Versatility of a colorless and directionless WSS based ROADM architecture

Prasanna. G[1], Sai Kishore. B[2], Omprasad. G. K,
Sathyanarayana Raju. K, Gowrishankar. R,
Venkataramaniah. K
Department of Physics
Sri Sathya Sai University
Prasanthi Nilayam, India
[1]gprasanna.sssu@yahoo.co.in, [2]mail2saikishore@gmail.com

Ron Johnson
Cisco Systems Inc.
San Jose
California, U.S.A
ronjohn@cisco.com

Pavan Voruganti
OpVista Inc.
Milpitas, California, U.S.A
pvoruganti@opvista.com

***Abstract*— In core/metro optical networks there are multi-degree nodes providing N path interconnections and alternate paths for protection. This paper presents the optimum implementation of a colorless and directionless add/drop switching feature in a mesh network, using the WSS based ROADM. The idea of scaling, viewed as an increase in route degree and number of wavelengths handled in each direction is then addressed. Subsequently, we suggest the best ways in which specific advantages like dynamically optimizing light paths by optical bridge-and-roll, avoiding O-E-O operations and blocking specific wavelengths can be leveraged. Finally, practical implementation issues like power loss, OSNR and cost considerations are discussed.**

Keywords- mesh optical networks, reconfigurable optical add/drop multiplexer, wavelength selective switch, colorless and directionless architecture, optical bridge-and-roll, O-E-O, MEMS.

I. Introduction

The demands for higher bandwidths at lower costs are increasing substantially in today's communication networks. The continued growth of video and other broadband services are pushing the service providers and equipment vendors to look for dynamic optical networks. Moreover, truck-rolls are required to be sent in the field in order to re-assign the optical paths and to launch new wavelengths, new equipment has to be installed which increases both Capital- (CAPEX) and Operational Expenditure (OPEX) for the service provider's network. Thus, it is very important for service providers to attain flexibility in handling the churn and growth of the optical network and also achieve complete control over every part of the network. This has led to the development of Reconfigurable All-Optical Networks (R-AONs) that can help them to maximize network capacity, adapt to the surge of traffic, reduce network complexity and provide transparent wavelength services to customers, while also being cost effective. The re-configurability mainly relies on the integration of Reconfigurable Optical Add/Drop Multiplexer (ROADM) modules in the present metro core optical networks. This is achieved by the intelligent control plane that controls optical networks dynamically in real time, providing a means of both automating the services, and offering a range of protection and restoration schemes, including sub-second restoration, through enabling fully meshed optical networks. This level of automation allows network operators to move beyond simple ring configurations towards fully meshed optical networks that not only allow the networks to survive multiple failures, but also automates them for delivering new services. The wavelength selective switch (WSS) based ROADM supports colorless add/drop, per channel optical power monitoring (OPM) and balancing, and multi-degree interconnection. These valuable features make the WSS based ROADM the choice for agile "all-optical" mesh networks.

Any agile optical mesh network calls for an architecture which can dynamically route wavelengths in any desired direction, terminate a certain wavelength and eliminate O-E-O operations during ring-to-ring interconnections. In addition, the architecture should be truly scalable to be future proof and support the possibility of remote optimization of network resources by optical bridge-and-roll during the evolution of the mesh network. These needs can be fulfilled by a colorless and directionless architecture [1]. We propose an optimum implementation of the colorless and directionless WSS based ROADM architecture. Subsequently, we address issues like scalability (from the perspective of increase in number of wavelengths and route degree), optical-bridge-roll and elimination of O-E-O operations.

II. Design Methodology

Before presenting the details of the proposed architecture, it is appropriate to begin with the description of a general design methodology for an optical mesh network [2]. In transparent optical networks built using intelligent switches like ROADMs the design is too complex to be accomplished by a single holistic computer design tool. Therefore, the entire design process is usually partitioned into different sub-modules with effective heuristics. The sub-modules include routing and ROADM choice, span engineering and power dynamics simulation – each accomplished by a single class of design tools [3].

The traffic pattern and the fiber network are the inputs to the routing and ROADM choice module. The output is a set of configured ROADMs that create the light paths required to satisfy the routing demands. The second module, span engineering requires the design resulting from the first phase and accordingly chooses the optical amplifiers (OAs) and dispersion compensating modules (DCMs) to correctly mitigate all optical impairments, at minimal cost. The detailed configuration produced by the first two modules is fed as the input to the power dynamics simulation module. During the addition of new services or failures (like fiber cuts) or transient scenarios the channel power levels and amplifier working change considerably. The power dynamics simulation module simulates such scenarios to determine suitable counter measures to restore stability to the network. In the following section we present an optimum implementation of the colorless and directionless WSS based ROADM architecture at the optical layer. Designing a network based on this architecture calls for a design methodology such as the one just described.

III. Colorless and Directionless Architecture

The colorless and directionless feature is defined with regard to the functionality of the local add/drop feature at a certain node in a mesh network. While *colorless* means the ability to drop or add any wavelength at any port, *directionless* refers to the ability to connect to all the directions or routes from the local transponders. Consider the following sample mesh network in Fig. 1.

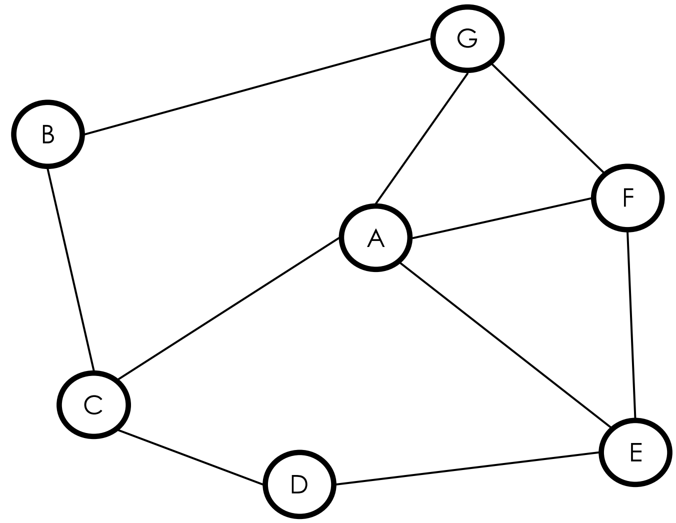

Fig. 1 A mesh optical network

As shown, A is a 4-degree node. A colorless and directionless architecture is realised at node A by using WSS based ROADMs and multi-port splitter combiners as shown in Fig. 2. The WSS shown are 1x9 devices.

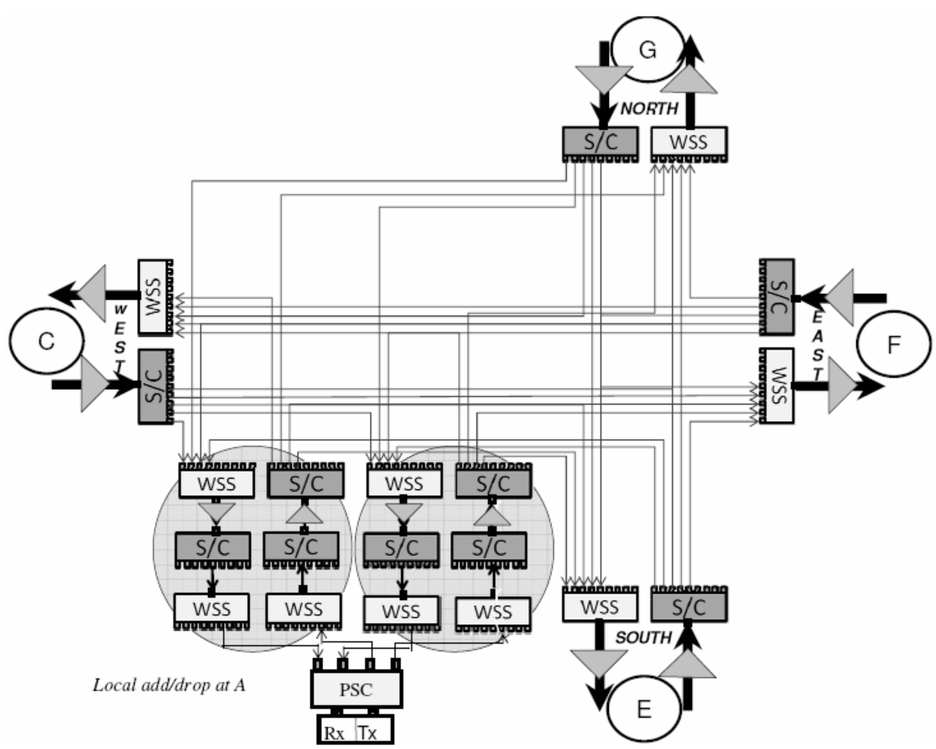

Fig. 2 Colorless and directionless architecture for a 4 degree node

Consider the connection along the west direction at node A. Wavelengths coming from C encounter a splitter that provides a 1:8 power-spilt. Of the eight ports in the splitter, three are connected to the WSSs along the other three directions, two are connected to the two WSSs that are local to node A, and the rest are for scaling in the future. Therefore, the wavelengths entering A from C can be routed in any direction, while making all of them available at the local drop of node A too. Similarly, the WSSs along the east, north, south directions and the two local add combiners are connected to the S/C along the west direction, providing a path to C from all directions. Thus every direction is connected to every other direction creating the possibility of routing a certain wavelength in any given direction. The colorless drop feature is realised as follows. At the local drop site, the WSS that is connected to the splitters in different directions consolidates the wavelengths. Subsequently, another WSS can provide a colorless drop to its ports. Since the number of wavelengths to be received could exceed the number of ports available on the WSS, an expansion facility is provided using a splitter prior to this WSS, which can have multiple WSSs connected to it. The colorless add feature is realised by using a WSS to consolidate all the wavelengths that originate at A. Since any wavelength can be added at a certain port of the WSS it becomes a colorless add. Next a combiner is present to provide expansion much like that addressed in the drop side. After this a splitter splits it 8 ways providing connections to all the directions. It is to be noted that the protection switch card (PSC) shown in Fig. 2, acts as a splitter on the add side making the same wavelength available at both the mux groups and also acts as a switch on the drop side choosing the same wavelength from one of the demux groups.

Along each direction the wavelengths encounter a WSS, which either blocks or allows a certain wavelength along that direction. Thus a wavelength that originates at A can potentially be sent along any chosen direction, realising a directionless feature. The idea of using the WSS instead of a combiner at the add side is to make available the intelligent functionalities offered by the WSS for all the add wavelengths. In the event of a transient wavelength or power drift in an add channel, the co-propagating channels face adverse effects like severe cross talk or even complete attenuation. Because of the channel specific blocking feature in a WSS, the drifting channel alone can be blocked, whereas the combiner being a passive device cannot provide such functionality.

IV. Advantages of the Colorless and Directionless Architecture

Apart from the valuable features offered by a ROADM based network, we suggest ways to leverage special advantages like dynamic optimization of lightpaths by optical bridge-and-roll, elimination of O-E-O operations and providing alternate paths for protection by having a colorless and directionless architecture in a mesh optical network.

A. Optical bridge-and-roll

Bridge-and-roll of wavelengths is a valuable management tool in a mesh optical network. Using this feature, it is possible for the network operators to perform a hitless reroute of an in-service wavelength to allow for optimization of network resources. When the network scales, newer nodes and thus routes come into existence. Therefore the network operators aspire to move a certain wavelength to its optimal path. To perform the bridge-and-roll of a primary wavelength path, a secondary bridged path is established via the ROADMs between the connection end points. Once the secondary path is established, the roll command is issued, and the connection is switched from the primary to the secondary path. The requirement for switching speeds is specific to the kind of service offered. The colorless and directionless architecture is very valuable in this regard as it permits a dynamic optimization of lightpaths that can be remotely performed in a hitless fashion.

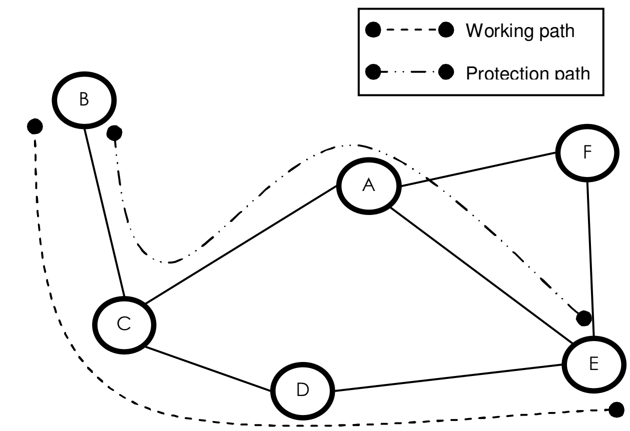

Fig. 3 Phase 1 of a mesh optical network

Consider the network shown in Fig. 3. It is in the first phase of its operation. The working and protection paths between nodes E and B are E-D-C-B and E-A-C-B respectively. Note

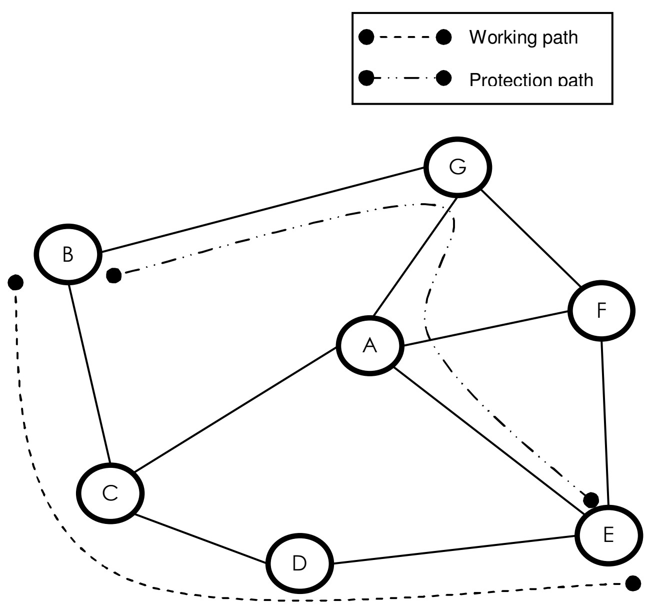

Fig. 4 Phase 2 of a mesh optical network

that both the paths are not entirely diversified as they share the common arm C-B. The second phase of the network is shown in Fig. 4 in which a new node G has come up and the presence of new route G-B calls for the optimization of the link between E and B. The colorless and directionless architecture at A enables a dynamic bridge-and-roll to switch the protection path from E-A-C-B to E-A-G-B. In Phase 1, as shown in Fig. 5(a) the wavelength taking the path E-A-C-B, on entering node A was split and sent to C and F. At A the WSS along F was configured to block it, while the WSS towards C passed it through. On the other hand, when the path is E-A-G-B in Phase 2, the WSSs along F and C are configured to block it, while it is passed through by the WSS facing G, as shown in Fig. 5(b). This diversifies the working and protection paths completely. An alternate protection path can also be E-F-G-B. It is thus evident that a colorless and directionless architecture implemented not just at A but also at E and B enables such a bridge–and-roll. Therefore, it is necessary to have a colorless and directionless architecture at all the nodes in a mesh network to carry out efficient bridge-and-roll operations. A bridge-and-roll also becomes significant when shorter paths for a certain link are available. For example if a route between A and B appears during a later phase of operation, then the communication link E-A-G-B could be rolled over to the shorter path E-A-B.

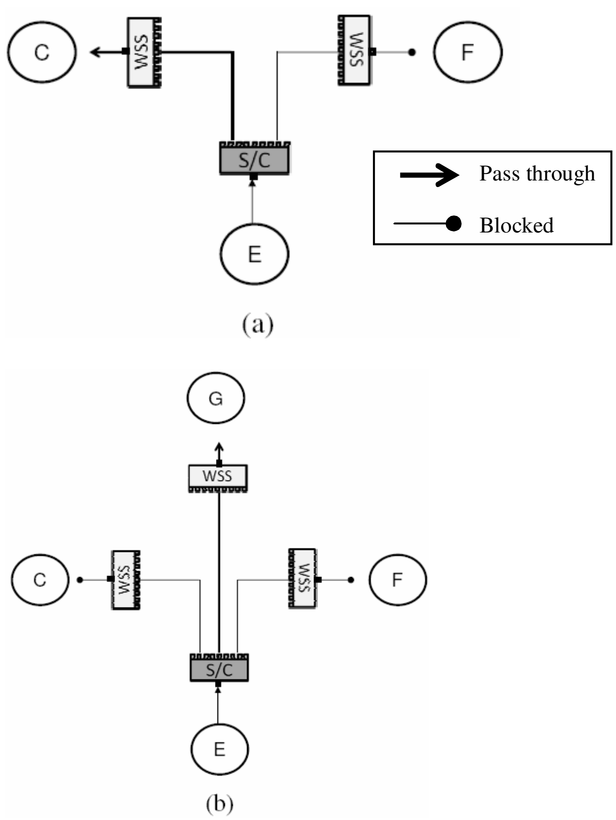

Fig. 5 (a) Phase 1, (b) Phase 2 - operation at node A

B. Elimination of O-E-O

A wavelength conversion is performed in fixed architecture based mesh optical networks when a wavelength contention is to be resolved during ring interconnections. This typically involves an optical-electrical-optical (O-E-O) operation specific for that wavelength. Another situation where an O-E-O operation is carried out is when two optical network domains are to be interconnected. Evidently, this means the cost of the nodal architecture increases due to additional transponders involved in the O-E-O process for such wavelengths [4]. A colorless and directionless nodal architecture enables the routing of any wavelength in any given direction from that node. The necessary power equalization is provided by the WSS. Such features are not present in a fixed or a direction dependent architecture where there is a limitation to the direction in which a certain wavelength can be sent. Consequently, for a given situation the fixed architecture would incur more O-E-O operations compared to the colorless and directionless WSS based ROADM architecture that can transfer the wavelengths all-optically [5], resolving contentions and performing power equalization.

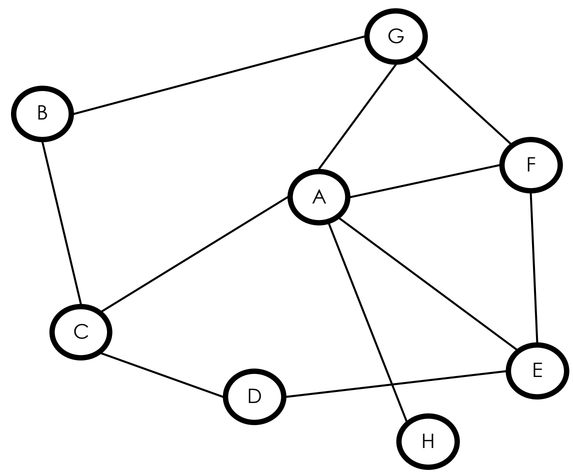

Fig. 6 Phase 3 of a mesh optical network

Consider the 3rd phase of operation of the mesh optical network shown in Fig. 6. Node H has been added, resulting in an extra route between A and H. Consequently, node A has become a 5 degree node. A wavelength contention occurs when a service at a wavelength λ is to be set up between H and G via A, while a service at the same wavelength already exists between E and G via A.

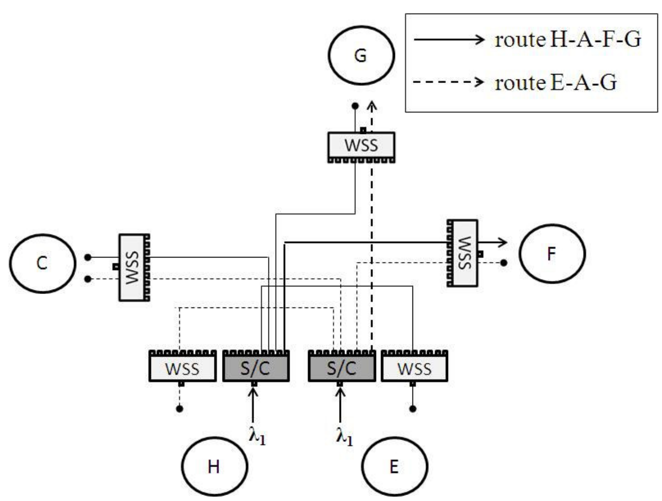

Fig. 7 Routing at node A

In a fixed architecture, a wavelength conversion would be required at node A for the service from H to G in order to resolve the contention. This is because of the limitation in the fixed architecture that a certain wavelength can be sent only in a particular direction fixed at the time of designing the network. In contrast, a colorless and directionless architecture can route the service from H to G as H-A-F-G, thus eliminating the need for an O-E-O operation. At node A this service is blocked in all directions except F. This is shown in Fig. 7. Travelling further, at node F it is passed on to G and blocked along E by the respective WSSs in those directions. It is also important to note that these two services at the same wavelength are to be resolved at node G. But since there are two sets of WSS drop modules present at the local site of G, the two services could be received independently. This is shown in Fig. 8.

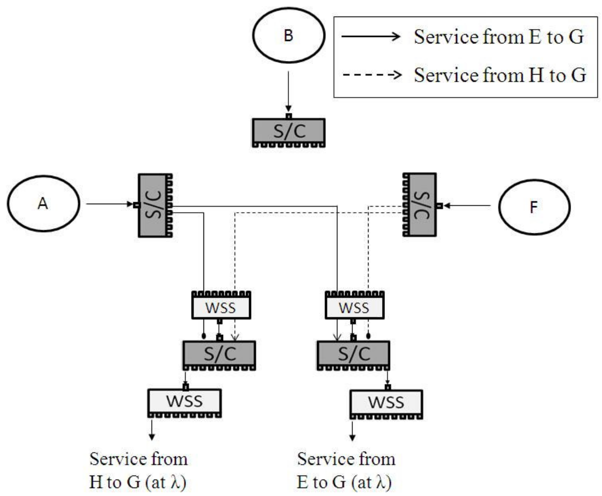

Fig. 8 Drop side at node G

C. *Alternate paths for protection*

Extensive protection mechanisms are available in the SONET/SDH and IP layers [6]. Of the many optical protection schemes 1+1 protection scheme and the MPLS fast re-route are the most common. In a colorless and directionless architecture a wavelength originating at certain node can be sent in any desired direction and can be received from any direction at the destination node. Consider a wavelength originating at A and destined for G in the network shown in Fig. 6. The protection path can be chosen as A-F-G while the working path remains as A-G. At A the wavelength is allowed to pass through in directions along G and F and blocked along C and E by the respective WSSs. At G the wavelength is received from both directions along A and F. It is to be noted that the protection and working paths are not necessarily static and can be changed dynamically as required in the event of any link failure.

V. SCALABILITY

Scalability refers to carrying increasing amounts of data and service flexibly while minimizing the operational complexity. The metro core backbone is becoming more diverse geographically and it needs to support a large volume of bandwidth. Many of the new services in residential, industrial and scientific sectors like Video on demand (VoD), IPTV, voice over IP (VoIP), distance learning, e-commerce, e-health, IP virtual private networks (VPN) etc. are very difficult to forecast in terms of bandwidth requirements and traffic routing patterns. As a result, traffic patterns are becoming diversified and unpredictable, thus creating a new operational challenge for service providers to effectively forecast bandwidth requirements at the numerous sites spread across the network. Alternatively, providing high bandwidth connectivity (e.g. a wavelength) to every single site requires a major capital investment and results in a significant increase in network complexity. Therefore, service providers are looking for a flexible and cost-effective solution to dynamically provide 'on the fly' high bandwidth connectivity to any network site without interrupting the existing services or re-engineering the network. In other words it means scaling the network as and when required. A colorless and directionless network architecture is truly scalable in this regard. In this paper, the issue of scalability is addressed with respect to increase in the number of wavelengths and route degree.

A. *Scalability as the number of wavelengths increases*

As shown in Fig. 2, the local site of node A has 1x9 WSSs that provide a colorless add/drop for 9 wavelengths at the most. As the mesh network scales, the number of wavelengths handled by A may increase considerably. This issue is addressed by having a 1:8 splitter-combiner before the drop WSS and after the add WSS giving a flexibility to handle a maximum of 72 wavelengths on the drop and add sides. While a 1x9 WSS handles 72 wavelengths, a 1x5 only 40, and with the emergence of a 1x20 WSS 160 wavelengths can be handled.

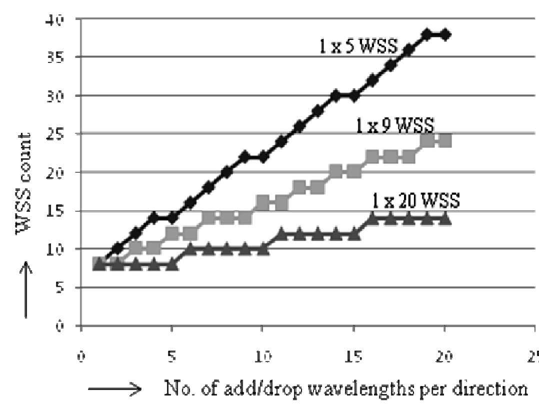

Fig. 9 WSS count for a 4 degree node

As shown in Fig. 9, lesser number of higher port count WSSs are required compared to lower port count WSSs as the number of wavelengths per direction increases. Therefore, a higher port count WSS can address scalability more efficiently.

B. *Scalability as the route degree increases*

In the third phase of operation of the mesh optical network shown in Fig. 6, a new route between A and H comes up making A a 5 degree node. The architecture shown in Fig. 2 can seamlessly scale to that in Fig. 10 without disrupting the

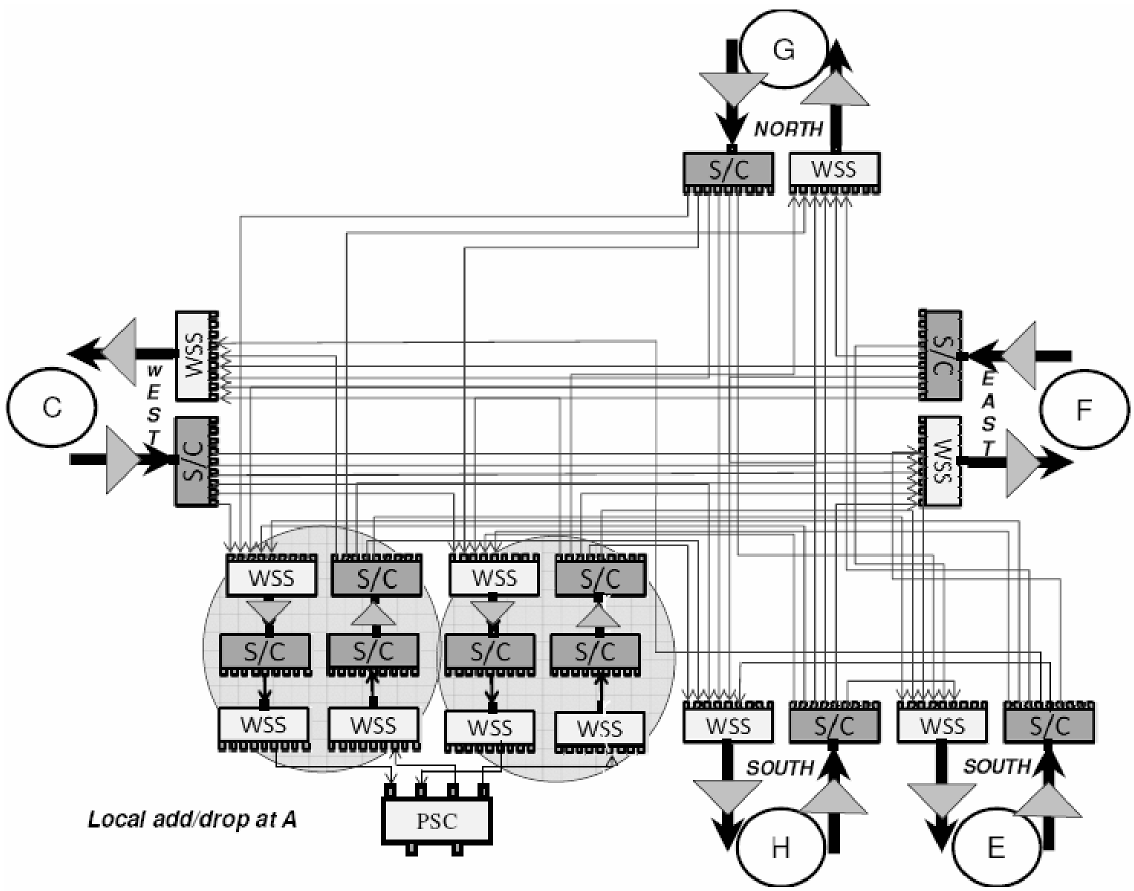

Fig. 10 Colorless and directionless architecture for a 5 degree node

existing services and also handle the new route much like the other routes. This is possible because of the multi-degree support provided by the inline WSSs in each direction.

VI. Practical Implementation Issues

Considering the issues in practically implementing the proposed architecture, a performance analysis is first presented to show that with the proper placement of amplifiers the system can meet the necessary power and OSNR requirements. The proposed architecture is not the only choice for a completely reconfigurable architecture. There are other alternatives with associated pros and cons. One such is presented below. Another major factor that determines the feasibility of implementing any architecture is cost which is also addressed.

A. *Performance analysis*

For the mesh network shown in Fig.1, power budgeting was performed and the OSNR was calculated along the different links. The parameters for the components were based on industry standards. The distances between the nodes were assumed much like in a real metro optical network (<80km). The launch power of a 10Gbps transponder was taken to be 4.5dBm (typical). The lowest the power level can fall to, at the receiver end is -26dBm (APD receivers).

From Fig. 10, it is evident that every channel added from a local node has to pass through a protection switch card (3.5 dB loss while acting as a power splitter on the add direction; 1dB loss when acting as a switch on the drop direction), two WSS cards (4dB loss each) and two 1X8 power splitters (9.7dB loss each) before entering the inline fiber. Even pass-through channels will have to go through a WSS and a power splitter (lumped loss of 12.7dB). The high loss associated with the design thus calls for higher or repeated amplification to sustain the strength of the signal. Consequently, the OSNR of the signal can potentially fall below the required level if the amplifier placement is not done appropriately. In our analysis, 15dB and 10dB amplifiers (with 6dB noise figure) were placed at the necessary points. The power and OSNR variation along one of the paths in the network, A-E-D-C, are shown in Fig. 11 and Fig. 12. By the proper placement of amplifiers the power level could be steadily maintained above the mark of -26dBm, while the OSNR much higher than the minimum requirement of 18dB. The total OSNR for the path was found to be 37.6 dB. In the light of this it is crucial to note that the proposed architecture could also be 40Gbps ready as it can still provide the 6dB higher OSNR margin required for 40Gbps signals [7].

B. *Alternate reconfigurable architecture*

An alternative to this architecture is the all-optical cross

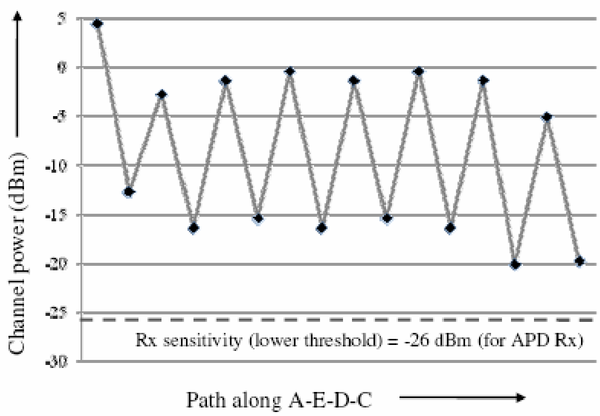

Fig. 11 Power variation along the path A-E-D-C

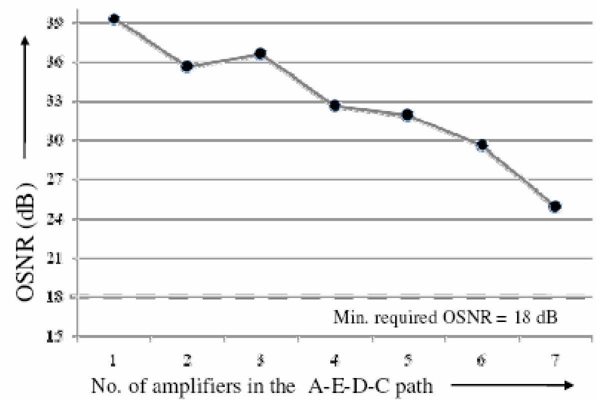

Fig. 12 OSNR values at15dB EDFAs along the path A-E-D-C

connect (OXC) based architecture, realized by using a centralized N X N switching matrix that allows flexible reconfiguration of the connections at the individual wavelength level. The major concern with such switches is that as the number of ports *N* grows, the number of possible connections grows as N^2. Over the years, the MEMS technology has emerged as a major candidate for building high port-count OXC switches suitable for deployment in the core-transport networks [8]. Using the 3D MEMS approach it is possible to realize OXCs with more than 1000 ports [9], [10]. Such MEMS based switching matrix with an insertion loss of 2.1dB on the average, 4dB maximum [11] and connection switching time <10ms [12] are available. Shown in Fig. 13 is a centralized switch matrix. After being demultiplexed any wavelength from any port can be switched to any other port in that core switching matrix. This functionality is very similar to what the WSS based architecture does. Only that the WSS based architecture has directionally independent modules, the OXC a centralized switching fabric, both based on MEMS technology. A major drawback of the MEMS based OXC is that the switching fabric acts as a single point of failure that can bring down the entire node and the routes passing through it, unlike the WSS based architecture where the failure of a WSS will affect the associated route alone. A solution to such a situation is the usage of a secondary switch fabric for protection. The second core can also be used for non-intrusive test access. But that needs a power splitter or a switch on a per port basis to switch between the cores. This is clearly depicted in Fig. 13. Nevertheless, during the failure of a switch matrix another can take over but the failure of a WSS along a certain route calls for a network level protection (like amplifier failure). One major feature provided by the WSS based architecture and not by the OXC solution is that of *multicasting*. From fig .2 it is evident that in the WSS based architecture multicasting a certain wavelength is possible because of the 1 X 8 power splitter feeding the WSSs in all the routes. Since both architectures are MEMS based with multiplexers at the ingress and egress, the nodal cascadability should be comparable.

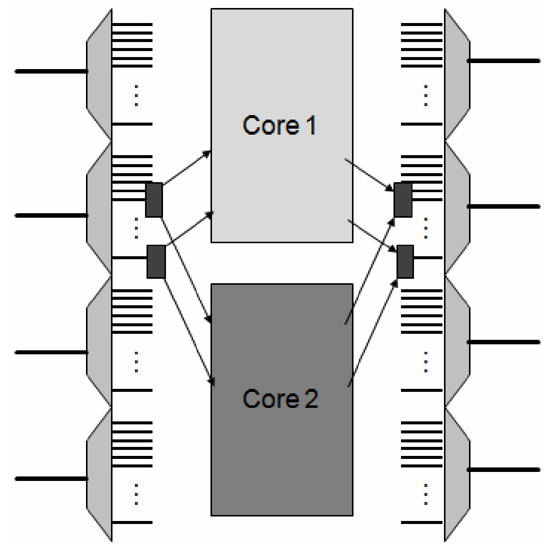

Fig. 13 OXC employed using a centralized switch matrix based on MEMS

C. *Cost consideration*

From Fig. 9 it is clear that the overall cost of the WSS based system depends critically on the number of WSSs and power splitters used. As mentioned earlier, the high loss associated with the cascading WSS and power splitters calls for many amplifiers. This contributes considerably to the overall cost too. Further, the number of individual modules is numerous and thus power consumption, heat dissipation and the space occupied in racks would also indirectly contribute to the cost. Therefore, the proposed reconfigurable WSS based architecture calls for a relatively higher CAPEX compared to a fixed architecture. But the OPEX savings are aplenty. Consider a situation where a lightpath is to be set up between two nodes, say X and Y, with five intermediate hops. In the case of a fixed architecture, truck rolls have to be carried out for every node. Alternately, in the case of a reconfigurable architecture, truck rolls need to be carried out for (at most) X and Y. The cost savings is not only in the form of lower OPEX but is also in the form of the shorter time period to set up the light path. The modularity of the architecture allows carriers to deploy the system in the most cost effective manner possible by initially deploying the minimal amount of equipment that can smoothly evolve to meet the future needs [13]. Traditional networks grow by adding and interconnecting stand-alone line systems, incurring substantial cost and complexity. ROADM based architectures such as the proposed one allow the modular deployment of additional ports and thus the network growth can benefit from both the equipment and operational efficiencies of integrating line systems as they are needed, into a seamless network. This pay-as-you-grow approach not only allows the expense to be spread out over the years, but also enables the network designers to respond to unforeseen traffic growth patterns in an appropriate manner. In addition, the powerful reconfigurable architecture could unlock additional revenue streams for network providers in yet unknown ways. One example in this direction is the provisioning of dynamic wavelength services, in which a customer turns up additional bandwidth on an on demand basis. In conclusion, there is a clear tradeoff between the cost involved and the flexibility provided by the architecture. With the wide spread acceptance of such architecture in building agile optical networks and with technological innovations coming into picture, the volume of production would increase, bringing down the cost involved to a much lower level.

On the other hand, the cost associated with an OXC based architecture is usually specified in terms of cost-per-port. The associated drawbacks from the cost perspective are numerous [14]. Since these massive components must be factory installed and aligned, such a system requires high installation and replacement cost even if only a limited number of ports are needed initially. A rigidly and permanently assembled system eliminates the possibility of component repair or replacement during service. Hence to reduce the chance of a complete switch replacement during service, an overbuilt of the component arrays and associated electronics may be necessary, which may further drive up the cost-per-port. As a solution to these challenges, modular switch architectures have been proposed [14]. In a modular $N X N$ switch architecture, where $2N$ is the total number of ports (input + output), the OXC is composed of several identical switch modules; each comprised of $k(<<N)$ ports.

VII. Conclusions

The suggested implementation of the colorless and directionless architecture enabled by the WSS technology provides valuable features like dynamic optimization of lightpaths by optical bridge-and-roll, elimination of O-E-O operations, alternate paths for protection in a mesh optical network. Moreover, the architecture is truly scalable in terms of handling additional wavelengths and routes efficiently.

Acknowledgments

We would like to thank Prof. Arun Somani and the referees for their insightful comments.

References

[1] Roorda. P, Collings. B, "Evolution to Colorless and Directionless ROADM Architectures," in Optical Fiber communication/National Fiber Optic Engineers Conference, 2008. OFC/NFOEC 2008, 24-28 Feb. 2008 Page(s):1 - 3.

[2] Oktay Gunluk, John. G. Klincewicz, "A design methodology for an optical mesh network," in Proc. SPIE, 2002, Vol. 4865, Page(s):37-46.

[3] Chandra Chekuri, Paul Claisse, René-Jean Essiambre, Steven Fortune, Daniel C. Kilper, Wonsuck Lee, Nachi K. Nithi, Iraj Saniee, Bruce Shepherd, Christopher A. White, Gordon Wilfong, Lisa Zhang, "Design tools for transparent optical networks," in *Bell labs technical journal*, Vol. 11, Issue 2, Papge(s):129-143.

[4] Joseph Berthold, Adel A.M. Saleh, Loudon Blair, Jane M. Simmons, "Optical Networking: Past, Present, Future," *Journal of Lightwave Technology*, Vol. 26, No. 9, May 1, 2008.

[5] *Trends in Dynamic Optical Networks,* Light Reading, November, 2007. http://www.lightreading.com/document.asp?doc_id=133896

[6] R. Ramaswami and K. N. Sivarajan, *Optical Networks: A Practical Perspective,* 2nd ed. San Francisco, CA: Morgan Kaufmann, 2001.

[7] A. Kung, A. Agarwal, S. Banerjee, D.F. Gros, D.N. Maywar, M. Movassaghi, T.H. Wood, "10Gb/s and 40Gb/s ultra-long haul transmission on a common all-Raman single-wide-band platform," ECOC 2002, Vol. 1, Page(s):1 – 2.

[8] L. Y. Lin, E. L. Goldstein, R. W. Tkach, "On the expandability of free-space micromachined optical cross connects," *Journal of Lightwave Technology*, Vol. 18, pp. 482–489, Apr. 2000.

[9] R. Ryf, J. Kim, J. P. Hickey,A. Gnauck, D.W. Carr, F. Pardo, C. A. Bolle, R. E. Frahm, N. R. Basavanhally, C. Yoh, D. A. Ramsey, R. Boie, R. George, J. S. Kraus, C. P. Lichtenwalner, A. R. Papazian, J. V. Gates, H. R. Shea, A. Gasparyan,V. Muratov, J. E. Griffith, J. A. Prybyla, S. Goyal, C. D. White, M. T. Lin, R. Ruel, C. Nijander, S. Arney, D. T. Neilson, D. J. Bishop, P. R. Kolodner, S. Pau, C. J. Nuzman, A.Weiss, B. Kumar, D. F. Lieuwen, V. A. Aksyuk, D. S. Greywall, T. C. Lee, H. T. Soh, W. M. Mansfield, S. Jin,W. Y. Lai, H. A. Huggins, D. L. Barr, R. A. Cirelli, G. R. Bogart, K. Teffeau, R. Vella, H. Mavoori, A. Ramirez, N. A. Ciampa, F. P. Klemens, M. D. Morris, T. Boone, J. Q. Liu, J. M. Rosamilia, and C. R. Giles, "1296-port MEMS transparent optical crossconnect with 2.07 Petabit/s switch capacity," in *Proc. Optical Fiber Communication Conf.*, vol. 4, Mar. 2001, Postdeadline Paper PD28, pp. 1–3.

[10] P. B. Chu, S. S. Lee, and S. Park, "MEMS: the path to large optical crossconnects," *IEEE Commun. Mag.*, vol. 40, pp. 80–87, Mar. 2002.

[11] J. Kim, C.J. Nuzman, B. Kumar, D.F. Lieuwen, J.S. Kraus, A. Weiss, C.P. Lichtenwalner, A.R. Papazian, R.E. Frahm, N.R. Basavanhally, D.A. Ramsey, V.A. Aksyuk, F. Pardo, M.E. Simon, V. Lifton, H.B. Chan; M. Haueis, A. Gasparyan, H.R. Shea, S. Arney, C.A. Bolle, P.R. Kolodner, R. Ryf, D.T. Neilson, J.V. Gates, "1100 × 1100 port MEMS-based optical crossconnect with 4-dB maximum loss," in *IEEE Photon. Technol. Lett.*, Vol. 15, no. 11, Nov. 2003, Page(s):1537 – 1539.

[12] Neilson. D.T., Aksyuk. V.A, Arney. S, Basavanhally. N.R, Bhalla. K.S, Bishop. D.J, Boie. B.A, Bolle. C.A, Gates. J.V, Gottlieb. A.M, Hickey. J.P, Jackman. N.A, Kolodner. P.R, Korotky. S.K, Mikkelsen. B, Pardo. F, Raybon. G, Ruel. R, Scotti. R.E, van Blarcum. T.W, Zhang. L, Giles C.R, "Fully provisioned 112×112 micro-mechanical optical crossconnect with 35.8 Tb/s demonstrated capacity," in OFC 2000, Vol. 4, Page(s):202 – 204.

[13] Ivan. P. Kaminov, Tingye Li, Alan. E. Willner, *Optical Fiber Telecommunications V B: Systems and Networks*, Academic Press, 2008.

[14] J.I. Dadap, P.B. Chu, I. Brener, C. Pu, C.D. Lee, K. Bergman, N. Bonadeo, T. Chau, M. Chou, R. Doran, R. Gibson, R. Harel, J.J. Johnson, S.S. Lee, S. Park, D.R. Peale, R. Rodriguez, D. Tong, M. Tsai, C. Wu, W. Zhong, E.L. Goldstein, L.Y. Lin, J.A. Walker, "Modular MEMS-based optical cross-connect with large port-count," in *IEEE Photon. Technol. Lett.*, Vol. 15, no. 12, Dec. 2003, Page(s):1773 – 1775.