A Study of Dynamic Routing and Wavelength Assignment with Imprecise Network State Information

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Abstract

In large networks, maintaining precise global network state information is almost impossible. Many factors, such as non-negligible propagation delay, infrequent state updates due to overhead concerns, and hierarchical topology aggregation, can affect the precision of the global network state information. In this paper, we investigate the impact of imprecise state information on the performance of dynamic routing and wavelength assignment (RWA) algorithms. We consider single fiber and multi-fiber systems and study dynamic routing with three wavelength selection schemes, namely first-fit, random-fit, *and* most-used. *The results show that the precision of global network state information greatly affects the performance of the dynamic RWA schemes. In particular, some RWA algorithms that are traditionally considered as effective algorithms perform poorly in the presence of imprecise global network state information. This indicates that more practical RWA algorithms that can tolerate imprecise state information may need to be developed for large scale optical networks. The results also show that networks with wavelength conversion capability and multi-fiber systems are less sensitive to the imprecise state information.*

1 Introduction

Optical wavelength-division-multiplexing (WDM) networks provide large bandwidth and are promising networks for the future Internet. Wavelength routed WDM systems that utilize optical crossconnects are capable of switching data in the optical domain. In such systems, end-to-end all-optical lightpaths can be established and no optical-to-electronic and electronic-to-optical conversions are necessary at intermediate nodes. Such networks are referred to as all-optical networks.

In this paper, we study two types of all-optical networks, wavelength routed networks with and without wavelength conversion. Wavelength routed networks without wavelength conversion are also known as wavelength-selective (WS) networks [11]. In such a network, a connection can only be established if the same wavelength is available on all links between the source and the destination. This is the *wavelength-continuity constraint*. Wavelength routed networks with wavelength conversion are also known as wavelength-interchangeable (WI) networks [11]. In such a system, each router is equipped with *wavelength converters* so that a lightpath can be setup with different wavelengths on different links along the path.

To establish a lightpath in a WDM network, it is necessary to determine the route over which the lightpath should be established and the wavelength to be used on all the links along the route. This problem is called the *routing and wavelength assignment* (RWA) problem. Routing and wavelength assignment requires that no two lightpaths on a given link may share the same wavelength. In addition, in WS networks, lightpaths must satisfy the wavelength continuity constraint, that is, the same wavelength must be used on all the links along the path. The RWA problem can be classified into two types: the *static* RWA problem and the *dynamic* RWA Problem. In the static RWA problem, the set of connections is known in advance, the problem is to set up lightpaths for the connections while minimizing network resources such as the number of wavelengths and the number of fibers. Alternatively, one may attempt to set up as many lightpaths as possible for a given number of wavelengths. Dynamic RWA tries to perform routing and wavelength assignment for connections that arrive dynamically. The objective of dynamic RWA is to minimize the blocking probability. We consider the dynamic RWA problem in this paper.

While extensive analytical and simulation study has been done to compare the performance of different RWA algorithms, all the existing results assume that precise global network state information is available. In a large network, however, maintaining precise global network state information is almost impossible. Many factors, such as non-negligible propagation delay, infrequent state updates due to overhead concerns, and hierarchical topology aggregation, can affect the precision of the global network state information. Thus, an effective practical RWA algorithm must be able to tolerate the imprecise global network state information and make effective routing and wavelength assignment decisions in the presence of imprecise global network state information. In this paper, we attempt to understand the effects of the imprecise global network state on existing RWA algorithms for different network architectures. We consider three types of systems: *WI networks*, *single fiber WS networks* (single fiber for each link), and *multi-fiber WS networks* (multiple fibers for each link). For each type of networks, we study dynamic shortest path routing with three wavelength selection schemes: *first-fit*, *random-fit* and *most-used*. More details about the systems and the wavelength selection schemes will be elaborated in Section 3. The conclusions we draw from this study include the followings. First, imprecise global network state information has significant impact on the performance of dynamic RWA algorithms. Second, some algorithms that are traditionally considered effective (when the global network state is precise) perform poorly when the state information is imprecise. Third, WI networks and multi-fiber WS networks are less sensitive to the imprecise global state information than single fiber WS networks. The study also indicates that current RWA algorithms that do not take imprecise global network state into consideration may not be practical for large scale networks.

The rest of the paper is organized as follows. Section 2 describes the related work. Section 3 presents the dynamic routing and wavelength selection algorithms. Section 4 reports the results of the performance study, and Section 5 concludes the paper.

2 Related work

The routing and wavelength assignment problem has been studied extensively. A summary of the research in this area can be found in [16]. This problem is typically partitioned into two sub-problems: the routing sub-problem and the wavelength selection sub-problem [2, 3, 5, 6, 7, 10, 14]. For the routing sub-problem, there are basically three approaches, fixed routing [6], alternate routing [6, 7, 14], and dynamic adaptive routing [9, 10]. Among the routing schemes, dynamic adaptive routing, which is studied in this paper, offers the best performance. A large number of wavelength selection schemes have been proposed: random-fit [5], first-fit [5], least-used[15], most-used[15], min-product[8], least-loaded [11], max-sum[2, 15], and relative capacity loss[17]. The schemes can roughly be classified to three types. The first type, including random-fit and least-used, tries to balance the load among different wavelengths. The schemes in this category usually perform poorly in comparison to other types of RWA schemes. The second type, including first-fit, most-used, min-product, and least-loaded, tries to pack the wavelength usage. These schemes are simple and effective when the network state information is precise. The third type, including max-sum and relative capacity loss, considers the RWA problem from a global point of view. These schemes deliver better performance and are more computational intensive than the other types of schemes. In this study, we investigate the impact of imprecise global network state information on the performance of the RWA algorithms.

3 Dynamic routing and wavelength assignment with imprecise state information

3.1 Imprecise state information

In large networks, global network state information is typically maintained by either a link state algorithm [13] or a distance vector algorithm [12]. In this paper, we assume that a link state algorithm is used to maintain the global network state information. Using the link state algorithm, a router obtains the global network state by exchanging the link state advertisements. Ideally, every time the state of a link is changed, e.g. a wavelength is used or released by a connection, the changing of the link state must be made known to all routers in the networks. However, due to the overhead concerns, the link state updates usually cannot keep up with the actual link state changes. Hence, the global state maintained at each node may not accurately reflect the current network situation. In addition to the overhead consideration, other factors, such as the large propagation delay and topology aggregation schemes, which summarize network state information in a concise representation, can contribute to the imprecision of the global network state information. Thus, a practical dynamic RWA algorithm must be able to deal with imprecise global state information and perform effective RWA in the presence of imprecise global state information.

In this paper, we assume a timer-based link state update scheme [1], that is, the link state update is triggered periodically with a given time interval. The imprecise global state information is modeled by adjusting the time interval for the link state updates. The larger the interval, the more imprecise the global state is. Notices that some other link state update policy, such as the threshold based link state update policy, are proposed to achieve better link state information with less link state updates [1]. Such update mechanisms may not be suitable for optical networks since they may result in very high blocking rate.

3.2 Dynamic routing and wavelength assignment

When connections are established and released dynamically, dynamic routing and wavelength assignment algorithms must be used to dynamically assign resources to the connection requests. In case when the network does not have sufficient resources to support a connection, the connection is *blocked*. In WS networks, a connection may also be blocked if there does not exist any common wavelength in all the links along a path. The objective of a dynamic routing and wavelength assignment algorithm is to select a path and a wavelength on each link along the path such that the blocking probability is minimized. Using the global network state information maintained by a link state algorithm, a router can compute the routes and select wavelengths to establish a connection with a RWA algorithm. The routing algorithm we study is a shortest path routing algorithm that guarantees to find a shortest path between the source and the destination that can be used to establish the connection. For a WI network, all the links along the selected path have at least one available wavelength. The routing algorithm for WI networks is basically the typical shortest path algorithm. For a WS network, we must find a path where at least one common wavelength on all the links along the path must be available. To ensure that, we use the concept of the layered graph [4]. Let the network be modeled as a graph $G(V, E)$, where V is the set of routers and E is the set of links. To find a path from src to dst in a network with k wavelengths that satisfies the wavelength continuity constraint, we construct the layered graph $G'(V', E')$ as follows:

- For all $n \in V$, $n_i \in V'$ for $i = 1, 2, ..., k$. In addition, two nodes src' and dst' are added to the graph.
- For an edge $(u, v) \in E$, $(u_i, v_i) \in E'$ if and only if the i-th wavelength on link (u, v) is available. In addition, links (src', src_i) for $i = 1, 2, ..., k$, and (dst_j, dst') for $j = 1, 2, ..., k$ are added to the layered graph.

Each layer in the layered graph corresponds to the availability of one wavelength. It can be shown that a path between src' and dst' in the layered graph G' implies a path in G with a common wavelength along all links in the path. Thus, running a shortest path algorithm over G' finds a shortest path that satisfies the wavelength continuity constraint. By associating a weight with each link in the layered graph, multi-fiber systems can be modeled. Once the route for a connection is determined, a wavelength is selected on each link for the connection. For WI networks, all wavelengths are equal and no particular wavelength selection algorithm is necessary. For WS networks, three wavelength selection methods are considered:

- *Random-fit*. Using random-fit, a set of wavelengths that can be used to establish the connection is determined. After that, a wavelength is randomly select with uniform probability distribution from the set.
- *First-fit*. In the first-fit scheme, the wavelengths are numbered. The lowest numbered wavelength that can be used to establish a connection is used for the connection. The idea of the first-fit scheme is to pack the usage of the wavelengths toward the lower end of the wavelengths so that high numbered wavelengths can contain longer continuous paths. Previous studies have shown [5] that this scheme performs better than the random-fit scheme. Due to its simplicity and high performance, this scheme is preferred in practice.
- *Most-used*. The most-used scheme furthers the idea of the first-fit scheme in packing the usage of wavelengths. In this scheme, all the available wavelength that can be used to establish a connection are considered, the wavelength that has been used the most is selected for the connection. The wavelength usage using the most-used scheme is more compact than that using the first-fit scheme. Studies have shown that with precise global network state information, the most-used scheme performs slightly better than the first-fit scheme.

4 Performance study

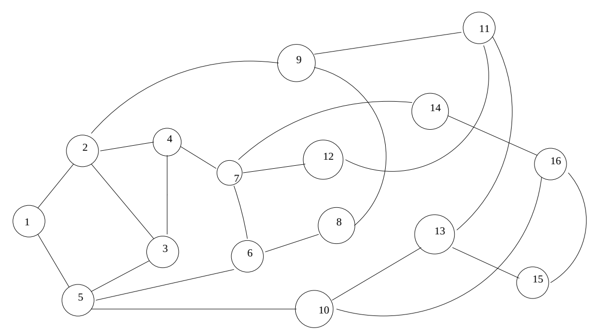

Figure 1. The ISP topology

In this section, we present the study of the performance of various RWA algorithms in the presence of imprecise global network state information. The topology used is shown in Figure 1. All the links are assumed to be bidirectional. Each link have a total of 32 wavelengths regardless of the number of fibers. Thus, for a single fiber system, 32 wavelengths are supported on each fiber; for a 2-fiber system, 16 wavelengths are supported on each fiber. The flow dynamics of the network are modeled as follows. Flows (connections) arrive at a node according to a Poisson process with rate λ. The destination node is chosen randomly from all nodes except the source node. The connection holding time is exponentially distributed with mean $1/\mu$. The offered network load is given by $\rho = \lambda N h' / \mu L C F$, where N is the number of source nodes, L is the number of links, h' is the mean number of hops per flow, averaged across all source-destination pairs, F is the number of fibers for each link, and C is the number of wavelengths supported on each fiber. The parameters used in the simulation are $N = 16$, $L = 50$. $h' = 2.28$. The mean connection holding time is 60 seconds, that is, $1/\mu = 60$. For a single fiber system, $C = 32$ and $F = 1$. For a 2-fiber system, $C = 16$ and $F = 2$. For a 4-fiber system, $C = 8$ and $F = 4$. The average flow arrival rate, λ, is set depending upon the desired load. In the experiments, a blocked flow is dropped without being retried. All the results are obtained with a 95% confidence level and a 5% confidence interval.

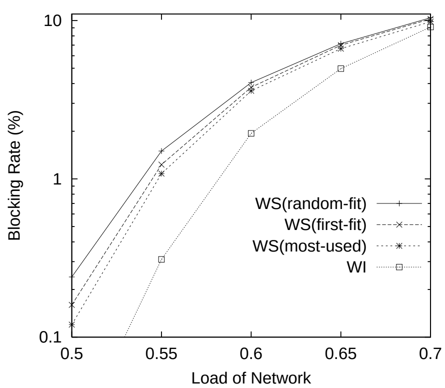

Figure 2. Performance of wavelength selection algorithm on a single fiber system with accurate state information

Figure 2 shows the performance of different wavelength selection algorithms on a single fiber system when the global network state information is accurate. The results in the figure are compatible with previous study: WI networks offer better performance than WS networks. For WS networks, different wavelength selection schemes result in different performance. Among the three schemes considered, the most-fit scheme is the most effective, while the random-fit scheme is the least effective. The performance difference between WI and WS networks is fairly large while the differences among different wavelength selection schemes for WS networks are smaller.

Figure 3 shows the performance of different wavelength selection algorithms on a single fiber system when the global network state information is inaccurate with a link state update interval of 10 seconds). We observe that WI networks perform significantly better than WS networks

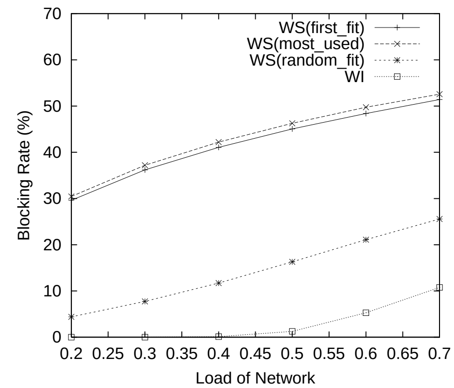

Figure 3. Performance of wavelength selection algorithm on a single fiber system with an update interval of 10 seconds

when the global network state information is inaccurate, which indicates that WI networks are less sensitive to the imprecise global network state information than WS networks. The results also show that the performance of wavelength selection algorithms is affected significantly by the imprecise global network state information. In particular, wavelength selection algorithms, such as the first-fit and best-fit schemes, that try to pack the usage of wavelengths in the system result in very poor performance in the presence of imprecise state information. This is because packing the wavelength usage using the imprecise state information results in the same wavelength on a link to be assigned to different connections and a very large blocking rate. Such wavelength selection schemes are extremely ineffective when the network state information is inaccurate. Notice that such wavelength schemes are traditionally considered effective when the global network state information is accurate. The wavelength selection schemes, such as the random-fit scheme, that try to balance the load on different wavelength adapt to the imprecise network state information better although the performance also decreases drastically. These results show that to design a practical wavelength selection algorithm, the issue of inaccurate global network state information needs to be taken into consideration.

Figure 4 shows the impact of the link state update intervals on the performance of different wavelength selection schemes. In this experiment, $load = 0.5$. As the global link state information becomes more inaccurate, all schemes have higher blocking rate. However, the performance of the first-fit and most-used schemes decreases much faster than the random-fit scheme. As the link state update interval increases from 0 to 10, the blocking rate in the WI network only decreases slightly. This demonstrates that WI networks

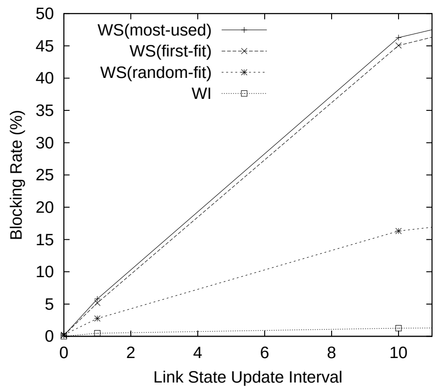

Figure 4. Impact of the link state update interval

can tolerate imprecise global state information much better than WS networks.

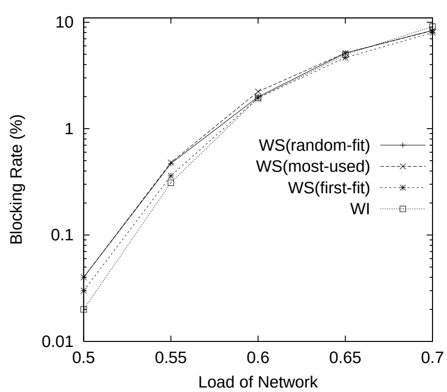

Figure 5. Performance of wavelength selection algorithm on a 4-fiber system with accurate state information

Figure 5 shows the results for a 4-fiber system when the global network state information is accurate. Comparing to Figure 2, we can see the difference between the performance of different wavelength selective schemes in the 4-fiber system is much smaller than that in the single fiber system. Essentially, 4-fiber per link creates the effect of "partial" wavelength conversion: one incoming wavelength can potentially have four outgoing wavelengths in each output port. In this particular experiment, performance of a 4-fiber system is very close to that of a network with full wavelength conversion. When the network is under heavy load ($load > 0.65$), the WI network has a higher connection blocking probability than the WS network with 4 fibers per link. The reason for this seemingly strange result is that in WI networks, a connection is easier to be established. When the network is under heavy load, more connections with large hop counts are established which blocks future connections with small hop counts.

Figure 6 shows the results for a 4-fiber system when the global network state information is inaccurate with a link state update interval of 10 seconds. The inaccurate state information still has a significant impact in a 4-fiber system as the performance of the wavelength selection schemes decreases significantly, especially the most-used scheme. However, comparing to Figure 3, the effect is less significant. The performance of the first-fit scheme in the 4-fiber system is much better than that in the single fiber system. The main reason is that the shortest path algorithm that we use is a widest-shortest routing algorithm, that is, among all shortest paths, the one that has the largest number of available wavelength is selected. In a multi-fiber system, this allows different paths between the same source and destination to be selected, which somewhat directs the traffic in a more balanced manner. This allows more flexibility in selecting a wavelength for a connection and improves the performance.

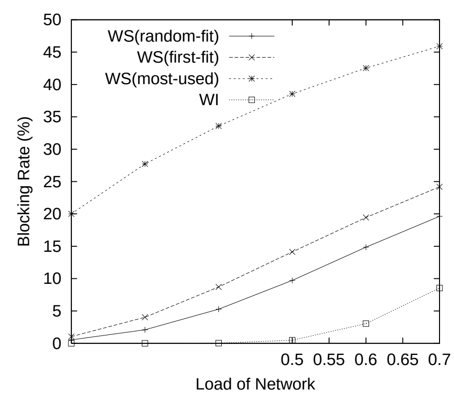

Figure 6. Performance of wavelength selection algorithm on a 4-fiber system (update interval $= 10$)

Figure 7 shows the impact of link state update interval on the performance of different wavelength selection schemes for a 4-fiber system. In this experiment, $load = 0.5$. The trend is similar to that in Figure 4 except for the first-fit scheme. As the global link state information becomes more inaccurate, all schemes have higher blocking rate. However, the performance of the first-fit and most-used scheme decreases much faster than the random-fit scheme.

Figure 8 shows the impact of the number of fibers per link in the system. This experiment assumes that all systems have the same capability (32 wavelengths per link realized by a different number of fibers). The network load is 0.5 and the link state update interval is 10 seconds. Having more fibers on each link always results in better performance for all different wavelength selection schemes. Hence, we conclude that multi-fiber systems can somewhat offset of the negative effect of imprecise global network state information in comparison to single fiber systems.

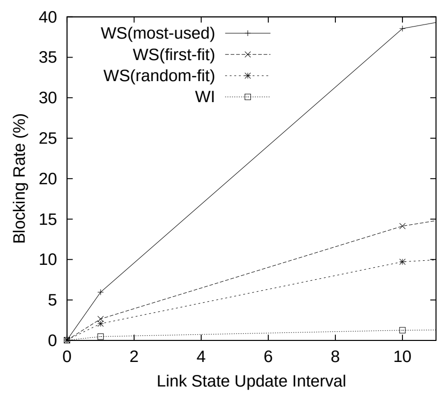

Figure 7. Impact of link state update interval on a 4 fiber system

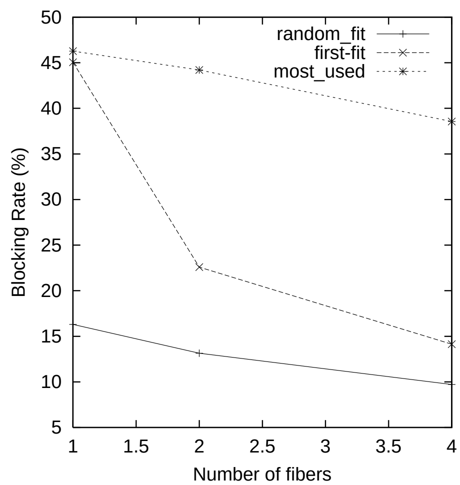

Figure 8. Impact of the number of fibers per link

5 Conclusion

In this paper, we investigate the impact of imprecise global network state information on wavelength interchange and wavelength selective networks and on different wavelength selection schemes for wavelength selective networks. We find that imprecise global network state information has significant impact on the performance of all different types of networks and of different wavelength selection schemes for wavelength selective networks. For wavelength selective networks, some wavelength selection algorithms that are traditionally considered efficient by packing wavelength usages, such as the first-fit and most-used, perform poorly in the presence of imprecise global network state information. We conclude that new RWA algorithms that can tolerate imprecise global network state information may need to be developed for the dynamic connection management in the future WDM networks.

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