Protection in Multi-Granular Waveband Networks

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***Abstract*— As the number wavelengths in WDM systems continue to increase, the switching fabric of optical cross connects (OXCs) becomes increasingly complex. This complexity can be reduced by introducing multi-granular optical cross-connects (MG-OXC) into the network. A MG-OXCs is capable of switching an entire group of wavelengths through a single switch port, thereby reducing the number of switching ports and reducing the complexity of the switch fabric. In this paper, we consider the problem of establishing active and backup paths for connections in networks with MG-OXCs. The problem of establishing protected connections for a given traffic demand in multi-granular networks differs from the protection problem in standard wavelength-routed networks in that the primary objective in multi-granular networks is to minimize the number of switch ports in the network. The mode of protection (dedicated or shared) affects the ability to aggregate and route traffic together. We propose a graph-based heuristic that attempts to solve the problem of routing and waveband assignment in an integrated manner. The heuristic reduces the total number of ports in the multi-granular network. We also study the effect of shared protection on the port count.**

I. Introduction

Wavelength division multiplexed (WDM) optical networks are seen as a solution for satisfying the requirements of emerging bandwidth-hungry applications such as video-on-demand, telemedicine, and peer-to-peer applications. In an all-optical WDM network, each fiber carries multiple wavelength channels, and each node routes each wavelength channel all-optically through an optical cross-connect (OXC). As WDM technology continues to mature, each fiber will be capable of supporting a greater number of wavelength channels. This increase in the number of WDM channels will increase the complexity of network management as well as the complexity of the switching fabric in the OXCs.

In order to reduce the OXC complexity, the number of ports in the switching fabric can be reduced by routing groups of wavelengths together through a single port. An OXC that is capable of routing different granularities of traffic at the same time is referred to as a *multi-granular OXC* (MG-OXC), and a network that uses MG-OXCs (Fig. 1) is referred to as a *multi-granular optical network* [1], [2]. In order to switch multiple granularities, a MG-OXC comprises of a Wavelength Cross-connect (WXC), a Waveband Cross-connect (BXC), and a Fiber Cross-connect (FXC). The WXC, BXC, and the FXC can individually switch wavelengths, wavebands, and fibers respectively. The FXC switches each fiber individually and demultiplexes a fiber at a particular node only if one or more wavelengths or wavebands in the fiber are being dropped or switched to different destinations at the node. The BXC demultiplexes a waveband into its component wavelengths if and only if at least one wavelength from the waveband is being dropped or switched to different destinations at the node.

For example, suppose we have an m-wavelength request from a source s to a destination d. The number of ports required by intermediate OXCs in a wavelength routed network (WRN) to route the connection are m ports. But in a multi-granular network, each intermediate MG-OXC would require just *one* waveband port for this request, if the waveband size is m.

The benefits of multi-granular networks are maximized when the bypass traffic at a node is aggregated together and switched as a single waveband unit. Hence, in addition to routing and wavelength assignment, the basic design issue that needs to be considered in multi-granular networks is that of waveband assignment. In waveband assignment, the objective is to band groups of wavelengths together at each node in order to minimize the total number of switch ports in the network.

The approach to addressing RWA and waveband assignment depends on whether the network environment is static or dynamic. In a dynamic environment, connection requests arrive to the network dynamically and depart after some time, while in a static environment, the set of connections is known in advance. The typical objective in a dynamic environment is to reduce the blocking of future connection requests, while the objective in a static environment is to minimize the resource usage. In this work, we will consider only the static case.

Another important network design problem in multi-granular networks is to provide a seamless flow of traffic between source-destination pairs in the event of a failure. This objective can be accomplished by routing traffic over a pre-calculated alternative backup path if the original working path is affected by some failure. Much research has been conducted in the domain of protection in WDM networks, and a number of techniques have been proposed to solve the problem of placement of active and backup bandwidth across the network [3]–[5].

A number of previous works have addressed the problem of routing and wavelength assignment in multi-granular networks [6], [7]. In some cases, the problem is addressed in the context of traffic grooming. Traffic grooming involves multiplexing lower granularities of traffic into coarser granularities, with the objective of minimizing the network cost. The work in [6] considers the problem of grooming traffic in multi-granular networks with mesh and ring topologies. Other works have looked at the problem of grooming traffic in networks with full wavelength conversion at all nodes [7]. A graph-based model is proposed in [8], to provision sub-wavelength traffic in WDM networks. The work in [9] addresses the problem of routing and wavelength assignment in multi-granular networks by banding together connections that have the same destination. An ILP model and heuristics have been proposed in [10] for banding lightpaths. The above works attempt to solve the problem of RWA in a sequential fashion and not in an integrated manner. To the best of our knowledge no work considers protection problem in multi-granular networks.

In this paper, we consider the protection problem in multi-granular network with static traffic and no wavelength conversion. Given a set of connection requests, the problem is to find an active and backup path, and to assign wavelengths to each of these paths,

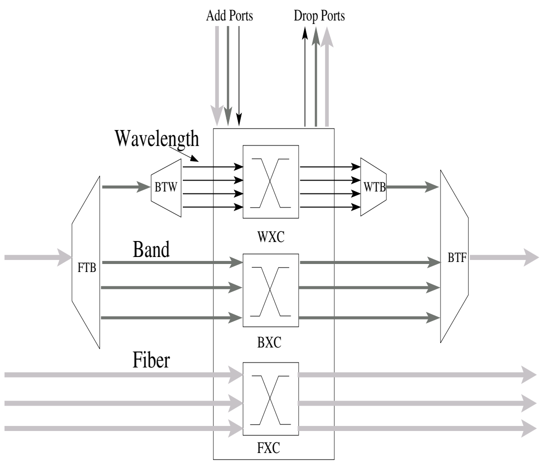

Fig. 1. Single Layer MG-OXC

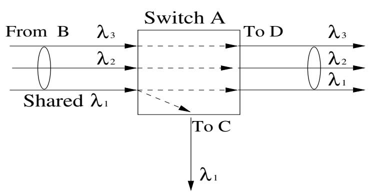

Fig. 2. Shared Protection Switching

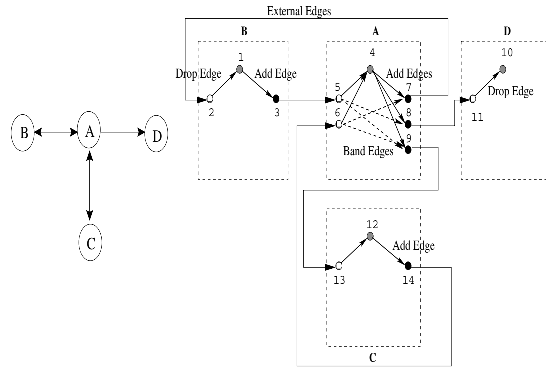

Fig. 3. Example Graph with Transformation

with the objective of minimizing the total number of switch ports in the network. We propose a graph-based heuristic that finds the route and the waveband in a single integrated step, thereby yielding better solutions than other approaches that attempt to solve the problem in a sequential manner. We also only consider protection against single-link failures, since the occurrence of multiple simultaneous failures is expected to be low.

The remainder of the paper is organized as follows. Section II discusses the general problem framework and the architecture of the MG-OXC. Section III introduces the graph-based heuristic for the problem. Section IV presents the simulation results and a discussion of the results. Section V summarizes the contribution of this paper.

II. General Problem Framework

We consider the problem of finding an active and a backup path for a set of connections in a multi-granular network equipped with MG-OXCs that have a single switching fabric to route fiber, wavebands, and wavelengths [11] (Fig. 1). In this architecture, we demultiplex a fiber into its bands using fiber-to-band demultiplexers (FTB), if and only if the bands or wavelengths in the fiber are switched to different output ports. If all the bands and wavelengths bypass the node and are switched to the same output port at a particular node, the fiber is not demultiplexed and is switched by the FXC. Similarly a band is not demultiplexed at a node, unless the wavelengths in the band are dropped or switched to different output ports. A band is demultiplexed into wavelengths using the band-to-wavelength demultiplexers (BTW). Wavelengths are multiplexed into wavebands in the output side of the switch using the wavelength-to-band demultiplexers (WTB). Similarly bands are multiplexed into fibers with the help of band-to-fiber (BTF) multiplexers.

The requirement of demultiplexing fibers and bands are the same for dedicated protection. However, in the shared protection problem, the demultiplexing criteria differs from the dedicated protection scenario. If the wavelength λ is reserved for protection on a link (i, j) and is shared by a set of active paths, $(\nu_w^{i,j})$, and if λ needs to be switched to different output ports at j depending on which active path failed, then λ needs to be switched individually at node j, and hence a band b containing λ has to be demultiplexed at j. This is illustrated in Fig. 2. λ_1 is shared by two backup paths that pass through A and go to C and D. In the event of a failure, the backup path on λ_1 from B to A has to be switched either to the output port of C or to the output port of D depending on which active path failed. Hence the band b has to be demultiplexed at A and the wavelengths must be switched individually at A, even though λ_2 and λ_3 are switched to the same node D at A. The likelihood that a specific λ has to be switched individually increases if a greater number of backup paths share λ. Hence as sharing increases, the chance that a wavelength has to be switched individually increases, resulting in an increase in the number of switch ports in the network. As is evident, sharing of wavelengths for backup paths and aggregation of wavelengths into wavebands are conflicting objectives. Due to the symmetry in the input and output side of the switches, we count the total number of switch ports only on the input side of the switches for our analysis.

III. Graph Based Heuristic

A. Graph Structure

The problem of establishing connections in a multi-granular network is initiated by constructing an auxiliary graph from the given network topology. A separate auxiliary graph for every waveband in the network is constructed by transforming the original graph G to graphs G'_b, where b represents the waveband. The waveband size (BS) is defined as the total number of wavelengths that can be routed together as a single unit. After the transformation of G, we have auxiliary graphs $G'_0 \cdots G'_{BS-1}$. Let G' be the set of $G'_0 \cdots G'_{BS-1}$. The OXC in the original network topology is represented as a node, and the links between OXCs are represented as edges in the graph. The original graph G is transformed to the auxiliary graph set G' by transforming the node in the original graph to an auxiliary node.

An example of a graph and its transformation is represented in Fig. 3. The links in the graph are directed. There is no restriction on the links to be directed. An undirected link is considered as two directed links in opposite directions. In our example there is an undirected edge between A and B and a directed edge from A to D, but no edge from D to A.

The various node types in the auxiliary graph are:

- *Incoming Interface Node* ($IINd_i^{n,b}$): If a node n in G has an incoming edge from node i, then $IINd_i^{n,b}$ is a node in G'_b. In Fig. 3, nodes B and C have outgoing edges to A and hence there are two incoming interface nodes $IINd_B^{A,0}, IINd_C^{A,0}$ as nodes 5 and 6 in the auxiliary graph G'_0.
- *Outgoing Interface Node* ($OINd_i^{n,b}$): If a node n has an outgoing edge to another node i in G then $OINd_i^{n,b}$ is a node in graph G'_b. A has outgoing links to $B, C,$ and D, and hence G'_0 has $OINd_B^{A,0}, OINd_D^{A,0}$, and $OINd_C^{A,0}$ as nodes 7, 8, and 9 respectively.
- *Add-Drop Node* ($ADNd_b^n$): This node is used for the adding or dropping of a waveband at a particular node. Every node in G has a $ADNd_b^n$ in G'_b. $ADNd_0^A, ADNd_0^B, ADNd_0^C, andADNd_0^D$ are represented as nodes 1, 4, 10, and 12 in Fig 3.

The various edge types in the auxiliary graph are:

- *External edges* ($EXT\_EDGE_{i,j}^b$): If there exists an link from node i to j in G, then there is an auxiliary edge from $OINd_j^{i,b}$ to $IINd_i^{j,b}$ in G'_b. The weight of this edge is the same as link (i,j) in the G. In Fig. 3 the edge from node 3 to node 5 is an example of an external edge.
- *Internal edges*: These auxiliary edges are among auxiliary nodes which represent the node in the transformed graph G'_b. The heuristic updates the weights of these edges to facilitate banding.
  - *Band edges* ($BAND\_EDGE_{i,j}^{n,b}$): These are edges from $IINd_i^{n,b}$ to an $OINd_j^{n,b}$, and represents the waveband b that is routed from the node input to the its output, without demultiplexing it at node n. The initial weight of $BAND\_EDGE_{i,j}^{n,b}$ is set to $0, \forall i, j$. The weights of the edge $BAND\_EDGE_{i,i}^{n,b}$ is set to $\infty, \forall i$ to avoid looping of paths. The edge from node 5 to node 6 in Fig. 3 is a band edge.
  - *Drop edges* ($DROP\_EDGE_i^{n,b}$): These are edges from an $IINd_i^{n,b}$ to an $ADNd_b^n$. The initial weight of these edges are set to BS. In Fig. 3, the edge from node 1 to 3 is a drop edge.
  - *Add edges* ($ADD\_EDGE_i^{n,b}$): These are edges from an $ADNd_b^n$ to an $OINd_i^{n,b}$. The initial weight of these edges are set to BS. In Fig. 3, the edge from node 2 to 1 is an add edge.

B. Heuristic - GRAPH-HEUR

The heuristic computes the route and waveband in a single step. It then attempts to find a wavelength in the chosen waveband that satisfies the wavelength continuity constraint. Computing a path from a source to destination in the auxiliary graph G' is equivalent to finding the route and the waveband. By varying the cost of the auxiliary internal edges, the choice of the route and the waveband can be made so as to promote the banding of connections.

The connections are routed one at a time, and the selection of the node pair is chosen based on the traffic requirement. The node pair with the maximum traffic is chosen first (*MTF*), and if there is a tie, the node pair with the maximum number of hops on their shortest path in the original network topology (G) is chosen. Let the node pair chosen by the selection scheme be $s-d$. The disjoint pair of paths between s and d is chosen using the active path first heuristic (*APF*). The heuristic computes the minimum cost path (sp_b^{s-d}), between the $ADNd_b^s$ and $ADNd_b^d$ in the graph G'_b for every waveband $b: 0 \cdots BS-1$. Let the set SP_{s-d} denote the set of $sp_b^{s-d}, \forall b$. The minimum cost path $sp_{b'}^{s-d}$ among all paths in SP_{s-d} is chosen as the active path. Wavelengths are assigned using the first-fit heuristic (FF). We assign as many wavelengths along the path $sp_{b'}^{s-d}$ in the band b', so that they meet the wavelength continuity constraint along the path. If the total demand is not yet met, the heuristic attempts to assign as many wavelengths as possible along the second shortest path in the set SP_{s-d} until the demand is met. Let the routes along which the active paths for $s-d$ are assigned be the set $Active_{s-d}$. After having assigned the active path, the edge costs in the affected graphs are updated to facilitate banding. The details of the update are discussed in section III-C.

The backup paths are assigned sequentially to each $ap \in Active_{s-d}$. If $EXT\_EDGE_{i,j}^{b'} \in ap$, then $EXT\_EDGE_{i,j}^b$ is removed from every G'_b, $b: 0 \cdots BS-1$, to yield G''_b. This is to ensure that the active paths are disjoint from the backup paths. For the dedicated protection problem, the backup route is found in G''_b, in the same way as the active route described above. The shared protection problem demands a slightly different approach, due to the constraint that the active paths whose backup path share wavelengths on the same link must be link disjoint themselves (i.e. in different failure scenarios). The conflict set ν_w^e is defined as the set of the active paths whose backup paths use wavelength w on edge e. If ap is link disjoint to every path $p \in \nu_w^e$, then wavelength w on edge e can be shared by the backup path for ap. Hence we update the cost of edge e in G''_b to be zero, where b is the band in which w is present. The shortest path is now searched in this modified graph and wavelength assignment for the shared protection path is done using the first-fit heuristic. After assigning the backup path, the edge costs in the affected graphs are updated based on the rules defined in section III-C.

It may be observed that wavelength assignment may fail on the minimum cost path $sp_{b'}^{s-d}$ for either the active path or the backup path or both. The reason is that the path chosen denotes the least cost route and waveband for the connection. This does not guarantee that a wavelength-continuous path exists along the same route and in the same waveband. Hence the heuristic must continue to look for a route and waveband assignment that has a wavelength continuous path along the same route and waveband.

C. Update of Edge Costs

Let $free_b^{i,j}$ be the number of free of wavelengths on $EXT\_EDGE_{i,j}^b$.

$$fr\_l_b^{i,j} = \begin{cases} \infty & \text{if } free_b^{i,j} = 0; \\ free_b^{i,j} & \text{otherwise} \end{cases}$$

fr_l decreases with the decrease in the number of free wavelengths on the links. Hence, assigning fr_l as a cost to the auxiliary edges promotes a link with more connections over other links with fewer connections, thereby facilitating banding of connections.

After the wavelength assignment is done for any node pair $s-d$ on path $sp_{b'}^{s-d}$, the cost of the edges in the auxiliary graph $G'_{b'}$ are updated based on the following rules:

- $\forall BAND\_EDGE_{i,j}^{n,b'}$ that exist on path $sp_{b'}^{s-d}$
  - $BAND\_EDGE_{i,k}^{n,b'} = \infty$, $\forall k$ except j,
  - $BAND\_EDGE_{k,j}^{n,b'} = \infty$, $\forall k$ except i,
  - $ADD\_EDGE_{j}^{n,b'} = fr\_l_{b'}^{n,j}$

  Since $BAND\_EDGE_{i,j}^{n,b'}$ is on the path, this implies that node n can route band b' from i to j without demultiplexing it at n. Hence band b' cannot be routed from any other incoming node (k) to the outgoing node j. Similarly, band b' cannot be routed from the incoming node i to any other outgoing edge (k). This constraint is adapted in the auxiliary graph by setting the cost of the respective band edges to ∞. The last update is made in anticipation that the band b' is not completely filled, so as to be routed as a waveband at n. By updating $ADD\_EDGE_{j}^{n,b'}$, the heuristic promotes the possibility that band b' will be routed as a waveband by the downstream node,j. The simulation yields better results with this update than without it.
- $\forall DROP\_EDGE_{i}^{n,b'}$ that exist on the path $sp_{b'}^{s-d}$,
  - $BAND\_EDGE_{i,j}^{n,b'} = \infty$, $\forall j$
  - If all the existing connections in band b' terminate at node n , then $DROP\_EDGE_{i}^{n,b'} = fr\_l_{b'}^{i,n}$ else $DROP\_EDGE_{i}^{n,b'} = BS$

  The use of $DROP\_EDGE_{i}^{n,b'}$ implies that band b' from node i is demultiplexed at node n. Hence band b' cannot be routed as a band to any of the outgoing nodes j. By updating the cost of $DROP\_EDGE_{i}^{n,b'}$ to $fr\_l_{b'}^{i,n}$, we are promoting all paths terminating at node n to use the link (i, n). This promotes the different source - same destination (*DS-SD*) banding scheme.
- $\forall ADD\_EDGE_{i}^{n,b'}$ that exist on the path $sp_{b'}^{s-d}$,
  - $ADD\_EDGE_{i}^{n,b'} = fr\_l_{b'}^{n,i}$
  - if n is the source of this path ($n = s$), then no cost updates, else, $BAND\_EDGE_{j,i}^{n,b'} = \infty$, $\forall j$ except i.

  By assigning fr_l as the cost of the $ADD\_EDGE_{i}^{n,b'}$, the heuristic promotes its choice (n, i) in subsequent paths. If n is not the source of the path, then n cannot route band b' from any node j to node i. Hence the edge costs of the $BAND\_EDGE_{i,j}^{n,b'}$ are updated accordingly. If n is the source of the path $sp_{b'}^{s-d}$, then the heuristic gives a higher priority to the edge (n, i) for all other paths that are sourced at n, thereby promoting same source - different destination (*SS-DD*) banding scheme.

IV. Simulation Results

We simulate a static network environment to evaluate the performance of the heuristic. The traffic is randomly generated for the node-pairs, and each node-pair is equally likely to have traffic flowing. The traffic is unidirectional and traffic from $s-d$ does not imply that there is traffic from $d-s$. The heuristic is used to route connections on a six-node network and the NSF network (Fig. 4). Results for the six node network follow the same pattern as the NSF network and hence the graphs for the six node network are not shown. To simulate the problem in traditional wavelength routed networks (WRN), we use the shortest path heuristic (*SP-HEUR*) to route the active and the backup paths. Since traditional WRNs aim to reduce the total wavelength usage, the *SP-HEUR* routes the connections on two disjoint paths with the least combined cost. The total number of wavelength hops in *SP-HEUR* is the minimum possible over all possible configurations. The wavelength assignment for the dedicated protection is done by the first-fit heuristic. For shared protection, the wavelength assignment is done so as to promote the maximum sharing among the backup paths. After assigning the wavelength for the active path, we choose the wavelength on the backup path that is shared the most with the other existing backup paths.

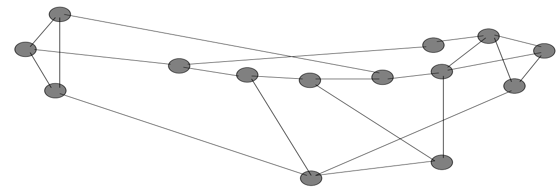

Fig. 4. NSF Network

Since no other heuristic has been proposed for protection in multi-granular networks, we use the RWA of *SP-HEUR* in the multi-granular domain to calibrate the performance of *GRAPH-HEUR*. We consider both dedicated and shared protection in our simulation, and hence we have four scenarios. Dedicated protection using the *GRAPH-HEUR* (DEDI-GRAPH), dedicated protection using *SP-HEUR* (DEDI-SP), shared protection using the *GRAPH-HEUR* (SHR-GRAPH), and shared protection using *SP-HEUR* (SHR-SP). We define the following ratios to compare the performance of multi-granular networks over WRNs and over various heuristics in the multi-granular domain.

- *Switch port ratio (SPR)* is the ratio of the number of switch ports in the multi-granular network to the number of ports in the WRN. In our simulation we count the number of ports in the WRN designed by *SP-HEUR*.
- *Wavelength hops ratio (WHR)* is the ratio of the total number of wavelength hops in the multi-granular network to the number of wavelength hops in WRNs.
- *Maximum switch size ratio (MSSR)* is the ratio of the maximum size of the switch over all nodes in the multi-granular network to the maximum size of a switch over all nodes in the WRNs.

Fig. 5 shows the variation in the savings of the number of ports as the band size varies. A band size of 4 is optimal for both the shared protection and the dedicated protection problem. The increase in the band size increases the number of ports with respect to WRNs. The *GRAPH-HEUR* outperforms the *SP-HEUR* by a sizable percentage (20-25%), illustrating the novelty of the *GRAPH-HEUR*. We also see the effect of sharing bandwidth for backup paths on the port count. Since sharing increases the likelihood of a band being dropped at a node, we see the savings drop by 10-15% for the case of shared protection when compared to dedicated protection for both heuristics.

Fig. 6 shows that aggregation of traffic leads to an increase in the total number of wavelength hops. The *GRAPH-HEUR* routes connections along longer paths to facilitate banding with other

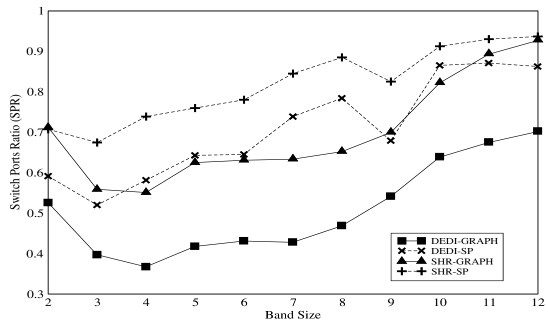

Fig. 5. Switch Port Ratio - NSF Network

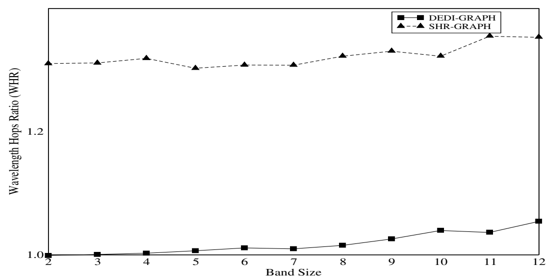

Fig. 6. Wavelength Hops Ratio - NSF Network

connections. WHR is always ≥ 1, illustrating the fact that longer paths are taken by connections to reduce the overall network complexity. Since the objective of the *GRAPH-HEUR* is to optimize the number of switch ports, it does not promote sharing, which is illustrated by a higher WHR for shared protection. The dedicated protection has less than 5% increase in the wavelength hops. Shared protection causes an increase of 30% increase over WRNs in the NSF network and about 10% increase in the six node network. This variation in wavelength hops is due to the larger choice of paths for a node pair in the NSF network. *GRAPH-HEUR* looks for paths that reduce the port count, and since the NSF network has more paths, it assigns longer paths to connections to reduce the port count. Since there are fewer choices of paths for the six node network, its WHR is ≈ 1.

Fig. 7 shows that waveband networks are very scalable. The maximum switch size over all the switches in the waveband network designed by *GRAPH-HEUR* are at least 30% less than WRNs, and about 15% less than *SP-HEUR*. Again we see an increase in the switch size for the case of shared protection.

The above results indicate that the reduction in switch complexity of multi-granular networks varies with waveband size. Larger wavebands promote more banding of lightpaths, reducing the number of ports required in the MG-OXCs. However, very large wavebands may not be useful, since when a single lightpath is dropped from the waveband, the entire waveband has to be demultiplexed, which requires a greater number of ports in the WXC as compared to a smaller waveband size. Hence the choice of the waveband size is an important factor in maximizing the savings. In our simulation, a waveband size of 4 gave optimal results for both the NSF and the six node network (Fig. 4). Sharing of wavelengths for backup paths also affects the number of switch ports in the network. If we have a higher sharing factor

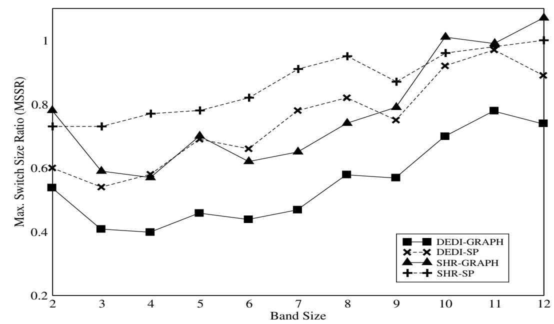

Fig. 7. Maximum Switch Size Ratio - NSF Network

(number of backup paths sharing a single wavelength), the number of switch ports in the network increases. Hence an optimal sharing factor needs to be chosen.

V. Conclusion

Multi-granular networks are seen as a way to implement scalable OXCs by reducing the port count and the complexity of the optical switching fabric. In this paper, we attempt to solve the problem of protection in multi-granular networks by proposing a graph-based heuristic. The graph-based heuristic attempts to solve the problem of determining the route and the waveband in an integrated manner which performs better than heuristics that solve the problem by assigning routes and waveband in sequential steps. The protection requirement of connections and the mode of protection also affects the RWA. Shared protection conserves wavelengths, but at the same time discourages banding. Hence there is a trade off between the number of wavelengths used to satisfy the traffic demand and the number of switch ports.

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