Dynamic Routing, Wavelength, and Fiber Selection Algorithms for Multi-Fiber WDM Grooming Networks

Khaled M. F. Elsayed, Senior Member IEEE
khaled@ieee.org

Department of Electronics and Communications Engineering
Faculty of Engineering, Cairo University
Giza, Egypt 12613

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Abstract: We consider the problem of dynamic routing in a multi-fiber time-slotted wavelength routed WDM network. Requests to establish a connection are dynamic and each connection requests an integer multiple of some basic unit. Each wavelength has capacity of carrying a *multiple* of these channels, where each channel is represented by a time-slot as in TDM networks. We represent the network as a layered graph model with multiple layers, where each layer represents a specific wavelength. Each link in the layered graph has one or more fibers and an associated cost. The cost of layered graph links could be a function of the loading state of the respective wavelength across the available fibers. We propose algorithms for fiber selection and for setting link costs and use a modified Dijkstra algorithm on the layered graph to select a route on the layered graph for a new connection request. The selected route on the layered graph represents the physical path and the selected wavelength. We evaluate the performance of these algorithms for a realistic mesh network topology for various combinations of the number of wavelengths, the number of fibers per link, the number of time-slots per wavelength, and the offered load for both uniform and non-uniform traffic loads. We identify the best performing fiber selection and link cost update methods. Our proposed algorithm for routing and wavelength assignment in mesh optical WDM grooming networks outperforms previously proposed work in the literature.

1. INTRODUCTION

Traffic grooming is the process of multiplexing low speed traffic streams onto high speed wavelengths. The traffic grooming problem has been extensively studied for WDM mesh and ring networks with static traffic. For an overview and literature survey, the reader is referred to the survey paper by Dutta and Rouskas [1]. With the evolution of transmission speeds in wavelengths from 2.4 and 10 Gbps to 40 Gbps in the near future, it is only natural that interest in efficient grooming methods increases. In addition, the interest in dynamic grooming has increased due to the emergence of GMPLS [2] as a control-plane for optical transport networks and the desire to transport IP connections directly over optical cross-connects (OXCs) via MPLS/MPλS.

One approach to optimize the use of optical bandwidth, is to divide the wavelength into multiple time slots and multiplex traffic on the wavelength and timeslots. The resulting optical network is referred to as a TDM wavelength routed network or a WDM grooming network. The nodes in such networks, for example an OXC, should be capable of multiplexing/de-multiplexing lower rate traffic onto a wavelength and establishing and releasing a lightpath. With such functionality available at the network nodes, Srinivasan and Somani [3] classify WDM grooming networks into three categories: add-drop multiplexer constrained grooming (ADM-CG), wavelength continuity constrained grooming (WC-CG), and Full Grooming (FG) networks. In ADM-CG, a node can only groom traffic on dropped wavelengths. In WC-CG, a node can switch traffic across different lightpaths but cannot convert from a wavelength to another, while in FG, a node can switch connections in any permutation.

The dynamic traffic grooming problem is formulated as follows. We have a WDM network with a set of OXC nodes and a certain physical topology consisting of fiber links interconnecting the OXCs. Each fiber link may contain $F \geq 1$ fibers with each fiber having W wavelengths. Each wavelength can carry upto T channels of some basic capacity C. Connections requests arrive one at a time and last for a variable period of time (which is usually large compared to inter-arrival time of the requests) and each connection requests sub-wavelength amount of capacity $t \leq T$ channels. The problem is now how to select a route, wavelength and fiber between the source and destination OXCs for the incoming connection in order to reduce the connection blocking rate and eventually result in better network resource utilization and throughput.

In this paper, we tackle the dynamic routing, wavelength, and fiber assignment problems in multi-fiber TDM wavelength-routed optical networks by representing the network as a layered graph model. This graph has W layers, where each layer represents a specific wavelength. Each link in the layered graph has F fibers and an associated cost which could be a function of the loading state of the respective wavelength across the available fibers. As previously proposed by [4] (for a WDM network without grooming) we use a modified

Dijkstra algorithm that has a reduced complexity due to the structure of the layered graph. By applying the modified Dijkstra algorithm on the layered graph, we obtain the route for a new connection request. As a result of the layering, the wavelength is automatically selected. We propose two algorithms for fiber selection and two algorithms for setting link costs. This work is related to the work reported by [5]. In essence, we handle the multi-fiber case and wavelength selection comes automatically by virtue of the layered-graph model. One of our algorithms is basically the available shortest path algorithm (AVSP) proposed by [3] as applied to the layered graph. We show that by adapting the link cost function of the layered graph, that an algorithm we call the least-utilized path (LUP) usually outperforms AVSP in most configurations.

1.1 Survey of Related Work

Static grooming is a well-studied problem. An in-depth coverage of the problem and literature survey has been reported by Dutta and Rouskas [1]. An overview of the related routing and wavelength assignment for static traffic is reported by [6]. Huang et al. [7] handle similar problem to the one presented here but for a given number of connections (static traffic) and with time-slot continuity constraint.

Dynamic routing and wavelength assignment is handled by Zang et al. [8]. They propose two approaches for dynamic lightpath establishment. The first is based on link-state routing and the second is based on distance-vector routing. Routing is done using fixed routing, alternate fixed routing, or least-congested path selection based on shortest-path algorithms. The paper reports results on connection setup delay, blocking probability, and the time required for nodes to update topology information after a connection has been established or taken down.

The area of dynamic traffic grooming in TDM wavelength-routed mesh optical networks is relatively young. It was first inspected by Yates et al. [9] who show that by using time-slot interchange in networks with a small number of wavelengths, each carrying a large number of time-division multiplexing slots, that significant gains can be achieved without wavelength conversion. Srinivasan and Somani [3] study a similar problem to the one studied in this paper. The routing and wavelength assignment are taken as two separate processes. They evaluate the performance of the available-shortest path, widest-shortest path, and shortest-widest path routing algorithms. The wavelength assignment algorithm is fixed.

Zhu et al. [10] present four fixed grooming policies and an adaptive grooming policy. The model presented is quite general and assumes the existence of pre-established lightpaths between the network nodes. If the established lightpaths cannot accommodate an incoming connection, a new lightpath is established and a portion of its capacity is allocated as needed by the connection. They show that a certain adaptive policy is superior to the fixed policies. However, the formulation uses a complex graph model and the application of proposed adaptive grooming policy depends on gathering global information about all network links.

Wen and Sivalingam [5] consider the grooming problem when the grooming nodes are not capable of time-slot interchange and therefore the time-slots assigned to a connection must be the same along the path of the connection. This assumption could lead to higher blocking probability than grooming networks with time-slot interchange capability. Wavelength assignment is done using the least-loaded method. They propose three methods for time-slot assignment: first-fit, least-loaded, and least-loaded with alternate wavelengths. Various cost functions for dynamic shortest-path routing are proposed. They show that a cost function that causes the routing algorithm to choose the least-congested path performs quite well. A related work on time-slot assignment is by Subramaniam et al. [11]. They consider the static multi-rate connection scheduling on wavelengths and timeslots. They provide a lower bound on frame length and propose various scheduling algorithms for contiguous and non-contiguous time-slot assignment.

The work presented here also relates to the area of quality-of-service routing and the area of routing in circuit-switched networks. A full survey of all related papers is outside the scope of this paper, however we refer the interested reader to [12][13] for overview and extended bibliography related to these two areas.

1.2 Contributions of this paper

Our proposed algorithms combines the selection of a route and a wavelength for a connection instead of doing separate route selection followed by wavelength assignment. We also handle the case of multi-fiber links and propose new fiber-selection algorithms. We also propose a new algorithm we call the LUP that enhances the blocking performance over the AVSP proposed by [3] while having similar complexity. A new metric is defined for measuring the capability of an algorithm to load balance the routed connections among the available wavelengths. This metric is called the wavelength fairness index. Another contribution is that we provide performance results under uniform and non-uniform traffic loading.

2. THE NETWORK MODEL AND THE LAYERED GRAPH REPRESENTATION

We consider a network with arbitrary topology represented by a graph $G(V, E)$ with a set of vertices $V=\{1, 2, \ldots, |V|\}$ representing the OXCs and a set of edges $E=\{E_{ij}\}=\{1, 2, \ldots, |E|\}$, $i, j \in V$ representing the physical links connecting the OXCs. Each edge has $F \geq 1$ fibers and each fiber has W wavelengths. Each wavelength has a capacity of T TDM slots (or circuits). An OXC is capable of switching in space and time between input and output ports. The feasibility of using time-slot interchange in the optical domain has been shown in [14]. Since the main focus in this paper is the study of grooming in all optical networks, we assume the OXC's has no wavelength conversion capability. However the model presented here can be readily extended to the case of wavelength conversion, or to the case when some nodes are capable of wavelength conversion and some are not by modifying the graph formulation discussed later. If full wavelength conversion is implemented in the nodes, the routing in the WDM grooming context would be equivalent to the well-known routing in circuit switched networks with the only exception being the multi-fiber case.

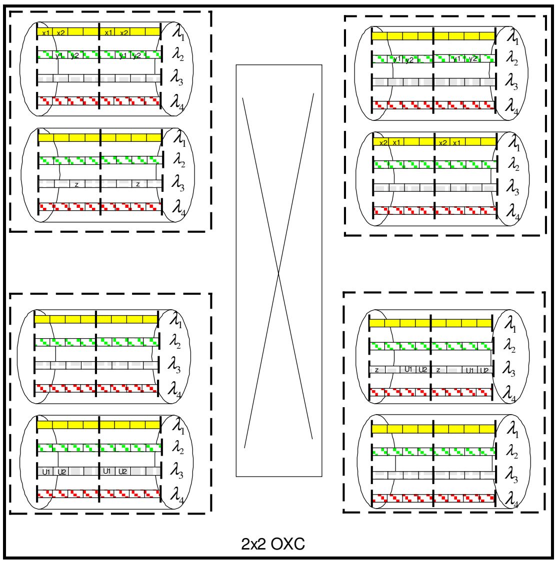
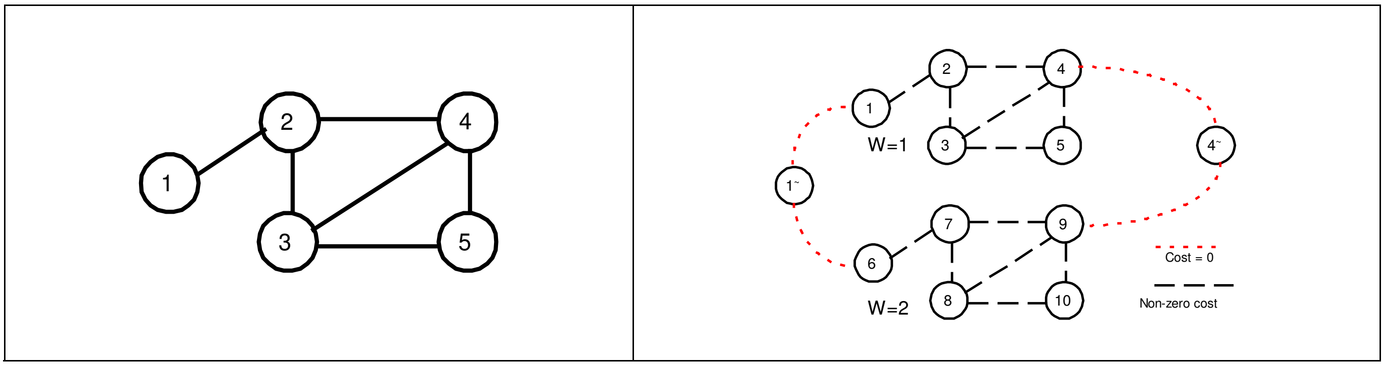


Figure 1. A 2x2 OXC node with F = 2, W = 4, and T = 4. Four connections U, X, Y, Z are switched in space and time.

The OXC switching capability is shown by a hypothetical 2x2 OXC with F=2, W=4, and T=4 in *Figure 1*. Four connections U, X, Y, and Z are switched in time and space from any input fiber and slot to any output fiber and slot given that they keep the same wavelength.

Our algorithm is based on constructing a layered graph LG which is constructed from the original graph G in the following manner. Each vertex and edge in the original graph is repeated W times to construct the W layers of the graph. The copy of a vertex i in V in layer w of LG is called the w^{th} image of i and is identified by the pair (i, w). The w^{th} image of an edge e in E is defined similarly and is identified by the pair (e, w). The layered graph $LG=(N, L)$ consists of the $W\,|V|$ nodes $N = \{\,[(1,1),(2,1),\cdots,(|V|,1)],\,[(1,2),(2,2),\cdots,(|V|,2)],\cdots,[(1,W),(2,W),\cdots,(|V|,W)]\,\}$ and the $W|E|$ links $L = \{\,[(1,1),(2,1),\cdots,(|E|,1)],\,[(1,2),(2,2),\cdots,(|E|,2)],\cdots,[(1,W),(2,W),\cdots,(|E|,W)]\,\}$. Note that we use the terms node/link for the layered graph while we use vertex/edge for the original graph. Since we do not allow wavelength conversion, the layers of the graph are not connected by any link. (Note that wavelength conversion can be represented by extending links of zero cost between all the graph layers for each two vertices in G connected with an edge in E). Each link l in L has an associated cost C_l which could be a function of the current loading level of the wavelength over the multiple available fibers.

The layered graph is used by the dynamic routing algorithm to select a path between a given source and destination pair. The wavelength is automatically selected as a result of executing the routing algorithm on the layered graph. The link costs of the links in the multiple layers are different and thus a good routing algorithm should be able select the current best path and wavelength combination. When the routing algorithm is executed between vertices s and d in G, the layered graph LG is further extended by two nodes (representing a virtual source and destination) and 2W links as follows. A virtual source node $\tilde{S}$ is added to N, whereas W links of zero cost are added to L by connecting $\tilde{S}$ and the W images of the vertex s in N, namely S, $S+|V|$, … , $S+(W-1)|V|$. Similarly, a node $\tilde{D}$ representing virtual destination is added to N, and W links of zero cost are added to L by connecting $\tilde{D}$ and the the W images of the vertex d in N, namely D, $D+|V|$, … , $D+(W-1)|V|$. The path selection algorithm is then executed between $\tilde{S}$ and $\tilde{D}$ which results in selecting the wavelength automatically when the path between $\tilde{S}$ and $\tilde{D}$ is calculated. An example of a simple graph and the associated layered graph when path selection between nodes 1 and 4 is performed is shown in *Figure 2*.



(a) (b)

Figure 2. (a) Original Graph (b) The associated layered graph for W = 2 for path selection between nodes 1 and 4.

3. DYNAMIC ROUTING, WAVELENGHT, AND FIBER SELECTION ALGORITHMS

Using the layered graph model, we can implement various routing methods for path selection. We use the standard shortest-path algorithms where the difference between the routing methods is in the way the link costs in the layered graph are computed as function of the load. Also, once a route/wavelength is selected, a fiber is to be selected such that the connection will be routed on that fiber at each selected link.

Consider an edge E_{ij} in *E*. In the layered graph representation *LG*, E_{ij} is represented by the *W* links $L_{ij}^1, L_{ij}^2, \cdots, L_{ij}^W$. Let the number of fibers on E_{ij} be *F* and let the capacity of the wavelength be T time-slots. Further, let $U_{ij}^{\lambda}(f)$, $0 \le U_{ij}^{\lambda}(f) \le T$, denote the number of time-slots used by the on-going connections at wavelength λ on link E_{ij} at fiber *f*, $1 \le f \le F, 1 \le \lambda \le W$. Let $A_{ij}^{\lambda}(f) = T - U_{ij}^{\lambda}(f)$ be the corresponding number of available time-slots at wavelength λ on link E_{ij} at fiber *f*. Define x_{ij}^{λ} as the current cost of link L_{ij}^{λ}. The proposed routing and wavelength selection algorithm works as follows:

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Given the source S and destination D and the required connection bandwidth t.
1- Set link cost $x_{ij}^{\lambda}$ of links $E_{ij}$ in LG to $\infty$ for those links with
    $A_{ij}^{\lambda}(f) < t, \quad 1 \le f \le F, 1 \le \lambda \le W$.
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2- Extend the layered graph by the nodes $\tilde{S}$ and $\tilde{D}$ and the associated zero-cost links to the images of S and D in the layered graph as explained in section 2.

3- Apply the modified Dijkstra algorithm on the resulting graph to find shortest path between $\tilde{S}$ and $\tilde{D}$.

4- If a path that can accommodate the request is found, do the following:

- Identify the links and wavelength selected
- Perform fiber selection algorithm on selected path
- Update link costs for the selected links and wavelength

When a connection is terminated, the costs of the used links and wavelength is updated. The routing algorithms studied here differ mainly in the way the link cost is updated.

Available Shortest Paths (AVSP): In this algorithm the cost x_{ij}^{λ} is fixed to 1 for all links in the layered graph. However, if we reach a state where all available capacity across all available fibers is utilized, we set x_{ij}^{λ} to ∞. This algorithm tends to fill lowest numbered wavelength, then the second wavelength and so on.

Least Utilized Path (LUP): In this algorithm, the cost x_{ij}^{λ} is set equal to $1/\left(1-\left[\frac{\sum_{f=1}^{F} U_{ij}^{\lambda}(f)}{F*T}\right]^{A}\right)$, $A \geq 1$. The higher the utilization of the fibers of a certain link, the higher its cost. This algorithm tends to use links that are less utilized. The used cost function has an effect akin to balancing the traffic across the available wavelengths. Note also that the cost function tends to ∞ as all capacity in a wavelength is used up. The parameter A determines the behaviour of the shortest-path route selection, the higher the value of A, the slower the growth in the cost function as function of the link utilization. In the limiting case as $A \to \infty$, the cost is fixed at 1 (equivalent to AVSP). We experimented with various values of A, and found that $A = 4$ is a good value. It remains an open problem to determine the best value of A for different network loading or topologies and traffic parameters.

3.1 Fiber Selection Algorithms

Once a connection with bandwidth t is assigned a path and a wavelength, then by virtue of the routing algorithms and the specific construction of the layered graph, there must be at least one fiber that can accommodate the bandwidth. If there is more than one available fiber, a fiber selection algorithm is used to select an appropriate fiber. In our implementation we propose two fiber selection algorithms: Least Loaded Fiber and Best Fitting Fiber.

Least-Loaded Fiber Selection (LLF): In the least loaded fiber selection, given the available fiber capacities on the selected link L_{ij} are $A_{ij}^{\lambda}(f), 1 \le f \le F$, we select the fiber f^* which has the largest $A_{ij}^{\lambda}(f^*) \ge t$.

Best Fitting Fiber Selection (BFF): In this best fitting fiber selection method, we select the fiber f^* that has the smallest available capacity after increasing its used channels by t. In other words f^* is obtained from the relation $A_{ij}^{\lambda}(f) - t \ge A_{ij}^{\lambda}(f^*) - t \ge 0, 1 \le f \le F, f \ne f^*$. This policy tends to pack used fibers as much as possible, then it starts to pack the next available fiber and so on.

3.2 The modified Dijkstra algorithm on the layered graph

The standard Dijkstra algorithm finds the shortest path between a given node in a graph and all other nodes in the graph. It is based on a greedy algorithm which finds the paths in order on increasing length from the source. For an overview of this algorithm and the associated terminology and operations defined within the algorithm, the reader is referred to [15] for more information. Going back to our layered graph model, the Dijkstra algorithm can be applied directly on the graph without modification rendering a computational complexity of order $O(|N|^2\ |W|^2)$. However, in the case of networks without wavelength conversion and where the wavelength continuity constraint is applied, by careful examining of the nature of the layered graph it becomes clear that the various layers are isolated. We therefore implement a modified version of the EXTRACT-MIN and RELAX operations of the Dijkstra's algorithm. We keep a heap of size W that contains the index of the nodes with minimum distance from the source in layer $\lambda, 1 \le \lambda \le W$. The EXTRACT-MIN is executed on a heap of size W instead of $|N|\ |W|$ in the usual case. This is because at each step we can find the minimum across all layers instead of all nodes. If a node is selected from layer λ of the layered graph, the RELAX operation updates *only* the nodes in layer λ. The distance of the nodes in the other layers do not change since these nodes cannot be reached from the selected node in layer λ. After the relax operation is executed, the node with the minimum distance in layer λ is found and the heap containing the minimum across all layers is updated (operation HEAP-UPDATE). In the worst case, these steps are repeated $|N|\ |W|$ times and each step has a complexity of O(W) for EXTRACT-MIN and HEAP-UPDATE, and O(N) for the RELAX operation. The overall complexity is $O(\max(N,W)\ |N|\ |W|)$ for networks with no wavelength conversion.

The proposed routing methods are suitable for distributed implementation using a link-state routing algorithm. The exchanged link state vectors should include the utilization of the wavelengths across the different fibers at a given link. A signalling protocol such as GMPLS [2] would be an ideal candidate for transport of the link state packets. GMPLS defines a four level switching hierarchy. The highest level are nodes with fiber switch capable (FSC) interfaces, followed by nodes that have lambda switch capable (LSC) interfaces, followed by nodes that have time division multiplex capable (TDM) interfaces, followed by nodes with packet switch capable (PSC) interfaces. In our model, the OXCs are TDM/LSC/FSC capable and GMPLS can be directly used. Link states updates should be triggered upon connection acceptance and release. In such a setting, it is only natural that link state updates would not place a large burden on the network since it is expected that the duration of a generic connection would be large compared to the time a signalling packet traverses the maximum distance between any two nodes in the network. In such circumstances, we can safely assume that the occurrence of a connection establishment and connection release in the same time link state updates are propagated in the network is negligible. In other words, the probability of outdated link state information in the network is insignificant. For a study of link state update effects on dynamic routing in WDM networks, reference [8] provides some good insight.

4. PERFORMANCE EVALUATION

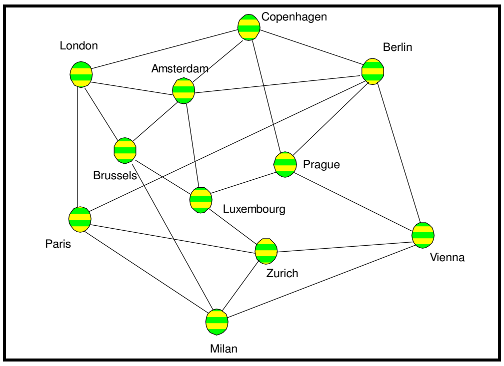


Figure 3. The Cost239 network topology used in the simulation.

We use the COST239 network topology [16] shown in *Figure 3* as our reference network topology. It has 11 nodes and 24 links with a good connectivity degree of 24/(11x10/2)=0.44. (The connectivity degree of a graph measures how dense a graph is as compared to a fully connected graph having the same number of nodes. It is obtained by taking the ratio of the number of links in the graph divided by the number of links in the corresponding fully-connected graph.) We use discrete-event simulation based on the Simpack [17] library to manage the event list containing connections arrival and departure information. Each simulation run is performed with at least 200,000 connections and each experiment is replicated five times with different random seeds. The mean of the five samples is used to show the results and to indicate the degree of accuracy of the results by calculating the variance/standard deviation around the calculated mean. It is to be noted that it is not possible to obtain reliable confidence intervals with such a low number of replications. However, for blocking probabilities higher than 10^{-4}, the results from the independent replications are quite close (to the mean). For lower values of the connection arrival rate (which result in low blocking rates), we tend to increase the number of generated connections (upto a certain upperbound) until we notice a connection blocking event. Each simulation run starts with an empty network and we set a warm-up period of 10,000 connections where no statistics are collected. The connections arrive in accordance with a Poisson distribution with rate R connections/unit time and last for an exponential duration with a mean of 1 unit. In all simulations, connections request a bandwidth t with equally likely probability from the set {1, 2, …, 8}. All network configuration have WxFxT=512. The values of W, F, and T, can be varied but we keep their product fixed at 512.

For each simulation, we obtain the following performance metrics: 1) The connection blocking probability, 2) The average path length of accepted connections, 3) The average bandwidth of accepted connections, 4) The wavelength fairness index (WFI) which is defined as follows: let the amount of total bandwidth routed on wavelength λ over all links in the graph be BW_λ, and let BW_λ^{AVG} be average of BW_λ across the simulation runs, then $WFI = \min_{\lambda \in \{1,2,\ldots,W\}} \{BW_\lambda^{AVG}\} / \max_{\lambda \in \{1,2,\ldots,W\}} \{BW_\lambda^{AVG}\}$. It is clear that $0 \leq WFI \leq 1$. The wavelength fairness index defines how a routing algorithm distributed loads into the various wavelengths. It is desirable to have high values of WFI (close to 1), especially at high loads.

In the results, we evaluate the following: the performance of fiber selection algorithm, detailed results on performance of the two routing algorithms under different configuration, and effect of non-uniformity in the traffic on the performance of the routing algorithms.

4.1 Performance of fiber selection algorithms

We use the COST239 topology and vary the arrival rate from 1150 to 1550 connection/unit time. The traffic is uniformly selected between all 110 source destination pairs. We test the network with LLF and BFF fiber selection algorithm in combination with the AVSP and LUP routing methods. We use two network configurations of 4x8x16 and 8x4x16. *Figure 4* shows that BFF fiber selection works better for both AVSP and LUP. It is clear that LUP performance is more sensitive to fiber selection algorithm than AVSP which is clear as the cost function used by LUP is a function of the fiber loading while AVSP which has an almost constant cost function. LLF causes LUP to perform very poorly (this is due to the fact that it causes the cost function of LUP to increase faster than BFF which tends to fill one fiber then the next and so on). We also note that for higher number of fibers (part (a) of *Figure 4*), the BFF advantage is more significant.

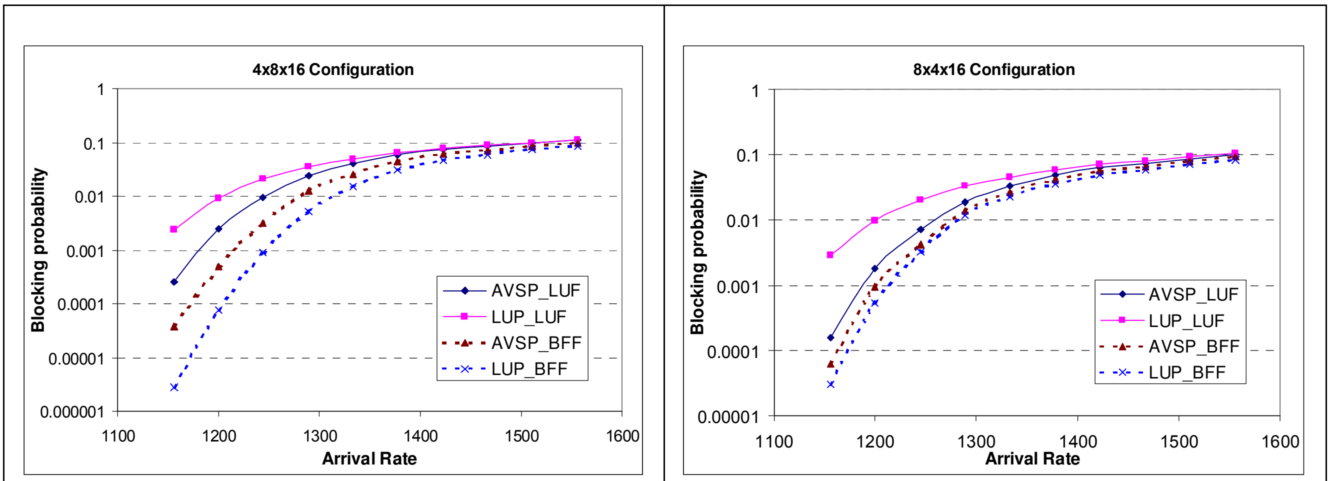


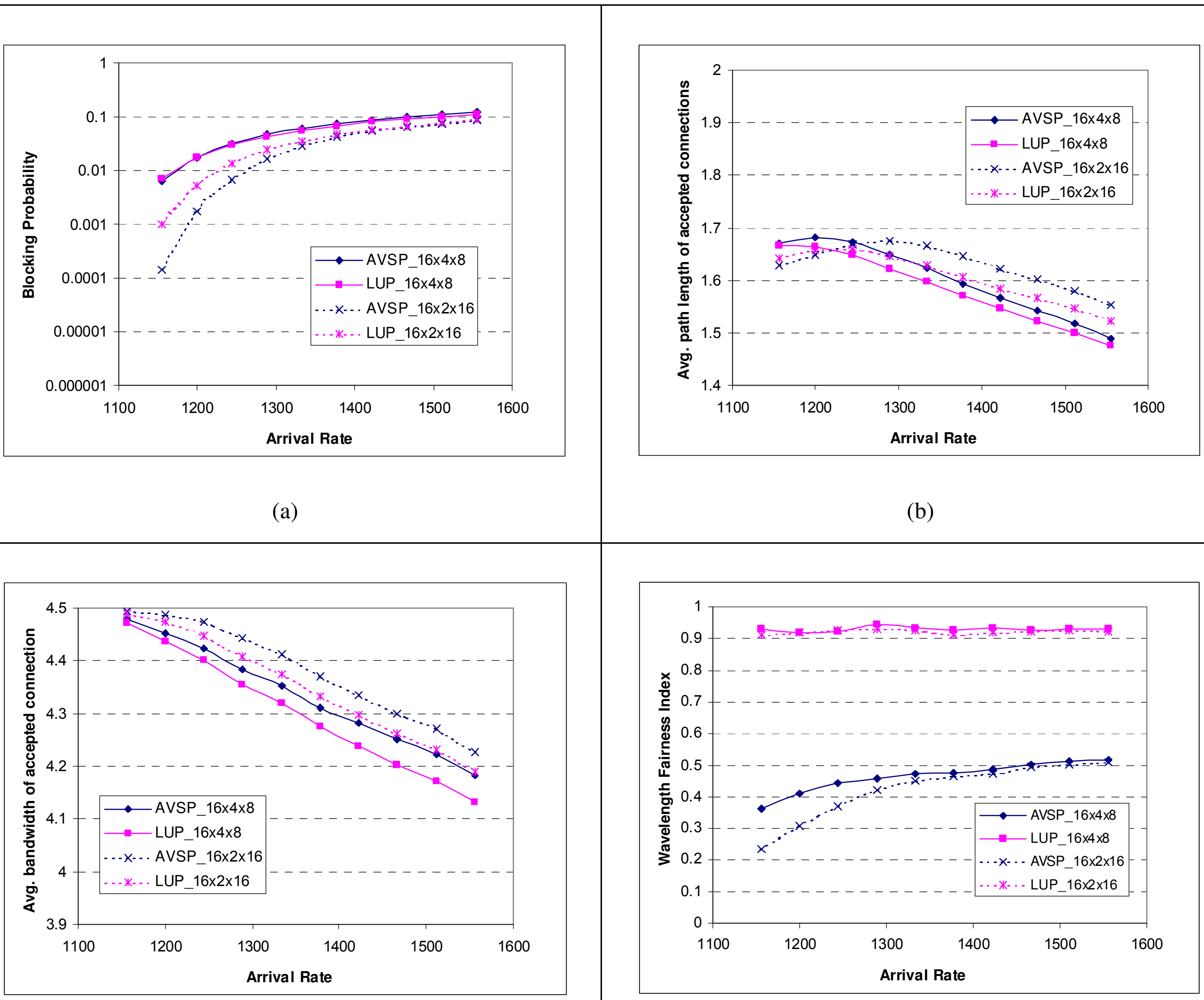
Figure 4. Results for fiber selection algorithms showing advantage of Best-Fit fiber selection over least-loaded fiber selection.

4.2 Performance of routing algorithms in the uniform traffic case

In this section we try to evaluate the performance of the AVSP and LUP routing methods for uniform traffic and different values of *W*x*F*x*T* using the BFF fiber selection algorithm. We report the results for *W*=16, *W*=8, and *W*=4. The traffic is uniformly selected between all 110 source-destination pairs. For each case we report the results on the four performance metrics defined above.

For *W*=16, we use the two configuration 16x4x8 and 16x2x16 and report the results in *Figure 5*. For this case the AVSP algorithm is the best performing method for low values of traffic load while in high loads, LUP starts to outperform AVSP. It is clear that AVSP distributes load very poorly across the wavelengths. This is OK for low values of arrival rate, but for higher loads, it could be argued that some wavelengths are not utilized and that fair distribution of connections over these wavelengths could lead to lower blocking rates (which is what LUP does). We observe that path length and bandwidth of an accepted connection tends to decrease as load increases. We also note that having more slots is more advantageous than having higher number of fibers for the same capacity. This is in accordance with well-know result of queueing theory that accumulating more channels into a single resource provides better performance.

By decreasing *W* to 8 and using the two configurations of 8x4x16 and 8x2x32, the LUP starts to outperform the AVSP especially at low loads as shown in *Figure 6*. For the case of *W*=4, we use the two configurations 4x4x32 and 4x2x64 and show the results in *Figure 7.* As in *W*=8, the LUP is the better method. By inspecting Comparing *Figure 5*, *Figure 6*, and *Figure 7*, we can see that by keeping the overall capacity fixed and using a smaller number of wavelengths with a larger number of time-slots per wavelength greatly enhances the performance of the network. We argue that it is advantageous to use coarse wavelength division multiplexing (CWDM) with large number of time-slots per wavelength than using dense wavelength division multiplexing (DWDM) with small number of time-slots per wavelength when connections have lower-rates than the full-rate of a wavelength. This is not surprising as it is in full accordance with basic known facts of queueing theory.

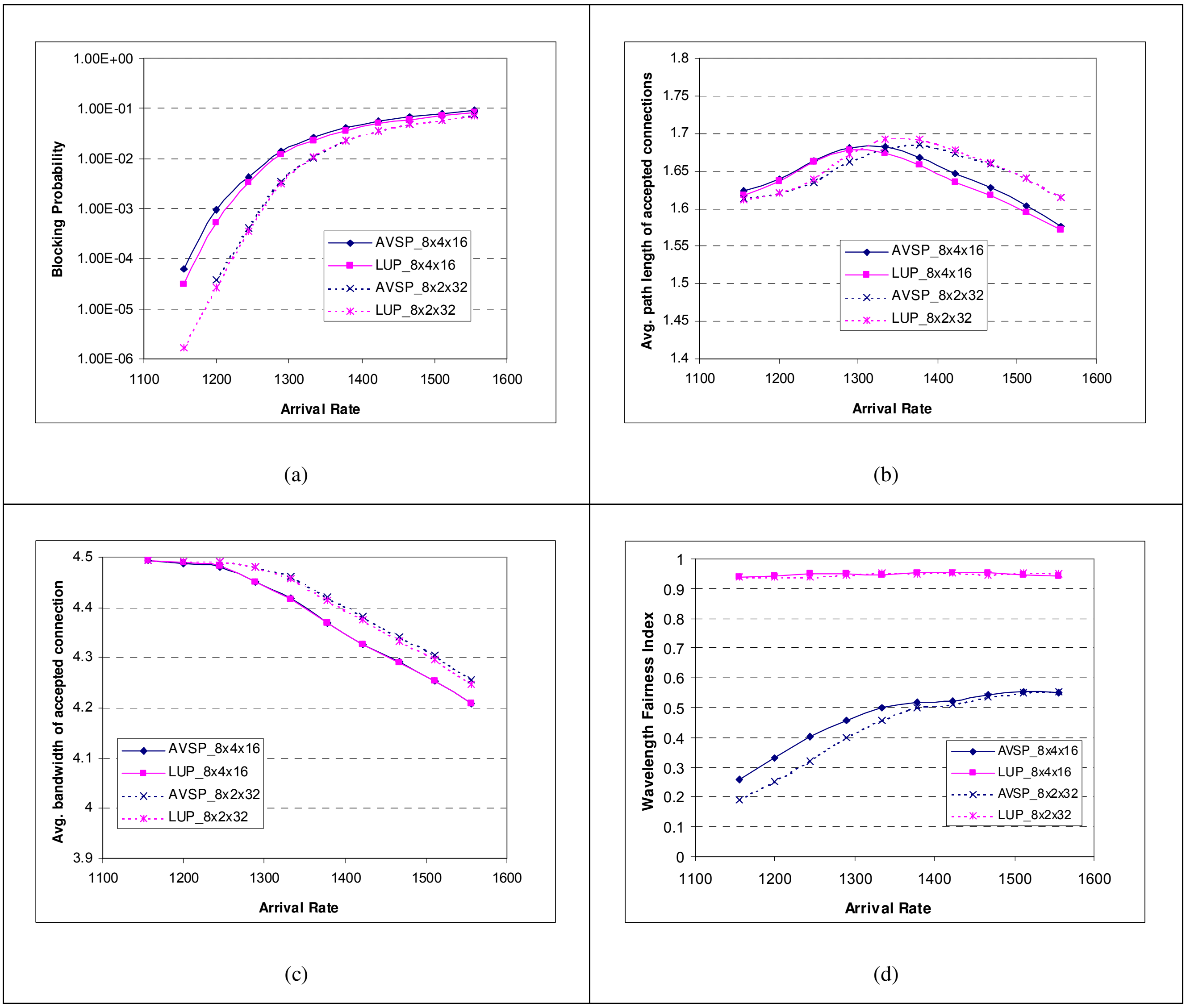


(a) (b)

(c) (d)

Figure 5. Results for W=16 for two different configurations.

We note from the six cases reported in this section that LUP exhibits the best fairness. However, this does not usually translate to better performance as in the case of W=16. We also note from the results that the average bandwidth of an accepted connection is a non-increasing function of traffic load. However, the average path length of an accepted connection may increase as traffic load increases, but after a certain traffic load, it is always a decreasing function. This is explained by the fact that for low loads, the connections are usually routed on shortest number of hops. As load increase the routing methods could find paths longer than shortest-hop paths that can accommodate a connection. By further increasing the load, paths becomes more congested, and connections spanning a higher number of hops, usually get blocked with a higher probability than connections spanning one or two hops.



(a)

(b)

(c)

(d)

Figure 6. Results for W=8 for two different configurations.

4.3 Performance of routing algorithms in the non-uniform traffic case

In this section, we evaluate the performance of the AVSP and LUP methods in the non-uniform traffic case. We select ten source destination pairs in the network as *hot pairs*. These hot pairs are assigned a portion $\alpha\%$ of the overall offered traffic. The rest $(1-\alpha)\%$ of the traffic is uniformly distributed over the other hundred source destination pairs. We define α as the non-uniformity factor of the network.

In the first two experiments, we use the two configurations 16x4x8 and 8x4x16 and vary α from 0.1 to 0.5 while fixing arrival rate at 1155 connection/unit time. The results are reported in parts (a) and (b) in *Figure 8*. We note that increasing non-uniformity causes network performance to decrease. For W=16, AVSP is better than LUP, while for W=8, LUP is better (but not significantly so). The corresponding values of the blocking probability for the uniform-traffic case is 0.0064 and 6.21E-5 for AVSP and 0.007 and 3.05E-5 for LUP in the 16x4x8 and 8x4x16 configurations respectively (these values are also shown as reference lines in *Figure 8* (a), (b).

In the second set, we report the results for fixed $\alpha = 0.2$ and show the performance against uniform traffic case as function of connection arrival rate. It is clear that non-uniformity adversely affect performance specially for low values of network loading. We note here that LUP start to outperform AVSP in the W=16 as load increases. For W = 8, LUP is consistently better than AVSP.

We can conclude from the results in section 4.2 and 4.3 that in most cases LUP outperforms AVSP. AVSP is only better in lightly loaded network with (a relatively) large number of wavelengths.

5. CONCLUSIONS

We presented a novel algorithm for handling routing, wavelength and time-slot assignment in multi-fiber TDM wavelength-routed mesh optical networks in the wavelength continuity constrained grooming (WC-CG) case. The algorithm is based on layered graph model and a modified Dijkstra's shortest-path algorithm. We also propose alternative cost function setting methods and fiber selection methods. We evaluate the performance of these methods in a realistic WDM network topology for different combinations of wavelengths, fibers, and time-slots of the network links under uniform and non-uniform traffic loading. We show that the combination of the LUP link cost update method and the best-fitting fiber selection provides the overall best performance for most configurations and network loads. We also showed that it is advantageous to use CWDM with large number of time-slots per wavelength than using DWDM with small number of time-slots per wavelength when connections have lower-rates than the full-rate of a wavelength.

Further work can be devised into enhancing LUP performance for low loads and higher number of wavelengths by tuning the value of the parameter A. Also, extending to the case when time-slots assigned to a connection must be the same across all selected links can be done. This would simply the architecture of an OXC and lead to cost reduction but needless to say the blocking rate will increase with such an implementation. Also, studying the grooming performance when only a subset of the network nodes are grooming capable (e.g. ADM's in the network edge are grooming-capable while the core OXC's perform no grooming) is worth investigating.

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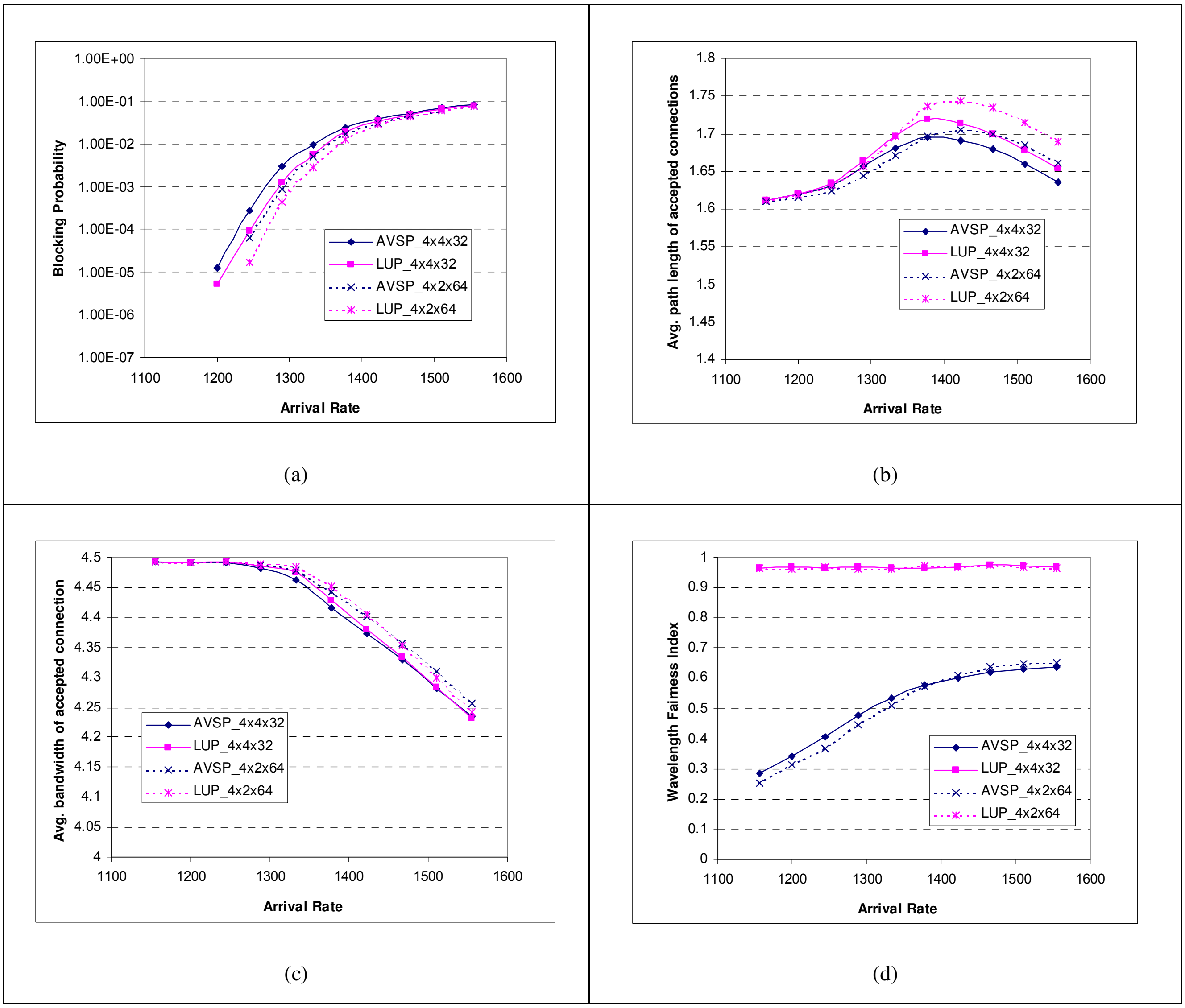


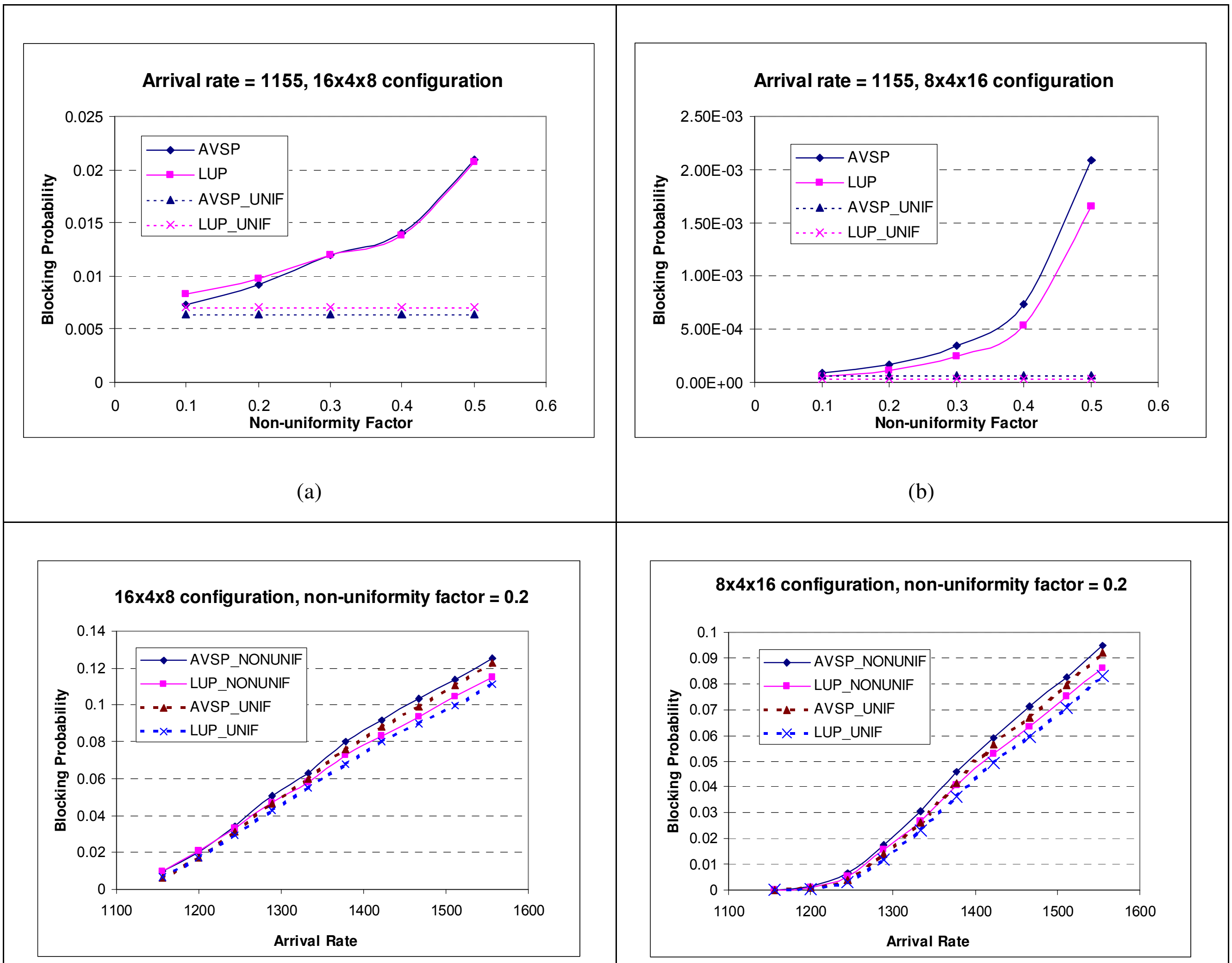
(a)

(b)

(c)

(d)

Figure 7. Results for W=4 for two different configurations.



(a)

(b)

(c)

(d)

Figure 8. Results for non-uniform traffic loading. (a), (b) performance as function of non-uniformity factor at arrival rate 1155 connections/sec. (c), (d) performance as function of arrival rate at non-uniformity factor = 0.2.