Wavelength Assignment in Optical Networks with Imprecise Network State Information

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***Abstract*— Efficient routing and wavelength assignment (RWA) in wavelength-routed all-optical networks is critical for achieving high efficiency over the backbone links. Extensive research has been conducted to find strategies to solve the RWA problem with exact network state available at the time of path selection. We consider the problem of minimizing the blocking probability in an all-optical network with partial wavelength conversion and with imprecise network state information. We model imprecision in link-state information (wavelength availability) probabilistically and use Markovian analysis to predict the availability of each link based on its previous advertisement and the estimated average traffic over the link. The estimated probabilities are then used to find the most probable path between a source destination pair. We also consider the problem of lightpath establishment with 1+1 protection. We use the same Markovian model to predict the link availability and then use the probabilistic estimate and a modified version of flow algorithm to find two link-disjoint paths between the source and destination. Simulations are conducted to compare the performance of random-fit and the proposed wavelength assignment schemes. We have also performed extensive simulations to study the performance of the proposed flow algorithm. It is observed that the proposed wavelength assignment scheme performs significantly better in terms of blocking probability than conventional wavelength assignment schemes.**

***Index Terms*— Routing and wavelength assignment, partial wavelength conversion, DWDM, optical networks, path selection.**

I. INTRODUCTION

Wavelength division multiplexing (WDM) [1] has recently emerged as a promising technology for the next-generation IP backbone. A wavelength-routed WDM network consists of a set of wavelength routers (WR) connected by fiber links, each of which can support multiple wavelength channels. A WR can switch a wavelength at the input to possibly different wavelengths at the output of the switch based on the wavelength assignment for the connection request and the availability of a wavelength converter at the WR. Two WRs communicate with each other by establishing a "lightpath", which is a direct optical connection that does not involve any intermediate optical-electrical-optical (O-E-O) conversion. The problem of finding a path and wavelength assignment along each link on the path between two WRs is referred to as the *routing and wavelength assignment* problem (RWA). Extensive research has been conducted on this problem [2], [3]. Previously proposed RWA policies mainly differ in the assumptions they make on the availability of wavelength converters and traffic pattern. According to traffic assumptions, RWA schemes can be categorized as static or dynamic. In static RWA, the traffic demand to be set up in the network are known in advance. The primary objective in this case is to accommodate all the demands while minimizing the number of wavelengths used on all links. On the other hand, in dynamic RWA, the arrival process for the lightpath request is assumed to be a random process with some known distribution (e.g., a Poisson process), and each lightpath request is associated with a random holding time (e.g., exponential distribution). The objective in this case is to minimize the total number of blocked calls over a given period of time. One common approach is to address the routing and wavelength assignment problems separately; first, a route from a predetermined set of paths is selected and then an appropriate wavelength assignment is found [4], [5].

Lightpath establishment requires same wavelength to be allocated on all the links along the path. This is called the *wavelength continuity constraint*, which makes modeling of wavelength-routed networks different from traditional circuit-switched networks. The wavelength continuity constraint can be eliminated by using wavelength converters, which can convert the optical signal of one wavelength to another at a WR. Wavelength conversion remains an expensive operation, a WR is typically equipped with a very few number of wavelength converters each of which enables a conversion of a wavelength to a fixed set of wavelengths for established connection over the WR at any time. It has been shown that a WR with limited wavelength conversion capability can achieve performance close to complete wavelength conversion capability [6]. A network in which only a small number of WRs have the capability of limited number of wavelength conversions is called Sparse Wavelength Conversion (SWC) network. SWC network have received much attention [7], [8] because they significantly save the number of wavelength converters and also enable network service providers to build the network gradually. Routing and wavelength assignment for such a network is a very important performance issue.

For efficient routing of lightpaths, each WR must have accurate information about each link; information about the set of available wavelengths on each link and the number

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of wavelength converters available at each node. Link-state advertisements periodically update the network state information at each node. There are several factors that contribute to imprecision of network state information at nodes [9], [10], [11], including information staleness due to the periodic nature of link-state protocols (e.g., OSPF) and topological aggregation. Zhau and Yuan [12] have shown that the frequency of link-state updates significantly affects the blocking probability in lightpath establishment using conventional wavelength assignment strategies such as random-fit and first-fit. The performance of an RWA scheme can significantly degrade if the information about wavelength availability along edges in the network are not accurately known at the time of connection establishment.

In this paper, we model the inaccuracy of network state information probabilistically and develop a new RWA strategy based on coarse estimation of link traffic to find a path and wavelength assignment that has a high probability of being available. In this approach, we use the most probable path routing between a given source-destination pair. We model each wavelength on a link as an *M/M/1/1* Markov process. We calculate the probability that a particular wavelength is available on a link by using the information about link status in the last advertisement and the average arrival rate on the link. We find the probability that atleast one wavelength converter is available and model the occupancy of wavelength converter as a Markov process. We then incorporate these probabilities in a layered graph and find the most probable path and the wavelength assignment between any source-destination pair. We later consider the problem of finding the most probable 1+1 protected path and corresponding wavelength assignment between a source-destination pair. We reuse the same Markovian argument to model the link and wavelength converter availability and then use a modified version of the successive shortest path algorithm described in [13] to find the two link-disjoint paths and wavelength assignment.

The rest of the paper is organized as follows. In Section II, we summarize the literature on wavelength assignment strategies for lightpath selection. We describe our RWA scheme for with and without wavelength conversion in Section III for unprotected circuits. In Section IV, we consider the problem of 1+1 protected lighpath selection and propose a scheme for finding two link-disjoint paths. Section V presents simulation results. Finally, the paper is concluded in Section VI.

II. Conventional Wavelength Assignment Schemes

We now describe the most commonly used wavelength assignment schemes: first-fit and random-fit [14]. Given a wavelength-routed network with W wavelengths on each link the first-fit wavelength assignment labels wavelengths arbitrarily. The wavelengths are listed in an increasing order based on their label values, for example, $\lambda_1, \lambda_2, \lambda_3, \ldots, \lambda_W$. The ordering is identical at all WRs and remains unchanged during network operation. When a switch wishes to select a free wavelength for establishing a connection request, it searches the wavelength list in this order until it finds a free wavelength to assign, or it exhausts the list (resulting in blocking of the connection request).

In the random-fit wavelength assignment scheme, among all *free* wavelengths (say W') available at the time of connection establishment in an outgoing link from the node, one is picked at random.

For wavelength-routed networks with precise network state information at all the nodes (i.e., wavelength assignment is done based on complete knowledge of wavelength availability on each link along the path), first-fit performs significantly better than random-fit [14]. However, when the network state information is not precise, the first-fit policy may result in poor performance [12]. To illustrate, consider the simple network in Figure 1. Suppose all the wavelengths are free in all the links

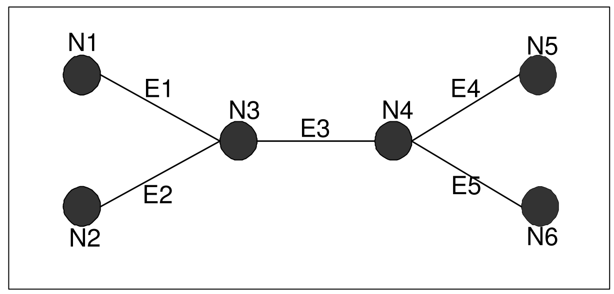


Fig. 1. Example to illustrate first-fit and random-fit wavelength assignment policies.

and a distributed connection establishment is performed (i.e., source node decides which path and wavelength assignment to choose based on the information gathered from previous link-state updates). Nodes N_1 and N_2 need to establish connections to nodes N_5 and N_6, respectively, via link E_3. According to the first-fit assignment scheme, since both WRs search for a free wavelength in the same order, it is highly likely that they pick the same wavelength, causing one of the connections to be dropped at node N_3. With random-fit, the probability that both switches select the same wavelength for the transmission is lower than the first-fit, which leads to better performance [12].

A. Connection Establishment

Conventional approach for path establishment enables a source node to fix the path and the wavelength assignment for a request. If the network state information is imprecise, this can cause significant increase in the blocking probability. In this paper, we use a two pass approach for connection establishment. For a connection establishment request at a source node, the source node finds a path and a wavelength assignment and sends a request message along the path. Each intermediate node along the path appends the exact information about the links and the number of available wavelength converter at the node, forwards this message to the next hop neighbor. The destination node receives the request message and decides if the wavelength assignment suggested by the

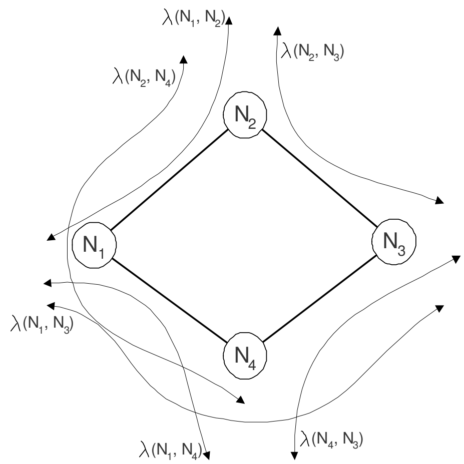


Fig. 2. Example that illustrates the estimation of traffic for all the links.

source node is feasible by using the exact state information of the path. If the wavelength assignment is not feasible then the destination node decides a feasible wavelength assignment along the path based on the exact information received from the request message. If there is a feasible wavelength assignment, the destination node initiates the route request message along the path specifying the wavelength assignment. If there is no feasible wavelength assignment, then the call is blocked and the destination node sends a failure message to the source node. We assume that a wavelength converter can convert any input wavelength to any output wavelength. However, the node may be equipped with only a limited number of such wavelength converters, referred to as partial wavelength conversion capability [15].

III. Wavelength Assignment Under Imprecise Network State Information

We now present our probabilistic RWA scheme. This scheme weighs each wavelength on a link based on its occupancy in the recent past and the average arrival rate over that wavelength. Path and wavelength assignment are performed based on the probability that a wavelength over a given link is available. We first estimate the traffic on a wavelength over a link and then calculate the probability that a wavelength is free based on the average arrival rate on the link and the last update received about the link. Finally, using Dijkstra's shortest path algorithm, we calculate the most probable path and wavelength assignment for a given connection request.

Consider an optical network with N nodes, L links, and W wavelengths per link. For simplicity, we assume that all traffic demands are of one wavelength capacity. We also make the following assumptions for the network architecture, traffic characteristics, and link-state updates:

- The call arrival process for the given network is a Poisson process with a given average rate.
- The holding time of a call is exponentially distributed with a given mean.
- Blocked calls are not reattempted.
- Calls once established may not be reconfigured during the lifetime.
- The maximum number of wavelength converters at a node is known. A wavelength converter can convert any input wavelength to any output wavelength.
- Traffic over a link is equally distributed among all the wavelengths (although this may not be true in general but it makes the analysis tractable).
- A link-state update contains the wavelengths that are occupied on a link and the number of wavelength converters that are free at a node.
- The link-state updates are performed periodically.
- Once a link-state update takes place, it is instantaneously available at all nodes.

Assume that a node u has the capability to convert $W_c(u)$ wavelengths, where $W_c(u) < W$. Let $\lambda(u)$ be the total traffic at node u (which includes add/drop and pass-through traffic), and let μ be the mean holding time of a connection. Let $p(u)$ be the probability that an incoming call request needs a wavelength conversion at node u. Hence, the arrival rate at the wavelength-conversion assembly of node u is $p(u)\lambda(u)$. We later explain the computation of $p(u)$ and $\lambda(u)$ in Section III-B.

A. Estimation of Arrival Rate on a Link

Let $\lambda(u, v)$ be the average total connection arrival rate on link (u, v). We assume that each connection request most likely gets routed along the shortest path from the source to destination. Hence, for estimating $\lambda(u, v)$, we sum the arrival rates of all source-destination pairs whose shortest paths (based on hop count) pass through (u, v). Consider, for example, the network in Figure 2, where each pair of nodes (i, j) has some pre-specified traffic λ_{ij}. We find the shortest path between these nodes based on their hop counts (in case of a tie we choose a path randomly) and then calculate the total traffic on a link. For the link between nodes N_1 and N_4, which is in the shortest path between $(1, 4)$, $(1, 3)$, and $(2, 4)$, the estimated average traffic on this link is $\lambda_{14} + \lambda_{13} + \lambda_{24}$.

Although the RWA scheme proposed in this paper does not route traffic along the shortest (min-hop-count) path, the above estimation approach still works well because with a very high probability the traffic gets routed along the shortest path. We assume that all wavelengths on a link are equally used. The traffic over each wavelength on link (u, v) is given by $\lambda_w(u, v)$ = $\lambda(u, v)/W$. We can also rely on statistical average of the arrival rate on a link over the time. The performance of the probabilistic RWA depends significantly on the estimation of traffic for each link. The estimation of link traffic should be performed periodically after a fixed interval of time based on traffic fluctuations over the network. The network designer can decide a suitable time after which average traffic from all the links in the network gets updated to all the nodes in the network. An appropriate threshold-based approach can also be preformed to reduce the total number of link state updates.

B. Estimation of $p(u)$

We now describe how $p(u)$, the probability that a connection request passing through a node u requires a wavelength conversion at u, is estimated. Suppose that no wavelength converter is available at the node u. Recall that $\lambda_w(u, v)$ is the arrival rate on each wavelength of the link. Consider the blocking probability at each wavelength of the link. The occupancy of a wavelength over a link is modelled as an *M/M/1/1* queuing system. For a given arrival rate $\lambda_w(u, v)$ and an average holding time μ, the blocking probability is given by $p(u, v) = \frac{\lambda_w(u,v)}{\lambda_w(u,v)+\mu}$. Since the arriving traffic over a link is assumed to be equally distributed among all the wavelengths, the blocking probability of all the wavelengths over a link is the same. Hence, if $\lambda(u, v)$ is the total traffic along the link (u, v), then $p(u, v)\lambda(u, v)$ is the total blocked traffic. Such traffic can not be routed on the desired wavelength and, therefore, requires wavelength conversion. Hence, $\lambda(u) = \sum_{v:(u,v)\in E} p(u, v)\lambda(u, v)$ is the total arrival at node u that requires wavelength conversion and $\sum_{v:(u,v)\in E} p(u, v)\lambda(u, v)/\sum_{v:(u,v)\in E} \lambda(u, v)$ is the probability that a connection request passing through u requires wavelength conversion. For example, in Figure 3 the total traffic that requires wavelength conversion is $p(1, 2)\lambda(1, 2) + p(1, 3)\lambda(1, 3) + p(1, 4)\lambda(1, 4) + p(1, 5)\lambda(1, 5)$.

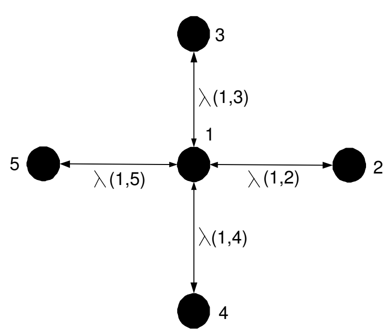


Fig. 3. Example that illustrates the estimation of traffic for a wavelength converter at a node.

C. Step 1: Construction of Expanded Graph

Consider a network graph $G(N, E)$ with W wavelengths per link (we refer such a network as basic network). For each node $u \in N$ in the basic graph, create W nodes in the expanded graph, one for each wavelength supported at node u. Number these expanded nodes as $u_1, u_2, ..., u_W$. For each link $(u, v) \in E$ in the basic graph create directed edges that are feasible in the expanded network, i.e., create directed edges (u_i, v_i) and (v_i, u_i) for $i = 1, 2, ..., W$ in the expanded graph. We refer these edges as direct edges. If there is atleast one wavelength converter at a node u then create directed edges (u_i, u_j) and (u_j, u_i) for $i, j = 1, 2, ..., W$ and $i \neq j$. we refer these edges as wavelength converter edges. Finally, for the given source s and destination d, add two auxiliary nodes s' and d'. Create directed edges $(s', s_i), (s_i, s')$ and $(d', d_i), (d_i, d')$ for $i = 1, 2, ..., W$. We refer to these edges as auxiliary edges. More generally, the expanded network can represent a wavelength assignment for a connection request and can also verify if a wavelength assignment for a path between a source-destination pair is feasible. We show in Figure 4 an example of a basic network and its expanded graph with $W = 2$. In the example network shown, node A has the capability to convert atleast one wavelength to another. Node S is the source node and node T is the destination node.

D. Step 2: Estimation of Wavelength Availability at a Link and a Wavelength Converter at a Node

We now describe how to calculate the probability that an edge in the expanded network is free at the time of connection establishment, which is same as the probability that a wavelength on a link is free in the basic network at the time of connection establishment. Let t_0 be the time of the most recent advertisement for a link and let t_1 be the arrival time of a connection request, $t_1 > t_0$. We model the availability of a particular wavelength on a link as an *M/M/1/1* Markov chain with an arrival rate estimated in Section III-A and a given holding time distribution of the calls. For this Markovian system, let $X(t)$ be the state variable which represents if the wavelength over a link is available or not at time t ($X(t) = 1$ if the wavelength is available and is 0 otherwise). We are interested in calculating the probability of the form $\Pr[X(t_1) = 1|X(t_0)]$, which is the probability that a wavelength over a link is available at time t_1 given its state at time t_0. We assign these probabilities for each wavelength in a link to weigh the direct edges in the expanded graph. We will show later in this section how we evaluate $\Pr[X(t_1) = 1|X(t_0)]$ for a more general case of *M/M/K/K* Markov model.

The probability that wavelength converter edges are available in the expanded network is same as the probability that there is atleast one free wavelength converter at the node at the time of path establishment. We are interested in calculating the probability that if at time t_0 there are i wavelength converters used at a node, then for a connection request at time t_1, there is atleast one wavelength converter available out of the given resources at the node. Recall that the estimated connection

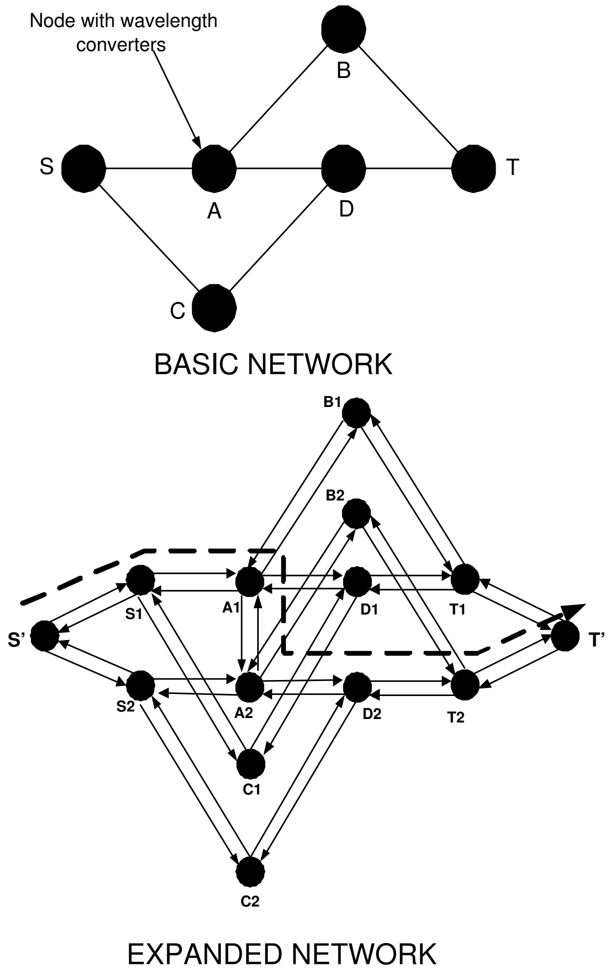


Fig. 4. Construction of expanded network from basic network.

arrival rate at the wavelength converter assembly of a node was obtained in Section III-B. The occupancy of a wavelength converter at a node is modeled as an *M/M/K/K* Markov chain, where K is the number of wavelength converters at the node. Although, the arrival process on the wavelength converter assembly is not a Poisson process, we approximate it for tractability that it can be characterized by a Poisson process. Such a model of wavelength converter assembly as an *M/M/K/K* Markov process is appropriate because we have approximated the arrival process at the wavelength converter assembly with a poisson process, the service rate is exponentially distributed and at a given time only K requests can be served. Let $Y(t)$ be the state variable which represents the number of wavelength converters occupied at any time t. Then, $\{Y(t) : t \geq 0\}$ is a birth-death process with a state space $\{0, 1, 2, ..., W_c\}$. We are interested in the probability $\Pr[Y(t) = W_c|Y(t_0) = i]$, $i = 0, 1, 2, ..., W_c$. Notice that $1 - \Pr[Y(t) = W_c|Y(t_0) = i]$ is the probability that there is at least one free wavelength converter for the new connection. We use this probability as the link weight of the corresponding edge representing wavelength conversion at a node. We now describe how this probability is computed.

For an *M/M/K/K* Markov chain with state variable $Y(t)$, we have [16], [17]:

$$P_{ij}(t_0, t) \stackrel{\text{def}}{=} \Pr[Y(t) = j|Y(t_0) = i] \quad (1)$$

and

$$\mathbb{P}(t_0, t) \stackrel{\text{def}}{=} [P_{ij}(t_0, t)]. \quad (2)$$

$\mathbb{P}(t_0, t)$ is given by,

$$\mathbb{P}(t_0, t) = e^{A(t-t_0)} = \sum_{i=0}^{\infty} \frac{A^i (t - t_0)^i}{i!}. \quad (3)$$

where A is the generator matrix of the Markov chain. Consider, the eigen decomposition of the matrix A as $A = C\Lambda C^{-1}$, where Λ is the diagonal matrix of eigen values $\{\lambda_1, \lambda_2, ..., \lambda_n\}$ and C is a matrix composed of eigenvectors of A. By simple manipulation we get $A^n = C\Lambda^n C^{-1}$. Substituting A^i in equation 3 we get

$$\mathbb{P}(t_0, t) = \sum_{i=0}^{\infty} \frac{C\Lambda^i C^{-1} (t - t_0)^i}{i!},$$

$$\mathbb{P}(t_0, t) = C\{\sum_{i=0}^{\infty} \frac{\Lambda^i (t - t_0)^i}{i!}\}C^{-1}.$$

On further simplification we get

$$\mathbb{P}(t_0,t) = Ce^{\Lambda(t-t_0)}C^{-1}.$$

Notice that, with given eigen values of the generator matrix A, $\mathbb{P}(t,t_0)$ can be evaluated with $\mathcal{O}(n^3)$ complexity, where n is the number of states of the Markov chain. Since, the average arrival rate is fairly constant, the eigen values can be computed once after a new traffic estimation is made and then can be reused.

E. Step 3: Path Selection Algorithm

After step 2 we have associated a probability of link availability (at the time of connection establishment) for each link in the expanded graph. We will find the most probable path between s' and t' in the expanded graph, the path that is most likely to be available at the time of path selection. More specifically, we run the Most probable bandwidth constraint path algorithm (MP-BCP) proposed in [11] to find the most probable path between s' and t'. The MP-BCP algorithm is a modified version of Dijkstra's algorithm. Specifically, the algorithm take the negative of logarithm of probability of link availability as the link weight, i.e., if $p(i,j)$ is the probability that a link (i,j) is available, then $w(i,j) = -log(p(i,j))$ is the weight of the link (i,j). For the resultant weighted graph Dijkstra's algorithm is used to find the shortest path between s and t.

For finding the route and wavelength assignment in the basic graph from the path returned by the MP-BCP algorithm, we apply the following procedure. If the two nodes corresponding to an edge in the path returned by the MP-BCP algorithm are associated with two different nodes in the basic network then use the wavelength number associated with these nodes for the link associated in the basic network. For example in Figure 5, the edge $(A1,A3)$ represents a wavelength conversion at node A. Similarly, the edge $(S1,A1)$ represents wavelength W_1 getting occupied on the link (S,A) in the basic network. The source node sends a request packet along the chosen path. Each node along the path forwards the request packet towards the destination node and appends it with the exact information about its adjacent links. The destination node checks if the required wavelength assignment is feasible (i.e., respective wavelengths are available along the links), otherwise it finds a wavelength assignment along that path based on the exact information received in the request packet. If there is no feasible wavelength assignment then the destination sends a failure packet to the source (this is considered as blocking).

F. Complexity

For a given network with N nodes, M links, W wavelengths per link, and L nodes with wavelength conversion capability, there are NW nodes and $2(MW+LW(W-1))$ links in the expanded network. For each link in the expanded network, we calculate the probability that the link is available. For the direct edges, the complexity of calculating the probability is $\mathcal{O}(1)$. For wavelength conversion edges the complexity of calculating the link availability is $\mathcal{O}(W^3)$ per node. Hence, in the worst-case the total complexity of calculating the probabilities for the complete expanded network is $\mathcal{O}(MW+LW^3)$. We know that $L=\mathcal{O}(N)$ ($L=N$ when all the nodes have wavelength conversion capability) and $M = \mathcal{O}(N^2)$ ($M = N^2$ for a fully connected network). The total complexity for calculating the probabilities is $\mathcal{O}(N^2W + NW^3)$. For finding the most probable path in the network, we use the MP-BCP algorithm, which is a modified version of Dijkstra's algorithm. For a network of $\mathcal{O}(NW)$ nodes, the complexity of finding the most probable feasible path is $\mathcal{O}(NW\log(NW))$. Hence, the total complexity of the proposed wavelength assignment scheme is $\mathcal{O}(N^2W + NW^3)$+$\mathcal{O}(NW\log(NW))$. The complexity is pseudo-polynomial because it depends on the value of the input parameter W. W is the number of wavelengths supported in the system and can not go out of bounds.

IV. Protected Path Selection

The problem of lighpath selection and the corresponding wavelength assignment for protected circuits has been investigated in [18] with complete link-state information available at all the nodes. We now consider the routing and wavelength assignment problem for 1+1 protected lightpath circuits under inaccurate network state information. We use a modified version of successive shortest path (SSP) algorithm described in [13] to solve the max-flow min-cost problem. We use the first two iterations of the SSP algorithm which results in an aggregate flow of two units. We follow the same preprocessing steps and step 1, 2, and 3 described in Section III to find the shortest path between auxiliary source and destination. We assume that the capacity of each direct edge in the expanded graph is one unit. We also assume that auxiliary edges have infinite capacity. After finding the first shortest path, we augment one unit of flow along the shortest path and construct the residual expanded network (described in Section IV-A). We then find the second shortest path in the residual expanded network. The algorithm augments one unit of flow along the second shortest path. Finally, the flow is aggregated to find the two link-disjoint paths. By using a slightly different forward and backward arcs in the residual expanded graph the final paths returned by the flow aggregation are link-disjoint in the basic network.

A. Step 4: Residual Graph Construction

We now describe the construction of residual graph after finding the first shortest path in the expanded network and augmenting one unit of flow along the shortest path. For each direct edge (u_k,v_k) in the first shortest path remove all the edges in the expanded network that correspond to (u,v) in the basic network, i.e. remove edges (u_i,v_i) and (v_i,u_i) for $i = 1,2,...,W$. Add a direct edge (v_k,u_k) in the expanded network with a unit capacity. For a wavelength converter edge (u_i,u_j) in the shortest path, keep all the wavelength converter edges. For an edge (i,j) (with weight $w(i,j)$) of the first shortest path in the expanded network, the weight of the edge (j,i) in the residual network is $-w(i,j)$.

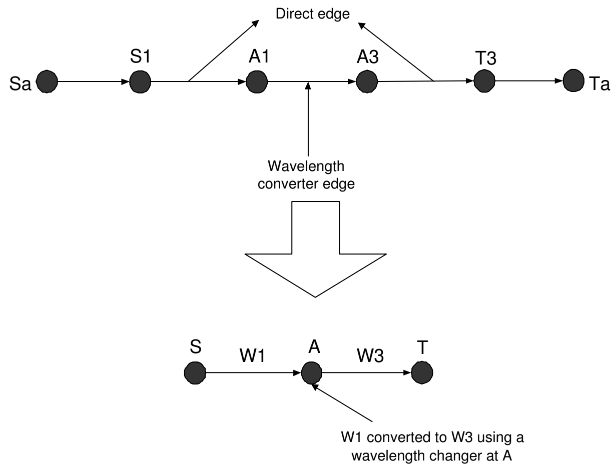


Fig. 5. Construction of route and wavelength assignment in basic graph using a path from expanded network.

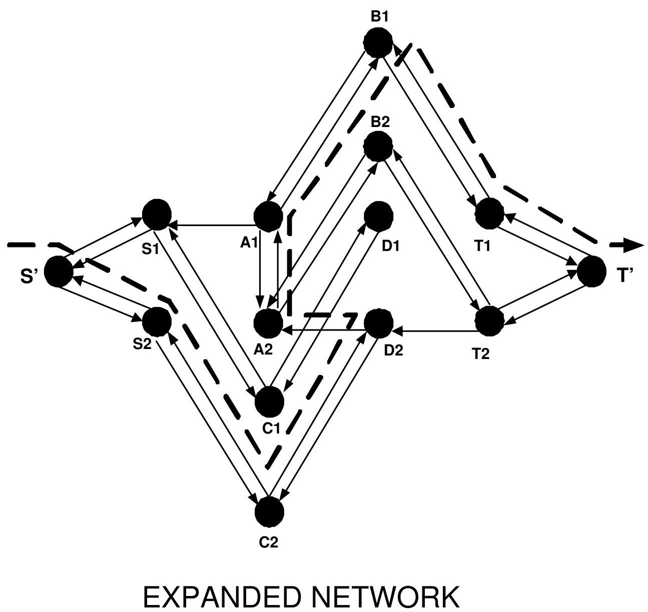


Fig. 6. Construction of residual graph after finding the first shortest path.

The resultant network is the residual expanded network. For example, consider the expanded network shown in Figure 4 with the first shortest path between the two auxiliary nodes S' and T' be $S' \rightarrow S1 \rightarrow A1 \rightarrow A2 \rightarrow D2 \rightarrow T2 \rightarrow T'$. The resultant residual expanded network after augmenting one unit of flow along the first shortest path is shown in Figure 6.

B. Step 5: Path Selection Over Residual Expanded Network and Flow Aggregation

For the constructed residual expanded graph, we find the second shortest path between the two auxiliary nodes. Any standard shortest path algorithm which finds the shortest path even with the existence of negative link weights can be used. Notice that, some of the arcs in the residual expanded network have negative link weights but it can easily be proved that these negative weights do not result in a negative weight cycle. After finding the shortest path we aggregate the flows along the two shortest paths, cancelling any pair of arc flow which are opposite of each other. For example, the second shortest path ($S' \rightarrow S2 \rightarrow C2 \rightarrow D2 \rightarrow A2 \rightarrow A1 \rightarrow B1 \rightarrow T1 \rightarrow T'$) in the resultant residual network is shown in Figure 6. The flow aggregation for the two shortest paths obtained in step 4 and 5 is shown in Figure 7. The reverse flow along two directed links gets cancelled and the resultant flow along arc represents two link disjoint paths as proved in the theorem below.

Theorem 1: The flow along various links in the expanded network results in two link-disjoint paths in the basic network.

Proof: To prove the theorem we consider two cases: first, when the two shortest paths in the expanded network are link-disjoint in the basic network and second, when the

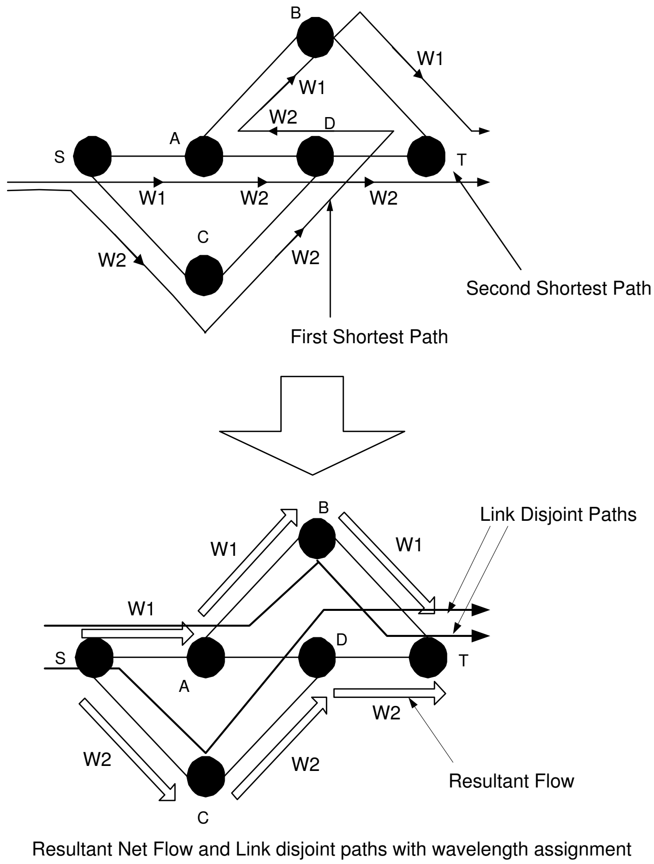


Fig. 7. Construction of link disjoint path from the two shortest paths.

they are not link-disjoint in the basic network. In the first case we do not need to prove anything. In the second case, where the two shortest paths have atleast a link in common, we will show that the flow along the common link cancel each other and the net flow along that link is zero. Let the common link be (u, v) in the basic network. Let (u_i, v_i) be the direct edge in the expanded network used by the first shortest path. Due to the construction of residual expanded network, the only direct edge corresponding to (u, v) in the basic network that is present among (u_k, v_k), (v_k, u_k) for k = $1, 2, ..., W$ in the residual expanded network is the direct edge (v_i, u_i). Hence, if the second shortest path passes through link (u, v) in the basic network, it must pass (v_i, u_i) in the residual expanded network. The direction of flow in this case will be opposite w.r.t. the direction of flow in the first shortest path along (u_i, v_i). Hence, when we aggregate the flows along the two shortest paths, the flows will cancel along all common edges. Therefore, the resultant paths are link-disjoint. ∎

C. Complexity

We now discuss the complexity of finding the 1+1 protected path. Step 1-4 have the complexity of $\mathcal{O}(N^2W + NW^3)$+$\mathcal{O}(NW \log(NW))$ as discussed in Section III-F. The worst-case complexity of Step 5 is $\mathcal{O}(NW)$, because the shortest path in the expanded network has a maximum of $\mathcal{O}(N)$ direct edges. The worst-case complexity of Step 6 is $\mathcal{O}(NW \log(NW))$, which is the complexity of running a Dijkstra's algorithm over the expanded network. Hence the overall complexity of finding 1+1 protected path is $\mathcal{O}(N^2W + NW^3)$+$\mathcal{O}(NW \log(NW))$.

V. Simulation Results

In this section, we describe the simulation model and compare the performance of the probabilistic wavelength assignment policy with the random-fit approach. We use three topologies of different link densities. ARPA-Net (21 Nodes, 26 Links, and 6 wavelengths per link) and Random-5 (25 Nodes, 65 Links, and 6 wavelengths per link) and Random-6 (25 Nodes, 153 Links, and 6 wavelengths per link) topologies. Random-5 and Random-6 are random graphs generated using waxman's method presented in [19]. The three topologies considered represent a sparse (ARPA-Net), a lightly connected (Random-5) and a densely connected network (Random-6). In our simulations, we generate calls randomly for different source-destination pairs. Each call is assigned an exponentially distributed holding time duration and has a traffic demand of one wavelength. In case of random-fit wavelength assignment scheme, source node uses the most recently received advertisement for a link and considers it as exact information for finding the path and wavelength assignment. In case of PWA, the algorithm uses link-state updates to find the most probable path and wavelength assignment using the information about the average arrival rate at a link. After finding the path and the wavelength assignment in both the methods, a request packet is generated and then the destination node figures out the best wavelength assignment for the connection request. We vary the advertisement time, i.e. the periodic time after which an advertisement is made about the state of all the links and simulate the performance of random-fit and the probabilistic wavelength assignment scheme for various call arrival rate in the network. In an advertisement, each node updates all other nodes about the available wavelengths and average traffic observed over all its adjacent links.

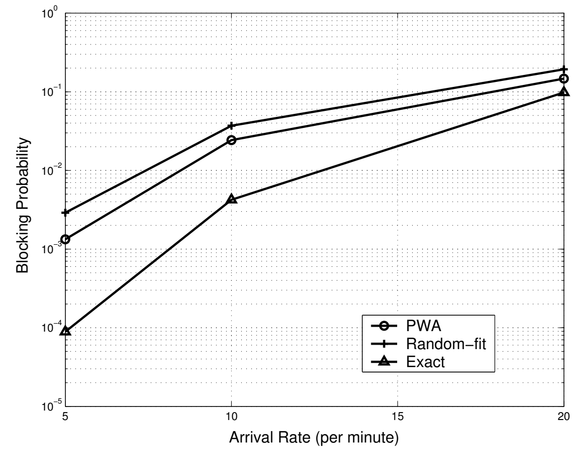
Figure 8 shows the performance of random-fit and probabilistic wavelength assignment scheme in terms of blocking probability vs. arrival rate, for an advertisement time of 10 mins for the three topologies considered. It is observed that the probabilistic wavelength assignment scheme performs consistently better than the random-fit wavelength assignment. We also compare the absolute minimum that can be achieved in all these cases by simulating the connection establishment process when exact network state information is available with the source, at the time of connection establishment. In this case, the path is chosen as the available shortest path and the wavelength assignment is chosen randomly. The blocking probability obtained by using the exact network state information gives an appropriate lower bound for the random fit and PWA schemes.

In Figure 9, we study the performance of random-fit and PWA schemes in terms of blocking probability by varying the advertisement time for an arrival rate of 30 per minute. The performance of PWA scheme is significantly better than the random-fit scheme for all advertisement times considered. It is observed that the blocking probability in all the schemes initially increases with the advertisement time and remains fairly constant for higher values of advertisement times. It should be noted that if the blocking probability achieved with higher advertisement times is acceptable then it is better not to update the network state information because late updates will not significantly change the blocking performance of the system.

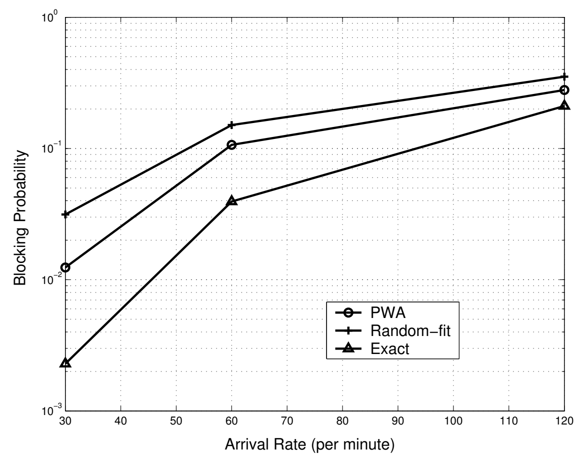
In Figure 10, we study the performance of random-fit and PWA schemes in terms of blocking probability for different arrival rates for Random-6 topology and for an advertisement time of 10 mins for 1+1 protected connection establishment. The PWA scheme performs consistently better than the random-fit approach. We also study the performance of PWA and random-fit schemes for different advertisement times in Figure 11 for arrival rate of 50 calls per minute. It should be noted that the performance of PWA scheme is significantly better than the random fit strategy.

VI. CONCLUSION

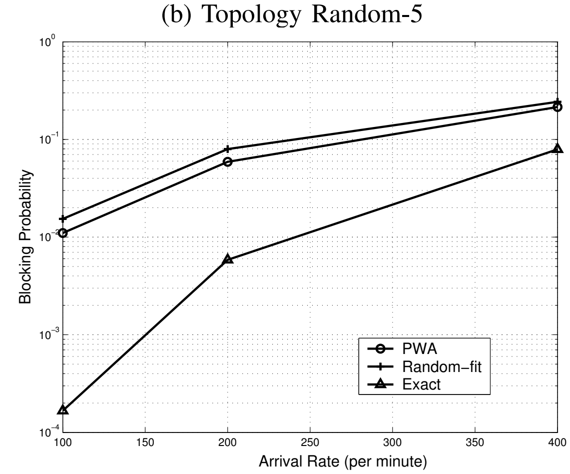
In this paper, we investigated the routing and wavelength assignment problem in a wavelength-routed network with imprecise network state information. We then propose a new



(a) Topology: Arpanet



(b) Topology Random-5



(c) Topology Random-6

Fig. 8. Blocking Probability vs. Arrival Rate for an advertisement time of 10 minutes.

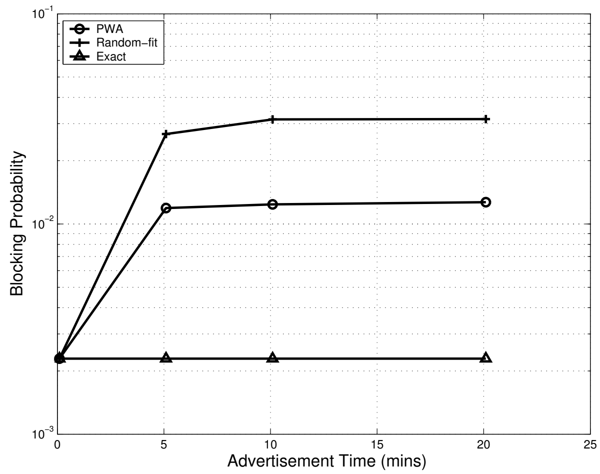


Fig. 9. Blocking Probability vs. Advertisement time for Random-5 topology, and an arrival rate of 30 connections per minute.

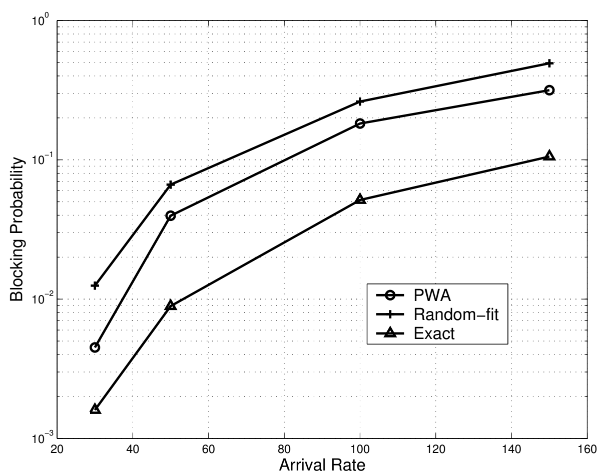


Fig. 10. Blocking Probability vs. Arrival Rate for 1+1 protected traffic (Random-6 topology and an advertisement time of 10 minutes).

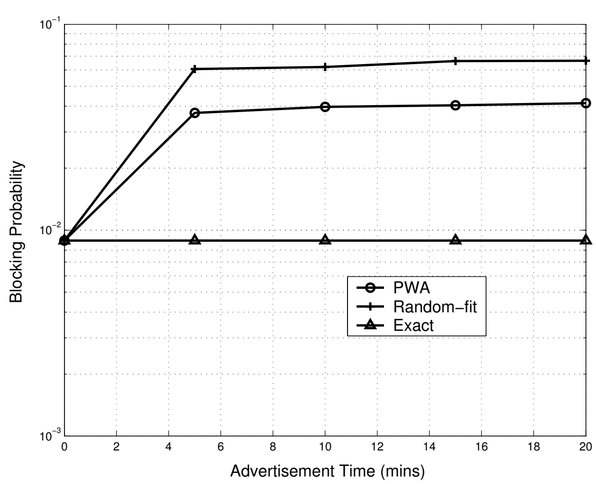


Fig. 11. Blocking Probability vs. Advertisement time for 1+1 protected traffic (Random-6 topology and an arrival rate of 50 connections per minute).

probabilistic path selection approach based on traffic estimation and Markovian prediction of link availability. The complexity of selecting a path using probabilistic path selection is polynomial in the number of nodes and wavelengths ($\mathcal{O}(N^2W + NW^3)+\mathcal{O}(NW\log(NW))$). The performance of the proposed path selection policy is compared with the random-fit scheme. It is observed that there is a significant drop in blocking probability if we use the probabilistic path selection scheme for routing and wavelength assignment.

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