Effect of Wavelength Conversion in Survivable Wavelength Routed Optical WDM Networks with Alternate Routing

Vishal Anand and Chunming Qiao
Department of Computer Science and Engineering
State University of New York at Buffalo Buffalo, New York 14260
Email:{vanand, qiao}@cse.buffalo.edu

Abstract

This study focuses on the routing and wavelength assignment in wavelength-routed optical wavelength-divisioned -multiplexed networks with circuit switching using wavelength conversion. Wavelength conversion has been proposed for use in such networks to improve the efficiency. The crucial factors which determine the efficiency of using wavelength conversion as opposed to not using them, is the number of wavelengths required to satisfy the network traffic demand and the blocking of traffic demands by the network. In addition to considering wavelength conversion, this study investigates the effect of having multiple paths between each source-destination pair. We consider the cases where protection is necessary for each of the primary paths between every source-destination pair and hence a backup path also has to be established during connection set up, and the case when no protection is necessary. We study the effect of wavelength conversion with different protection schemes. By simulating and analyzing a large number of randomly generated networks we report results of our study of the above schemes under both incremental and dynamic traffic conditions. The study shows that utilizing wavelength conversion has a considerable impact on reducing network blocking under both incremental and dynamic traffic conditions, on the other hand we find the difference in wavelength requirements of the various schemes considered is minimal.

Keywords

Optical network, Wavelength Division Multiplexing (WDM), Routing and Wavelength assignment (RWA), all-optical networks, wavelength conversion, network survivability, Traffic models, network blocking, alternate routing.

I. Introduction

Optical networks using wavelength-division-multiplexing (WDM) [1] networks are considered to be promising candidates for the future wide-area backbone networks. By using the WDM technique such networks make use of the enormous bandwidth of an optical fiber. WDM divides the tremendous bandwidth of a fiber in to many non-overlapping wavelengths (or wavelength channels) which can operate simultaneously, with the fundamental requirement that each of these channels operate at different wavelengths.

We consider a WDM network whose *physical topology* consists of (optical) wavelength-routers connected by point-to-point fiber links in an arbitrary mesh topology as shown in Figure 1. Between two connected wavelength-routers, there is a pair of unidirectional fibers (or equivalently, a bidirectional link). Each wavelength-routing node takes in a signal on a wavelength at one of its inputs, and routes it to a wavelength at a particular output, without undergoing opto-electronic (O/E) conversion. An access station (e.g., an IP router) may be connected to each optical wavelength-router, which can transmit/receive signals through either a tunable transmitter/receiver or a transmitter/receiver array. A connection request is satisfied by establishing a *lightpath* from the source node (access station or wavelength-router) of the connection to the destination node. A lightpath uses one wavelength on each link it spans to provide a circuit-switched interconnection between the source and destination nodes. A wavelength-routed network [2] which carries data from one access station to another without any intermediate O/E conversion is referred to as an *all-optical* wavelength-routed network. As shown in Figure 1., two lightpaths, one between nodes 3 and 5, and the other between nodes 3 and 7, must use different wavelengths, (λ_1 and λ_2) on a common fiber link ($3 \rightarrow 4$), in order to prevent interference of the optical signals.

This study is organized as follows: In section I, we introduce wavelength-continuous and wavelength-convertible networks, we then introduce various survivability schemes in such WDM networks. Next, we introduce RWA in such wavelength-continuous and wavelength-convertible networks. In section II, we explain the network and traffic models we consider in our study. Section III, describes our simulation model in detail and also explains the results of our simulations case by case. Finally section IV concludes this study with a summary of its major contributions.

A. **Wavelength Conversion**

If we assume that none of the wavelength-routers has wavelength conversion capabilities, then a lightpath has to occupy the *same* wavelength on all the links that it spans (this is called the *wavelength-continuity constraint*). Hence in Figure 1. the two lightpaths between (3,7) and (3,5) use the same wavelength λ_1 and λ_2 respectively, on each of the links their respective lightpath traverse. Networks having no *wavelength conversion* abilities are said to be *wavelength-continuous-networks*.

Wavelength conversion capabilities can be incorporated in the optical cross-connects (OXC) of an optical network. Wavelength conversion can be achieved all-optically without O/E/O conversion or by electronics via O/E/O conversion at the wavelength converting nodes. If we assume that each of the nodes in the network is capable of full wavelength conversion, then the lightpaths need not be assigned the same wavelength on each of the links they traverse. For example in Figure 1., we could now have the lightpath (3,7) using λ_1

on link $3 \to 4$ and λ_2 on link $4 \to 7$, similarly lightpath (3,5) could now use λ_2 on link $3 \to 4$ and λ_1 on link $4 \to 5$. Note, still we need to make sure that two lightpaths must use different wavelengths, on the common fiber link $3 \to 4$, in order to prevent interference of the optical signals. Networks having wavelength conversion capabilities are said to be *wavelength-convertible-networks*.

A wavelength-convertible network can support *complete* conversion at every or at a few strategically placed OXC nodes, i.e. at these nodes *any* incoming wavelength can be converted to *any* wavelength at the output. The wavelength continuity constraint distinguishes wavelength-continuous-networks from a wavelength-convertible-network, which blocks only when there is no capacity (wavelengths) on any of the links along a particular route. Thus we can do away with the wavelength-continuity constraint in wavelength-convertible-networks, which have *complete* wavelength conversion capabilities at *all* their nodes.

Figure 2., illustrates the difference between, wavelength-continuous and wavelength-convertible networks. The figure shows nodes 3, 7 and 6 of figure 1. in more detail. Suppose that each link in the network has 2 wavelengths λ_1, λ_2 and there are three lightpath requests (2,7), (7,6) and (2,6). In the figure, figure 2(a)., 2(b). show nodes without and with wavelength conversion capabilities respectively. Now assume that lightpath request (2,7) and (7,6) are satisfied on λ_1 and λ_2 as shown. Now suppose we have another lightpath request (2,6), we can see from figure 2(a). that such a lightpath request can not be satisfied in a wavelength continuous network, even though there is a free wavelength along the path. This is because the available wavelengths are different and hence the wavelength-continuity constraint is not satisfied along the path. On the other hand, now consider figure 2(b)., the lightpath request can be satisfied along the shown path, if wavelength conversion is allowed at node 7. Thus, a wavelength-continuous network may suffer from a higher blocking as compared to wavelength-convertible network.

Wavelength conversion can be achieved through the use of opto-electronic techniques [3,4], which require O/E conversion at the OXC's or all-optically [5–7] requiring no O/E conversion at the OXC nodes. Another classification of wavelength converters is based on the placement of the wavelength converters in the network, wavelength converters can be dedicated or shared, further this sharing can be done on a per-node or per-link basis. For further details on these classifications we point the reader to [8–10]. Research in [9, 11], focused on the effect of using sparse location of wavelength converters in the network. In [8], the authors study the effect of sharing of wavelength converters at the switching ports of an OXC. The authors in [12] study the effect of limited-range wavelength conversion in WDM networks.

B. **Survivability in WDM networks**

The adoption of the WDM technology has resulted in an ever increasing degree of concentration of traffic on a single fiber-link, whose failure in a WDM network may affect upwards of a Terabit of traffic per second, motivates the study of WDM network survivability and reliability. The concept of survivable optical networks has been discussed extensively in [13–19]. In addition, Path and link recovery schemes have also been researched in [20–22]. These studies have shown that path protection provides a better spare-capacity utilization than link protection, but suffers from longer recovery times.

We assume that the network is survivable or protected against any *single* link failure at the optical layer. In our work, such protection is provided by using a *path-based* protection scheme, more specifically, at the time of establishing a *primary path* (working), a link-disjoint *backup* (protection) path is also established. The results in this paper are valid for both *1+1* and *1:1* based protection as long as we assume that no backup path bandwidth sharing occurs.

For the wavelength-continuous-networks we consider two different cases for protection:

- Type I: The primary path and the backup lightpaths need to be assigned the *same* wavelength. This sort of wavelength assignment may be necessary when the source and destination of a lightpath have agreed in advance on the emitting and sinking wavelengths and/or routes according to some policy constraints. This constraint could also be necessary when there are not enough tunable transmitters and/or receivers at the source and destination nodes, or at any other nodes in the network.
- Type II: The primary path and the backup lightpaths can be assigned *different* wavelengths. This sort of wavelength assignment assumes there are no constraints as described in Type I path protection above.

For the wavelength-convertible-networks, with complete conversion at every node, *any* available wavelength on *any* link along the route can be assigned to the primary and backup lightpaths by definition. Here again it is implicitly assumed that there are no constraints on RWA as in Type I protection scheme described above.

C. **Routing and Wavelength Assignment**

In such a wavelength-routed network, to establish a lightpath from a source s to a destination d one has to determine a route along which the lightpath can be established and then assign a wavelength (or wavelengths in the case wavelength-convertible-networks) to the selected route. This is termed as the routing and wavelength assignment (RWA) [23, 24] problem.

Routing

In general, a routing scheme can be classified as *static* or *dynamic*. In static routing algorithms the routing procedure does not vary with time and the route(s) for a given source-destination pair is (are) pre-determined based on the topology as well as certain policies or constraints, but independent of the current traffic condition in the network. In dynamic routing algorithms on the other hand, the routing procedure can vary with time, such algorithms can be *adaptive*, in the sense that they can select a route based on the current network conditions. In our work here, we will consider *alternate routing*, in which each source-destination is associated with a set of (primary and backup) routes. If resources along one route are not available, then another route in the set will be examined. The behavior of alternate routing thus approximates that of dynamic routing algorithms [25], in which the current traffic condition in the network is used to select a route.

In our study we consider alternate routing, such that each $s-d$ pair is associated with a maximum of M primary routes and each of the M primary routes are associated with K link-disjoint backup routes. We do not require that the primary or backup paths be link-disjoint amongst themselves. The link-disjointedness constraint is only required for a primary path and its corresponding backup path.

When there are multiple primary and backup routes to choose from, the routing algorithm first tries to establish the primary path along the shortest possible (minimum hop) route and then tries to establish its corresponding backup paths also on the shortest possible route. If the shortest routes are not available then the next longer route is tried. If two routes have the same length, then one of them is chosen at random.

Wavelength Assignment

The second component of the RWA problem is to assign a wavelength on each link along the chosen route. In [25], the authors compared different wavelength assignment policies which consider the wavelengths according to a fixed-order as in [26], a random-order, or according to the utilization of the wavelengths as in [27] along with both fixed and unconstrained routing (which is similar to alternate routing with a large enough set of routes). The authors of [25] showed that the wavelength-packing policy, which attempts to assign the most utilized wavelength first, performs the best when compared to other wavelength assignment schemes. In this paper, we will use the *First-Fit* wavelength assignment policy for its simplicity. It is important to note that, First-Fit is an example of fixed-order wavelength assignment whose performance was shown to be very close to that of the wavelength-packing policy in [25].

We consider the following adaptive wavelength assignment schemes in our study for the wavelength-continuous-networks.

1. Pack: This algorithm attempts to route the paths first on that wavelength which has the most utilized wavelength channels, i.e. the wavelengths are searched in descending order of utilization, in the hope that this would maximize the utilization of the available wavelengths.
2. Spread: This algorithm attempts to route the paths first on that wavelength which has the least utilized wavelength channels, i.e. the wavelengths are searched in ascending order of utilization, in the hope that this would maximize the utilization of the available wavelengths by distributing the load uniformly over the available wavelengths.
3. First-Fit: This algorithm attempts to route the paths on the first available wavelength in the wavelength set, First-Fit is an example of fixed-order wavelength assignment.

For the wavelength-convertible-networks we also use the First-Fit wavelength assignment scheme hop-by-hop, i.e. we assign the first available wavelength on a link, we repeat this process for every hop (link) along the route of the path.

We again emphasize that the routing is done before the wavelength assignment, in both the wavelength-continuous and wavelength-convertible cases. Hence the routes to be assigned wavelengths are chosen first in increasing order of length. Thus our RWA scheme is *exhaustive*, in the sense that all of the wavelengths are first searched for the shortest available route in one of the ways (Spread, Pack, First-Fit) described above.

Although significant research has been done on the use of wavelength conversion in [8, 9, 11, 12, 28–30], none of the research considered a comprehensive evaluation. To the best of our knowledge, this work is the first study which evaluates the benefits of wavelength conversion in both fault tolerant and intolerant networks, under incremental and dynamic traffic conditions. Further, this paper is also the first paper which studies the effect of alternate path routing in such networks using wavelength conversion. This comparison is done in terms of the wavelength requirements and the blocking of each these schemes, which are critical parameters for a WDM network.

II. **Modeling and Performance Analysis of WDM networks with wavelength conversion**

A. **Network Model**

The network physical topology consists of N nodes arbitrarily connected by L bi-directional fibers. Each fiber can carry $2 \cdot W$ unidirectional wavelengths. We assume a single fiber system, hence if two nodes a and b are shown connected then there are W unidirectional wavelengths from node a to node b, and also another W unidirectional wavelengths from node b to node a. Each node in such an optical network can be assumed to have two functionalities: (1) a lightpath or connection request generation/termination capability and (2) a wavelength routing capability. This essentially means that a node can either act as the source/destination of a lightpath or act as wavelength routing node. The wavelength routing nodes do not terminate or generate lightpaths but route the lightpath from the source to destination, hence acting as a bypass.

The results shown in this paper are for the NSF network shown in Figure 3. The results for other randomly generated topologies were found to be very similar and hence not shown. The NSF network has a physical topology which enables us analyze and study various interesting aspects related to alternate routing in both fault tolerant and non-fault tolerant networks, wavelength assignment schemes and also helps us to study the effect of having wavelength translating cross-connects. The *physical connectivity* α is defined as the normalized number of bidirectional links with respect to a physically fully connected network of the same size. Thus, $\alpha = \frac{L}{N \cdot (N-1)}$, for the NSF network: $\alpha = 0.23, N = 14, L = 21$.

B. **Traffic Model**

1. Static Traffic: Here it is assumed that all the requests for lightpaths that are to be set up in the network are known initially. The objective then could be for example, to maximize the total throughput (or decrease blocking) in the network, i.e. the total number of lightpaths which can be established simultaneously in the network. Since all the lightpath requests are known beforehand the RWA problem is simpler under such traffic conditions. Integer linear programs (ILP) can be formulated to find the optimal solution, several heuristic-based approaches can also be used to solve the RWA problem, but these usually provide sub-optimal results.

2. Incremental Traffic: In our study we assume that the connection requests for a maximum of D lightpaths arrive in the network one after the other *incrementally*, and once a connection request is satisfied, it remains in the network i.e. uses the resources allocated to it for an infinite time. We assume that the lightpath requests are *uniform* and random, i.e. the probability of lightpath request from a source s to a destination d, is the same $\forall s,d \in N$ and there is no knowledge of future lightpath requests. Also note that we assume that every node in the network can act as a source or a destination.

3. Dynamic Traffic: In contrast, when we also study the schemes under dynamic traffic, where lightpath requests between $s - d$ pairs arrive at random and each lightpath if established has a random holding time after which it is torn down and the resources allocated to it freed. We use a dynamic traffic model in which a lightpath request arrives at each node with a uniform probability according to a poisson process with a network-wide arrival rate β. An arriving request is equally likely to be destined to any node in the network. The lightpath holding time is assumed to be exponentially distributed with mean $1/\mu$. Thus, the load, ρ, per $s - d$ node pair is $\rho = 2 \cdot \beta / N \cdot (N-1)\mu$, the factor of 2 in the numerator occurs because we assume that every node in the network can act as a source and/or a destination.

Hence note that in both the above cases, a node may engage in sourcing and/or sinking multiple lightpaths and in addition many parallel lightpath requests can occur and be established depending on the network resources and the dynamic traffic lightpath request arrival and holding rate parameters.

III. **Simulation Results and Performance Analysis**

This section describes the manner in which the results were obtained from simulation for each of the scenarios enlisted below. The results to be described below are obtained via extensive simulations on the NSF network topology shown in Figure 3. For the case of incremental traffic, in each run of the simulation a maximum of D demands were generated randomly and for each value of wavelengths, W in the network, the blocking B is then reported by averaging the blocking over 100 such runs. For the case where dynamic traffic is considered, in each simulation run, a maximum of 10000 lightpath requests are generated randomly for various values of W and load per $s-d$ pair in erlangs, the blocking is then reported by averaging the blocking over 100 such runs.

A. **Without Protection**

In this section we compare and explain the performance of RWA schemes, those using wavelength conversion and those not using wavelength conversion and present results obtained from simulations. We assume that no protection is necessary and hence to satisfy a lightpath request only a primary path needs to be established.

A.1 Comparison of the various wavelength assignment schemes

We first compare the various wavelength assignment schemes Pack, Spread and First-Fit described previously. We compare the lightpath blocking by each of these schemes. The blocking is compared for different number of wavelengths per link of the network and for different total number of incremental lightpath requests generated. Figure 4. depicts this comparison. The value of D in the figure denotes the total number of lightpath requests that were generated for that simulation run. The figure shows that there is very little difference in the performance of each of these wavelength assignment schemes. On closer examination and study, our results indicate that, on the average the First-Fit scheme provides the lowest blocking followed by Pack, followed by Spread. We have already indicated that First-Fit is a special case of Fixed-order wavelength assignment. It is also easy to see that the First-Fit scheme essentially tries to pack wavelengths and hence is a special case of the Pack wavelength assignment scheme. In each of our simulation we assume that for each $s-d$ pair, a maximum of $M=10$ shortest paths are tried, in increasing order of their length.

Based on these results, from now on we use the First-Fit wavelength assignment schemes to assign wavelengths to the primary (and backup paths, if they exist) paths in both the wavelength-continuous and wavelength-convertible networks.

A.2 Comparison of the blocking with and without wavelength conversions

Figure 5. shows the blocking obtained by the First-Fit wavelength assignment scheme in wavelength-continuous and wavelength-convertible networks under incremental traffic conditions with no protection provided for the primary paths. The figure shows that there is a significant lowering of blocking that can be obtained by providing wavelength conversion. Table I shows the wavelength requirement with and without wavelength conversion for achieving 100% throughput, i.e. establishing all the D demands. The table shows that there is *very little* difference in the number of wavelengths W_{maxD} needed to satisfy all the lightpath requests with and without wavelength conversion. On the other hand notice that wavelength conversion *consistently* achieves *lower* blocking than the no wavelength conversion case, when $B > 0$ for a particular D. When the number of wavelengths W, is 1 the blocking in the two cases is exactly the same as there is no room for wavelength conversion. As the W increases and the blocking B, is such that $B > 0$ for a particular D, i.e. all the requested lightpaths have still not been met, we find that the blocking achieved by using wavelength conversion is *very similar* to that got by no wavelength conversion for small values of W. This can be explained as follows, with small number of W, the flexibility offered to wavelength-convertible paths is lower and hence the number of lightpaths established is similar to the no wavelength case. As W increases further to larger values (but still $B > 0$ and $W < W_{maxD}$), wavelength conversion achieves *significantly lower* blocking than the no wavelength conversion case. For lower and intermediate values of W, ($B > 0$ and $W < W_{maxD}$) we notice that there are cases where wavelength conversion achieves *higher* blocking than no wavelength conversion.

This phenomenon can be explained as follows, allowing the primary lightpath to choose a route from amongst M multiple routes, of increasing length, essentially gives more flexibility to wavelength-convertible paths to establish a route. Hence, when wavelength conversion is allowed, the probability that the initial requests are satisfied by using *longer* (more hops and wavelength-channel consuming) routes is higher than the no wavelength conversion case which do not have this flexibility. This has a negative impact on the performance of RWA schemes using wavelength conversion, since now the probability of future requests to be blocked, is higher. Thus by consequence RWA schemes using wavelength conversion occupy more wavelengths and cause an increase in overall blocking. This phenomenon is depicted in Figure 6., which plots the number of wavelength-channels used by wavelength conversion and no wavelength conversion cases for a particular value of D and W. The figure shows that the number of wavelength-channels used by wavelength conversion is always *higher* than the no wavelength conversion case. Further as W increases the difference between wavelength-channels used by wavelength conversion and no wavelength conversion also increases.

Figures 7. and 8. plot the mean path lengths of the established lightpaths and the mean number of lightpaths established by not using the shortest possible route, when wavelength conversion is used and when wavelength conversion is not used respectively. The figures show that these values are typically larger when wavelength conversion is used. This can be explained along the same line of argument as before.

B. **With Protection**

In this section, we compare and explain the simulation results obtained from having wavelength conversion and no wavelength conversion capabilities in survivable networks using path protection without backup path bandwidth sharing. We assume that each lighpath request always requires 100% protection and the protection can be provided in the manner explained section I-B. We make the following assumptions, for each primary path, there are a choice of M possible routes and each of the M routes are associated with K possible backup routes as explained in section I-C . Further we assume that the length of the primary path is always smaller than or at most equal to the length of the backup path. The simulation results shown here are for the case when $M = 10$ and $K = 3$.

B.1 Comparison of the blocking with and without wavelength conversions–Incremental traffic, with protection

Figure 9. shows the performance of the networks with and without wavelength conversion using Type I and Type II protection under incremental traffic conditions. In the figure, P-I, P-II and P-wc, denote type I (no conversion) wavelength assignment for the lightpaths, type II (no conversion) wavelength assignment for the lightpaths and full wavelength conversion cases respectively. D, denotes the total number of lightpath requests generated in a simulation run. The comparison is done in a similar manner as explained in section III-A.1. The figure shows that the blocking achieved by having wavelength conversion is *consistently lower* than that obtained by having no wavelength conversion, Type I and II wavelength assigned protection. Further we notice that the blocking of Type I protection is much higher than the Type II and the wavelength conversion case.

Table II enumerates the total number of wavelengths, W_{maxD} required to satisfy all the D incremental lightpath requests in each of the cases – no wavelength conversion with Type I, llightpaths, no wavelength conversion with Type II lightpaths and lightpaths setup using wavelength conversion. We enlist only those cases where our simulation results indicate that W_{maxD} with wavelength conversion is different (higher) than the W_{maxD} in the no wavelength conversion with Type II protection. Also notice that W_{maxD} in the no wavelength conversion with Type I protection is always higher. We attribute these results to the similar phenomenon as explained in section III-A.1 and figures 7. and 8., which do not consider protection. The flexibility offered by wavelength conversion in terms of multiple routes for the primary and backup paths, has a negative impact on the performance, as longer routes are now chosen to establish the initial requests. We do not repeat the figures and data for the sake of conciseness.

B.2 Comparison of the blocking with and without wavelength conversions–Dynamic traffic, with protection

In this section we present simulation results that compare the efficiency of wavelength conversion versus no wavelength conversion when the lightpath requests are dynamic in nature. We compare the performance of networks using wavelength conversion to set up primary and backup paths with those using no wavelength conversion in conjunction with Type I and Type II wavelength assignment to set up the backup paths. The performance metric used for comparison is the blocking of each of these schemes under different loads per $s - d$ pair and wavelength, W in the network. Figure 10. shows the result of such a performance comparison. From the figure we first notice that *irrespective* of the values of W and the load per $s - d$ pair, using wavelength conversion achieves a *lower* blocking as opposed to not using wavelength conversion. Further we notice that the blocking of the algorithm using Type I scheme for wavelength assignment to the backup path is the highest, followed by that using a Type II scheme.

The blocking of each of the schemes increases as we increase the load per $s - d$ pair, or decrease W, these results are intuitive. Next, the results show that the difference in blocking of the different schemes when W is small (e.g. $W \leq 4$, but still using wavelength conversion provides the lowest blocking. As W increases (e.g. $W > 4$), the difference in the blockings of each of these schemes becomes more apparent. This is explained as follows, small values of W do not provide enough flexibility to schemes using wavelength conversion, so that they can provide a considerable improvement in network resource usage efficiency compared to similar schemes using no wavelength conversion. Thus at low W, the blocking is mainly determined by the resource limitations. As W increases, wavelength conversion achieves a significantly lower blocking.

Next we analyze the performance of these under varying load per $s - d$ pair. From the figure we notice that for small loads the blocking achieved from using wavelength conversion as opposed to not using wavelength conversion is very similar. This is because for very-small to small loads, network resource availability does not tend to determine the blocking as long as there are at least a minimal number of wavelengths. The difference in blocking of the schemes tend to be maximum for intermediate-load values, with wavelength conversion providing maximum lowering of blocking at such loads. At intermediate-load values, wavelength conversion makes use of its inherent flexibility in choosing wavelengths (and by consequence routes) for the primary and backup paths, which the other schemes do not posses. Further notice that, the larger the value of W, the more the decrease in blocking by using wavelength conversion. It is interesting to note that, alternate routing does not seem to negatively affect the use of wavelength conversion, at intermediate-loads. As the load per $s-d$ pair increases further, again the network resources, W becomes the limiting factor for blocking and all the schemes are confronted with blocking. Note that using wavelength conversion still provides the lowest blocking.

Finally in Figure 11., we plot the wavelength requirements of each of the schemes to satisfy all the requested lightpath demands for different values of load per $s-d$ pair. The figure shows that the wavelength requirement of the scheme using no wavelength conversion with Type I wavelength assignment for protection is the highest, followed by the scheme using Type II wavelength assignment for protection, which is closely followed by the scheme using wavelength conversion to set up the paths. It is interesting to notice that the difference in wavelength requirement between Type II and that using wavelength conversion is minimal. In fact, there are many cases when they are exactly the same. We also highlight the case when the load is 0.1, when the wavelength requirement of Type II is lower, albeit slightly. This is because using wavelength conversion uses longer, resource consuming paths for some of the earlier lightpath demands and hence ends up occupying more wavelengths finally. In addition, in Figures 12-15, we provide other interesting results and insights to show how the *mean primary and backup path lengths* vary for the different protection schemes, varying number of wavelengths and with and without the use of wavelength conversion.

IV. **Summary and Conclusion**

There has been significant debate and research on the use of wavelength conversion in WDM networks. In this study, we examined the need and usefulness of wavelength conversion in WDM networks. We studied and compared the effect on blocking and wavelength requirement in networks employing complete wavelength conversion and those not using any wavelength conversion. The study compared networks which require protection and those that do not require protection, for survivable networks we apply the concept of alternate routing to both the primary and backup paths and compared the efficiency of wavelength conversion. The comparison of these schemes was done under both incremental and dynamic traffic conditions. Using the results from detailed and extensive simulations, we find that the use of wavelength conversion can considerably reduce the blocking of the network, but there is minimal difference in the wavelength requirements of each of these schemes. We then provide insights and explanations of these results. Finally, we believe that several issues in the design of routing protocols and efficient use of wavelength converters still remain unresolved.

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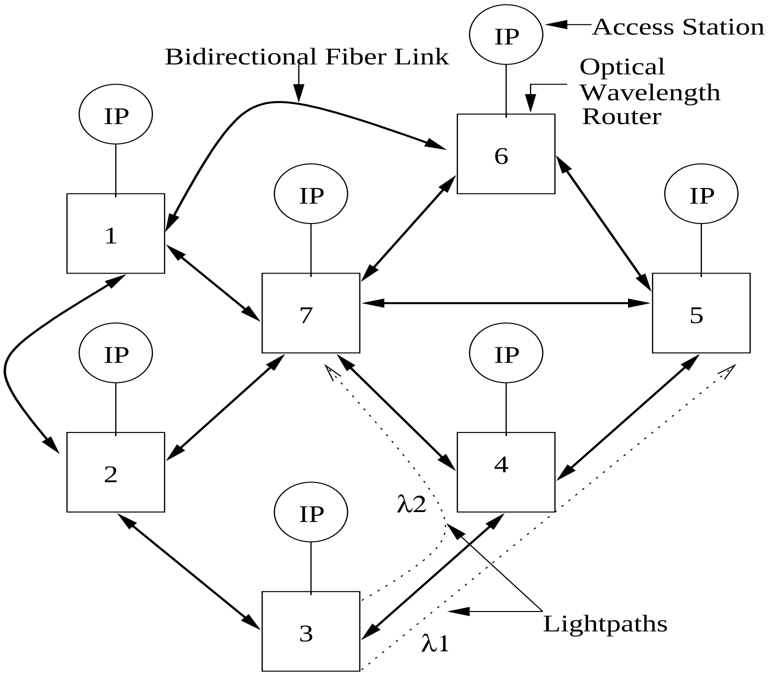
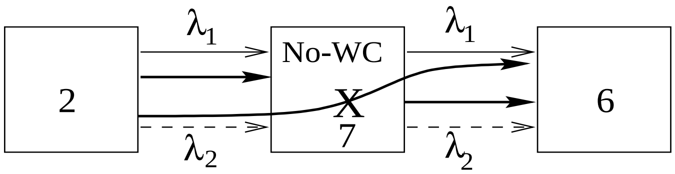
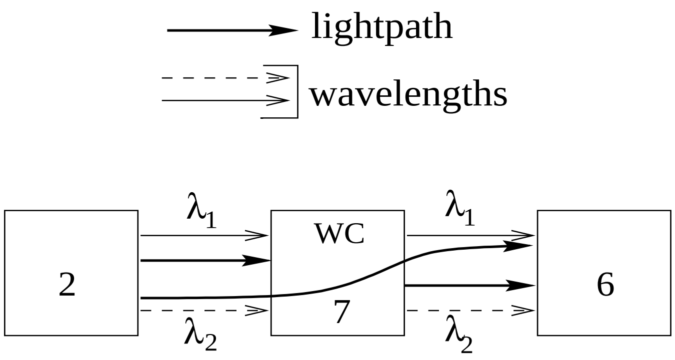


Fig. 1. Architecture of a WDM Network.



(a) Wavelength continous network



(b) Wavelength convertible network

Fig. 2. Wavelength-continuity versus wavelength-convertibility

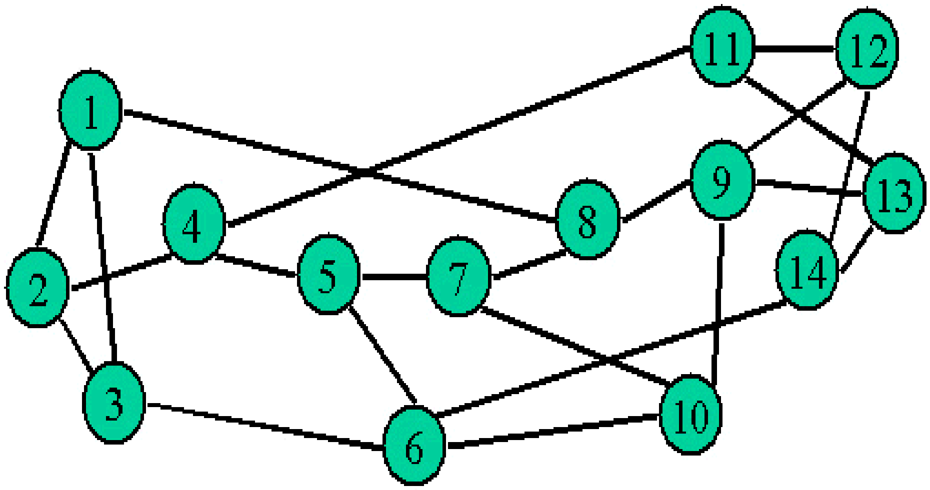


Fig. 3. The 14 nodes 21 link NSF Network used for simulation purposes.

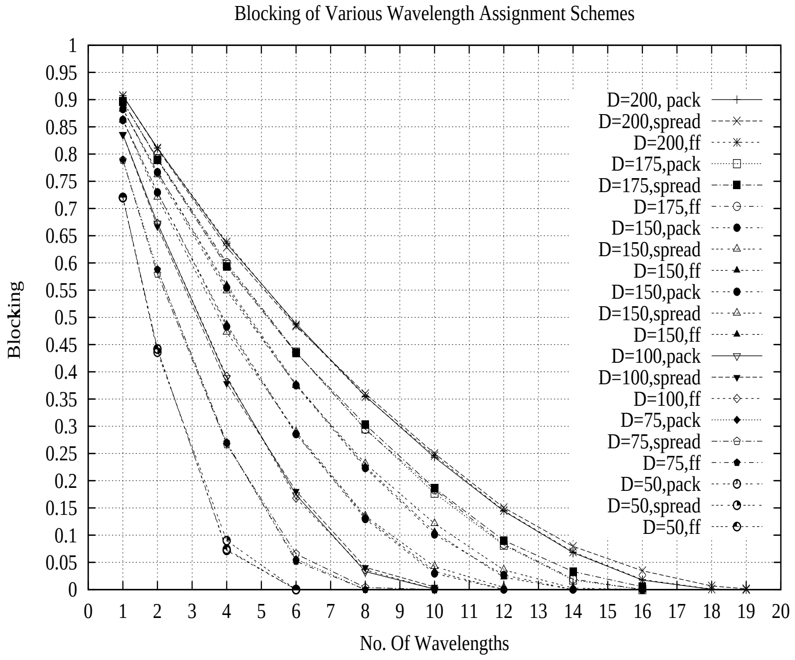


Fig. 4. Blocking of various wavelength assignment schemes–Incremental traffic, no protection.

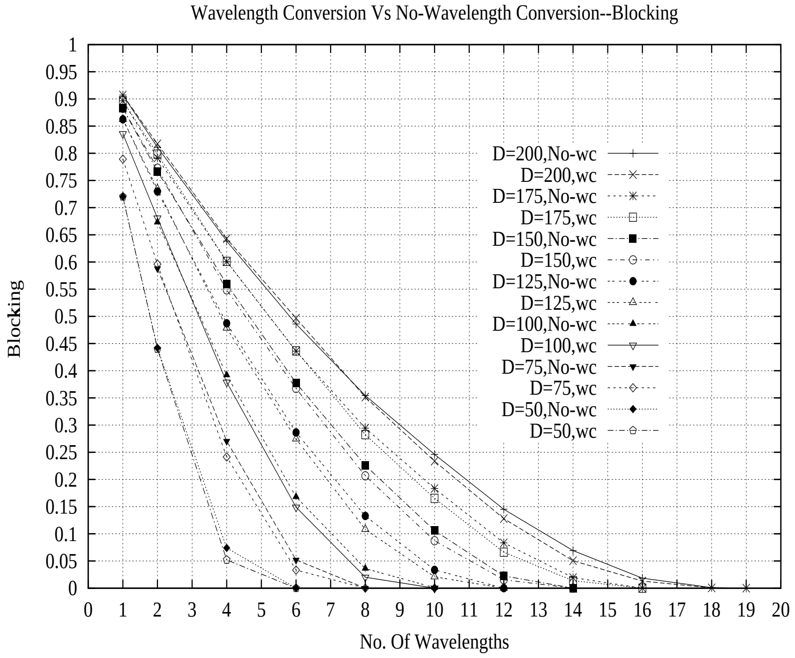


Fig. 5. Effect of having wavelength conversion–Incremental traffic, no protection.

No. of Demands (D)	No. of Wavelengths W_{maxD}	
	No-WC	With-WC
50	6	6
75	8	8
100*	11	10
125	12	12
150	14	14
175	16	16
200	19	19

TABLE I

WAVELENGTH REQUIREMENT FOR 100% THROUGHPUT–INCREMENTAL TRAFFIC, NO PROTECTION. $\star$ – ONLY CASE WHEN WAVELENGTH CONVERSION ALLOWS USE OF FEWER WAVELENGTH.

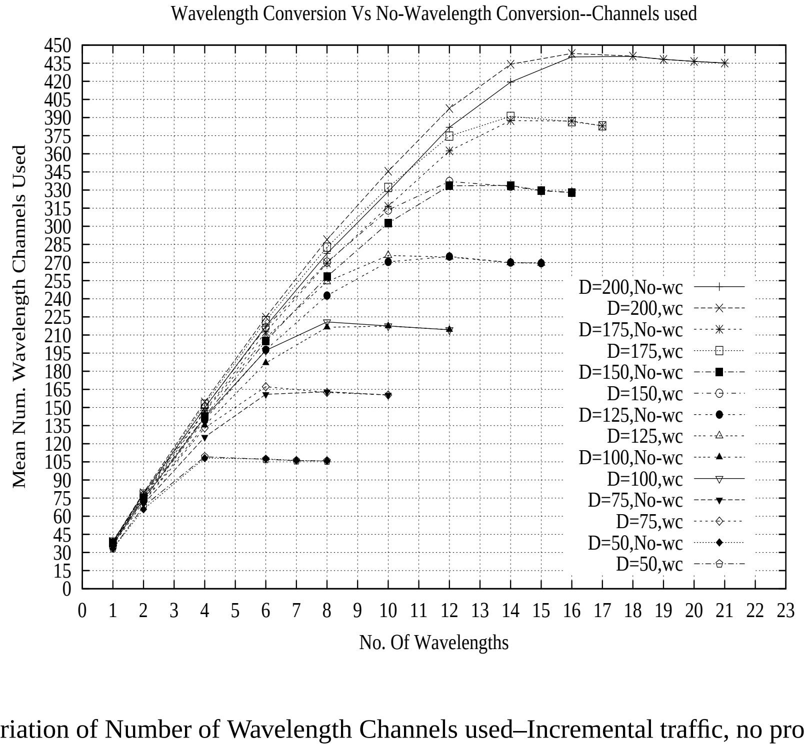


Fig. 6. Variation of Number of Wavelength Channels used–Incremental traffic, no protection.

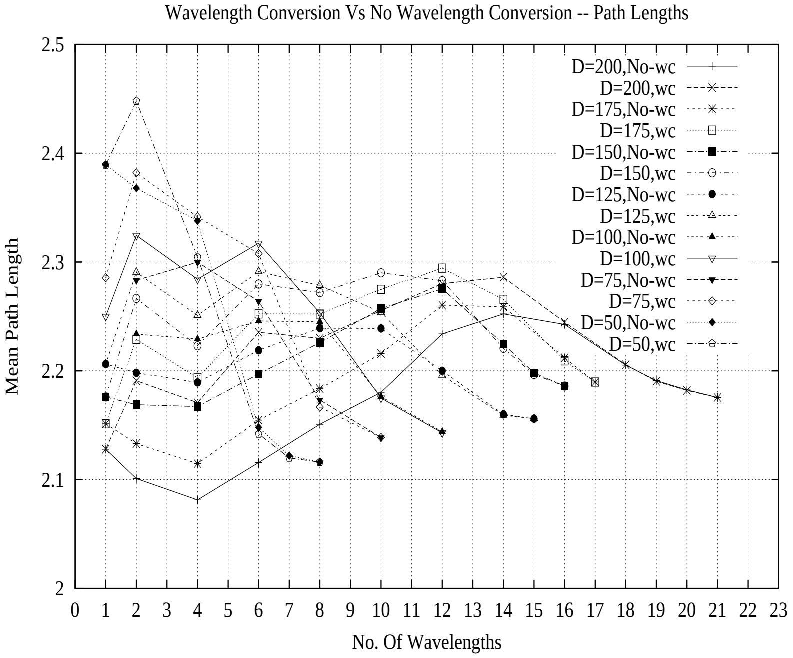


Fig. 7. Variation of the Mean Path Lengths–Incremental traffic, no protection.

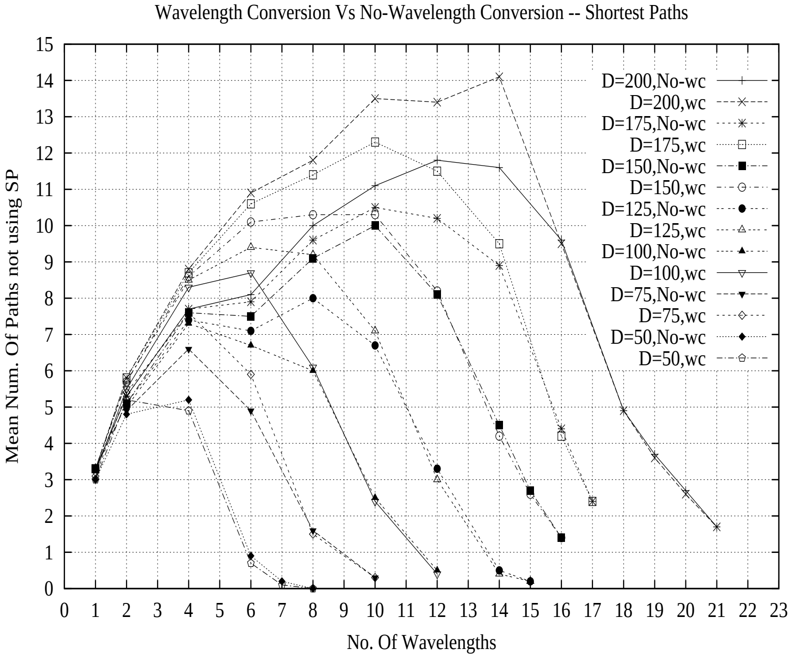


Fig. 8. Average Number of routes not using the Shortest Path–Incremental traffic, no protection.

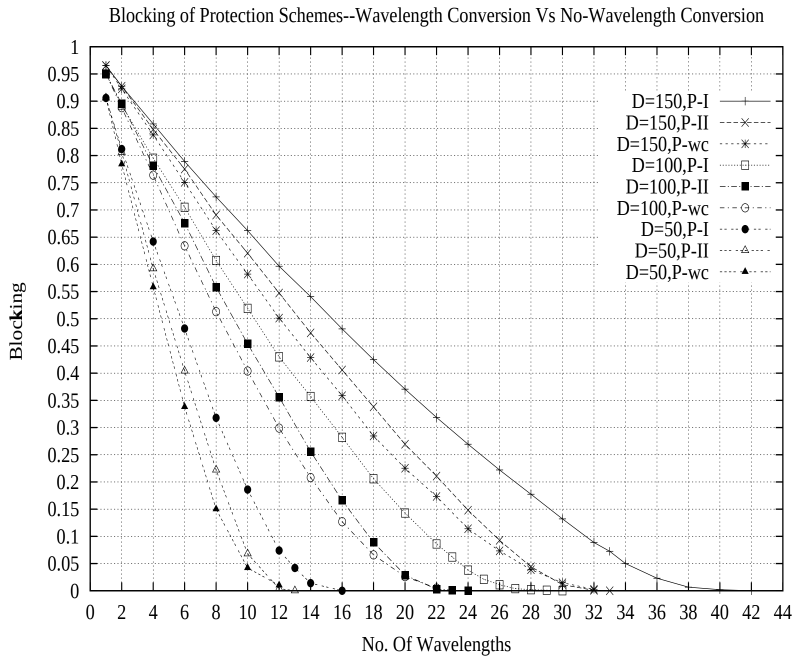


Fig. 9. Blocking probabilities of various protection schemes – Incremental traffic, with protection.

No. of	No. of Wavelengths W_{maxD}		
Demands (D)	No-WC Type I	No-WC Type II	With-WC
$50^\star$	16	13	14
100	30	24	23
$150^\star$	42	33	34

TABLE II

WAVELENGTH REQUIREMENT FOR 100% THROUGHPUT–INCREMENTAL TRAFFIC, WITH PROTECTION. $\star$ – USING WAVELENGTH CONVERSION REQUIRES MORE WAVELENGTHS

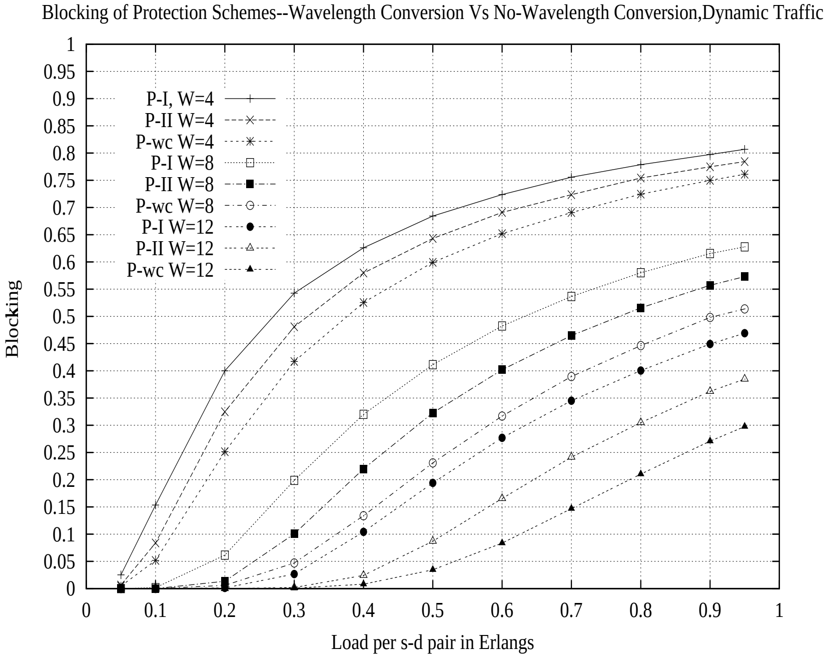


Fig. 10. Blocking probabilities of various protection schemes–Dynamic traffic, with protection.

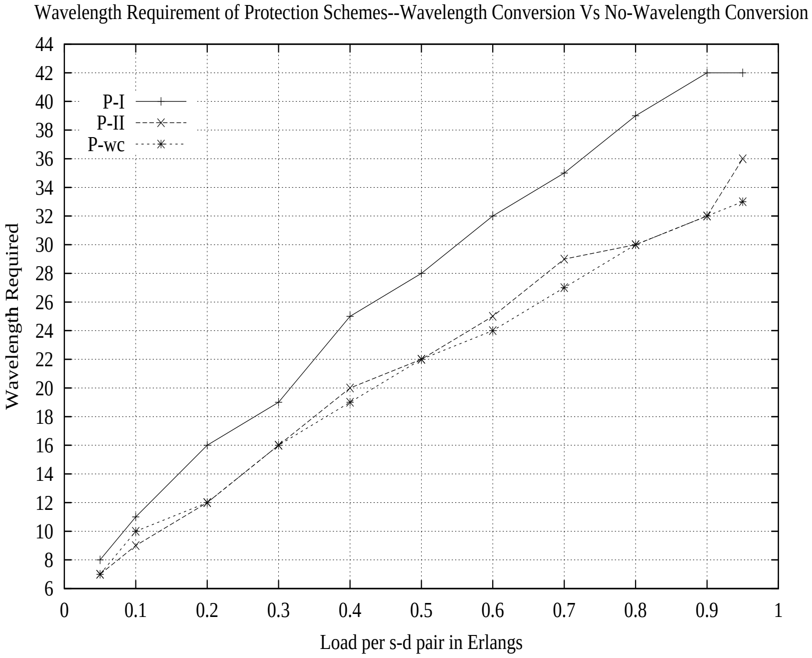


Fig. 11. Wavelength requirements of various protection schemes–Dynamic traffic, with protection.

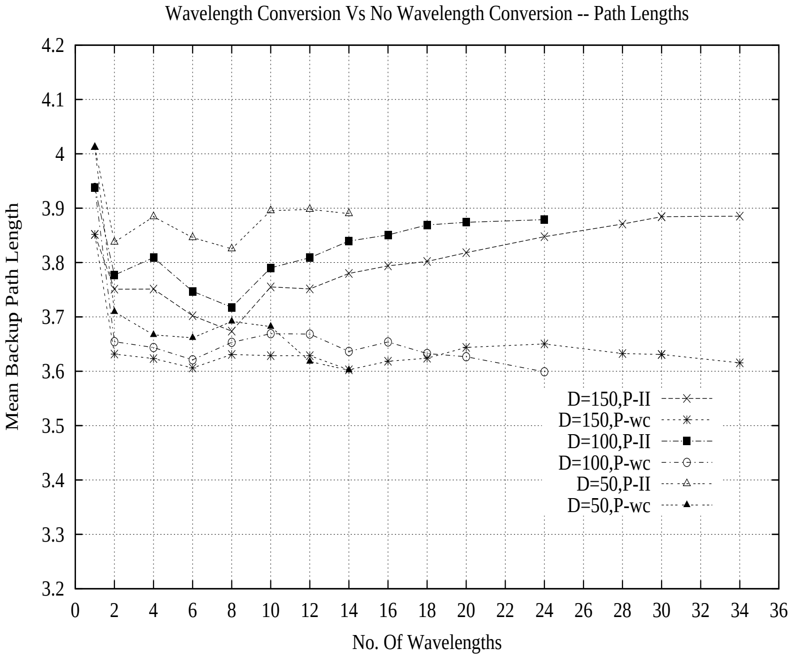


Fig. 12. Average Backup path lengths–Incremental traffic.

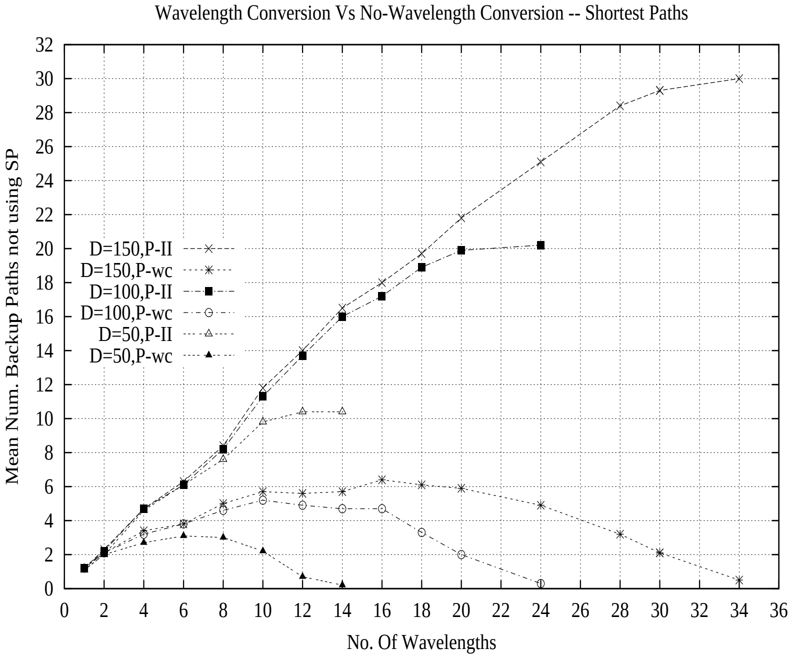


Fig. 13. Average Number of Backup paths not using the Shortest Path–Incremental traffic.

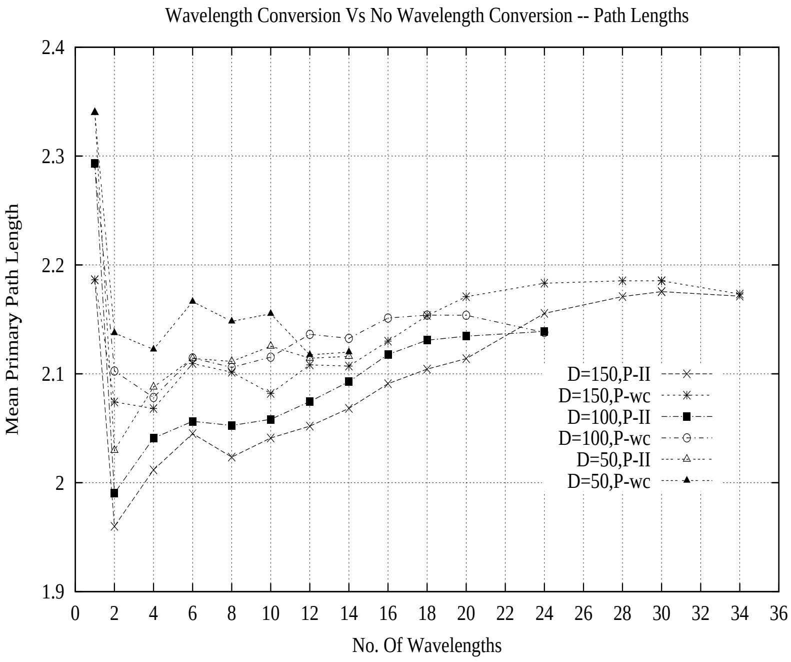


Fig. 14. Average Primary path lengths–Incremental traffic.

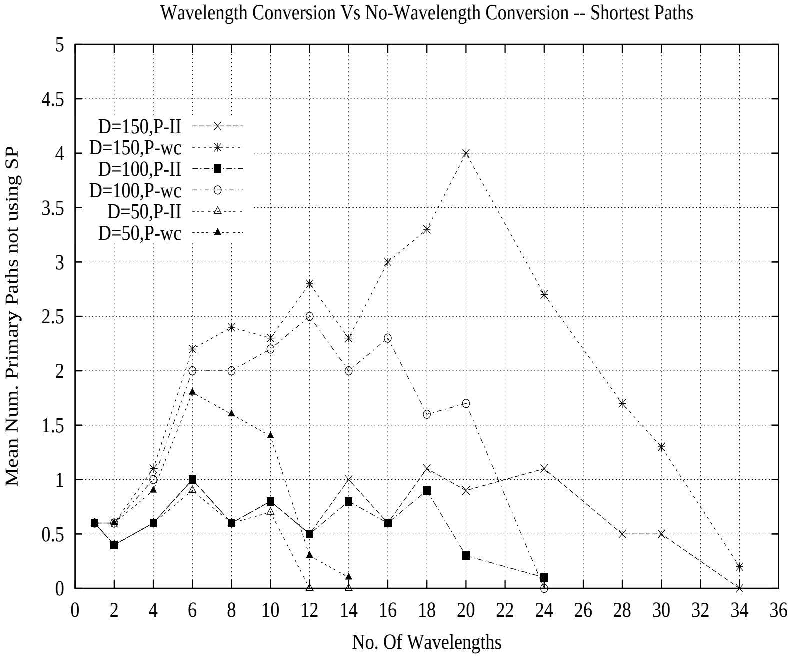


Fig. 15. Average Number of Primary paths not using the Shortest Path–Incremental traffic.