On Optimal Converter Placement in Wavelength-Routed Networks

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Abstract—Wavelength converters increase the traffic-carrying capacity of circuit-switched optical networks by relaxing the wavelength continuity constraints. In this paper, we consider the problem of optimally placing a given number of wavelength converters on a path to minimize the call-blocking probability. Using a simple performance model, we first prove that uniform spacing of converters is optimal for the end-to-end performance when link loads are uniform and independent. We then show that significant gains are achievable with optimal placement compared to random placement. For nonuniform link loads, we provide a dynamic programming algorithm for the optimal placement and compare the performance with random and uniform placement. Optimal solutions for bus and ring topologies are also presented. Finally, we discuss the effect of the traffic model on the placement decision.

Index Terms—Call blocking performance, optimal converter placement, sparse wavelength conversion, wavelength-routing.

I. INTRODUCTION

ALL-OPTICAL wavelength-routing networks have been studied with great interest because of their promise as backbone wide area networks (WAN’s). The impact of wavelength converters on the performance of such networks has been of particular interest to the optical networking community. The potential benefits of wavelength conversion have been studied through different traffic models [1]–[9]. Performance of distributed control algorithms for lightpath establishment with and without wavelength conversion has been discussed in [10]. The high cost of all-optical wavelength conversion has led to some recent focus on networks with sparse or limited wavelength conversion [4]–[7]. In a network with limited wavelength conversion, each routing node can perform a limited number of wavelength conversions simultaneously [5]–[7]. In contrast, in a network with sparse wavelength conversion, a fraction of routing nodes are equipped with wavelength converters capable of performing an arbitrary number of simultaneous wavelength conversions [4]. In this paper, we focus our attention on networks with sparse wavelength conversion. Analytical models were presented in [4] for evaluating the blocking performance of such networks under dynamic Poisson traffic; these methods employed ensemble averaging over all possible placements of a random number of converters with a given mean. Here, we consider a closely related and more practical problem. Given a network topology, a certain number of converters, and traffic statistics between the nodes, the problem of interest is the optimal placement of converters in the network. There are several approaches to optimal converter placement depending on the optimality criterion and the traffic model.

In one approach, the maximum offered traffic (the number of sessions) \( \lambda_{sd} \) for all node pairs \( (s,d) \) is given. Let \( M_{sd} \) be the actual number of sessions established between \( s \) and \( d \). The problem is to determine the converter locations so that \( \sum_{s,d} M_{sd} \) is maximized subject to the wavelength continuity constraint on segments between successive converters and traffic demand constraints, i.e., \( M_{sd} \leq \lambda_{sd} \). Note that this problem contains the routing and wavelength assignment (RWA) problem as a subproblem. The placement problem can be posed as an integer-linear programming problem similar to the formulation given in [11], which in fact is a special case of the problem at hand. Previous work has shown that this special case is an NP-complete problem for arbitrary topologies, and even for rings [12]. Note, however, that in the case of a bus network, the converter placement problem is trivial in this formulation. This is because any set of sessions that can be accommodated with full wavelength conversion (where every node has a wavelength converter) can also be accommodated with no wavelength conversion. This follows from the properties of an interval graph [13].

In this paper, we assume a dynamic traffic model in which connections arrive and depart from the network as a random point process. The objective is to place the given number of converters in the network such that the network call blocking probability is minimized. A brute force approach to this problem is computationally infeasible since there are \( \binom{N}{K} \) possibilities for placing \( K \) converters over an \( N \)-node network. (A more efficient exhaustive search algorithm has been suggested in [14].) We present a dynamic programming solution for minimizing the blocking probability on a path. This solution is then generalized to bus and ring networks. The time complexities of the proposed algorithms are \( O(N^2K) \) for...
the bus and $O(N^3K)$ for the ring, which are significantly less than the $O(N^K)$ complexity of exhaustive search. Moreover, our solution to the problem can be used in conjunction with any traffic model for dynamic traffic. For arbitrary topologies, heuristics based on the approaches presented here may need to be used. Some heuristic approaches to this problem in arbitrary topologies have been suggested by [15]–[17].

There are many factors which affect the optimal solution to the converter placement problem. Intuition would suggest that converters be placed at nodes which process the highest amount of transit traffic. However, placing a converter at a node that has a high transit traffic rate but does very little mixing (or switching) of traffic may not be desirable, as it would result in a simple swapping of the assigned wavelengths. On the other hand, if the transit traffic rate at a node is very low, then the optimal strategy may not place a converter at that node, even if it mixes a significant amount of traffic. Furthermore, the distances between converters are likely to affect the optimal placement. As the distance between converters increases, the blocking probability increases. Since the number of available converters is limited, a judicious placement of converters is necessary to balance these trade-offs.

In Section II, we consider a single path of length $H$ and assume link load independence. There are several motivating factors for studying the placement problem on a path. Firstly, since long paths have high blocking probabilities, quality-of-service (QoS) considerations may require that converters be optimally placed so that blocking probabilities on longer paths are minimized. Secondly, converter placement in an arbitrary network is a complex problem in general, and suboptimal heuristics to this problem would probably be necessary. In such a case, we envisage the overall problem to be broken into several subproblems. The placement process could proceed in multiple phases where at each phase a certain number of converters are placed optimally on a path. Note, however, that because of the interaction between the paths, the phases may need to be iterated over to obtain a satisfactory solution. Finally, as we show in this paper, the solutions to the placement problem on a path can be extended to two important network topologies—the bus and the ring.

In Section II, we first consider uniform link loads on the path and show that uniformly spaced converters minimize the blocking probability of an end-to-end call. We also derive a recurrence relation for the blocking performance when the converters are placed randomly along the path. We then obtain an approximate expression for the utilization gain achievable with uniform/optimal placement relative to random placement and show that significant gains are achievable with a good placement policy. Next, we relax the uniform link load assumption and obtain the optimal solution via dynamic programming. In the last part of the section, we extend the optimality criterion to take into account the average blocking probability $(P_b)$ over all source-destination $(s,d)$ pairs along the path.

In Section III, we consider a bus network. The difference between this topology and the path considered in Section II is that the traffic on the links is entirely due to the traffic originating at the nodes of the bus network, whereas the link traffic in the path is possibly due to merging traffic from other parts of the network. The low connectivity of the bus network induces a strong correlation among link loads. This correlation is taken into account by modifying the traffic model accordingly. The solution in Section III can also be used to optimally place converters in a path of an arbitrary network where link-load independence is not justified. In Section IV, we extend the dynamic programming solution for the path to obtain the optimal converter placement for the ring topology.

The blocking performance model we use primarily in this paper is the wavelength independence model of [1] which we refer to as the Binomial model because the number of busy wavelengths on a link is assumed to be binomially distributed. A similar model was introduced earlier in the context of time division multiplexed optical interconnections in multiprocessor systems [19]. As mentioned earlier, our solution technique is independent of the link traffic model and we compare some of the results obtained with the binomial model and the Poisson model of [4] in Section V. Conclusions are presented in Section VI.

II. CONVERTER PLACEMENT IN A PATH

In this section, we consider a path of length $H$ with negligible correlation between link loads. We first assume uniform link loads and derive an approximate expression for the utilization gain achievable by optimal converter placement relative to a random placement of a given number of converters. We start by considering an end-to-end call on a path of length $H$ shown in Fig. 1. Let the nodes along this path be numbered $0, 1, \ldots, H$, and let the link loads per wavelength be $\rho_{i,j} = 0, \ldots, H - 1$. That is, the probability that a given wavelength is occupied on link $i$ is $\rho_i$, and the wavelength occupancy events are assumed to be statistically independent of other wavelengths on the same link and on other links. (This is the binomial model of [1].)

A. Uniform Link Loads

First suppose that all the $\rho_i$’s are equal. The number of wavelengths on each link is assumed to be $F$ and each link has a single fiber. The performance model we use is obtained by assuming that each wavelength is used on a link with probability $\rho$ independently of the other wavelengths $^2$ [1]. The goal is to place $K$ converters among the $H - 1$ intermediate

1 Note that this model is different from the binomial model of [18], in which it is the steady-state distribution of busy wavelengths on a link that is binomial as opposed to the occupancy distribution upon arrival.

2 The average number of busy wavelengths on a link using this model is $F\rho$, the same as would be obtained by assuming Poisson traffic and ignoring the effects of blocking on carried load. This model will serve our purpose here. More accurate numerical results for Poisson traffic could be obtained by choosing the wavelength occupation probability as in [2]. The assumption of random wavelength assignment to an arriving connection is implicit in this model.
Define a segment to be the set of links between two consecutive converter nodes. Let $l_i$ be the hop-length of the $i$th segment, $i = 0, \ldots, K$ (nodes 0 and $H$ can be assumed to contain dummy converters). Let $L_K = (l_0, l_1, \ldots, l_{K-1}, l_K)$, where $\sum_{i=0}^{K} l_i = H$, be the vector denoting the hop-lengths of the $K+1$ segments, called the length vector henceforth. The success probability of the call in a sub-segment of length $l_i$ denoted by $f(l_i)$ is given by

$$f(l) = 1 - (1 - \bar{p})^F \quad (1)$$

where $\bar{p} = 1 - \rho$.

The success probability of the end-to-end call when the length vector is $L_K$ is denoted by $S(L_K)$, and is given by

$$S(L_K) = \prod_{i=0}^{K} f(l_i). \quad (2)$$

Let the length vector in the optimal placement be $L_K^{opt}$, i.e.,

$$S_{opt}(H, K) = S(L_K^{opt}) = \max_{L_K} S(L_K),$$

where $S_{opt}$ denotes the success probability of an end-to-end call when $K$ converters are optimally placed along an $H$-hop path. Suppose that $(K+1)$ divides $H$. We show below that $L_K^{opt} = H/(K+1), i = 0, 1, \ldots, K$ is the optimal length vector. To prove this, we need to show that $\Pi_{i=0}^{K} f(l_i^{opt}) = f(H/(K+1))^{K+1} \geq S(L_K)$ for any feasible $L_K$.

Equivalently, we must show that $\ln f(H/K + 1) \geq (1/K + 1) \sum_{i=0}^{K} \ln f(l_i)$ where the $l_i$’s are the elements of a feasible length vector. This follows from the lemma below which shows that $\ln f(l)$ is a concave function of the continuous variable $l \in (0, H)$. We remark here that the concavity of $\ln f(l)$ is sufficient but not necessary for the optimality of uniform placement.

Lemma: $\ln f(l)$ is a concave function of $l \in (0, H)$.

Proof: Let $g(l) = \ln f(l)$, we have the second derivative

$$g''(l) = \frac{f''(l)f(l) - [f'(l)]^2}{f^2(l)}. \quad (2)$$

Evaluating $f(l), f'(l)$, and $f''(l)$, and substituting in (2), we obtain

$$g''(l) = \frac{f(1-\bar{p})^F \ln \bar{p}^2 (1-F \bar{p}^2 -(1-\bar{p})^F)}{f^2(l)}. \quad (3)$$

Now notice that for every $0 \leq \rho \leq 1$ and $F \geq 1$,

$$(1-\rho^F) + F \rho^F \leq 1 \leq (1-\rho)^F + F \rho^F$$

is lower bounded by 1. (To see this, note that $(1-\rho)^F + F \rho^F$ is a nonincreasing function of $l$) Since the remaining factors are all positive, $g''(l) \leq 0$.

The success probability of an end-to-end call under optimal placement is therefore

$$S_{opt}(H, K) = \left[ f\left(\frac{H}{K+1}\right) \right]^{K+1} \quad (4)$$

$$= \left[ 1 - (1-\rho^{H/(K+1)})^F \right]^{K+1}. \quad (5)$$

It must be noted that this expression is exact only if $(K+1)|H$. When this is not the case, the integral constraint on the segment lengths will make the expression in (3) an upper bound on the actual success probability. In that case, the optimal strategy is to place the converters as uniformly as possible, i.e., converters are placed so that there are $y = H - a(K+1)$ segments of length $a+1$ and $K + 1 - y$ segments of length $a$, where $a = [H/(K+1)]$.

1) Random Placement: We now derive a recurrence relation for the average success probability of the end-to-end call when the $K$ converters are placed randomly on the path, i.e., each of the $H-1$ converter placement configurations is equally likely. Let us define $S_r(H, K)$ to be the average success probability of an end-to-end call when $K$ converters are randomly placed along a path of length $H$. Then, by conditioning on the position of the converter that is placed at the lowest node index, we obtain the recursive relationship

$$S_r(H, K) = \frac{1}{(K+1)} \sum_{i=1}^{H-K} f(i)S_r(H - i, K - 1) \frac{H - i - 1}{K - 1} \quad (6)$$

for $1 \leq K \leq H - 1$. Obviously $S_r(H, 0) = f(H)$. In (4), $(\frac{H-1}{K-1})/\binom{H-1}{K-1}$ is the probability that the converter with lowest node index is placed at node $i$. In obtaining (4), we used the fact that all $\binom{H-1}{K-1}$ possible converter placement configurations, given that node $i$ is the lowest index node with a converter, are equiprobable.

An approximation to $S_r(H, K)$ can be obtained by assuming that each of the $H-1$ intermediate nodes is a converter with probability $q = K/(H-1)$ independently of the other nodes. Let this approximation be denoted by $S_a(H, q)$. Then

$$S_a(H, q) = (1-q)^{H-1}f(H) + \sum_{i=1}^{H-1} f(i)S_a(H - i, q) \quad (7)$$

for $1 \leq K \leq H - 1$ and $S_a(H, 0) = f(H)$. This gives the ensemble average blocking probability over a binomially distributed number of converters, with expected value $K$, randomly placed among the $H-1$ nodes. Note that $S_a(H, q)$ is easier to compute than $S_r(H, K)$ given in (4), because (4) is a recursion in the two variables $H$ and $K$, while (5) is a recursion in one variable ($H$) only. The ensemble average performance was used in [4] to study the benefits of sparse wavelength conversion under uniform traffic. It helped avoid the cumbersome process of evaluating the blocking probability on each path of the network separately.

To see the benefits of optimal placement over random placement of a given number of converters, we plot the end-to-end blocking probability $(P_b)$ as a function of $\rho$ for $H = 10$ and $F = 10$ and $K = 1, 2$ in Fig. 2. (Unless otherwise specified, all numerical results presented in this paper are for

The parameter $q$ is referred to as the conversion density [4].
H = 10 and F = 10.) We observe that the performance with two converters randomly placed is poorer than the performance with one converter optimally placed. Also notice that the performance difference between optimal and random is slightly enhanced as K increases from 1 to 2.

The performance effect of the number of converters can be seen more clearly in Fig. 3 where \( P_b \) is plotted as a function of \( K \). Notice that wavelength conversion plays a significant role in improving the blocking probability. This is due to link-load independence and the long path length, as predicted by previous models [1], [3], [4]. More importantly, there is a large improvement in performance between random and optimal placement, reaching a maximum of about two orders of magnitude at \( K = 4 \). Also plotted for comparison in Fig. 3 is the performance when a random number of converters (with mean \( K \)) are placed randomly on the path. We have observed through numerical experimentation that the ensemble average \( P_b \) estimate is consistently higher than the actual blocking probability with an exact number of converters randomly placed. As expected, all curves converge at \( K = 0 \) and \( K = H - 1 \). Notice that the \( R_r \) and \( O \) curves also converge at \( K = H - 2 \). This is because random placement of \( H - 2 \) converters produces \( K \) segments of length 1 and one segment of length 2. Since link loads are uniform, the location of this 2-hop segment does not matter and the performance is exactly the same as obtained by optimally placing \( H - 2 \) converters.

The effect of the length of the maximum segment on \( P_b \) is worth mentioning here. Consider the \( O \) curve. The length of the maximum segment under optimal (uniform) placement as \( K \) increases from 0 to 9 are, respectively, 10, 5, 4, 3, 2, 2, 2, 2, 2, 1. It can be seen from Fig. 3 that there is a significant performance change when the maximum segment length changes, and the performance improvement when the maximum segment length does not change (from \( K = 4 \)–8) is only marginal.

Another metric to study the importance of converter placement is the utilization gain \( G_u^r \) [1]. Let the target blocking probability \( P_{b,t} \) and the number of converters \( K \) be given. Let \( \rho_0 \) be the maximum load per link per wavelength achievable for the given \( P_b \) with the converters optimally placed, and let \( \rho_r \) be the maximum load achievable with the converters randomly placed. Then the utilization gain is defined as

\[
G_u^r \triangleq \frac{\rho_0}{\rho_r}.
\]

\( G_u^r \) is plotted as a function of \( K \) in Fig. 4. \( G_u^r \) can be as high as 1.6 for \( K = 4 \) and \( P_b = 10^{-5} \). This curve was obtained by numerically solving for \( \rho \) in (4) to obtain a blocking probability that is within 1% of the given \( P_b \).

To gain some qualitative insight into the importance of optimal converter placement for various values of \( F \) and \( H \), we plot \( G_u^r \) as a function of \( F \) for \( H = 6, 11, 16, \) and \( 20 \) and \( K = 0.2(H - 1) \) in Fig. 5. These curves were also obtained numerically as the curve in Fig. 4. Observe that the utilization gain increases sharply with \( F \), initially, for all values of \( H \). As \( F \) becomes very large, the “trunking” effect is expected, to reduce the utilization gain due to wavelength conversion [1], and therefore due to optimal placement of wavelength converters, as well. However, it can be seen from the figure that for moderate values of \( F \) (up to a few tens), optimal converter placement can produce significant gains, especially for large values of \( H \).
B. Non-Uniform Link Loads

We next consider the case when the link loads \( \rho_k \) are not all equal. Clearly, the optimal placement is, in general, nonuniform in this case. Before we provide an optimal solution, we modify (4) to obtain an expression for random placement.

1) Random Placement: We change some of the earlier definitions as follows. Define the subpath from node \( i \) to node \( j \) comprising links \( i, i + 1, \ldots, j - 1 \) to be the chain \([i, j]\). Let \( S_r(i, j, k) \) denote the success probability of an end-to-end call in the chain \([i, j]\) with \( k \) converters randomly distributed among the \( j - i - 1 \) intermediate nodes. Then, a recurrence relation for \( S_r(i, j, k) \) can be obtained as

\[
S_r(i, j, k) = \begin{cases} 
  f(i, j), & k = 0 \\
  \sum_{l=i+1}^{j-k} f(i, l) S_r(l, j, k-1) \left( \frac{j-l-1}{k-1} \right) \left( \frac{j-l-1}{k-1} \right), & k = 1, 2, \ldots, j - i - 1
\end{cases}
\]

where

\[
f(i, j) \triangleq 1 - \left( 1 - \prod_{m=i}^{j-1} p_m \right)^F
\]

is the success probability in the sub-segment\(^4\) from node \( i \) to node \( j \). Note that this subsegment contains the links \( i, i + 1, \ldots, j - 1 \). The success probability of an end-to-end call when \( K \) converters are randomly placed on the path is simply given by \( S_r(0, H, K) \).

2) Optimal Placement: When the link loads are not equal, there does not appear to be a closed-form expression for the optimum length vector as in the uniform link-load case. We obtain a solution based on dynamic programming along the lines of [20]. In [20], the problem of placing erasure nodes in DQDB networks to maximize slot reuse is considered, and optimal solutions based on dynamic programming are presented. The nature of the objective function in our case is different from theirs; however, their approach can be modified to solve the problem at hand, as we will demonstrate below.

For any integer \( m \), we define the converter placement vector \( \mathbf{a} = (a_1, a_2, \ldots, a_m) \) with \( 0 < a_i < a_{i+1} \leq H, \ i = 1, \ldots, m-1 \), where \( a_i \) is the location of the \( i \)th converter. (The reason for the inclusion of node \( H \) as a possible converter location will be apparent soon.) Also, \( \beta(j, \mathbf{a}) \) is defined to be the probability that an end-to-end call is successful in chain \([0, j]\) when \( \mathbf{a} \) is the placement vector, and the set of all converter placement vectors with the \( m \)th converter at node \( j \) is defined as

\[
\Theta(m, j) \triangleq \{ \mathbf{a} \in \mathbb{Z}^m_+ : 0 < a_i < a_{i+1} < a_m = j, \ i = 1, \ldots, m-2 \}
\]

where \( \mathbb{Z}^m_+ \) is the set of positive integer \( m \) vectors. Then

\[
\gamma(m, j) \triangleq \max_{\mathbf{a} \in \Theta(m, j)} \beta(j, \mathbf{a})
\]

denotes the success probability in the chain \([0, j]\) with the first \( m - 1 \) converters optimally placed among nodes \( 1, \ldots, j - 1 \), and the \( m \)th converter at node \( j \). Let us also define

\[
\Gamma(m, j, k) \triangleq \{ \mathbf{a} \in \Theta(m, j) : a_{m-1} = k \}.
\]

\(^4\) According to our terminology here, a chain may contain converters, while a segment does not.
We can obtain $\gamma(m,j)$ using the following dynamic programming procedure:

\[
\gamma(m,j) = \max_{a \in \mathcal{C}(m,j)} \beta(j,a)
\]

\[
= \max_{m-1 \leq i \leq j-1} \max_{a \in \mathcal{C}(m,j,i)} \beta(j,a)
\]

\[
= \max_{m-1 \leq i \leq j-1} \max_{a \in \mathcal{C}(m,j,i)} \beta(i,a)f(i,j)
\]

\[
= \max_{m-1 \leq i \leq j-1} \gamma(m-1,i)f(i,j)
\]  \hspace{1cm} (8)

for $2 \leq m \leq K + 1$, $m \leq j \leq H$. Clearly, $\gamma(1,j) = f(0,j)$ for $1 \leq j \leq H$.

The above recurrence relation directly leads to a $O(H^2K)$ dynamic programming algorithm for obtaining the optimal placement vector. The optimal placement vector is the solution obtained when $K + 1$ converters are placed among nodes $1, 2, \ldots, H$, such that the $(K+1)$th converter is at node $H$, i.e., $\mathbf{a}^{\text{opt}} = \arg \max_{a \in \mathcal{C}(K+1,H)} \beta(H,a)$. The resulting success probability is $\gamma(K+1,H)$.

The end-to-end blocking probability is plotted as a function of the converter position for $K = 1$ for two different link load patterns in Fig. 6. The top curve is for uniform link loads and $\rho = 0.1$, and the bottom curve is for linearly increasing link loads from link 0 to link 9. We take $\rho_0 = 0.065$, $\rho_0 = 0.1$, and $\rho_i = \rho_{i-1} + c$, $i = 1, \ldots, 8$, where $c = (\rho_0 - \rho_0)/9$. Intuitively, the optimal converter location should shift to the right for the linear traffic pattern and this is indeed what is observed in the figure. However, it cannot be determined a priori that the converter is optimally placed at node 6 for this traffic pattern. Note that, in the figure, converter placement in a nonoptimal position would increase $P_b$ by a factor of at least two, and the performance degradation could be as high as two orders of magnitude.

The performances of random (R), uniform (U), and optimal (O) placement are compared for a linear link-load traffic pattern in Fig. 7. The uniform placement performs quite poorly for a large number of converters. This is due to the fact that converters are best placed toward the end of the path, whereas uniform placement would place some toward the beginning of the path, where they are expected to be less useful. The optimal placement results in dramatically better performance than random placement.

Finally, we remark that the dynamic programming procedure can be applied to the case of uniform link loads as well. Indeed, we have observed that the dynamic programming procedure obtains the uniform placement as the optimal solution when the link loads are uniform.

C. Placement for Optimal Average Performance

Until this point, we have considered the placement problem from the point of view of a call going from node 0 to node $H$. However, when a path is part of a large network, it may be of interest to minimize the average blocking probability over all traffic using the path, rather than just the end-to-end traffic. We now modify the solution above to take this into account. Random placement is considered first.

1) Random Placement: Let $\alpha(m,j,s,d)$ denote the ensemble average of the probability that a call from node $s$ to node $d$ will be successful in the chain $[0,j]$ when $m$ converters are placed in $[1,j]$ with the $m$th converter at node $j$ and the other $m - 1$ converters randomly distributed in $[1,j-1]$. Define $\delta(j,a,s,d)$ to be the probability that an $(s,d)$ call succeeds in
the chain \([0, j]\) when \(a\) is the placement vector. Then
\[
\alpha(m, j, s, d) = E_{a \in \mathcal{C}(m, j)} \delta(j, a, s, d)
\]
where \(E_x\) denotes the expectation over \(x\). Then, similar to (6), we can write
\[
\alpha(m, j, s, d) = \begin{cases} 
  h(0, j, s, d), & m = 1 \\
  \sum_{i=1}^{j-1} \alpha(m-1, i, s, d) h(i, j, s, d) \frac{(i-1)}{(m-2)}, & m = 2, \cdots, j
\end{cases}
\]
(9)
where \(h(i, j, s, d)\) is the probability that an \((s, d)\) call is successful in segment \([i, j]\). \(h(i, j, s, d)\) is given by
\[
h(i, j, s, d) = \begin{cases} 
  f(s, d), & i \leq s < d \leq j \\
  f(i, j), & s \leq i, d \geq j \\
  f(i, j), & s \leq i, j + 1, d \leq j - 1 \\
  1, & d \leq i, or \ s \geq j
\end{cases}
\]
(10)
where \(f\) is as defined in (7). The success probability averaged over all \((s, d)\) calls is then \(E_{(s, d)} \delta(K+1, H, s, d)\).

2) Optimal Placement: The optimal placement vector \(\mathbf{a}^{\text{opt}}\) that minimizes the average call blocking probability is given by
\[
\mathbf{a}^{\text{opt}} = \arg \max_{a \in \mathcal{C}(K+1, H)} E_{(s, d)} \delta(H, a, s, d).
\]
Note that the \(\min\) and the \(\max\) operators cannot be interchanged, and as a result, it is not possible to obtain a recurrence relation such as the one in (8). However, an approximate solution to this problem can be obtained as follows. Instead of maximizing \(E_{(s, d)} \delta(H, a, s, d)\), we will obtain the placement configuration that maximizes \(E_{(s, d)} h(H, a, s, d)\). Note that \(1 - \delta(H, a, s, d)\) is the probability that the \((s, d)\) call is blocked in the chain \([0, H]\) when the placement vector is \(a\). For reasonably low blocking probabilities \(<10^{-2}\), because of the fact that \(x \approx x - 1\) when \(x \approx 1\), \(E_{(s, d)} h(H, a, s, d)\) is an excellent approximation for \(-E_{(s, d)} (1 - \delta(H, a, s, d))\) which is the original objective function to maximize.

Define \(\zeta(i, a)\) to be
\[
\zeta(i, a) \overset{\text{def}}{=} E_{(s, d)} h(i, j, s, d).
\]
(11)
Now if \(\xi(m, j) \overset{\text{def}}{=} \max_{m \leq i \leq j-1} \max_{a \in \mathcal{C}(m, j)} \zeta(i, a)\) then
\[
\xi(m, j) = \max_{m \leq i \leq j-1} \{ \max_{a \in \mathcal{C}(i, j)} \left[ \zeta(i, a) + E_{(s, d)} h(i, j, s, d) \right] + E_{(s, d)} h(i, j, s, d) \}
\]
(12)
for \(2 \leq m \leq K + 1\), \(m \leq j \leq H\), and \(\xi(1, j) = E_{(s, d)} h(0, j, s, d)\) for \(1 \leq j \leq H\).

The optimal placement \(\mathbf{a}^{\text{opt}}\) is now given by \(\arg \max_{a \in \mathcal{C}(K+1, H)} \zeta(H, a)\) and (12) defines a recurrence relation that can be solved via dynamic programming as before. Fig. 8 depicts the average blocking probability for optimal (with respect to the average blocking performance) and random placements and the following traffic pattern. The load per wavelength between each \((s, d)\) pair, \(\lambda_{sd} = 0.01, d > s\), so that the load per wavelength on link \(i\), \(\rho_i = 0.01(i + 1)(H - i)\). In this traffic pattern, the link loads increase from link 0 until link 4 and then decrease from link 5 to link 9. We also plot the performance for an end-to-end call in the figure for comparison. (In the figure, the optimal performance of an end-to-end call is obtained under optimal placement with respect to end-to-end calls only.) We observe that optimal placement provides considerable improvement in average performance as well, relative to random placement. For instance, to achieve an average \(P_b \approx 10^{-3}\), three converters suffice if placed optimally while seven converters would be required if placed randomly. Finally, it is observed that the end-to-end blocking performance of an optimized system is significantly better than the average blocking performance under random placement.

III. CONVERTER PLACEMENT IN A BUS TOPOLOGY

In the previous section, we considered the problem of optimally placing a given number of converters on a path, assuming that link loads are independent. In this section, we show how that framework can be applied to a bus network in which the traffic is solely due to the traffic originating at the nodes of the bus. In such a scenario, the link-load independence assumption of the previous section is not appropriate due to significant load correlation in successive links. We show in this section how our dynamic programming solutions are applicable in the presence of link-load correlation.
A key step in the derivation of the recurrence relation in (12) is the second equality, where we have assumed that the success probability of an \((s, d)\) call in chain \([0, i]\) is independent of the success probability of the call in segment \([i, j]\) when node \(i\) is a converter. This assumption is still used; that is, we continue to assume that the success probabilities of a call in disjoint segments are statistically independent. However, note that we do not need the independence assumption between the links of the same segment. Since the fraction of the nodes with converters is typically small, the most important effects of link load correlation will be taken into account in our formulation.

The performance model we use here is the one proposed by Barry in [1], [2]. For completeness, we present the relevant details of Barry’s model here. The only quantity of interest to us here is the probability of success \(f(i, j)\) in a subsegment \([i, j]\) since all other quantities are defined in terms of it.

Consider the bus in Fig. 9 and let \(\rho_n(i)\) be the load per wavelength that enters the network at node \(i\), \(\rho(i)\) the load per wavelength that leaves the network at node \(i+1\), and \(\rho_c(i)\) the load per wavelength that continues through node \(i+1\) and uses links \(i\) and \(i+1\). Also, let us denote the total load per wavelength on link \(i\) by \(\rho(i)\).

Since wavelengths are considered to be independent of each other in this model, it suffices to look at a single wavelength, say \(\lambda_i\). Then, \(P_n(i) \triangleq \rho(i)/\rho(i)\) is defined as the probability that a call on wavelength \(\lambda_i\) uses link \(i\) and leaves at node \(i+1\). Also, let \(P_n(i)\) be the probability that a new call enters the network at node \(i\) and uses link \(i\) on wavelength \(\lambda_i\) given that \(\lambda_i\) is not used by another call on link \(i\). \(\rho(i)\) is then given by [1]

\[
\rho(i) = \rho(i-1)\left[1 - P_n(i-1) + P_n(i-1)P_n(i)\right] + (1 - \rho(i-1))P_n(i)
\]

and therefore

\[
P_n(i) = \frac{\rho(i) - \rho(i-1)\left[1 - P_n(i-1)\right]}{1 - \rho(i-1)\left[1 - P_n(i-1)\right]}.
\]

The probability that at least one wavelength is available on all links of a subsegment \([i, j]\) is now found as

\[
f(i, j) = 1 - \left[1 - P\left(\lambda_i \text{ free on link } i\right) \prod_{k=i+1}^{j-1} P\left(\lambda_k \text{ free on link } k\right)\right]^F
\]

\[
\cdot P\left(\lambda_j \text{ free on link } j\right) \prod_{k=i+1}^{j-1} \left(1 - P_n(k)\right)
\]

\[
= 1 - \left[1 - (1 - \rho(i)) \prod_{k=i+1}^{j-1} (1 - P_n(k))\right]^F.
\]

Fig. 9. A bus of length \(H\).

Fig. 10. \(P_h\) versus \(K\) for uniform link loads, \(\rho = 0.4\).

Given the traffic matrix \(A = [\lambda_{sd}]\) where \(\lambda_{sd}\) is the load per wavelength between nodes \(s\) and \(d\), \(\rho(i), \rho_n(i), \rho_c(i)\), and \(\rho(i)\) are calculated in the following way:

\[
\rho(i) = \sum_{s=0}^{d} \sum_{d=1}^{H} \lambda_{sd} \quad \\
\rho_n(i) = \sum_{s=0}^{d} \lambda_{si+1} \quad \\
\rho_c(i) = \rho(i) - \rho_n(i).
\]

As before, (9) and (12) are used to evaluate the performance under random and optimal placement, respectively. However, (13) is used instead of (7) for computing the success probability in a subsegment, thus taking the link load correlation in the bus topology into account.

We show \(P_h\) as a function of \(K\) for a 11-node bus with \(F = 10\) in Fig. 10. The link loads are kept constant at \(\rho = 0.4\). This is done by setting \(\rho_n(0) = \rho\), and \(\rho_n(i) = \)
Fig. 11. $P_b$ versus converter position for $K = 1$ and uniform link loads, $\rho = 0.3$.

$$\rho - \frac{\sum_{j=0}^{i-1} (H-i+j) \rho_0(j)}{H} \quad i = 1, 2, \ldots, H - 1,$$  
and  
$$\lambda_{ij} = \rho_n(i)/(H-i)$$  
for $j > i$, and 0 otherwise. Here, we observe that the performance improvement with optimal converter placement is not as high as in a path with independent link loads. However, given that the performance improvement with an increasing number of converters is marginal, the small reduction in blocking probability obtained by optimal placement may still be significant.

Notice further that uniform converter placement is no longer optimal, even though link loads are uniform; this is due to link-load correlation as well as the fact that we have considered the optimal placement with respect to all traffic and not just end-to-end traffic. $P_b$ versus the converter position is plotted in Fig. 11 for $K = 1$ and a uniform link load of $\rho = 0.3$. The three curves correspond to the blocking probabilities obtained by using the binomial model, the Poisson model of [4], and simulations with Poisson traffic. It is certainly not clear beforehand that the optimal solution would place the converter at node 7 for this traffic pattern. This is, in fact, surprising considering the fact that node 7 is neither the node with the highest transit (continuing) traffic, nor the node mixing the highest amount of traffic (high $\rho_n$ and low $\rho_c$ for each node) are plotted in Fig. 12 for this traffic pattern.\footnote{By our previous definition, $\rho_c(i)$ is the traffic that continues through node $i + 1$; however, in the figure, $\rho_c$ refers to the traffic continuing through the corresponding node number.} Observe the similarity in trends between the curves in Fig. 11. Even though the binomial model provides numerically inaccurate blocking probabilities and produces the same optimal converter position as the binomial model, the dynamic programming procedure can be used with any link traffic model.

For $K = 2$ and for $K = 3$, the optimal converter locations turn out to be at nodes 5, 8, and at nodes 4, 7, 9, respectively, again seemingly unintuitive. These are consistent with the positions obtained using the Poisson model and simulations. In the simulations, we obtained the blocking probability for each of the $\binom{9}{2}$ possible converter placement configurations, and chose the configuration with lowest blocking probability.

We remark here that this formulation can be applied to a double-bus network as well. The only necessary change is that the objective function must now maximize the average success probability over both buses together. The traffic model will have to be applied to the two buses separately.

IV. CONVERTER PLACEMENT IN A RING TOPOLOGY

The ring is a popular optical network topology because of its simplicity [3], [6], [4], [21]. In this section, we present a dynamic programming solution for optimal converter placement in a ring topology. As in the bus, the optimality criterion is the average blocking probability. We will mainly be interested in the results obtained using the binomial model here, i.e., we continue to assume that all wavelengths are used on a link with the same probability and the usage of different wavelengths on the same link are statistically independent. However, the correlation between the usage of the same wavelength on consecutive links will be taken into account as in the previous section.

Consider a unidirectional ring network with $H$ nodes, numbered from 0 to $H - 1$, where the link from node $i$ to node $(i+1) \mod H$ is labeled as link $i$. The optimal placement for the ring is obtained by using the fact that if a converter...
is placed at a node, say \(i\), then because of the assumed independence of the success probability of a call in disjoint segments, the ring can be logically broken at node \(i\) to create two nodes \(i'\) and \(i''\) and a bus of length \(H\) (see Fig. 13). Let the left end-node of the resulting bus be \(i'\) and the right end-node \(i''\). The traffic matrix \(A\) for the ring is modified to form a traffic matrix \(\hat{A}\) for the bus as follows: \(\hat{\lambda}_{s'd'} = \lambda_{s'd} = \lambda_{s'd}\) if chain \([s, d]\) contains node \(i\) as an intermediate node in the ring, and \(\hat{\lambda}_{s'd} = \lambda_{s'd}\) otherwise.

Given an \(H\)-node ring and \(K\) converters, the average success probabilities can be obtained by conditioning on the lowest indexed node \(i\) having a converter, \(i = 0, 1, \ldots, H-K\). The ring is then broken at node \(i\) as described above, and the optimal placement of \(K-1\) converters on the logical bus given \(i\) is the lowest indexed node with a converter is obtained as in the previous section. The optimal placement for the ring is the placement that maximizes the success probability over all \(i\), and the performance with random placement is the performance averaged over the possible values of \(i\). This is stated formally below.

For ease of notation, suppose that the nodes and links of the bus derived from the ring are relabeled so that node \(i'\) is node 0, node \(i''\) is node \(H\), and the link out of the relabeled node \(i\) is link \(i\) [see Fig. 13(b)]. Note that there are no converters that are placed in nodes \(H-1\) through \(H-1\) of the relabeled bus since node \(i\) was assumed to be the lowest indexed node of the ring with a converter.

A. Random Placement

To obtain the performance with random placement, we define

\[
\kappa(m, j) \overset{\text{def}}{=} E_{a \in \Theta(m, j)} \zeta(j, a)
\]

where \(\zeta(j, a)\) is as defined in (11), to be the expected value (over all \([s, d]\) calls) of the logarithm of the success probability in \([0, j]\) when \(m-1\) converters are randomly placed in nodes \(1, 2, \ldots, j-1\), and the \(m\)th converter is placed at node \(j\) of the relabeled bus. Let

\[
\Upsilon(K, H, t) \overset{\text{def}}{=} \{a \in \Theta(K, H); a_{K-1} \leq t\}
\]

denote the set of placement vectors which place converter \(K\) at node \(H\) and converter \(K-1\) at a node whose index is no more than \(t\).

Then, under random converter placement, we have

\[
- P_b \approx E_i E_{a \in \Theta(K, H-1-i)} \zeta(H, a)
= E_i E_{a \in \Theta(K, H-1-i)} E_{(s,d)} \ln \delta(H,a, s,d)
\]

\[
\overset{\approx}{=} E_i \left\{ E_{K=1} \left( \frac{K-1}{K-2} \right) \right\} \left( \frac{K-1}{K-2} \right) \frac{1}{H-1-i} E_{(s,d)} \ln \delta(i, a, s, d)
\]

\[
= E_i \left\{ E_{K=1} \left( \frac{K-1}{K-2} \right) \right\} \left( \frac{K-1}{K-2} \right) \frac{1}{H-1-i} E_{(s,d)} \ln \delta(i, a, s, d)
\]

\[
+ E_{(s,d)} \ln h(i, H, s, d) \left\{ \frac{H-2}{H-1-i} \right\} \left( \frac{H-2}{H-1-i} \right) \frac{1}{K-1} E_{(s,d)} \ln h(i, j, s, d)
\]

\[
= \frac{1}{H-K} \left\{ E_{i=0} \left( \frac{H-1-i}{K-1} \right) \right\} \left( \frac{H-1-i}{K-1} \right) \frac{1}{H-K} \left( \frac{H-1-i}{K-1} \right) \frac{1}{K-1} \ln h(i, j, s, d)
\]

\[
= \frac{1}{H-K} \left\{ E_{i=0} \left( \frac{H-1-i}{K-1} \right) \right\} \left( \frac{H-1-i}{K-1} \right) \frac{1}{H-K} \left( \frac{H-1-i}{K-1} \right) \frac{1}{K-1} \ln h(i, j, s, d)
\]

where \(\kappa(m, j)\) is obtained, similar to \(\alpha\) in (9), to be

\[
\kappa(m, j) = \begin{cases} \frac{H-1-i}{K-1} & \text{if } m = 1 \\ \frac{H-1-i}{K-1} & \text{if } m = j+1 \\ \frac{H-1-i}{K-1} & \text{if } m = j+2, \ldots, j \end{cases}
\]

\[
\kappa(m, j) = \begin{cases} \frac{H-1-i}{K-1} & \text{if } m = 1 \\ \frac{H-1-i}{K-1} & \text{if } m = j+1 \\ \frac{H-1-i}{K-1} & \text{if } m = j+2, \ldots, j \end{cases}
\]

In Step (a) of (14), \(\left( \frac{H-1-i}{K-1} \right) / \left( \frac{H-1-i}{K-1} \right) \) is the probability that the \((K-1)\)th converter is placed at node \(k\) given that \(K-1\) converters are placed randomly among nodes \(1, 2, \ldots, H-1-i\). In Step (b), \(\left( \frac{H-1-i}{K-1} \right) / \left( \frac{H-1-i}{K-1} \right) \) is the probability that node \(i\) is the lowest indexed node of the ring, given that \(K\) converters are placed randomly. We also have used the definitions of \(\zeta, \kappa, \) and \(h\) in (14). Note that we did not employ...
the logarithm approximation in computing the performance for random placement in Section II. In the ring, however, because the traffic through a node is split into two streams, the logarithm approximation is necessary in Step (a) of (14).

**B. Optimal Placement**

Along similar lines, the optimal placement vector $\mathbf{a}^*_{\text{opt}}$ is obtained as the placement vector $\mathbf{a}$ which achieves 
\[
\max_{\mathbf{a} \in \mathcal{T}(K, H, H-1)} \zeta(H, \mathbf{a}).
\]
Now
\[
\max_i \max_{\mathbf{a} \in \mathcal{T}(K, H, H-1-i)} \zeta(H, \mathbf{a})
\]
\[
= \max_i \max_{K-1 \leq h \leq H-i} \max_{k \in \mathcal{O}(H-1, k)} \cdot \{E(s, d) \ln \delta(k, \mathbf{a}, s, d) + \ln h(k, H, s, d)\}
\]
\[
= \max_i \max_{K-1 \leq h \leq H-i} \{\zeta(H-1, k) + E(s, d) \ln h(k, H, s, d)\}
\]
and $\zeta(m, j)$ is given by (12). For a given $i$, the inner maximization is performed via dynamic programming as before, and the outer maximization considers all the $H-K+1$ possible values of $i$.

**C. Results**

We consider a 10-node ring network with $F = 10$. Fig. 14 shows $P_b$ plotted as a function of $K$ for optimal/uniform and random placement of converters when the link loads are uniform (as are loads between any $(s, d)$ pair) with $\rho = 0.4$. In the ring, as in the case of the bus, there is significant load correlation. This leads to a modest performance improvement of optimal placement over random placement. Recall that in a path with negligible load correlation, the performance improvement with optimal placement was considerable.

However, optimal placement could assume importance when the traffic is not uniform. For instance, if all traffic were local traffic (from a node to its neighbor) except for some traffic that goes from node 0 to node $H - 1$, then the situation is similar to the one in the path with no load correlation. In that case, we observed that optimal placement can provide a significant boost in end-to-end blocking performance (see Fig. 3). Note that converters do not affect the blocking performance of local calls.

**V. EFFECT OF TRAFFIC MODEL ON CONVERTER PLACEMENT**

In this section, we discuss the effects of the traffic model used in obtaining the blocking probabilities for random and optimal placements. As mentioned earlier, our dynamic programming solution techniques do not assume a specific traffic model, even though the results we have presented thus far are for the binomial model. Note, however, that the solution methodology in this paper is critically dependent on the assumption of statistical independence of wavelength usage between successive converterless segments.

The effect of the traffic model appears in our solutions in the form of the probability $f(i, j)$, the success probability of a call in segment $[i, j]$. In the binomial model, this probability was given by (7) and (13) when link loads are independent and strongly correlated, respectively. This probability can also be obtained via the models presented in [3] and [4] for Poisson traffic, when link loads are independent and correlated, respectively. Note that those models were presented for uniform link loads; when the link loads are nonuniform, the two-hop model presented therein will need to be applied to every pair of consecutive links in the network. We omit the details here and present only a comparison of a sampling of the results obtained using those models and the binomial model we have used so far in this paper. We proved in Section II that in a path with uniform link loads and the link load independence assumption, uniform placement is the optimal placement for the end-to-end traffic. This was achieved by showing the concavity of $\ln f(I)$ [see (1)]. When the traffic model is Poisson, it appears difficult to prove analytically that concavity still holds, but the function appears to be concave for a wide range of the parameters $\rho, F$, and $L$.

In Fig. 15, we plot end-to-end $P_b$ as a function of $K$ for a path with $H = 10, F = 10$, and the load per wavelength per fiber, $\rho = 0.1$, assuming link-load independence and the Poisson traffic model. Comparing this with Fig. 3, we see that the numerical values of $P_b$ are higher for the Poisson model, but the conclusions regarding converter placement are the same. For example, the performance difference between optimal and random placement increases with $K$ until it reaches a maximum at $K = 4$ and then starts decreasing, in both cases.

6 This is due to the fact that the busy wavelength distribution on a link offered Poisson traffic has a heavier tail than the binomial distribution for the same load (when loads are low enough so that effects of blocking on carried load can be ignored).
Fig. 15. $P_b$ of an end-to-end call versus $K$ for a 10-hop path with optimal/uniform (O), random ($R_c$) placement of $K$ converters, and random placement of a random number of converters ($R_u$) with mean $K$. Poisson traffic model.

This is also evident from Fig. 16, where $P_b$ is plotted as a function of the converter position for uniform link loads ($\rho = 0.1$) and for linearly increasing link loads ($\rho_1 = 0.05, \rho_5 = 0.1$). Poisson traffic model.

VI. Conclusion

In this paper, we considered the problem of placing a given number of converters on a path such that the blocking probability is minimized. Optimal converter placement on a path was motivated by the following considerations. Firstly, quality-of-service requirements may indicate that converter placement on a particular path (for example, the longest) be optimized. Secondly, the solution methodology for a path can be extended to two important topologies; namely, the bus and the ring. Furthermore, the path converter placement algorithms presented in this paper could be used to optimally place converters in an arbitrary network topology.

By using a simple traffic model, we first showed that uniformly spaced converters produce optimal performance for an end-to-end call on a path when the link loads are uncorrelated and uniform. When the link loads are nonuniform or when other calls are considered, we provided solutions based on dynamic programming for the optimal placement of converters. Recursive expressions for blocking probability when the converters are randomly placed were also obtained.

The results indicate that optimal converter placement is an important problem, especially when there is negligible correlation between link loads. For example, the blocking probability of an end-to-end call on a 10-hop path with negligible link load correlation can be reduced by more than two orders of magnitude when 4 converters are optimally placed (relative to random placement of converters) with 10 wavelengths per link when the load per wavelength per hop is 0.1.

Even though most of the results presented here were for the binomial model, our solutions are applicable to any traffic model provided that the blocking events on successive converterless segments on a path can be assumed to be statistically independent. Our results on converter placement using the binomial model and the Poisson model indicate that optimal converter placement decisions are, to a large extent, independent of the actual traffic model used.

Finally, blocking probability is not the only metric of interest in a wavelength-routing network. Optimal placement of converters with other performance metrics may be appropriate in some cases. For example, the problem of placing converters such that the carried traffic is maximized may be of interest in the provisioning of lightpaths with static traffic.

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