempt to select the first available wavelength in numerical order.
    * Most used schemes attempt to allocate the most utilized wavelength first.
    * Least used schemes attempt to allocate the least utilized wavelength first.
    * Random schemes attempt to allocate a wavelength randomly.
- Combinatorial selection
  - Optimal selections can solved by exhaustive search. Exhaustive search algorithms always generate the best coloring result for a given graph. But, they do not ensure that the algorithm can handle considerably large graphs, too.
  - Heuristic selection algorithms work very well with graph coloring problems, that are further divided into
    * Genetic algorithms (GA) are standard techniques for hard combinatorial optimization problem. The basic idea is to simulate evolution of genotypes and natural selection, which has been applied to global optimization especially combinatorial optimization problems. The idea is based on the specification of three operations (each one is probabilistic) on objects called "strings"; reproduction-combining strings in the population to create a new string (offspring), mutation-spontaneous alteration of characters in a string, and crossover-combining strings to exchange values, and creating new strings in their place. The reproduction and crossover operations can include competition within populations.
    * Simulated annealing algorithms (SA) are another standard techniques for hard combinatorial optimization problem. The idea is to simulate annealing of some object in order to overcome a local minimum point in a sense of iterative improvement. Basically, it is based on the metaphor of how annealing works: reaches a minimum energy state upon cooling a substance, that is, it allows a non-improving move to a neighbor with a probability that decreases over time. The rate of this decrease is determined by the cooling schedule, often just a parameter used in an exponential decay. With some assumptions about the cooling schedule, this will converge in probability to a global optimum.
    * TABU algorithms are relatively new heuristic methods. The basic idea is a random local search, but some movements are forbidden. This should make it possible to get away from local minima.

III. Performance Comparison

Table I surveys the functional elements of static RWA algorithms. By analyzing each functional element in Table I, we can estimate the performance of RWA algorithms. Let's compare search methods for routing algorithms. Given that N is the number of nodes and M is the number of links, the shortest path between two nodes can be obtained by using either Dijkstra's or the Floyd's algorithm. Both algorithms have a computational complexity of $O(MN^2)$ which is based on addition and minimization operations. A weighted shortest path algorithm is a kind of the shortest path algorithm that dynamically considers the link cost. The only difference with the shortest path algorithm is updating the link cost such as bandwidth utilization, number of connections, etc. The third algorithm is Floyd-Warshall's k-shortest path algorithm. K-shortest path algorithm provides a relaxation of the route selection, but has the computational complexity of $O(kMN^2)$.

TABLE I
EXAMPLES OF STATIC ROUTING AND WAVELENGTH ASSIGNMENT ALGORITHMS

ref	function							
	routing				wavelength assignment			
	search (order)	selection			search	selection		
		sequential	combinatorial			sequential	combinatorial	
		greedy(order,rule)	heuristic	optimal		greedy(order,rule)	heuristic	optimal
[8]	SP				AW	(LF,FF)		
[15]	SP				AW	(LF,FF)		
[15]	SP				AW	(RN,FF)		
[20]	SP				AW	(LF,FF)		
[20]	SP				AW	(LF,MU)		
[13]	SP				AW	(LN,FF)		
[13]	SP				AW		GA	
[13]	SP				AW		SA	
[13]	SP				AW		TABU	
[13]	SP				AW			ES
[9]	SP				AW			ILP
[9]	SP				AW	(LTF,FF)		
[23]	WSP(FX)				-	-	-	-
[10]	WSP(LTF)				AW	(-,FF)		
[11]	k-SP			ILP	-	-	-	
[23]	k-SP			MFP	-	-	-	-
[7]	k-SP		RR		AW	(LN,FF)		
[25]	k-SP		RR		AW		RR	
[33]	2-SP		RR		AW	(LF,FF)		
[33]	2-SP		RR		AW	(RN,FF)		
[28]	k-SP		RR		AW	(LF,FF)		
[24]	-	-	-	-	AW	(RN,FF)		

SP: shortest path, k-SP: k-shortest path, WSP: weighted shortest path
AW: all available wavelengths, ILP: integer linear programming, MFP: multicommodity flow programming
ESP: exhaustive search programming, LTF: largest traffic first
GA: greedy, RR: random rounding, GA: genetic, SA: simulated annealing, TABU: TABU
FX: fixed, LF: longest-first, LN: largest neighbor-first, FF: first-fit, MU: most-used, RN: random

As a result, we can see that the shortest path algorithm is the simplest one among the algorithms discussed before. However, the k-shortest path algorithm has a better performance than others even if the computational complexity is extremely high.

In the k-shortest path routing, the optimal selection modeled by multi-commodity flow problem always finds the best solution, but it does not promise that the algorithm can handle considerably large networks. Some heuristic, such as Random Rounding (RR), algorithms can considerably reduce the combination space even though they provide almost the same performance as the optimal solution. Nevertheless, the selection algorithm has to run several times. Comparing to the random rounding algorithms, the simplest one is the sequential algorithm called greedy algorithm. The sequential algorithm runs the selection function just once.

In wavelength assignment, the search function is trivial since any wavelengths can be assigned for the route determined. However, selection is a hard combinatorial problem when the objective is to minimize the number of wavelengths used. The sequential approach is clearly the fastest, comparing to other heuristic algorithms. The optimal search programmed by exhaustive search ranks the third one. It is clear that exhaustive search leads to better solutions than other.

A number of heuristic algorithms such as Genetic, Simulated Annealing (or random rounding), and TABU have been proposed and they provide good performance, while the computation time is not exponentially increased. Among them, the TABU algorithm generates the best performance result even though the running time of the TABU is the same as the running time of SA algorithms. GA are also successful, but in [13] the results obtained are worse than the TABU algorithm. The sequential algorithm (Greedy) is clearly the fastest compared to heuristic algorithms such as SA, GA, and TABU, even though it provides inferior performance results.

In the search order, there may exist better algorithms for graph coloring, however, the largest number of neighbors (LN) first method may have the good performance among the selection ordering mechanisms. The LN method is based on the number of neighbors that are the light-paths shared the same link. Intuitively, if a light-path has large neighbors, it is hard to assign a wavelength since an unallocated identical wavelength must be found on more light-paths. The wavelength allocation of the light-path with the largest number of neighbors early will avoid the need for using a large set of wavelengths. Therefore, by establishing LN light-paths first, a better wavelength reuse should be achievable, leading to an overall smaller requirement of wavelengths for a given light-path set. Longest-first algorithm achieves almost same performance of the LN method since a long path is more likely to have more neighbors.

When the number of wavelengths is small, the selection rules of most-used, least-used, first-fit and random schemes are almost identical [34]. As the number of wavelengths increases, the most-used scheme outperforms all other schemes by a significant margin. Random scheme effectively equalizes the load on the wavelengths and therefore has performance which is close to, but better than, least-used.

IV. Conclusion

In this paper, we give an overview of well-known RWA algorithms, and develop a novel classification for some of their main features. Based on this classification, we compare different solutions for each category. Finally, several challenges and trade-offs are identified. Although no algorithm in our study is a clear winner, advantages and disadvantages of several functional characteristics are discussed in order to help a system developer make a reasonable choice among candidate algorithms.

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