Least Constrained Slot Allocation in Optical TDM Networks

Hassan Zeineddine and Gregor V. Bochmann,
{hzeined,bochmann}@site.uottawa.ca,
School of Information Technology and Engineering,
University of Ottawa,
Ottawa, ON-K1N 6N5

Abstract - **In this paper, we propose a timeslot allocation scheme in all-optical TDM networks with no traffic buffering. The purpose of the new scheme is to take the blocking rate to an optimal level close to what can be achieved with the use of buffers. Previous works considered the first fit and least loaded approaches to reserve timeslots in networks that include buffers and multi-fibers. Our proposed scheme applies to more basic networks that have single unidirectional fibers and no buffers.**

I. INTRODUCTION

The question of optical bandwidth allocation between node pairs in a given network has been a focal topic since the inception of optical communication. From routing algorithms to light path allocation and lately timeslot reservation schemes, the greed to optimize has been enormous. Amidst the search for an optimal routing algorithm, WDM rose up to add another dimension, which is wavelength allocation. Researchers pounded the topic with dozens of papers [1] describing competing allocation schemes, which reduce network resources usage and improves performance. This trend prevailed for few years before optical time division multiplexing (OTDM) [2,3] became a feasible technology. Ever since, part of the research focus shifted towards optimized slot reservation schemes to reduce buffering requirements and improve performance. However, the interest in OTDM timeslot reservation has been shy and living in the shadow of WDM wavelength allocation. Always under the assumption that slot reservation is nothing but a wavelength allocation at a finer granularity [2,4,5], researchers gave lesser weight to the former question in favor of the latter. This assumption holds true when considering either an optical TDM network with opto-electronic interfaces or an all-optical TDM network synchronized on frame boundaries. Frame boundaries synchronization is a nice concept that guarantees frame alignment and reduces the problem of slot reservation to a wavelength allocation issue. In another term, it makes each slot on a given wavelength appear as a unique lambda with a smaller bandwidth. Before getting carried away with the bright side, it is worthwhile noting that frame boundaries synchronization is easier said on paper than put in practice due to the need of lengthy optical synchronizer buffers. We use the term "synchronizer buffer" in this paper to distinguish from the common term "buffer", which we call here "switching-buffer"; the former is used as a mandatory correction of boundaries misalignments induced by propagation delays, while the latter is used as an optional storage during slot switching operations. In the absence of optical RAM, a synchronizer buffer is built with Fiber Delay Lines (FDL) and must provide variable delay period to account for the temperature-sensitive propagation delay [4]. On the other hand, several research papers assumed slot boundaries synchronization [6,7] instead of frame. Buffering for a single slot is cheaper than buffering for an entire frame when correcting the lag caused by propagation delay. However, that comes with the price of loosing frame alignment, and hence the benefit of adopting wavelength allocation schemes as possible solutions for the slot reservation problem. Thus, finding an effective slot reservation scheme in an optical network, where transmission is synchronized on slot and not frame boundaries, becomes a vital question. Papers, considering all-optical TDM networks with slot boundaries synchronization, studied the first fit and least loaded approaches to assign timeslots along a route. With the first fit (FF) approach in [2], the first available timeslots along a route are reserved to satisfy a communication request. In addition, various forms of optical timeslot interchangers (OTSI) are used to improve network performance in terms of blocking rate [8]. In [6], the least loaded (LL) scheme reserves the least used slot in a multi-fiber link. Slot usage on a given link is a weight reflecting the number of fibers that have the slot in a reserved state. For instance, if a timeslot is used in 2 fibers of a 5-fibers link, its weight will be equal to 2. On a given route, the LL approach selects a series of timeslots that have the lowest total weight. In [9], the minimum cost search (MCS) approach was introduced for optical star networks synchronized on frame boundaries. The scheduling is achieved on a frame by frame basis. Each edge node sends a request for a number of timeslots during an entire frame. A centralized algorithm allocates timeslots to the edge nodes in a pattern that saves switching cost and retains flexibility for future call. Other papers talked about scheduling traffic in a star network on a slot by slot basis, but focused on signaling protocols, buffering delay at edge nodes, and fairness in request allocation [10].

In this paper, we propose a novel slot reservation schemes in all-optical TDM mesh network with no switching-buffers, where transmission is synchronized on slot boundaries. The introduced scheme aims at reducing calls blocking to an optimal rate close to what can be achieved with buffering. Each slot has a constraint which is the number of fixed routes that might use it at a given point in time. It selects the least constrained slots on the route, hence the name least constrained slot (LC). We use the FF approach with full timeslot interchanging capability as a benchmark to measure our results. It has been proven that employing full wavelength interchanging yields optimum results with fixed routing [8]. This is true because blocking would not occur unless one of the links along the route is saturated. In addition, we compare the performance of the LC approach to the LL approach in a multi-fiber environment. We also investigate how LC behaves in a star network synchronized on slot boundaries.

In the following section, we explain the LC reservation scheme and introduce an example. Subsequently, we describe our simulation model and discuss the performance of the different slot allocation approaches. In addition, we include a section on complexity comparison. Finally, we conclude the paper with a brief summary.

II. LC ALLOCATION SCHEME

Before describing the basic step of LC, we should clarify the nomenclature used in this paper to provide a better understanding of the presented concepts. Route, route-slot and link-slot are essential concepts used in describing our work.

A network route is a series of unidirectional links interconnected through intermediate nodes from a given source node to a given destination node. Two routes are considered intersected if they have at least one link in common. A node transmits data into a link in the form of repeating frames of N equal timeslots. Due to link propagation delay, frame alignment is not preserved along the route. Considering link AB, a traffic segment forwarded on a given timeslot at egress node A might be intercepted on a different timeslot at ingress node B. Thus, a timeslot is better identified with reference to a link; we use the term link-slot AB_x to describe timeslot x on link AB. There is no need to mention the corresponding wavelength since only one wavelength plane is considered in this study. Formally speaking, a link-slot is a timeslot on a link with reference to the local clock of its egress node. In general, a transmitted traffic segment from source node S to destination node D travels through different links along a fixed route, and hence occupies a series of different link-slots. For instance, if A and B are two intermediate nodes between S and D, a series of link-slots would be described as $SA_x\ AB_y\ BD_z$. Knowing the delay of each link, an intermediate link-slot UV_j corresponds to a source link-slot SA_i according to the general rule $j = (i + d_{SU}) \bmod N$, where d_{SU} is the total delay of all links from node S to node U. Thus, knowing the fixed route between a source-destination pair and all associated link delays, one can easily derive the entire series of link-slots when given a starting link-slot. In this case, we can describe the series $SA_x AB_y BD_z$ in a simple notation $\overline{SD_x}$, which we call a route-slot. The upper bar is essential to differentiate between link-slot and route-slot. A route-slot $\overline{SD_x}$ is considered available if all its constituent link-slots are available; otherwise, $\overline{SD_x}$ is unavailable. In a single fiber environment, a link-slot is available if it is not reserved. On the other hand, in a multi-fiber case, a link-slot is available if it is free at least on one of the link fibers. To make our approach generic enough, we develop it based on a multi-fiber environment, and apply it to a single-fiber network as a special case.

The exercise of allocating resources, for a communication request, from node S to D is to find and reserve an available route-slot $\overline{SD_x}$ along a given fixed route.

A. Definitions

If a link-slot XY_j is part of a route-slot $\overline{SD_i}$, we write:

$$XY_j \ in\ \overline{SD_i}, where\ j = (i + d_{SX}) \bmod N\ . \tag{1}$$

Considering M fibers per link, we define a link-slot availability A_{XY_j}, an integer between 0 and M, to be the number of fibers on which XY_j is free. If A_{XY_j} is equal to zero, then XY_j is unavailable. Furthermore, we define the availability $\mathrm{A}_{\overline{SD_i}}$ of a route-slot to be equal to the minimum A_{XY_j} among its constituent link-slots,

$$\mathrm{A}_{\overline{SD_i}} = \underset{XY_j\ in\ \overline{SD_i}}{MIN}\left(\mathrm{A}_{XY_j}\right). \tag{2}$$

Knowing the associated fixed route of each source-destination pair, we derive the set Ω of all possible route-slots in the network. We define Ω_{XY_j} to be a subset of Ω consisting of all route-slots that contain link-slot XY_j.

$$\Omega_{XY_j} = \left\{\overline{SD_i} \in \Omega \ \mid XY_j\ in\ \overline{SD_i}\ \right\}. \tag{3}$$

We further define Ω'_{XY_j} to be a subset of Ω_{XY_j} consisting of all route-slots whose availabilities are equal to A_{XY_j}.

$$\Omega'_{XY_j} = \left\{\overline{SD_i} \in \Omega_{XY_j} \ \mid \ \mathrm{A}_{\overline{SD_i}} = \mathrm{A}_{XY_j}\right\}. \tag{4}$$

The purpose of Ω'_{XY_j} is to identify all route-slots whose availabilities are decremented when reserving XY_i.

We designate the weight of link-slot XY_i to be the sum of the availability of all route-slots belonging to Ω_{XY_j}.

$$W_{XY_j} = \sum_{\overline{SD_i} \in \Omega_{XY_j}} \mathrm{A}_{\overline{SD_i}}\ . \tag{5}$$

In a single fiber environment, $A_{\overline{SD_i}}$ becomes a binary variable showing whether the route-slot is available (1) or not (0); and hence, W_{XY_j} would reflect the number of available route-slots containing XY_j. In other words, it indicates the number of routes that can potentially use the designated link-slot.

Last, we define the weight of a transmission channel to be equal to the total weight of all its constituent link-slots:

$$W_{\overline{SD_i}} = \sum_{XY_j \, in \, \overline{SD_i}} W_{XY_j} \,. \tag{6}$$

B. Allocation Principle

It is essential to reserve a link-slot which has the lowest interference with other intersecting route-slots, i.e. having the lowest weight. This keeps more available route-slots in the network, hence improving the blocking rate for subsequent communication requests. Thus, the route-slot that has the lowest weight $W_{\overline{SD_i}}$ would be the best choice on a given route between *S* and *D*. In this case, only a minimal number of route-slots in the network become unavailable when serving a given call.

C. Weight Update

After identifying the best route-slot, all constituent link-slots are reserved. Consequently, the weight of each link-slot in each route-slot in Ω'_{XY_i} is modified according to an algorithm, shown in Fig. 1.

foreach $XY_j \; in \; \overline{SD_i}$ **do**

    $W_{XY_j} = W_{XY_j} - 1$

    foreach $\overline{RT_n} \in \Omega'_{XY_j}$ **do**

        if $\overline{RT_n} \equiv \overline{SD_i}$ **skip**

        foreach $UV_k \; in \; \overline{RT_n}$ **do**

            $W_{UV_k} = W_{UV_k} - 1$

        endfor

    endfor

endfor

Fig. 1. Weight update algorithm

By definition (4), Ω'_{XY_j} contains all route-slots whose availability are decremented due to a reservation of XY_j. For instance, when reserving XY_j in a single fiber environment, all route-slots in Ω'_{XY_j} become unavailable, and accordingly, their availabilities flip from 1 to 0. Therefore, the weight of their constituent link-slots must be decremented since a link-slot weight is the sum of the availability of the intersecting route-slots.

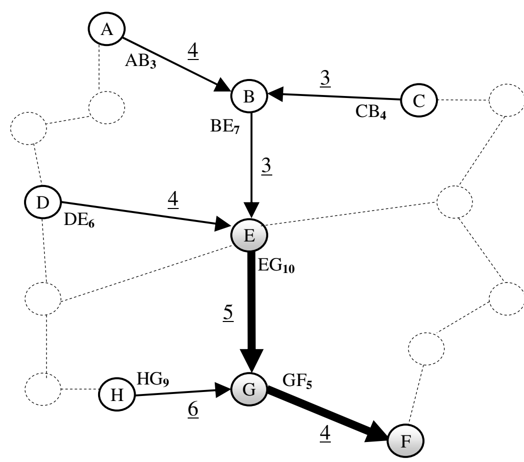

Fig. 2. Route-slot $\overline{EF_{10}}$ and related link-slots

Finally, the same algorithm is repeated when freeing resources, but the weights are increased instead.

D. Illustrative Example

In the network of Fig. 2, a circle defines a node, and an arrow represents a unidirectional single fiber link during a particular link-slot. Next to each arrow is an underlined delay value in slot unit. The dashed area represents network segments where no communication is possible from/to EG_{10} and GF_5 due to unavailability of matching link-slots.

Considering a transmission request from node *E* to node *F*, we should find an available route-slot that has the lowest weight on route *EGF*. We assume 3 available route-slots were identified, $\overline{EF_2}, \overline{EF_8}, and \; \overline{EF_{10}}$. Let us start with weighing $\overline{EF_{10}}$ based on the logistics of Fig. 1. By definition (6), the weight of a route-slot is equal to the total weight of all its constituent slots, $W_{\overline{EF_{10}}} = W_{EG_{10}} + W_{GF_5}$. Assuming a single fiber environment, to get the weight of EG_{10}, we would benefit from identifying $\Omega'_{EG_{10}}$; $\Omega'_{EG_{10}} = \{\overline{AF_3}, \overline{AG_3}, \overline{BF_7}, \overline{BG_7}, \overline{CF_4}, \overline{CG_4}, \overline{DF_6}, \overline{DG_6}, \overline{EF_{10}}, \overline{EG_{10}}\}$. Since the availabilities are either 0 or 1 in a single fiber network, a route-slot being in $\Omega'_{EG_{10}}$ means that its indicator is 1. Thus, $W_{EG_{10}}$ is given by $Size(\Omega'_{EG_{10}})$, which is 10. Similarly for GF_5, we find $\Omega'_{GF_5} = \{\overline{AF_3}, \overline{BF_7}, \overline{CF_4}, \overline{DF_6}, \overline{EF_{10}}, \overline{GF_5}, \overline{HF_9}\}$ and $W_{GF_5} = 7$; and hence, $W_{\overline{EF_{10}}} = 10 + 7 = 17$. Repeating the same process for $\overline{EF_2}$ and $\overline{EF_8}$, which have different logistics not shown in Fig. 2, we may find $W_{\overline{EF_2}} = 21$ and $W_{\overline{EF_8}} = 19$. As a result, $\overline{EF_{10}}$ has the lowest weight and is chosen for reservation. We reserve the constituent link-slots EG_{10} and GF_5, and decrement the weight of each link-slot found in each route-slot in $\Omega'_{EG_{10}}$ and Ω'_{GF_5}, except for $\overline{EF_{10}}$.

III. SIMULATION RESULTS

In this section, we compare the performance of the LC approach against the FF scheme and FF with OTSI in a single fibre network, and also with LL in a multi-fibre network. In addition, we determine its effectiveness in a star topology. Our observations are based on simulation results plotted with 95% confidence intervals.

The simulation experiments are based on the 14-node 21-link NSFNET network topology. A link between two nodes consists of dual unidirectional fibres with a fixed capacity of 10 timeslot channels per fibre. Fixed shortest path routing is used to derive paths between all source destination pairs. Each path serves up to 10 concurrent connections at the granularity of a transmission channel, i.e. one timeslot per link along the path. Each simulation is repeated for 30 runs; each run goes until 100,000 calls are attempted. Calls arrive according to a Poisson process, and lasts for an exponentially distributed period.

We study our scheme under two different traffic distributions among source-destination pairs, uniform and non-uniform. In the uniform traffic case, every pair is chosen with a uniform random distribution, and hence having the same traffic load in Erlang. In the non-uniform case, random sets of SD node pairs are assigned different percentages of the network traffic load. For example, assume that 3% of random SD pairs are assigned 30% of the load; this translates, in a network of 200 SD node pairs, to 6 random SD pairs each having 5 percent chance of generating traffic calls.

Fig. 3 shows the improvement in blocking probability that the LC approach achieves in comparison to the FF approach. The LC approach, under uniform traffic distribution, provides a performance gain almost identical to the case of using optical timeslot interchangers with the FF approach. It is worthwhile noting that with the use of interchangers all blocked calls, in our simulation, happened due to link saturation along the fixed route. Hence, the performance results of employing OTSIs are the optimum any reservation scheme can achieve under a fixed routing approach. Thus, the LC approach achieves close to optimum performance.

Fig. 4 reflects the results of applying non-uniform traffic distribution among source destination node pairs. The blocking rate in all cases was higher than what was achieved under uniform traffic distribution. However, the LC approach maintained its optimal performance as compared to the FF approach with OTSI. The charts show that LC and FF with OTSI yielded identical performance. The reason for this is the randomness in distributing calls among source destination pairs at each simulation run. Considering two routes under similar loads, the route that intersects with more other routes would make more impact on network performance. This route is considered more critical than the other. Take for example one simulation run for the FF approach with OTSI. If a large number of critical routes get a high percentage of the load, the performance tends to go below average. Now, consider a simulation run with the LC approach. If a similar number of less critical routes get the same high load percentage,

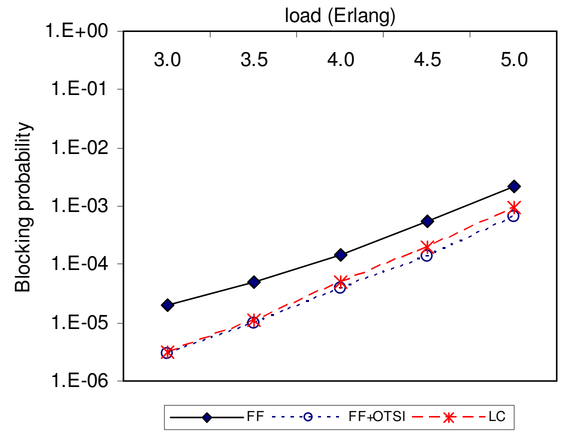

Fig. 3. LC vs. FF with uniform traffic

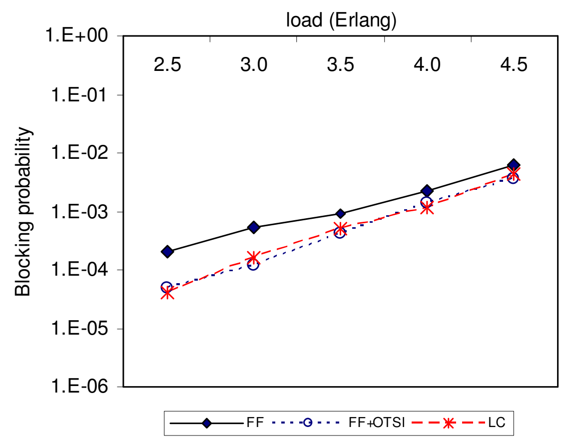

Fig. 4. LC vs FF with non-uniform traffic

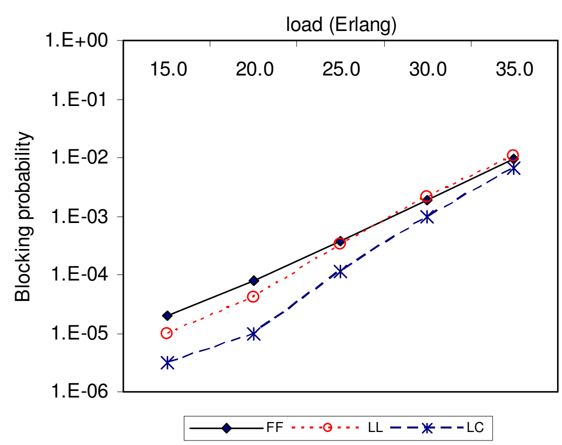

Fig. 5. Comparing LC to LL in multi-fiber networks (3 fibers per link)

performance tends to be above average. Due to random load distributions, simulation runs produced numbers below and above average in both cases, LC and FF with OTSI. However, after 30 runs of each case, performance averages out to the same level as shown in Fig. 4.

Fig. 5 shows that the LC approach provided better performance results than the LL approach when applied to a multi-fibers network consisting of 3 fibers per link. It outperformed LL at every load level. In addition, the LC approach can be applied to single and multi-fiber environments; On the other hand, the LL approach collapses to an FF approach in single fiber networks, and hence loses its benefit.

Fig. 6 shows the performance of the LC approach in a star network topology. It provides identical results to the FF approach. This result is expected since all links in a star have the same number of intersecting 2-hops routes; hence, all link-slot weights were initially equal. In addition, when a reservation is made on a link-slot, corresponding link-slots in all other links get equally updated. Thus, the LC approach collapses to an FF approach in a star topology since the weighing scheme would have no impact.

IV. Complexity Comparison

Having compared the LC approach to the FF and LL approaches, we discuss the complexity of these reservation schemes. The complexities of the FF and LL approaches are in the order of *N*, where *N* is the frame size. In the worst case scenario, it takes the FF approach $N \times h$ steps to reserve an available route-slot, where *h* is the hop count. When OTSI is used with FF, the complexity becomes in the order of N^h. In the worst condition, the number of steps to reserve an available route-slot on a given path is $N^h + (h \times C_O)$, where C_O is the average cost of finding a free OTSI. In the case of the LC approach, the complexity figure is in the order of *N*. For the worst cases, it takes $(N \times h) + (h \times C_R)$ steps to reserve an available route-slot on a given path, where C_R is the average cost of updating the weights of link-slots under all route-slots in Ω_{XY_j}.

It is evident that the complexity of the LC approach is close to the FF approach and almost N^{h-1} smaller than FF with OTSI.

V. Conclusion

After proposing the least constraint slot reservation approach (LC) in all-optical TDM networks, we compared its performance to the first fit (FF) approach, and FF with optical timeslot interchangers (OTSI). The LC approach provided a performance gain close to the FF approach with OTSI, but at a reduced complexity close to FF without OTSI. The result was consistent under uniform and non-uniform traffic distribution. In addition, we found that the LC approach outperformed the least loaded (LL) approach in multi-fiber environments. Thus, LC has and edge over LL, since the former is not restricted to

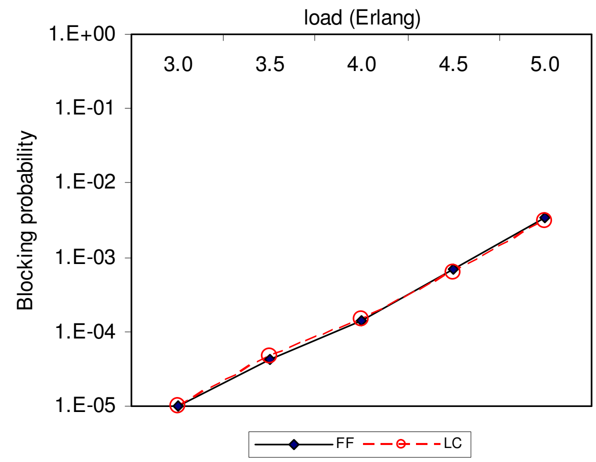

Fig. 6. Measuring LC in a star network

multi-fibers networks as is the latter. On the other hand, the LC approach did not show any performance improvement over the FF approach when considering a star topology synchronized on slot boundaries. The reason for this result was attributed to equal slot weights and fixed hop counts in the star topology. As a conclusion of this work, we say that the LC approach provides close to optimum performance in optical TDM networks with no buffering.

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